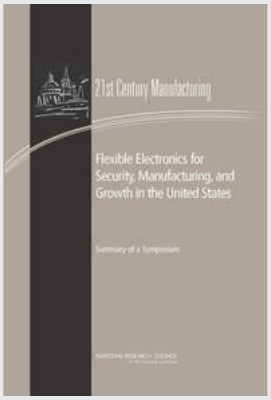

Flexible Electronics for Security, Manufacturing, and Growth in the United States: Summary of a Symposium

DETAILS

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Flexible Electronics for Security, Manufacturing, and Growth in the United States

Summary of a Symposium

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Committee on Best Practice in National Innovation Programs
for Flexible Electronics

Board on Science, Technology, and Economic Policy

Policy and Global Affairs

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For the National Research Council (NRC), this project was overseen by the Board on Science, Technology and Economic Policy (STEP), a standing board of the NRC established by the National Academies of Sciences and Engineering and the Institute of Medicine in 1991. The mandate of the Board on Science, Technology, and Economic Policy is to advise federal, state, and local governments and inform the public about economic and related public policies to promote the creation, diffusion, and application of new scientific and technical knowledge to enhance the productivity and competitiveness of the U.S. economy and foster economic prosperity for all Americans. The STEP Board and its committees marshal research and the expertise of scholars, industrial managers, investors, and former public officials in a wide range of policy areas that affect the speed and direction of scientific and technological change and their contributions to the growth of the U.S. and global economies. Results are communicated through reports, conferences, workshops, briefings, and electronic media subject to the procedures of the National Academies to ensure their authoritativeness, independence, and objectivity. The members of the STEP Board* and the NRC staff are listed below:

*As of August 2013.

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Preface

Flexible electronics refers to technologies that enable flexibility in the manufacturing process as well as flexibility as a characteristic of the final product. Features such as unconventional forms and ease of manufacturability provide important advantages for flexible electronics over conventional electronics built on rigid substrates. Today, examples of flexible electronics technologies are found in flexible flat-panel displays, medical image sensors, photovoltaic sheets, and electronic paper.

According to some industry estimates, the global market for flexible electronics products is expected to grow from a few billion dollars today to $60 billion by the end of the decade, but most experts believe that the United States is not currently poised to capitalize on this opportunity. A recent study commissioned by the National Science Foundation and the Office of Naval Research concluded that "the relatively low prevalence of actual manufacturing and advanced systems research and development in the United States has led to an incomplete hybrid flexible electronics R&D scenario for this country." Furthermore, the report observed that "manufacturing is moving to regions of the world that provide greater investment and commitment to product development. It then becomes questionable as to whether this approach is a healthy one and can be sustained in the long term."[1]

Responding to a congressional request, the National Research Council's Board on Science, Technology, and Economic Policy (STEP) is examining and comparing selected innovation programs, both foreign and domestic, and their potential to advance the production of flexible electronics technology. The analysis includes a review of the role of research consortia around the world to advance flexible electronics technology. It seeks to understand their structure, focus, funding, and likely impact, and to determine what appropriate steps the United States might consider to develop a robust flexible electronics industry.

[1] Ananth Dodabalapur et al., "European Research and Development in Hybrid Flexible Electronics," Baltimore: World Technology Evaluation Center, July 2010.

Statement of Task

An ad hoc committee will examine and compare selected innovation programs, both foreign and domestic, and their potential to advance the production of flexible electronics technology in the United States. The analysis, carried out under the direction of the committee, will include a review of the goals, concept, structure, operation, funding levels, and evaluation of foreign programs similar to major U.S. programs, e.g., innovation awards, science and technology parks, and consortia. To assess these programs, the committee will convene a series of meetings to gather data from responsible officials and program managers and encourage a systematic dissemination of information and analysis as a means of better understanding the transition of flexible electronics research into products and to identify specific recommendations to improve and to develop U.S. programs.

Specifically, the committee will examine the role of research consortia around the world to advance flexible electronics technology, comparing their structure, focus, funding, and likely impact, and determining what appropriate steps the United States might consider to the develop the industry. This review will include the potential of the industry, the possible contributions of a consortium, and other measures contributing to the development of the industry in the United States. The committee will undertake workshops to carry out this analysis, prepare a workshop summary capturing the tacit knowledge expressed, commission additional analyses, and develop findings and recommendations for inclusion in the committee's final consensus report.

THE CONTEXT OF THIS PROJECT

Since 1991, the National Research Council (NRC), under the auspices of the Board on Science, Technology, and Economic Policy, has undertaken a program of activities to improve policy makers' understandings of the interconnections of science, technology, and economic policy and their importance for the American economy and its international competitive position. The Board's activities have corresponded with increased policy recognition of the importance of knowledge and technology to economic growth. New economic growth theory emphasizes the role of technology creation, which is believed to be characterized by significant growth externalities. In addition, many economists have recognized the limitations of traditional trade theory, particularly with respect to the reality of imperfect international competition. Public-private partnerships are increasingly recognized for their contributions to the commercialization of state and national investments in research and development (R&D). Such partnerships help address the challenges associated with the transition of research into products ready for the marketplace.

One important element of NRC analysis has concerned the growth and impact of foreign technology programs. U.S. competitors have launched substantial programs to support new technologies, small firm development, innovative production at large companies, and consortia among large and small firms to strengthen national and regional positions in sectors they consider to be strategic for the development of their economies. Some governments overseas have chosen to provide public support to research and the commercialization of that research to overcome the market imperfections apparent in their national innovation systems. They believe that the rising costs and risks associated with new potentially high-payoff technologies, and the growing global dispersal of technical expertise, underscore the need for national R&D programs to support new and existing high-technology firms within their borders.[2]

THIS REPORT

To launch this study, the STEP Board convened a workshop of business leaders, academic experts, and senior government officials in September 2010 to review challenges, plans, and opportunities for growing a robust flexible electronics industry in the United States. This report includes an introduction that highlights key issues raised at this workshop and a summary of the conference presentations. This workshop summary has been prepared by the workshop rapporteur as a factual summary of what occurred at the workshop. The planning committee's role was limited to planning and convening the workshop. The statements made are those of the rapporteur or individual workshop participants and do not necessarily represent the views of all workshop participants, the planning committee, or the National Academies.

ACKNOWLEDGMENTS

On behalf of the National Academies, we express our appreciation and recognition for the insights, experiences, and perspectives made available by the participants of this meeting. We are indebted to Alan Anderson for summarizing the proceedings of the meeting.

ACKNOWLEDGMENT OF REVIEWERS

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies' Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will

[2]For a comparative review of national policies and programs to advance innovation based competitiveness, see National Research Council, *Rising to the Challenge: U.S. Innovation Policy for the Global Economy*. C. Wessner and A. Wolff, eds, Washington, DC: The National Academies Press, 2012.

assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the process.

We wish to thank the following individuals for their review of this report: Ana Arias, University of California, Berkeley; Miko Cakmak, University of Akron; Pradeep Fulay, West Virginia University; and John West, Kent State University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the content of the report, nor did they see the final draft before its release. Responsibility for the final content of this report rests entirely with the rapporteur and the institution.

Donald Siegel Sujai Shivakumar A. Michael Andrews

I

OVERVIEW

Overview

Flexible electronics describes advances in circuits that can bend and stretch, enabling significant versatility in applications and the prospect of low-cost manufacturing processes. Given this advantage over conventional electronics built on rigid substrates, flexible electronics technologies—including flexible displays, sensors, batteries, and solar panels—have the potential to become highly pervasive.[1] Some industry observers believe that, at current rates, the global market for a range of flexible electronics products can grow from a few billion dollars a year now to $60 billion a year by the end of this decade.[2]

THE FLEXIBLE ELECTRONICS OPPORTUNITY

Although the United States has some very good basic research programs in flexible electronics, a key issue is whether the nation is poised to capitalize on this opportunity to develop a robust manufacturing industry in this emerging technology. A recent report commissioned by the National Science Foundation (NSF) and the Office of Naval Research (ONR) of European programs to promote flexible electronics research and manufacturing took a sober view of U.S. prospects:

> "The relatively low prevalence of actual manufacturing and advanced systems research and development in the United States has led to an incomplete hybrid flexible electronics R&D scenario for this country: it is strong in basic research

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[1]Recognizing its growing potential, a 2003 National Research Council report predicted that "in the future, structural materials will incorporate sensing reporting and even healing functions into the body of the material." See National Research Council, *Materials Science and Technology: Challenges for the Chemical Sciences in the 21st Century*. Washington, DC: The National Academies Press, 2003.

[2]See remarks by Andrew Hannah in the Proceedings chapter of this volume. Estimate of the projected global market vary. Other speakers at the workshop presented different if roughly similar estimates.

> and in innovation but weak in advanced development for manufacturing, mirroring trends in some other sectors as well. Although the United States may be doing what it does best, manufacturing is moving to regions of the world that provide greater investment and commitment to product development. It then becomes questionable as to whether this approach is a healthy one and can be sustained in the long term."[3]

A Lost Opportunity or a New One?

Is flexible electronics a lost opportunity to develop a U.S.-based industry in a major emerging technology, or can the United States take steps to ensure that U.S.-based manufacturers can actively compete in this rapidly developing market? To describe the nature and potential applications of flexible electronics technologies and to document national programs to support the research, development, and commercialization of this emerging technology by leading U.S. competitors, the National Academies convened a conference on "Flexible Electronics for Security, Manufacturing, and Growth in the United States" as a part of its study of "Best Practice in National Innovation Programs for Flexible Electronics."

During the conference, views were sought on steps the United States can take to build manufacturing capabilities and enhance the competitiveness of American firms in this emerging technology.[4] The conference drew together leading figures from the governments, universities, and industry in the United States as well as representatives from Germany, South Korea, and Taiwan. This overview highlights key issues raised during this conference. The proceedings provide a detailed summary of the presentations by the conference participants.

WHAT IS FLEXIBLE ELECTRONICS?

Flexible electronics refers to both products and manufacturing techniques, according to Ross Bringans of the Palo Alto Research Center. In the first category, conference participants cited a number of applications that can take advantage of flexibility.

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[3] Ananth Dodabalapur et al., "European Research and Development in Hybrid Flexible Electronics," World Technology Evaluation Center, July 2010. This report was sponsored by NSF and ONR.

[4] For a comparative review of national programs to foster innovation and manufacturing, and the challenges and opportunities facing the United States in the face of growing global competition, see National Research Council, *Rising to the Challenge: U.S. Innovation Policy for the Global Economy*, C. Wessner and A. Wolff, editors, Washington, DC: The National Academies Press, 2012. Chapter 6 of this report provides an overview of support by leading nations to develop their semiconductor, photovoltaic, advanced batteries, and pharmaceuticals industries.

- **Lighting:** Dr. Bringans described flexible displays and lighting that can be mounted on curved surfaces and can be rolled up to provide more versatility, energy efficiency, and robustness than rigid, flat displays.
- **Displays:** In her presentation, Julie Brown of Universal Display Corporation (UDC) said flexible display technologies could give consumers not only the flexibility and convenience of a newspaper, but also the vivid color and energy efficiency of cell phones. Dr. Brown previewed some of the design concepts being discussed by Nokia, Sony, and other companies that envision flexible displays that will be vivid and efficient, but also thin and rugged.
- **Photovoltaic panels:** Flexible photovoltaic (PV) panels that conform to curved surfaces are another application that offers both practical and aesthetic advantages over heavy and rigid glass-based PV panels.
- **Sensors:** Embedded in medical implants, flexible sensors can offer the benefits of flexibility and biocompatibility. In his conference presentation, Devanand Shenoy noted that the Defense Advanced Projects Research Agency (DARPA) is investigating the use of flexible sensors in clothing and protective gear that can record the cumulative impact of blasts and other impacts on the brain. This application, he added, can also be used to track sport injuries such as those sustained by football players.

The second category of flexible electronics, Dr. Bringans said, concerns the manufacturing process. Describing ongoing efforts to use flexible substrates to develop roll-to-roll manufacturing at Hewlett-Packard (HP), Carl Taussig noted that a key goal was to produce kilometers of material at a time. Dr. Taussig noted that HP is also interested in adapting paper-like displays, using reflected but high-performance lighting displays, and leveraging the developments in organic light-emitting diode (OLED) lighting. “We see that as the first opportunity to get this stuff commercialized,” he said, adding that other groups, including UDC and General Electric, had demonstrated a roll-to-roll process for making white OLEDs. “We’d like to take that white OLED developed by others for a lighting application and turn it into a display,” he said. “The challenge there is whether we can process this material afterward when it is manufactured and laminated to a roll-to-roll backplane.”

> “We like to be able to drop our tablet computers and not have them break, and I think that is going to happen. There are many by-products under development that can benefit from both flexibility and robustness, including RFIDs, photovoltaics, smart labels, lighting, smart phones, and tablets.”
>
> Ross Bringans, Palo Alto Research Center

Key Applications for Flexible Electronics

Dr. Bringans further noted that although flexible electronics will lead to a variety of new technologies—and give rise to interesting business opportunities—in the end, "applications will drive the technology." He noted, however, that consumers are less interested in technology for technology's sake; people want technology to solve their problems. Moreover, these technological solutions, he said, have to come together in a way that is practical for consumers to use. Likewise, Andrew Hannah of Plextronics observed that applications of flexible electronics technologies that appeal to consumers would be needed to "kick-start these industries, which we all believe is going to be very important." The priority, he stressed, must be a focus on the end users.

Speaking at the symposium, John Pellegrino of the Sensors and Electron Devices Directorate of the U.S. Army Research Laboratory noted that the military is seeking to be an early adopter of flexible electronics products. He added that many applications of flexible displays have similar or even identical military and civilian uses. The main difference, he added, is that the military versions may have to be packaged more ruggedly to endure operation in extreme environments, such as higher temperature or lower humidity, with no change in capability. In his conference presentation, Dr. Pellegrino identified key flexible electronics technologies that have dual uses:

- **Sensors:** Having learned to place sensors on airframes and air structures, the aircraft industry is in a position of leadership to adapt flexible sensors for both military and civilian helicopters and fixed-wing aircraft.
- **Displays:** Electronic readers, perhaps resembling a light and flexible iPad^{TM}, would show high-quality graphic images, such as photos and maps, and other information and network with other devices simply and securely. In military applications, such a device could be patched onto a combat uniform, significantly reducing the load that soldiers must carry.
- **Arrays and grids:** Manufactured by a roll-to-roll or hybrid process, flexible solar cells on tents, mess halls, or other structures in the field can generate their own power, reducing the logistical load of transported fuel.

FEDERAL AND STATE INITIATIVES TO SUPPORT FLEXIBLE ELECTRONICS

Given that a robust flexible electronics industry has the potential to improve the nation's international competitiveness, generate high-value employment, and address national needs in areas like defense and energy, a number of federal agencies have supported the research, development, and commercialization of a variety of flexible electronics applications. Representatives from the National Institute of Standards and Technology (NIST), NSF, DARPA, and the Army described their role in advancing flexible electronics technologies at the conference.

The NIST Role

Michael Schen of NIST summarized the many ways NIST can play a positive role in advancing emerging technologies. The process begins with the discovery, or proof of principle, where the NIST laboratories can help. As the technology begins to mature, NIST may become part of a consortium, such as the FlexTech Alliance, that helps to nurture the technology. This can both strengthen leadership of a new firm and clarify the objective of the technology and gaps that must be addressed. NIST can respond to this process both by assisting individual firms and by partnering with groups like the International Electronics Manufacturing Initiative (iNEMI).

As a technology continues to emerge, Dr. Schen said, NIST laboratory programs continue their involvement. He noted that, when funding was available, NIST's Technology Innovation Program had scaled up its competitions for advanced materials competitions in recent years to support the commercialization of flexible electronics. In addition, NIST's Manufacturing Extension Partnership can help facilitate linkages between users and providers of emerging technologies. This program specifically helps to lower business risk and promotes the confidence of small firms as they move forward.

The NSF Role

Pradeep Fulay reviewed the involvement of NSF in supporting flexible electronics research. He said that flexible electronics itself was funded primarily through the Foundation's Division of Electrical, Communications, and Cyber Systems, and that the Small Business Innovation Research (SBIR) program had funded many of the small companies working in the area. NSF also covered many areas of basic research of relevance to flexible electronics, as well as technology transfer and translational research.

He also reported that NSF supports a wide variety of flexible hybrid electronics research, organic and polymer electronics and optoelectronics, inorganic thin-film devices, organic and inorganic hybrid devices, and hybrid circuits and systems. Dr. Fulay noted that a central challenge for each of these areas of research concerned fabrication and manufacturing—how to achieve low-cost, high-throughput, and print compatibility.

Dr. Fulay said that NSF also provides research support and opportunities, including programs that encourage university-industrial partnerships. Depending on definitions, he said, NSF supported about 200 projects in flexible electronics, including work on transistors, OLEDs, zinc oxide, and flexibly printed electronics research. "Typically, these are small, single-investigator projects, though the NSF does support an Engineering Research Center in solid-state lighting and a lot of instrumentation through the Materials Research Initiative. The NSF also encourages strong industrial interaction, including a number of programs directed at SBIR/STTR programs and GOALI programs."

The Army's Support for the Flexible Display Center

Dr. Pellegrino described the Army's sponsorship of the Flexible Display Center (FDC) at Arizona State University as a "nontraditional" kind of partnership, including industry as a full participant with the academic community. This helps to solve the "interstitial" problems between different domains, he said, and allows the partnership to focus on the applications important to the industry, as well as those the Army needs. At the same time, he said, until the industry can move past the fundamental manufacturing challenges, "no single industry is going to be able to jump ahead. This [an organization like the FDC] is just one way of getting some of those common problems solved."

He noted that, while cost is always a consideration, the Army also seeks value. Balancing the cost of products are their potential new uses, and characteristics such as ruggedness and reduced weight. Already, he said, the partnership was seeing the value of creating large-area devices that had relatively high resolution and that could be lifted off and packaged as a flexible organic device.

Dr. Pellegrino said that "in very round numbers" the Army was spending about $2 million a year on the FDC, much of which supported research related to flexible electronics. In addition, several million dollars went into related activities, such as infrastructure, developing tool sets, and early applications of materials devices, an amount that holds relatively steady from year to year. This amount was increased by matching dollars from industry, which, in the case of the FlexTech Alliance, was a 60-40 match.

Targeting Transformative Technologies with DARPA

Dr. Shenoy, then the Program Manager at the Microsystems Technology Office at DARPA, noted that his agency seeks to leverage breakthroughs, not just advance an area of interest. In the area of flexible electronics, the primary opportunity is to manufacture at low cost, moving past the current industrial approach of using foundries and masks, and moving into custom design and rapid prototyping. Whereas conventional processing of electronics can take about six weeks, printing electronics can be done in about six days. "There will be tremendous savings when we are able to print," he said. "But you have to achieve the performance to make this more interesting."

He reviewed some of the most promising and application-rich areas, including thermal applications, portable imaging technologies, and imaging

Box A
An Example of a Government-Industry Partnership Flexible Lighting

In her remarks at the conference, Julie Brown of UDC said that her company's core OLED technology sits on a flexible substrate about 100 microns thick and is rugged enough to absorb hammer blows. Development of the technology began in DARPA and moved into the Army, and UDC had been funded by the Army to build full-color, active-matrix OLED flexible displays. UDC works with L3 Communications and several other partners who were responsible for the backplane and systems integration. She noted that UDC had delivered the first units to the Army in Fort Dix the previous August for field testing, with good early results. "They had all our units laid out on the table with streaming video from the UAV [unmanned aerial vehicle] above the tent," Dr. Brown said. "So we have flexible electronic technology now being fed into the military."

sensors integrated with amplifying circuitry. In the last area, he said neither the sensors nor the amplifiers were yet good enough, and DARPA was working to address those challenges. Like Dr. Pellegrino, he emphasized the promise of physiological monitoring for warfighters, in which sensors could continuously monitor vital signs; he also mentioned structural prognostics using sensors on platforms to monitor wear and tear on systems continuously.

Responding to a query on the scale of DARPA's investments, Dr. Shenoy said that the size of any program would depend on the objective. As an example, the Micro-Systems Technology Office may invest "something like $10 million per program per year." A curved focal plane program he was managing received $25 million for four to five years. The work of his office was also accompanied by other related programs, such as the flexible electronics program recently initiated by the Defense Sciences Office.

A State's Effort: Building a Flexible Electronics Custer in Ohio

Byron Clayton of the Northeast Ohio Technology Coalition (NorTech) noted that his organization is spearheading efforts to create a new cluster in flexible electronics in Northeast Ohio.[5] Dr. Clayton said that NorTech's efforts are supported by a number of broader state initiatives to encourage technology-based growth. Key among these initiatives is the Ohio Third Frontier program, which invests $2.3 billion to support applied research, commercialization,

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[5]For an extended review of public, private, and university-based initiatives under way in Ohio to grow a flexible electronics cluster, see National Research Council, *Building the Ohio Innovation Economy: Summary of a Symposium*, C. Wessner, Rapporteur, Washington, DC: The National Academies Press, 2013, pp. 117-128.

entrepreneurial assistance, early-stage capital, and worker training in the state. For example, the state's Edison Technology Centers are designed to help existing businesses commercialize their products and expand, while the Ohio Venture Capital Fund provides funding to firms that channel at least 50 percent of their investments into technology firms in Ohio.

Dr. Clayton noted that a key factor in successfully building an innovation cluster was to develop a shared agenda among cluster members that included pursuit of not only state funding, but also federal and private funding. A second point was to connect competencies across the state. Talent and resources across northeastern and northwestern regions of Ohio are now being connected with a near-term focus to develop a more widely shared agenda among a greater number of participants. A final point was to encourage the state to provide funding for market pull.

He said that Ohio had seven programs specifically designed to foster cluster development but had not yet supported one for flexible electronics. Even without that support, he said, a flexible electronics cluster emerged on its own. "That shows the power of what can happen as an industry emerges," he said. He estimated that although flexible electronics was relatively new to Ohio as an area of investment, about $8 million has already been invested in the field since 2008, with an additional investment expected from the Ohio Third Frontier program.

EUROPEAN AND ASIAN INITIATIVES FOR FLEXIBLE ELECTRONICS

Seeking to capture the global market opportunity in flexible electronics, major U.S. competitors have initiated large and dedicated programs, supported with significant funding. The conference included representatives of research efforts from Germany, South Korea, and Taiwan who described their nations' initiatives to develop and commercialize flexible electronics technologies.

German Initiatives to Support Flexible Electronics

In his presentation, Christian May of the Fraunhofer Institute for Photonic Microsystems in Dresden provided an overview of German strengths in the development and commercialization of flexible electronics. Germany's advantages, he said, include strong research and development programs in OLEDs, printed radio-frequency identifications (RFIDs), and transistors; a very good supply chain, especially in materials and production machinery; and the draw of the large European market. He cited, on the other hand, a notable lack of startups and entrepreneurs "with a clear view from research to manufacturing."

Turning to the organic electronics situation in Germany, he noted the major role of government support in the development of flexible electronics technologies, beginning with the German Federal Ministry of Education and

Research, which over 10 years has provided about €30 million in funding for organic electronics research. Dr. May also described several key instruments to fund the development and commercialization of flexible electronics in Germany.

- **OLED Alliance:** Started in 2006, this alliance is focused on flexible lighting applications. The three large private partners were the dominant German lighting companies—Osram and Philips, and Applied Materials. The OLED Alliance has received €120 million from the government, with industry commitments to invest five times that amount, i.e., about 700 million euros.
- **Innovation Alliance OPV**: Started in 2008 to develop organic photovoltaics (OPV), this alliance has received €60 million in funding and uses the same basic partnership model as the OLED Alliance.
- **Clusters of Excellence:** Candidates have been invited to compete for nomination as Clusters of Excellence, where each cluster would consist of a consortium of universities, research and development (R&D) organizations linked to universities, and companies. Dr. May noted that a cluster in Dresden had been selected to work on silicon-based, high-efficiency devices for computing. A second cluster in Heidelberg was designed to emphasize organic electronics, for which it received €40 million in funding, matched by industry contributions, for the period 2008-2013.
- **The Fraunhofer Institute for Photonic Microsystem (IPMS):** A part of the Fraunhofer network, this institute is funded by several levels of government: the German federal government, the local government of the Free State of Saxony, and the European Commission. Led by Dr. Hubert Lakner and Dr. Karl Leo, IPMS has a permanent staff of 207, with a budget of €23 million. Dr. May noted that IPMS has a large number of research and industrial partners, both in Dresden and in the surrounding area. This network consists of collaborators who support the "full value chain" of activities "from materials and modeling to organic technology to tools to products."

Taiwanese Initiatives to Support Flexible Electronics

In his conference presentation, Janglin Chen of the Taiwan Display Technology Center began by observing that the R&D effort in Taiwan is primarily driven by the national government through the Ministry of Economic Affairs. ITRI, a not-for-profit organization, plays the leading role in identifying and developing promising new technologies, along with the major research universities. "At a certain point in technology development," he said, "they invite industry to participate and invest, and then the government will come in with matching funds. That's how the industry is gradually built up."

Box B
Germany's Fraunhofer-Gesellschaft

Fraunhofer-Gesellschaft is widely seen as a major factor behind Germany's continued export success in advanced industries. Established in 1949 as part of the effort to rebuild Germany's research infrastructure,[a] the nonprofit organization is one of the world's largest and most successful applied technology agencies. Fraunhofer's 80 research institutes and centers in Germany and around the world employ some 18,000 people—4,000 of them with Ph.D.s and master's degrees—and operate under an annual budget of €2 billion in 2012. Fraunhofer engineers develop intellectual property on a contract basis, hone product prototypes and industrial processes, and work with manufacturers on the factory floor to help implement new production methods.

One-third of Fraunhofer's funding consists of core money provided by the German federal and state governments, roughly another third comes from research contracts with government entities, and a final third is provided through research contracts with the private sector, which are frequently supported by government grants and other financial assistance. While some studies suggest that well over 80 percent of funding comes from taxpayers,[b] as Dr. May noted, the institutes' direct contracts with industry demonstrates the attractiveness of the work they are doing is for industry, "which is to bridge the gap between basic research and the work done by industry."

[a]For a history of the organization, see *60 Years of Fraunhofer-Gesellschaft*, Munich: Fraunhofer-Gasellschaft, 2009. The publication can be accessed at *<http://www.germaninnovation.org/shared/content/documents/60YearsofFraunhoferGesellschaft.pdf>*.
[b]House of Commons Science and Technology Committee, *Technology and Innovation Centres*. Second Report of Session 2010-11, Volume I, Report, p. 27.

Dr. Chen said that flexible electronics was formally emphasized in Taiwan beginning in 2006. In the five years since then, the Taiwanese government has invested close to $200 million in this technology. "So the government is really behind the whole incentive," he said. "We believe this is the first significant opportunity in flexible electronics. Basically, our strategy focuses on two main themes that have to do with lifestyle. One is the mobile lifestyle, and the other is green energy-saving display."

These large investments help Taiwanese firms become more internationally competitive in emerging technologies. Dr. Chen observed that the recent financial crisis, which had put great pressure on some innovative but small Western companies to seek additional funding or even buyouts, was seen as an opportunity for Taiwan. The best-known example was the absorption of E Ink into the large Taiwanese firm PVI, the combination that is now known as E Ink Holdings, Inc. E Ink Holdings now supplies e-paper modules to Amazon, Sony, Barnes & Noble, and many other firms. In another case, the giant Taiwanese firm AU Optronics Corp bought another American company called SiPix that had developed a microscale e-paper that is imprinted with minute holders for nanoquantities of fluid or particles and can be produced in sheets by roll-to-roll technology. In summary, he said, "one firms' demise happened to be the other firm's fortune." As a result, much of the world's e-reader technology is now concentrated in Taiwan.

Korean Initiatives to Support Flexible Electronics

In his presentation, Changhee Lee of Seoul National University noted that Korea is very active in developing printing technology for displays, especially large-area, low-cost eco-displays, and flexible displays. In commercializing these technologies, Korea could draw on its strong supply chains and the manufacturing and marketing strengths of leading companies like Samsung and LG.

Dr. Lee provided a detailed map of clusters of Korean universities, research institutes, and corporations that are working cooperatively to advance a variety of flexible electronics technologies.

- Daejeon City is home to the Electronics Telecommunications Research Center (ETRI). One of the largest such centers in Korea, ETRI focuses on flex and OLED lighting. Also located there is the Korean Research Institute of Chemical Technology, which conducts research on printing technologies; the Korean Institute in Machinery and Mechanics, for research on printing machines and technology; and the Korean Advanced Institute for Science and Technology, a largely theoretical research institute.
- Jeonju City hosts a branch of KETI, and the Korean Printed Electronics Center. The Ministry of the Knowledge Economy provided $70 million from 2004 to 2009 in support for the center, with the local government contributing as well. In all, some 59 universities, small companies, and other participating organizations collaborate at the center.
- Sunchon City is home to a Regional Innovation Center (RIC) and a leading university program that is supported by the Ministry of Education, Science, and Technology. Sunchon National University has a printed electronics department with both undergraduate and graduate students that is "quite unique," he said.
- Pohang City is home to the premier Korean research facility for nanotechnology, the Pohang Science and Technology University, a small research university and cluster.
- Suwon City is home to Samsung, one of the major technology companies in Korea investing in flexible electronics, Samsung

maintains most of its facilities at a large complex in Kiheung, including Samsung Electronics (R&D on semiconductors, liquid-crystal displays [LCDs], and Si-solar cells) and Samsung SMD (OLED R&D).

- Kumi City and Paju City are home to LG Display. Dr. Lee said that LG intends to invest more than $1 billion in 2010 and 2011 to develop and commercialize OLED products.
- Sunchon City is home to several small companies that make roll-to-roll RFIDs.

Dr. Lee highlighted the important role that the Korean Display Industry Association and the Korea Printed Electronics Association are playing in moving the industry forward, saying they have "allowed the display industry to become strong." In addition, the government helped by asking industry (especially Samsung and LG) to support the Korean research institutes, while investing about $5 million per year in public funds. The industry associations have also urged Samsung and LG to start developing facilities to produce large-area OLEDs, which the country did not yet have. Dr. Lee noted that each company is forming a consortium to develop this technology and will compete for a contract to develop it.

BUILDING A GLOBALLY COMPETITIVE FLEXIBLE ELECTRONICS INDUSTRY IN THE UNITED STATES

With the potential to revolutionize electronics, flexible electronics is expected to be a destabilizing technology. Furthermore, as Malcolm Thompson of RPO Inc. observed, the industry is moving along a rapid growth path similar to those of semiconductors in the 1990s, and then flat-panel displays of the 2000s. While acknowledging the inherent limitations of predicting the future, he cautioned that the potential of this market is such that the United States should not neglect to develop a strong domestic flexible electronics industry.

Seeking to capture global markets, governments in Europe and East Asia are making substantial investments in the development and commercialization of flexible electronics technologies with funding levels that dwarf U.S. investments. One point of comparison is the nearly $720 million in funding commitments by the European Union and various European national

> Where will the leaders of this new technology be? "In Asia, the U.S., Europe, or some mixture?"
>
> Ross Bringans

governments for the period 2001-2013 vis-à-vis the U.S. government commitment of $327 million over the same period.[6]

"Invented Here; Manufactured There?"

Sridhar Kota, then of the White House Office of Science and Technology Policy, cited in his keynote remarks the benefits to consumers of low-cost flexible electronics applications—from smart phones and sensors to monitor health, to smart bandages and batteries. "This is all exciting stuff," he said. "Hopefully we still have an opportunity to manufacture them here, in the U.S., so we can reap the benefits of our investments in basic research."

Dr. Kota cautioned that domestic investments in flexible electronics research and development do not automatically translate into a competitive advantage for the United States. Given the significant investments being made in Europe and Asia in applications for flexible electronics, he warned, there could be a repeat of "things invented here but manufactured elsewhere; industries we have already lost, and others that are at risk." Citing research by Gary Pisano and Willy Shih, he cited a partial list of technologies that have already been lost to manufacturers abroad. This list includes, he said, "fabless" chips, compact fluorescent bulbs, LCDs for monitors, TVs, and mobile phones; lithium-ion, lithium polymer, and nickel–metal hydride (NiMH) batteries for cell phones, portable consumer electronics, laptops, and power tools; crystalline and polycrystalline silicon solar cells; desktop, notebook, and netbook PCs; low-end servers; hard disk drives; consumer-networking gear such as routers, access points, and home set-top boxes; advanced composites used in sporting goods and other consumer gear; advanced ceramics; and integrated circuit packaging."[7]

The Future of Customizable Manufacturing

Contrasting the case of the LCD platform display industry, which moved to the Far East "because a lot of the drivers and backplane technology required to manufacture the devices were there," Mr. Hannah said that the flexible electronics would have "a much simplified device structure" and could be manufactured and distributed locally in the United States. This would bring an advantage in transportation and lower overall costs of ownership. "I think a new model can exist, especially when there's not a lot of low-cost labor associated with the manufacturing process. I think you can build that industry in the U.S. and you can keep it here."

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[6]FlexTech Alliance, "Flexible Electronics: Government Investment and R&D Programs in the U.S. and the European Union," November 2008.

[7]Gary Pisano and Willy Shih, "Restoring American Competitiveness," *Harvard Business Review* July-August, 2009.

In his remarks, Malcolm Thompson noted that "manufacturing is going to be customizable, and diversified products are going to be manufactured closer to the end user." He offered the "simplistic" example of printing, which 20 or 30 years ago would be done at a print shop, which "manufactured" the print for the customer. Today, he said, we each have a printer in our home, which means that each person is the manufacturer of printed documents. He said that the new paradigm would feature much smaller manufacturing facilities located much closer to the point of use. Most importantly, he said, "you're going to turn around a product very quickly, in a matter of a few days. I think that's a really important difference." Other future electronics opportunities, he said, would emerge in the category of flexible and potentially printed electronics at human scales. These were likely to include conformable and portable photovoltaics, wearable health monitors, sensors, and flexible displays and e-books.

Reflecting on the potential implications, Mr. Hannah noted that Europe seems to be betting on this outcome in its efforts to bring the manufacturing base back to Europe. "That's why all these initiatives are happening in the U.K. and Germany, for example. They want the next-generation manufacturing industry to happen in their back yard. We should be feeling the same."

Growing the U.S. Flexible Electronics Industry

In his presentation, Mr. Hannah noted that establishing state-of-the-art manufacturing in the United States requires advances in the manufacturing process, including testing, validating, and improving technology through prototypes and demonstrators. To do this, he said, firms in the industry need to share infrastructure, especially for the prototyping stage of development. This, in turn, requires effective government-industry collaboration.

Describing the scenario for the flexible display and lighting industry, Julie Brown suggested that developing a significant flexible OLED lighting industry in the United States would need incentives to bridge the gap between prototyping and marketing. OLED lights were not likely to be launched at a price of $20 or $30, but at $2 or $3. Arriving at lower prices would require both incentives and collaboration between the Department of Energy and potential users. She urged more collaboration between "good work being done in the Department of Energy and various partners, especially U.S. infrastructure companies, universities, and government agencies." A goal of such partnerships, she said, is to view OLED lighting as an overall system. For flexible displays, she suggested that mandating both efficient lighting and wall plug applications, such as television monitors, would inspire new applications and advance the industry.

The Role for Industry Consortia

In his conference remarks, Dr. Thompson said that, given that materials, equipment, and processes cut across many research areas, which are beyond the reach of any single company, a consortium would allow collaboration to overcome challenges that are common to all sectors and companies. For example, all of them need expensive, precompetitive research that reaches across applications and is capable of broad adoption. “What the consortium essentially does is to make sure the picture is complete and allow identification of technology gaps.” This can be done through roadmapping and by ensuring that everybody is working together in a coordinated way, while avoiding having too many people working on the same thing.

The Importance of Roadmaps

In his conference remarks, Dan Gamota noted that iNEMI has developed three iterations of a flexible electronics roadmap, “each one lasting two years.” One purpose of the roadmap was to stimulate standards. It also provided the members who were entrepreneurs an opportunity to see the most significant “gaps and needs” of the industry. With this perspective of the supply-chain landscape from customers, competitors, and suppliers, firms had a better chance of producing a product that could meet real needs and generate significant markets. Some of those needs, such as high-performance materials, had begun to emerge at the very beginning of the roadmapping process.

Dr. Gamota noted that the iNEMI roadmap is similar to the International Technology Roadmap of Semiconductors created by SEMATECH, which served as a model. It contains a situation analysis of technology and product, such as substrates and their quantified key needs, gaps, and “showstoppers.” The roadmap goes on to give physical tables listing the attributes today, those that are midterm goals five years from now, and those that are goals 10 years from now.

Need for an Industry Champion

Among the objectives of a consortium, Dr. Thompson said, is to provide leadership, synergy, and collaboration. It must also address dual-use requirements and create an IP policy that encourages innovation and commercialization. It must focus on U.S.-based companies and the creation of state-of-the-art manufacturing jobs. He emphasized that manufacturing is no longer a dirty industry, but a job that requires much more training, intelligence, focus, and fast turnaround. Creating such an organization, he emphasized, requires a champion, and the consortium itself must be one “that we can trust, because that’s what we need.”

Partnering with Government

One reason to support a consortium, Dr. Thompson said, was that the interests of the electronics industry and government are intertwined. For example, defense and homeland security are dependent on the leadership of the

U.S. electronics industry. Another is the realization that the electronics industry has the potential for powerful job creation. He said that the U.S. Display Consortium and its successor, the FlexTech Alliance, had done well in coordinating the interests of the government and the industry.

Strengthening the Supply Chain

Dr. Thompson said that he believed that a national consortium could have a catalytic impact on flexible electronics industries. A primary task, he said, would be to oversee the development of the supply chain, which would be very complex and dynamic. He also suggested sponsorship of academic and industry R&D, a traditional strength, to maintain a flow of new manufacturing materials and equipment.

A Network of Facilities

In his Roundtable remarks, Ananth Dodabalapur of the University of Texas at Austin said that he wanted to recommend a closer look at what he termed the "successful" model of NSF-sponsored National Nanofabrication Infrastructure Network (NNIN) to support the development of flexible electronics technologies. This program was started in the days of the semiconductors and expanded with the advent of nanoelectronics and was still "very functional."

He said that the NNIN model was based on a network of host universities throughout the country. Each host university maintains a set of fabrication equipment, which was used by students and postdocs of that university, as well as by startup companies and larger companies that pay a certain fee. He said that one such facility, focusing on conventional microelectronics, was located in Texas. Many startups, including one or two that he had created, benefited from the infrastructure. "So it's an equal-access system where I see a lot of value and a lot of creative intellectual property generated—not just by university researchers, but also by startup people."

Dr. Dodabalapur proposed the creation of a similar network of infrastructure facilities for flexible electronics, "some kind of national flexible electronics research infrastructure network to be used by university researchers and industry, which includes both startup companies as well as larger companies." He noted that something similar already functioned well in Arizona, facilitating interactions. "I think that could be a powerful way of keeping our innovation engine running smoothly, and also helping to make the important transition to commercialization."

THE TASK AHEAD

Michael Andrews acknowledged the "great debates" in the United States about how best to sustain domestic manufacturing and economic growth.

"Many other nations don't have such debates," he said, "they just go do it. Our challenge is how we can better do these things, which is always tough. We've invested reasonably well in the basic research, and in some of the applied technology areas. It's time to hit harder on developing prototypes and demonstrations, and in advancing the technology to the next level of manufacturing."

Based on this workshop and additional reports and deliberations, he said, the Board on Science, Technology, and Economic Policy panel on Best Practice in National Programs for Flexible Electronics would develop recommendations on these questions to the nation. It would be looking in particular at better models for collaboration and community to develop the technologies, which were both "very difficult." He said that the virtue of collaboration was that it could make "one plus one equal three," but the hard question was how to apply the best balance of incentives to make this happen.

II

PROCEEDINGS

Welcome

Charles Wessner
The National Academies

Dr. Wessner welcomed the participants, offering a brief review of the National Academies. The original National Academy of Sciences, he said, was founded during the Civil War when there was an effort to draw on new science and technology emerging from the industrial revolution and to apply them to the challenges of sustaining and developing the Union. The force of conflict again played a role when the National Research Council was founded in 1916 as the operating arm of the National Academy of Sciences. The growing relationships between science and other disciplines underlay the major additions of the National Academy of Engineering, in 1964, and the Institute of Medicine, in 1970. An emphasis on the increasing interdisciplinarity of the sciences, including the social sciences, continues under the current format of the National Academies.

The creation of the Board on Science, Technology and Economic Policy (STEP) in the early 1990s was an additional effort by the Academies to reach across disciplines by recognizing the central role of economic activity in formulating science policy. The mission of STEP, said Dr. Wessner, is to better integrate scientific and economic understandings of innovation and competitiveness in order to formulate more effective national policies for the federal government.

The United States has a distinguished history of scientific innovation and science-based economic power, he continued, but the connection between those two processes has frayed over the past few decades. The U.S. economy, he said, risks coming to resemble that of Great Britain during the 1950s and 1960s, when British innovators created new products and American manufacturers produced them and reaped the profits. In the same way, other nations have learned to manufacture and profit from American inventions, while American firms have been slower to take advantage. “We’re happy that other countries are progressing up the value chain,” he said, “but many of us think it’s important for the United States to have a place on that chain as well.”

Dr. Wessner said that the mandate of the STEP board is to address the need to connect science-based innovation with success in the marketplace. This mandate is expressed in two steps:

- Integrating understanding of scientific, technological, and economic elements; and
- Formulating national policies affecting the economic well-being of the United States.

One objective of today's policies, he said, was to integrate the elements of competition and cooperation. "The world is a very competitive place," he said, "but it's also increasingly important to address large challenges by cooperating with other nations. The efforts to address climate change and environmental security simply cannot happen through the actions of any one nation. In the same way, even though the semiconductor industry is a global industry, it is very important that the U.S. remain a major nodule in the innovation and production system."

In response to this new reality, the STEP board has undertaken studies attempting to identify the best ways to accelerate innovation, advance competitiveness, and improve our understanding of the nation's economy performance and other nations' policies and practices. "Our board is trying," he said, "to help improve our understanding of where we are, where we've been, and, ideally, where we're going."

A GLOBAL INNOVATION IMPERATIVE

Dr. Wessner said that an emphasis of the STEP program on technology innovation and entrepreneurship is defined as "the innovation imperative." While this imperative is not unfamiliar in the United States, it was being adopted with greater energy by other countries, which have "enormous interest" in learning about innovation policies in the United States. At home, he said, Americans tend to assume that innovation is necessary to maintain our position of leadership in the world, and yet our budgets, investments in education, and mechanisms to move applied research into the marketplace do not clearly reflect that imperative.

A second theme of the global innovation imperative, he said, was the importance of collaboration among small and large businesses and universities. This, he said, is essential if the nation is to capitalize on its considerable investments in education and research. And here lies a role for the federal government, which is positioned to facilitate collaborative activities. He said that one of the most important results of the last 15 years of analysis by the STEP board had been the demonstration that even modest investments by the federal government, especially those used to empower small businesses, can have a disproportionate impact in bringing together partners from different parts of the economy. Proven tools for making such partnerships productive, he said, were incentives that motivate faculty in the direction of collaborative research and support for public-private partnerships that support and advance new ideas toward commercialization.

STEP STUDIES ON INNOVATION

This work by the STEP board, he said, had been championed by experts on different aspects of global innovation. Gordon Moore, Chairman emeritus of Intel, had led a program-based analysis of U.S. government-industry partnerships that focused on (1) the drivers of cooperation among industry, government, and universities; (2) operational assessments of current programs; and (3) the changing role of government laboratories, universities, and other research organizations. One outcome of the study was catalyzing new science and technology parks at NASA's Ames Research Center, in Mountain View, California, and Sandia Park, near Albuquerque, New Mexico.

The STEP board had also conducted a study of innovation in global industries, led by David Morgenthaler, of Morgenthaler Ventures, and a study of patents in the knowledge-based economy, co-chaired by Richard Levin, president of Yale University, and Mark Myers of the University of Pennsylvania.

Ongoing STEP innovation-oriented projects included the following:

- *Comparative National Innovation Policies: Best Practice for the 21st Century,* chaired by Ambassador Alan Wm. Wolff, a former Deputy U.S. Trade Representative. "While we always talk about the global economy," said Dr. Wessner, "we actually focus mostly on ourselves and pay little attention to what is going on elsewhere."
- *Best Practices in State and Regional Programs*, chaired by Prof. Mary Good of the University of Arkansas and former Under Secretary for Technology at the Department of Commerce: "In the last decade there has been a surge of activity at the state level," he said. "In my experience, there are governors on the left and governors on the right, but they all believe in growing their economies, creating jobs, and attracting industry. There are fewer ideologues, it seems, in state houses."
- *Crossing the Valley of Death: An Assessment of the SBIR Program,* chaired by Jacques Gansler of the University of Maryland and former Under Secretary for Technology and Acquisition at the Department of Defense. "We make huge federal investments in basic research, and we do little to help new research-based companies reach commercialization. There is precious little funding for the crucial work to be done between

the laboratory and the marketplace, and this 'valley of death' has in fact been widening in the last decade."

GOVERNMENT SUPPORT FOR NEW INDUSTRIES

Dr. Wessner turned to the day's symposium on flexible electronics, which he said would follow themes seen in previous STEP studies. "We're here today to look at the role of research consortia around the world. We'll compare the structure, focus, and funding of our industry here with those elements in foreign countries, and we'll also try to discuss what would be the appropriate policy steps the U.S. should take, if any." There is no presumption that the government should take an active role in advancing the flexible electronics area, he emphasized, and yet the weight of history does show how effective the government can be once the value of a new industry is clear. "Industries grow most effectively when they have a supportive regulatory environment," he said, "and they often require infusions of cash or reductions in cost. My view and the view of many is that we should simply recognize that we as a country have always supported new industries seen to have national value—in the case of the railroad, the telegraph, the radio, the nuclear power industry, and many others. Put simply, we're quite good at picking winners. The losers usually take care of themselves."

He expressed gratitude to the National Institute of Standards and Technology, which supported the symposium, and introduced the two project chairmen. The first was Dr. Donald Siegel, the dean and professor of management at the School of Business, University at Albany, SUNY. He described Dr. Siegel as an expert on entrepreneurship and technology-based economic development, editor of the *Journal of Technology Transfer*, and president of the Technology Transfer Society, which focuses on the interdisciplinary and scholarly analysis of technology transfer from universities to federal laboratories.

Dr. A. Michael Andrews, the co-chair, was vice president for research and engineering and chief technology officer of L-3 Communications. He served previously as deputy assistant secretary of research and technology and chief scientist for the U.S. Army.

Introduction

Michael Andrews
L-3 Communications

Dr. Andrews began by noting that the study of future of the flexible electronics industry is a part of a larger subject—the role of manufacturing in the growth and economic security of the United States. He said that the first point to clarify was the definition of flexible electronics. This was a point often left unanswered, he said, because it means different things in terms of substrates and technological application. "But at the end of the day," he said, "it gets down to where it fits into some desire for products that are lighter weight, more rugged, and more capable, both for the commercial world and for providing security for the nation." He said that the workshop was likely to struggle with this issue to some extent, and that it might strive to develop an "umbrella" definition that would capture the general features of flexible electronics.

In a broader context, he said, the likelihood that flexible electronics will produce jobs is great. "A new technology always has the potential to create many jobs," he said, "but the underlying elements of this technology can reach across many applications." He said that his own familiarity with the subject came out of a military perspective, from which he saw "great advantages in being able to lighten the load that our soldiers and marines on the ground have to carry." He noted that flexible electronics was also bringing a new generation of sensors to aircraft, including more information about structural dynamics. The subject applied as well to the work of the Department of Homeland Security, where it promised to address critical infrastructure issues. But the "heart of the debate" about flexible electronics, he said, was its potential to spawn many new subindustries and applications throughout the economy, especially in new forms of display, lighting, sensing, and imaging, all of which may be manufactured by efficient roll-to-roll technology.

Dr. Andrews acknowledged the "great debates" in the United States about how best to sustain domestic manufacturing and economic growth. "Many other nations don't have such debates," he said, "they just go do it. Our challenge is how we can better do these things, which is always tough. We've invested reasonably well in the basic research, and in some of the applied technology areas. It's time to hit harder on developing prototypes and demonstrations, and in advancing the technology to the next level of manufacturing."

Based on the workshop and the deliberations of the STEP board members, he said, the STEP panel would develop recommendations on these questions to the nation. It would be looking in particular at better models for collaboration and community to develop the technologies, which were both "very difficult." He said that the virtue of collaboration was that it could make "one plus one equal three," but the hard question was how to apply the best balance of incentives to make this happen.

Panel I:

The Flexible Electronics Opportunity and Industry Challenges: Perspectives from Industry

Moderator:
Sridhar Kota
Office of Science and Technology Policy (OSTP)
The White House

Dr. Kota began by thanking the National Institute of Standards and Technology (NIST) for making the workshop possible, and Senator Jeff Bingaman's office for leadership. He noted that the office where he was working, OSTP, was not a funding agency, but lies within the Executive Office of the President, along with the Office of Management and Budget (OMB) and the National Economics Council. One of its functions is to convey the administration's priority areas to the federal agencies and to offer budgetary guidance on meeting these priorities. Another objective of OSTP is to promote interagency cooperation through a shared vision, which is "especially useful in a fiscally constrained environment, such as the one we have now, when we really do need to make one plus one equal three, or four." This shared vision involved not only manufacturing but also many other areas, including energy, climate, health, and space.

He began with a brief review of major features of innovation and manufacturing. He showed a graphic of the innovation cycle that began with basic research, "the great scientific discoveries," most of which are federally funded. "But that's only the first step," he emphasized. "We need to be able to go past that and take the best ideas to prototypes and physical testing. Among all the discoveries, only a few will bear fruit." Prototyping and testing were followed by the essential step of scaling up, or increasing yield and reliability of a production process. "Once you scale," he said, "you gain understanding about essential process innovations and product innovations that are needed to feed into the next cycle. Without doing that, no matter how good we are at generating ideas, we just don't score any runs."

THE VALUE OF THE "INDUSTRIAL COMMONS"

Developing the skills required for this great overlapping ecosystem of activities, Dr. Kota said, required an "industrial commons" of shared skills, knowledge, and instrumentation. During the recent decades when much manufacturing capability had been outsourced, he said, the capacity of the "industrial commons" in the United States had eroded appreciably, along with our manufacturing leadership.[1] "Without the industrial commons, you lose that ability to innovate the next generation of products. And although some people might think otherwise, innovation and manufacturing are closely tied. So the question is, how do we establish and strengthen these commons so that we can create new industries and sustain existing industries."

He described some of the elements required to create new industries, including innovation, early adoption, and access to capital. Radical technological innovations, he said, emerge from research and development (R&D), primarily the research-dominated R&D funding from the federal government. In the case of federal funding for robotics, for example, there is far more support for research than there is for development. At the other extreme, he said, most of the funding from industry is directed at manufacturing and commercialization, but not at prototyping and the other preliminary steps. This is partly a function of the loss of much of the basic science that was once carried out at Bell Labs and other large, centralized industrial research facilities. The lack of support for activity between R&D and commercialization, he said, creates a problematic innovation gap. "This is where the great ideas coming out of universities need to be translated into products that are actually manufactured here. Closing this innovation gap is a big challenge."

CLOSING THE INNOVATION GAP

There are different ways to close the innovation gap, Dr. Kota said. One is through strong public-private partnerships that support the kinds of precompetitive research that can be shared by all firms and other parties to the value chain. Doing this, he said, requires careful planning and agreement about how to distinguish appropriate portions of the work.

Another force for closing the gap is existing industries, which provide the incremental innovations and business innovations required to save existing jobs. The government, too, has a role in providing infrastructure and tools, such as automation, resources, and modeling and simulation, as well as a skilled

[1]See Gary Pisano and Wily Shih, "Restoring American Competitiveness," *Harvard Business Review* July 2009. The authors define an industrial commons as "engineering R&D, materials, standards, tools, equipment, scalable processes, components, and manufacturing competencies in platform technologies need to product cost-effective, safe and reliable products."

workforce. These elements are needed to build infrastructure for manufacturing, but they can also have an economy-wide impact. Finally, the structural nonproduction costs are important, including taxes, benefits, energy, and pollution abatement costs.

In accord with the goal of strengthening the industrial commons, he described his own work at OSTP to promote advanced manufacturing in terms of three areas: how to create new industries, how sustain and grow existing industries, and how to coordinate manufacturing better across the federal agencies. Among the topic areas were flexible electronics and nanocellulose materials, which have the potential to revitalize the paper and pulp industry, as well as to create new plastics and composites. He noted that the potential of nanocellulose materials had been clarified over the past 10 years, and that it was "now time for us to scale up and take the best of it and move forward. That's how we complete the innovation cycle." Robotics, too, he said, is at "a tipping point," thanks to advances in sensors and control systems that have taken place in the past 20 years. "Now we have the notion of robots as co-workers, co-inhabitants, and co-explorers, which is very different than the early-style robots" that were much more limited in what they could be expected to do. "The opportunity is there," he said, "not only to enhance manufacturing, but also to create new industries, especially in health care and defense."

ADMINISTRATION SUPPORT FOR MANUFACTURING

Other new aspects of advanced manufacturing, he said, included the use of modeling and simulation to design materials at the molecular level, at one end of a spectrum; at the other end is the use of multiscale, multiphysics models and algorithms for multicore computations in cloud computing.[2] While the value of such processes is becoming clear, he said, few small and midsized manufacturers use the modeling and designing tools that already exist because of lack of expertise and access. OSTP, he said, had been trying to develop ways to make available this ability and access in order to enhance firms' productivity and competitiveness.

Last year, Dr. Kota noted, the administration signaled its focus on manufacturing by the appointment of Ron Bloom as the special counsel for manufacturing. In addition, the White House and others had requested a special study on advanced manufacturing. OSTP had convened interagency meetings

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[2]"Multiphysics treats simulations that involve multiple physical models or multiple simultaneous physical phenomena. For example, combining chemical kinetics and fluid mechanics or combining finite elements with molecular dynamics. Multiphysics typically involves solving coupled systems of partial differential equations." See Wikipedia, <*http://en.wikipedia.org/wiki/Multiphysics*>.

with NIST, the Defense Advanced Research Projects Agency (DARPA), and others to identify priority areas.

He said that the administration had released a document in December 2009, *Revitalizing American Manufacturing*, in which the White House identified seven principles to strengthen the manufacturing base, and addressed various cost drivers such as labor, access to markets, regulation, taxes, technology, and business practices.

He noted the importance of integrating manufacturing with information technology in order to advance process manufacturing and create cyber physical systems. He said that the president's 2011 budget contained a series of technology investments for this purpose, including a doubling of the research budget for the National Science Foundation (NSF), more basic research funding for the Department of Defense (DoD) 6.1/6.2 basic research, an increase in the budget for the NIST Technology Innovation Program (TIP) to $150 million by 2015, and funding for NSF university innovation centers. It also included measures to ensure better access to capital for businesses, including loan guarantees and a manufacturing tax credit, which achieves a leverage of private-sector returns by a factor of three or four.

Dr. Kota also reviewed excerpts from OMB and OSTP budget guidance to agencies for the fiscal year 2012 budget. In science and technology, he said, six areas were identified: economy, clean energy, health care, climate change, ecosystem diversity, and national defense. He noted that the first one, economy, included promoting sustainable economic growth, and the administration's priority in advanced manufacturing was the lead priority.

THINGS INVENTED HERE, MANUFACTURED ELSEWHERE

Dr. Kota said that while he did not have technical expertise in flexible electronics, he had learned from experts in industry and academia that the opportunity to advance this field is great. But without policy changes, he said, the "picture was somewhat scary." By this he meant the specter of "things invented here but manufactured elsewhere; industries we have already lost, and others that are at risk." Citing recent research by Gary Pisano and Willy Shih, he showed a list of technologies that had been lost to manufacturers abroad, including "fabless" chips, compact fluorescent bulbs, liquid-crystal displays (LCDs) for monitors, TVs, and mobile phones; lithium-ion, lithium polymer, and nickel–metal hydride batteries for cell phones, portable consumer electronics, laptops, and power tools; crystalline and polycrystalline silicon solar cells; desktop, notebook, and netbook PCs; low-end servers; hard disk drives; consumer-networking gear such as routers, access points, and home set-top boxes; advanced composites used in sporting goods and other consumer gear; advanced ceramics; and integrated circuit packaging.[3]

Among the opportunities for flexible electronics, he summarized, are the potential for high-tech, high-profit manufacturing, job creation, and low-cost manufacturing of electronics with more flexible substrates—distributed among such application domains as smart phones, health care monitoring, structural health monitoring, smart bandages, and batteries. "This is all exciting stuff," he said. "Hopefully we still have an opportunity to manufacture them here, in the U.S., so we can reap the benefits of investments in basic research."

Dr. Kota said there were many opportunities for partnerships as well, among large companies, small companies, and innovative companies of any size, the research universities, and the federal laboratories. Partnerships could affect multiple sectors, he said, and take the form of horizontal consortia, or vertical consortia, as in the case of SEMATECH, or a hybrid. They could also leverage existing research from universities to new clusters, such as the Flexible Display Center at Arizona State University.

The primary challenges for flexible electronics, he said, were similar to those facing any new technology, including packaging, reliability, and yield. The task was to determine which research challenges could be addressed in a precompetitive manner, with benefits for all, and which would be deemed proprietary.

In summary, he challenged the workshop participants with two closing questions. First, what technological breakthroughs are needed to establish and then to sustain the industries that can grow up around flexible electronics? Second, what kinds of public-private partnerships (PPPs), business models, or government policies would enable the United States to gain global manufacturing leadership in this area? "What is at risk, what has been lost, and what are the things we can catch?"

Dr. Kota closed with a quote from President Obama about the technology goals of his administration: "Our goal has never been to create a government program, but rather to unleash private-sector growth."

[3]Gary Pisano and Willy Shih, "Restoring American Competitiveness," op. cit.

CHALLENGES AND OPPORTUNITIES FOR THE FLEXIBLE ELECTRONICS INDUSTRY

Ross Bringans
Palo Alto Research Center, Inc.

Dr. Bringans began his review of the field of flexible electronics with a description of the Palo Alto Research Center (PARC) as "different from most institutions in being not truly industry, and not academia." PARC was established by the Xerox Corporation four decades ago, in 1970, with the objective to "invent the office of the future for Xerox." In 2002, the parent company transformed PARC into a new subsidiary to work with other entities, including the government and commercial clients. It organized itself into four divisions, two in computer science and two in hardware. In hardware, a chief area of focus was large-area electronics, which included flexible electronics. Several other PARC topics also related to flexible electronics, including microelectromechanical systems, or MEMS; optoelectronics, including activities in laser devices and optical detectors; printing systems, which grew out of the Xerox tradition; biomedical systems; and clean technology, including energy systems.

Another unusual feature of PARC, he said, is its method of doing research as a business; customers include private companies and the government. It operates by partnering with many small companies, including many at the startup stage that consist of "two or three people and an idea." PARC also incubates businesses on its own, spinning out new companies. Finally, it licenses and transfers technologies from its historical and current portfolios.

The overarching concept behind flexible electronics, he said, is that it replaces traditional means of placing electronics on rigid silicon with something that is much more paper-like or plastic-like and is therefore relatively lightweight and robust. He noted the concept of Nokia, which is that flexible electronics brings the ability to "morph from one shape to another," which cannot be done with current technology. He also recalled an image from *Scientific American*, created six years ago, that showed a display going in and out of a cell phone. "You will see that this is not too far from reality." He cited the "really interesting" prospect of medical patches: thin, flexible material that has the ability to monitor heart rate and other vital signs and communicate those readings to physicians and hospitals. "Something like that would be tremendous," he said.

Defining Flexible Electronics

Dr. Bringans suggested that flexible electronics might be defined in two ways, according to applications. Many applications are likely to utilize flexibility per se, which in itself is valuable. But he suggested that a second, larger market would be other electronics that benefit secondarily from the quality of flexibility. This market would create a new industry of electronics that are much lighter and more robust, potentially lower the cost of manufacturing dramatically, and allow custom systems to be manufactured without large new infrastructures. "If you look at it this way," he said, "it's pretty clear that it can be a destabilizing technology. And as in all cases of destabilizing technology, the winners are not obviously the incumbents of the previous technology. They could be, but there could be new ones, and the question is where they will be—in Asia, the U.S., Europe, or some mixture."

He said that "in the spirit of an overview" he would review each of those component areas, or "partitions." The first included applications that benefited from flexibility.

- Many displays, for example, have added value if they are mounted on curved surfaces and rollable. He noted that Sony earlier this year showed the ability to wrap an active display around a very small diameter. Rollable displays, he said, would naturally be more robust than rigid, flat displays.
- Manufacturers would want to place photovoltaics on curved surfaces—both for practical reasons and for aesthetics. This would increase the number of places such products can be used.
- In making and viewing x-ray images, which is an area of PARC interest, flexibility might allow them to be conformal, surrounding the objects under view; this would also bring robustness.
- The medical device area, he said, was an exciting market, for which both electronic patches and implantables could benefit from flexibility and biocompatibility. He showed an image from the University of Washington of electronic devices embedded in a contact lens.
- "Systems on a foil," he said, would include wearable, flexible devices that were "designed for people, not imposed upon them."

A second category, he said, was one that needs the flexible substrates for particular uses but also bring benefits to manufacturing as a whole. The element most often mentioned was roll-to-roll manufacturing. This technique exists now and produces newspapers, packages, and other products at low cost and high volume, and many firms were trying to move that technology into electronics. Another element was light, thin substrates which could lead to ultralight and stackable systems. Flexibility also brings the element of robustness because the products are not brittle. "We like to be able to drop our tablet computers and not have them break," he said, "and I think that is going to happen. There are many by-products under development that can benefit from both flexibility and robustness, including RFIDs, photovoltaics, smart labels, lighting, smart phones, and tablets."

Applications Must Drive the Technology

The perspective of PARC, he said, was that "flexible electronics is a very exciting direction, and there will be a lot of new technologies. We are certain that interesting business opportunities will flow out of that." He said that these opportunities are beginning to open, particularly in Europe. He also said that "applications will drive the technology. In the end, people are not particularly interested in the technology. It's kind of cute, but they really want the solutions." Furthermore, he said, people want not just solutions, but "a convergence of all the solutions in one place, whether it be a smart phone or an iPad."

Two major barriers stood in the way, however. The first was the commercial challenge of launching the industry. "It's hard to get something started that's going to be as large as this," he said. The second challenge, he said, concerned the role of the federal government. "Where," he asked, "is the best place to apply its leverage?"

Dr. Bringans said that PARC had viewed the field of flexible electronics from many angles. Its first approach was to make standard technologies flexible, such as the placement of amorphous silicon on plastic and polycrystalline silicon on thin steel foils. They had also spent a good deal of time exploiting printing technology, especially ink-jet printing, and were now beginning to look into traditional printing technologies, such as gravure. "We've done a lot of development in organic electronics," he said. "Those two sit together well, because many of the organic materials are printable, and many of the printable materials are organic. We are doing basic research, but trying to demonstrate applications at the prototype level." Those applications include displays, sensors, and systems. He showed an image of a nonflexible x-ray imaging system for looking at improvised explosive devices (IEDs). It was, he said, "basically an imaging x-ray detector that you'd put behind a suspicious object. If you shine x-rays through the object you get a one-to-one image, like seeing it through a window." PARC was about to start work with partners to develop this imaging device into a flexible and robust system. "This is to show that we have worked from fairly basic materials science all the way through to assembly of fully working systems."

He showed the example of an all-additive printed array, which functions without photolithography. The patterning is done with ink-jet printing; the metal layers, the semiconductor, and the insulator are all created with solution-based materials and can yield a fully working backplane for display.

Why is this important?, he asked. First, producing a printed array takes many fewer steps than photolithography. For example, a transistor can be made with four steps, yielding four layers if it is all printed in an additive way. Traditionally, depending on the design, making an array by photolithography can require 16 to 20 steps. The other, perhaps more important, advantage, he said, was that by simplifying the structure to this level, it is possible to contemplate simpler applications, such as smart labels, that might not be feasible as separate industrial technologies.

Sensors to Monitor Brain Injury

A second example, he said, was an effort, funded by DARPA, to use printing technology to develop a blast dosimeter that measures and tallies the cumulative effects of multiple blasts in warfare. "The issue," he said, "is that traumatic brain injury does not come only from very large explosive impacts; it's a cumulative effect. There can be as much damage from a sequence of small impacts, or even a very separated series of moderate impacts, as from a large one. We want to develop something like a radiation monitor that soldiers wear on their uniforms or helmets." These sensors would monitor events of pressure, acceleration, sound, and light, put them into memory for up to a week, and then read them out.

"That sounds straightforward," Dr. Bringans said, "except for the requirement that the sensors cost a dollar apiece." The challenge is to find ways to print each of the major circuit components—the ring oscillator, shift register, amplifier, and memory—on a flexible substrate. He said that PARC had been able to develop some sensing from laminated elements that could potentially be produced inexpensively through roll-to-roll techniques. "The next step," he said, "is to integrate these so the impact measured by the MEMS sensor is amplified by the printed amplifiers and then stored in printed memory cells." This experience, he said, had confirmed PARC's view that flexible sensor systems would be important not only for the military but for many applications, such as monitoring elderly people at home.

"The other thing we've learned," he said, "is that hybrid devices are promising, and probably necessary—certainly in the beginning. Some things can be done well with printing and customized circuits, but others make more sense on silicon, such as the communication chips." He noted also the opportunity to combine the new technologies with traditional printing and manufacturing, such as silicon manufacturing or techniques like lamination.

He said that PARC had also learned the lesson "that putting all this into a system is hard—as is taking it to the next level. To get applications that are inexpensive—the $1 patch—you need a lot of volume. In order to create volume, you need applications. So the big question is, does the whole industry have to wait until a company with enough money and a particular demand will drive the development of not only that particular piece, but also the industry itself. That's asking a lot, but it seems to be happening."

His view, he said, is that flexible electronics has "a huge future." This view, he said, reflected PARC's activity across the industry and its work with a wide range of partners. "We get a view on this, and what we do is invent, develop, and demonstrate both processes and prototypes, and then put them into applications. Then we ourselves are investing in developing components and trying to partner with manufacturers to move to the next level." Beyond that stage, he said, it would be interesting to focus on the development of applications. "There's clearly some funding already for processes and infrastructural capabilities," he said, "and this needs to be enhanced. But it would be interesting if we could put this together with applications, which you could argue is one of the big missing pieces in the United States."

Dr. Bringans offered a quote from a report by NSF and Office of Naval Research on the state of flexible electronics: "…the relatively low prevalence of actual manufacturing and advanced systems research and development in the United States has led to an incomplete hybrid flexible electronics R&D scenario for this country…."

"We think that by pushing the applications," he concluded, "we could really help kick-start this industry, which we all believe is going to be very important."

IMPACT OF A FLEXIBLE FORM FACTOR FOR DISPLAYS AND LIGHTING

Julie Brown
Universal Display Corporation

Dr. Brown began by introducing her company, which was founded in the mid-1990s as "an innovation gap company." The original goal of Universal Display Corporation (UDC) was to fund basic research, she said, and to "really inspire innovation." Two researchers at nearby Princeton University[4] had identified the chemistry and technology to make an organic light-emitting diode (OLED) 100 percent efficient, and the company was founded to exploit that discovery. She predicted widespread uses for flexible electronics. "As a person who does not have pockets in her suit to carry a cell phone," she said, "I look forward to being able to wear one on my wrist. She said that the mission of her own firm was to develop all kinds of organic flexible electronics for displays and lighting.

The history of displays, she suggested, might be said to have started with the first symbols scribbled on a rock, which evolved eventually into the portable convenience of newspapers. The other key element of lighting

[4]Steven R. Forrest and Mark E. Thompson, who have collaborated in patenting numerous organic thin-film devices, worked with UDC in developing the firm's technology.

technology, she continued, began with the fire that produced light, then became portable with the use of lanterns. She compared the cathode ray tube of the 20th century to the stone, only to be replaced by “beautiful LCD technology,” which has become the first truly portable display technology in its use for laptop computers. Today, she said, the technologies of both the newspaper and the portable display are poised to converge in OLED technology. “We’re moving very quickly toward having the technology pieces in place,” she said. “We’re actually building flexible displays today for our government customers.” UDC began its research in this field in the late 1990s, she said, in response to early work at DARPA on flexible displays. UDC now works with the U.S. Army. It is also conducting lighting research supported by the Department of Energy (DoE).

Rollable and Almost Paper-Like Displays

As the technology moves ahead, she said, consumers will want not only the flexibility and convenience of a newspaper, but the vivid color and energy efficiency of cell phones. She noted the design concepts being discussed by Nokia, Sony, and other companies, which envisioned products that will not only be vivid and efficient, but also nonbreakable, thin, and rugged.

To date, Dr. Brown said, beautiful products are being designed with electrophoretics, or e-ink, which produces a thin and potentially flexible technology. The goal is to advance this technology with a technology platform and manufacturing process that will add more essential features, including full color, vivid images, video rate display, and “green low power.” These features can then be combined with the manufacturing capability to make “rollable and almost paper-like displays.”

She noted that the current generation of cell phones, such as the Galaxy S, already generates vivid color by combining flexible silicon backplanes with OLED front planes. They also have low power consumption, which grew out of the work by Forrest and Thompson, who identified the chemistry and technology needed to achieve 100 percent efficiency for OLEDs in turning electricity into light. UDC has a pilot manufacturing line outside Princeton, with the objective of producing “light without heat.” With additional improvements in phosphorescent technology, the power consumption of OLED lighting will continue to decline.

The “big win” for OLED technology, she said, would be to develop the process that allows it to be placed on a flexible substrate. Her company already employs a designer, she said, whose job is to imagine future uses for flexible OLEDs beyond the current cell phone.

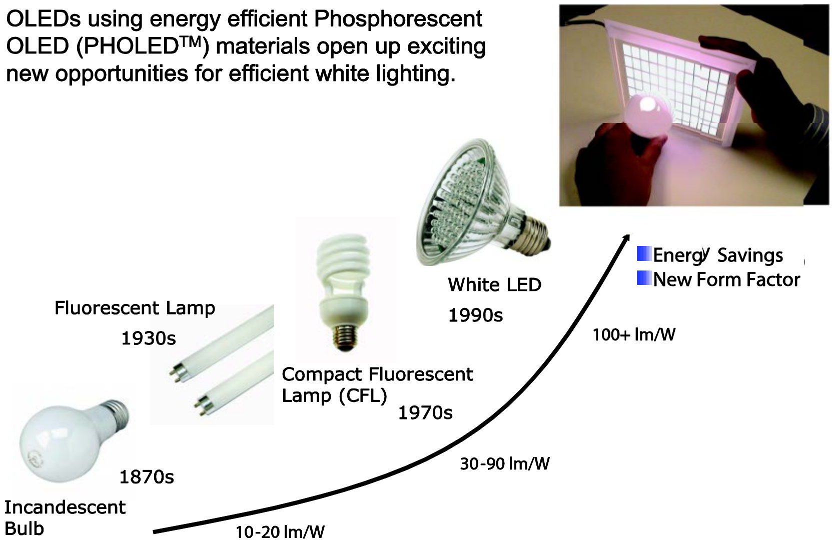

FIGURE 1 Evolution of lighting.
SOURCE: Julie Brown, Presentation at September 24, 2010, National Academies Symposium on "Flexible Electronics for Security, Manufacturing, and Growth in the United States."

Rugged Enough to Absorb Hammer Blows

Dr. Brown said that the company's core OLED technology sits on a flexible substrate about 100 microns thick and is rugged enough to absorb hammer blows. Development of the technology began in DARPA and moved into the Army, and UDC had been funded by the Army to build full-color, active-matrix OLED flexible displays. UDC works with L-3 Communications and several other partners who were responsible for the backplane and systems integration. UDC had delivered the first units to the Army in Fort Dix the previous August for field testing, with good early results. "They had all our units laid out on the table with streaming video from the UAV [unmanned aerial vehicle] above the tent," she said. "So we have flexible electronic technology now being fed into the military."

In addition to the goal of producing a better technology, she said, the lighting industry as a whole is "focused on green—on energy efficiency, which is a huge issue here in the U.S. and globally." Lighting currently consumes 22 percent of the total electricity generated in the United States, she said, and 8 percent of the total energy. "Right now, whether we're talking about an inorganic LED or an organic LED, all the technology development is going after lumens per watt. And the numbers are getting better. Programs in lighting are heading toward 100 lumens per watt."

She said that one application with high potential is transparent light sources on pieces of flexible material. She showed an example of white OLEDs for applications in ceiling systems. UDC, in partnership with Armstrong Industries, had built a fully integrated OLED ceiling system that plugs into the Armstrong Tech Zone Ceiling using 24-volt rails. "My OLED plugs in," she said, "and saturates the camera with bright light." She said that flexible lighting would provide great opportunities to bring together diverse manufacturing expertise with end uses. "Lighting is really different from the display industry," she said. "A lot of people involved in lighting are doing infrastructure development. And today the technology blocks are in place: flexible encapsulation, low-power OLED, flexible substrate."

A Need for Global Relationships

Dr. Brown said that from both national and international perspectives, there is great momentum toward development of technology for flexible displays. In the United States, this momentum has been initiated within the U.S. government, and leadership is apparent in other sectors, as seen in the Flexible Display Center in Arizona and small firms such as the Arsenal Company. At the same time, she said, the relationships required to build an industry are global.

Within the United States, she said, military applications are being launched first and are beginning to point at directions for commercialization. She added that the emerging industry can take advantage of the many manufacturing technologies related to flexible electronics that are already in place. Another pressing task is to begin to prioritize and integrate issues at the systems level and "talk about how are we actually going to use these flexible systems. There are a lot of very important mechanical and electrical issues to solve."

While acknowledging that she was "not a public policy person," she suggested that a flexible OLED lighting would need incentives to bridge the gap between prototyping and marketing. OLED lights were not likely to launch at a price of $2 or $3, she estimated, but at $20 or $30. Lower prices would require both incentives and collaboration among the DoE and potential users. She urged more collaboration between "good work being done in the DoE and various partners, especially U.S. infrastructure companies, universities, and government agencies." A goal of such partnerships, she said, is to regard OLED lighting as an overall system. For flexible displays, she suggested that mandating both efficient lighting and wall plug applications, such as television monitors, would inspire new applications and advance the industry.

From a global perspective, she said she saw a huge amount of research, development, and prototyping of OLED lighting displays in Asia, especially in Taiwan, China, Korea, and Japan, with China emphasizing mass installations.

The Chinese government, she said, was determined not to miss an opportunity for leadership in OLEDs as they may have done in LCD technology. Likewise, she said, European countries were vigorously working on technologies of flexible lighting.

She concluded with the opinion that "for all of this, the big win is in the flexible organic electronics. There's a technology platform out there, there's a commercial need, and there's a lot of progress being made. This is a huge opportunity, and an exciting new area."

Discussion

In response to a question about cost, Dr. Brown said that estimated costs for manufacturing on glass, including the glass and the electrodes, were about $600 per square meter, with the main cost for the substrate. Using a metal foil or plastic substrate would drive the cost down, she said, and some industries were experimenting with these technologies. The organic materials for R&D, she said, were produced by her company, which bought the substrates commercially. The large lighting companies preparing to launch products were finding materials overseas.

PLASTIC DISPLAY RESEARCH AT HEWLETT-PACKARD

Carl Taussig
Hewlett-Packard Company

Dr. Taussig, director of advanced display research for Hewlett-Packard Company (HP), said that he had "a visceral reaction to the terms flexible electronics and flexible displays. For me personally, and for HP, it has been about low cost, and flexibility is a nice side effect of very-low-cost manufacturing using roll-to-roll processing."

He said that HP was one of the world's largest purveyors of displays, selling about 65 million displays last year as part of most of the products made by the company, including not only computers, laptops, and handhelds but also network switches, printers, and many other products.

When HP was studying the future of displays, he said, the company realized that plastics were going to have a huge effect on the display industry. He said that the primary function of plastics would be to enable low-cost, roll-to-roll manufacturing. Other benefits flowed from the fact that plastics are not glass. "If we'd had a choice," he said, "we wouldn't have used glass as a substrate in the first place. It's friable, it's heavy, and it's rigid. Plastic is lightweight, unbreakable, and conformable. These are great benefits and make it suitable for high-volume, low-cost manufacturing."

LCD as an "Entrenched Competitor"

Among other factors driving the trend toward plastics, he said, was that many emerging display technologies were inherently better suited to a plastic substrate. An example was OLEDs, which could usually be manufactured at the low temperatures compatible with plastics and bring the additional benefit of a simple, efficient stack structure. This alone might be sufficient to replace the entrenched liquid-crystal industry, he said, noting that OLED had been considered the "next display technology" since the mid-1990s. A reason it had not emerged, he suggested, is that an entrenched competitor, such as liquid crystal, continues to evolve, making it difficult for a new and even superior technology to take its place. However, he suggested that the new opportunity presented by plastics might be sufficient to bring change.

Another emerging technology that appears to be compatible with plastics is ultra-low-power displays, such as e-ink, or reflective electro-optic devices. These are potentially bistable and may need no power to maintain a static image. Helping to drive introduction of these new displays is a worldwide desire to have increased mobility and to be able to have information available and visible everywhere, even outdoors in bright sunlight.

Dr. Taussig also described a clear opportunity to enhance the capabilities of existing form factors for displays used in appliances already on the market. Once a technology is developed that has the attributes of plastics, such as very low cost and very large area, it would be possible to extend flexible lighting to billboards, food packaging, "talking cereal boxes," apparel, and many other products. He noted the plans of Nike to instrument running gear with a display that sends information to the wearer from other parts of one's apparel. He noted that most of the work in this area had been funded by the government for military applications. The support of government had made it possible for even a very large company such as HP to benefit from the leverage of public-private partnerships to work with e-Ink, Power Film Solar, and other companies. He said that his company saw this as a change from "simple, segmented, fixed-pattern enunciators" into a "cross-point addressing structure that could be passively addressed, and then into an active-matrix technology." Each of these would have its own development trajectory, as well as trade-offs in difficulties and technologies that need to evolve.

Faster Electrophoretic Displays and Roll-to-Roll Manufacturing

HP Labs focused on two aspects of this change, he said. The first was current reflective displays, which hold advantages in mobility applications, such as e-ink, which he called a "tremendous and exciting product. It uses incredibly low power, and you can see it in bright light." In two areas, he said, improvement would be desirable. The first would be to speed the uptake and develop a color version. Because it is an electrophoretic display, it functions by moving pigment particles in a solvent. This process, which is dominated by viscous forces, is inherently slow. In addition, the technology is based on the motion of oppositely charged pigments within a microcapsule. This allows for two kinds of charge, and only two options for the pigments—black and white. The simplest way to render these pigments in color is to place a color filter in front of them, subdivide the pixel into red, green, and blue subpixels, and turn off the blue and green channels to gain a saturated red. This technique, however, results in a dim and washed-out display.

The other major thread of HP research, he said, is roll-to-roll electronics. Developing this feature—not flexibility or any other qualities—was the company's initial motivation in entering flexible electronics. It wanted to learn how to make the product with the lowest possible manufacturing costs at high volume. "We've been working on this for the last 10 years," he said, "and maybe for the last six years with a focus on displays."

The Color Reflective Problem

Dr. Taussig returned to the color reflective problem, saying that he had referred to "side-by-side color," in which a color filter is placed in front of a black-and-white light valve. This technique is fundamentally limited, he said, because it subtracts much of the available light. And in a reflective system of this type—unlike the transmissive or emissive system of OLEDs or LCDs—the problem cannot be solved by increasing the back light or the current; the only light available is what is reflected from the ambient. Side-by-side color essentially gives away 67 percent of that amount, yielding a dim display. An alternative is to stack layers, which HP has been investigating. A difficulty with this approach is that it involves a number of interfaces, and the light has to go through each of them and return. About 2 to 3 percent of the light is lost at each interface, and when light must pass through 20 or 30 interfaces, only about 50 or 60 percent of total reflectivity remains.

A major innovation his company had made in reflective displays, he said, was to place selective mirrors within the stacked system, which causes the light to be intercepted as soon as possible within the stack. This means that the light does not have to travel all the way through the stack, losing a small amount at each mirror. In addition, he said, HP researchers had made this into a "transflective" system. That is, the mirrors also transmit 10 percent of the backlight—more than the transmission of a conventional LCD.

He showed a video clip of this system, featuring a stacked color reflective system developed in the HP Labs, and behind it an e-ink display. The black-and-white performance of the system was similar to that of e-Ink in terms of contrast and brightness, he said, but the HP system also had "a reasonably wide color gamut," which he noted was almost as fast as video. He said that the metrics they used to evaluate the system were those developed in the printing industry

The problem with a stacked display, he continued, is that it uses at least three displays, which is more expensive than a side-by-side design. A simpler approach to reduce cost is to develop a process called photoluminescent enhancement. Here, luminescent materials capture the shorter-wavelength light and reemit it in the longer-wavelength portion of the spectrum. This effectively produces light that is "redder than red"—200 percent or more of the original light. "This may give us an intermediate step at a reasonable cost point," he said. "We can then use approaches like ink-jetting to put these photoluminescent materials into wells that we've defined with an imprinting structure." He said that HP is working with the Flexible Display Center in Arizona and with e-ink to demonstrate color filters made by this approach. Compared to conventional ink-jetting, he said, the photoluminescent system, in template wells, gave "much better resolution."

Dr. Taussig also showed an e-ink–based display, with e-ink as the front plane and an HP roll-to-roll backplane behind it. His firm had worked for years with a company called Power Film Solar to develop a one-third-meter-wide pilot line at the HP Palo Alto research facility, which makes the backplanes. The technology had been licensed to Power Film, which had formed a subsidiary called Phicot, Inc., a recipient of Army Research Laboratory funding, to make a self-powered, wrist-worn cuff display for the military. The technology, known as self-aligned imprint lithography, or SAIL, had been successful enough to win awards, he said.

Kilometers of Material

Dr. Taussig then described the HP approach to roll-to-roll manufacturing that combined all the lithography processes used in one kind of display. The roll was able to produce kilometers of material at a time. His company, he said, was also interested in adapting these paper-like displays, using reflected but high-performance lighting displays, and in leveraging the developments in OLED lighting. "We see that as the first opportunity to get this stuff commercialized," he said, adding that other groups, including UDC and General Electric, had demonstrated a roll-to-roll process for making white OLEDs. "We'd like to take that white OLED developed by others for a lighting application," he said, "and turn it into a display. The challenge there is whether we can process this material afterward when it is manufactured and laminated to a roll-to-roll backplane."

To advance from the technology of e-ink displays, he said, it was necessary to enhance the performance of the pixel circuit. "They're a little more complicated when you're driving an OLED," he said. His lab had been using metal oxide semiconductors, which have about 10 times the mobility of amorphous silicon. He showed an early prototype of such a product, a nonaligned roll-to-roll process for assembling a white OLED with a roll-to-roll process backplane, in this case amorphous silicon.

Dr. Taussig closed with a plea for more public-private partnerships in the United States. He said that he firmly believed that even a very small investment on the part of the federal government, if designed properly, can "make an enormous difference in the commercialization of technologies in the United States." Without such support, he said, "it is virtually impossible to contemplate initiating a manufacturing-based industry in the U.S. because of pressure from overseas, where firms have the support of their governments to make these things happen. As a group, it's incumbent on us to make that different."

DISCUSSION

A questioner noted two opinions about the appropriate level of government investment in flexible electronics. One was the need for large investments in infrastructure to move consumer-oriented products into the marketplace, from photovoltaics and other similar areas. The second was the need for only a small government investment, primarily to stimulate the formation stage of the industry. He asked for some more context on those opinions.

Dr. Brown said that she favored a new government initiative to help companies bring flexible OLED lighting, and perhaps flexible solar photovoltaics (PV), into the marketplace. This would mean initiatives in manufacturing and related technologies. She said that she was not calling for large government investments as much as a different type of support. She noted that DoE gave a great opportunity to UDC and its partners by providing funding to initiate OLED manufacturing plants in the United States. This allowed the company to attract a desirable subcontractor from India, Moser Baer, in setting up the plant in the United States. "What I see missing," she said, "is bringing in the designers and end users and initiatives for energy efficiency, and integrating everything with industry programs."

Dr. Taussig said that the relatively modest investments that the government had made to date had been important in the early phases of technology development and had catalyzed significant results. "I expect that in that chasm between universities and industrial research labs and then mass production, there needs to be a mechanism to bootstrap that in a similar way. That is where the process falls down."

Dr. Schen, of NIST, said that his institute was involved with small to medium-sized manufacturers in the United States. He asked about the ability of U.S. firms to compete with China, where the government is investing significantly in flexible substrate technology. A critical need in the United States, he said, was for help in generating high-volume manufacturing "so that

John Smith Incorporated doesn't have to compete with China Incorporated. I understand that the substrates are coming from overseas now. Our research from the universities and research labs is excellent, but when it comes to manufacturing, somewhere the link is broken."

Dr. Kota said that the subsidies offered by China and other countries include buildings, 10-year tax holidays, and other help, but that "this is not the world we operate in." The United States makes significant investments in basic research, he said, but its free-market principles do not usually include a role for direct subsidies. Rather than seeking to compare itself to countries using subsidies, he said, the United States might better address the gap between research and manufacturing through public-private partnerships. A second point worthy of discussion, he said, was the issue of market failure in technology development. This term is often used to describe the private sector's reluctance to invest in complex functions, such as roll-to-roll processing, if a single company or even industry does not expect to reap a sufficient return on the required investment. In such cases, he said, when research in key platform technologies might benefit multiple industries, such as lighting and displays, the federal government may have a legitimate role.

Dr. Wessner noted that the Obama Administration, especially through the Department of Energy, had targeted substantial funding for technology research in areas of great promise, such as batteries. Two elements of concern for such technologies, he said, are (1) how to drive the supply into production and (2) how to drive the demand for the product. DoE policy, he said, had been effective in demonstrating that the chief barrier to establishing new businesses in the United States was no longer low wages, but the cost of capital. "That is a new area of global competition," he said, "that we have been slow to participate in."

Dr. Brown agreed that the United States should not emulate the kinds of support initiatives featured in China, but do a better job of integrating products and moving them into the market. "Whether in solar energy, display, lighting, or other areas," she said, "I think we have a great opportunity to place the same emphasis as other countries, in flexible electronics, but working at product integration. There are lots of flexible substrate systems in the U.S. that could be integrated, and a lot of opportunity."

James Sturm of Princeton University commented that there is a "missing piece: the focus should be on applications." Dr. Bringans said that he favored the model of ARPA-E that had emerged in the energy area, which seemed effective in many ways, such as raising the "technology readiness level" (TRL) of a technology. "We sometimes talk just about putting big consortia together," he said, "when in fact things can be jump-started by pushing them beyond what is normally people's comfort zone in R&D more toward manufacturing. We should keep that model in mind, as well as more traditional consortium models."

Panel II:

The U.S. Interest: Security, Manufacturing, and Growth

Moderator:
Jon Epstein
Office of Senator Jeff Bingaman

Mr. Epstein opened the panel by noting Senator Bingaman's long-standing interest in science and technology, including his efforts to support the LED industry in its early stages. The senator also had a strong interest in flexible electronics, he said, and in "the competitive nature of our nation." Mr. Epstein voiced his concern about insufficient continuity of U.S. policy, however. In his experience, he said, the United States "develops great ideas, and gets them funded by the government." Too soon, however, the program ends, or competitor countries see the same promise and invest more heavily and quickly. "Then we are the ones who are importing the technology," he said. "The continuity issue is one I worry about."

ARMY APPLICATIONS FOR FLEXIBLE DISPLAYS

John Pellegrino
U.S. Army Research Laboratory

Dr. Pellegrino, of the Sensors and Electron Devices Directorate, said he would describe the Army's approach to flexible electronics, beginning with a discussion of the term itself. The word "flexible," he said, is important in itself, but along with flexibility come other attributes: "it can be inherently rugged, is likely to save packaging weight and cost, and can be printed by a roll-to-roll or other large-scale and efficient process."

All these attributes have value for the Army; for example, a flexible or "conformable" material may have great medical value, such as the ability to incorporate various multifunctional sensors that detect situational awareness, stress, fatigue, or mental function, or to place sensors in conformable bandages.

Sensors in flexible materials may be used by the military not only for people, but also for vehicles, engines, or temporary structures.

Many applications of flexible displays, he said, can find similar or even identical uses in both the military and the civilian commercial marketplace. The military versions may have to be packaged more ruggedly to endure operation in extreme environments, such as higher temperature or lower humidity, with no change in capability. The military also likes to be an early adopter, he said, so it can maintain a technology edge and give its soldiers an advantage.

In some prognostic and diagnostic technologies, he said, the aircraft industry is in a position of leadership, having learned to place various sensors on airframes and air structures. Although these structures are not strictly regarded as flexible, they are carrying the kinds of cheap, printed electronics that can be situated in many ways. Such applications can be adapted directly into the military for use in both helicopter and general aviation.

Tracking Military Equipment

A central need for the military is tracking the enormous flow of equipment and material that flows overseas and returns to the United States. A current goal, said Mr. Pellegrino, is to make better use of electronic circuits that can be placed easily on every kind of equipment and tracked accurately. He noted the leadership of Wal-Mart in this area, which has pioneered the use of printable electronic labels and other tracking devices for merchandise.

In building more capabilities into flexible displays, he said, the military will begin with fully flexible circuit boards and add further displays that may involve many other technologies, such as solar cells, thermoelectrics, and photovoltaics. Such different technologies can be integrated into several places to make the kinds of lightweight, rugged devices suitable to military uses. One obvious need, he said, is good displays for e-readers that can be used for maintenance manuals, situational awareness, robotic controllers, and many other applications. Such readers, perhaps resembling the iPad, would provide the soldier with a device that may be rechargeable and easy to carry. It may show high-quality graphic images, such as photos and maps, provide orders of the day and any other information, and network with other devices simply and securely. One of the greatest contributions of such a device would be its light weight and low power needs. The average soldier, he said, carries gear that may weigh nearly 100 pounds for a mission; the batteries needed to power communication and other devices account for up to 30 percent of that weight. “So we need to reduce power consumption and make it easier to generate the power.”

Successful use of the new technologies, he said, would depend on their integration. The readers might require one kind of program for storing and reading maps, another for information access, another for health monitoring, and still another for unattended ground sensors that can be mostly or wholly self-powered. The antennas would require more power, perhaps generated by solar cells or supplied by a fuel cell and battery. "The key is to have an integrated package that can bring all the pieces together," he said.

Larger Arrays and Grids

Beyond the level of sensors and circuits, he said, the Army would explore larger arrays and grids of devices that could be manufactured by a roll-to-roll or hybrid process. These arrays and grids, which could gather both geospatial and temporal information, might include flexible solar cells on tents, mess halls, or other structures in the field, generating their own power at efficiencies of at least 30 percent. This would reduce the logistical load of transported fuel. Already, he said, a number of balloons, airships, and other aerostats gather visible and some infrared data nearly around the clock, but their sensor pods are fairly expensive and require maintenance. These drawbacks could be reduced by turning the skin of the aerostat into a large-area sensor, coupled with a large-area charging device to provide some of its power. He said that the Army is also studying the use of sensors and reconfigurable antennas on the skin of aerostats, micro air vehicles, or small unmanned aerial vehicles.

Another area of rapid development, Dr. Pellegrino said, is microautonomous systems, such as microrobotics. In partnership with the Michigan Center for Microelectronics and Sensors, the Army is studying a number of handheld devices that can be released into urban buildings, for example, to gather information about hostages, weapons caches, and other conditions. Some concepts include various "backpackable" units that can release smaller robots capable of walking, flying, crawling, or hopping while carrying various sensors in their skins. These skins can also contain conformable photocells and antennas.

Dr. Pellegrino said that the current challenge is to integrate the many different building blocks that exist in bits and pieces—imaging sensors and arrays, energy harvesting and storage, manufacturing and packaging, multiscale modeling and simulation—into a coherent industry. He said that "first substantiations" of many of these applications had been achieved, including the order-of-magnitude improvement of mobility and stability over what is currently available in amorphous silicon technology. The primary "pacing issue," he said, is the manufacturing and packaging technologies. "The people driving the applications would buy any of these things, this instant, if they existed," he said. "They do exist, in configurations of ones and twos, but I can't go place an order for 10,000 this afternoon."

Developing the needed manufacturing science and capability, he said, depends on multiple complex challenges, such as reliability, resolution, placing the needed structures on the substrate, and encapsulation of large areas. "We believe there are lots of solutions potentially out there, but we need to integrate them for specific applications. We need to focus on applications, but also on the manufacturing to enable those applications. Then those orders will come."

A Need for Partnerships

Dr. Pellegrino touched on the need for different kinds of partnerships. He noted that the Flexible Display Center in Arizona was a "nontraditional" kind of partnership, including industry as a full participant with the academic community. This helps to solve the "interstitial" problems between different domains, he said, and allows the partnership to focus on the applications important to the industry, as well as those the Army needs. At the same time, he said, until the industry can move past the fundamental manufacturing challenges, "no single industry is going to be able to jump ahead. This is just one way of getting some of those common problems solved."

He noted that while cost is always a consideration for the Army, it was probably not primary. The value of the products would balance cost in many ways, such as the new uses, "inherent ruggedization," and reduced weight of battlefield structures. Already, he said, the partnership was seeing the value of creating large-area devices that had relatively high resolution and that could be lifted off and packaged as a flexible organic device.

Dr. Pellegrino concluded with a note about his experience at the Flexible Display Center with "all the wonderful partners." As the results began to come in, he said, the tendency was simply to take the traditional technology and replace it with what was effectively a plastic substrate. "So let me see," he said. "If I have a rigid controller on my wrist and I'm just going to change the glass to plastic, what did that buy? A little savings in packaging. Almost nobody had the imagination to take advantage of the extra degrees of freedom. I submit that this technology has many more degrees of freedom than we've begun to plumb at this point. Some companies, individuals, and universities are beginning to explore that, and I predict that there's a whole lot more out there."

THE ROLE OF DARPA IN PRINTABLE ELECTRONICS

Devanand Shenoy
Microsystems Technology Office
DARPA

Dr. Shenoy, a program officer at the Microsystems Technology Office (MTO) at DARPA, began with a brief overview of his agency and office. He recalled some of the accomplishments of DARPA, including its leading role in creating the Internet, global positioning system, and stealth technology, and said that the focus of the MTO was to leverage opportunities in electronics, photonics, and especially MEMS. "The key for the development of programs within MTO," he said, "is the fact that we are looking to leverage breakthroughs, not just pushing some area because we think it's interesting. I need to say this, because it addresses the question why are we not spending more in this area."

In the area of portable electronics, he said, a primary opportunity is to work at low cost. This is a result of moving past the current industrial approach of using foundries and masks into thinking in terms of custom design and rapid prototyping. "This is unique," he said. In fact, he said, some tasks done by conventional processing take about six weeks, but with printing can be done in about six days. "There will be tremendous savings when we are able to print," he said. "But you have to achieve the performance to make this more interesting."

Dr. Shenoy reviewed some of the most promising and application-rich areas, including thermal applications, portable imaging technologies, and imaging sensors integrated with amplifying circuitry. In the last area, he said, neither the sensors not the amplifiers were yet good enough, and DARPA was working to address those challenges. Like Dr. Pellegrino, he emphasized the promise of physiological monitoring for warfighters, in which sensors could continuously monitor vital signs; he also mentioned structural prognostics, by which sensors could be placed on platforms to continuously monitor wear and tear on systems.

The Challenge of High Performance

The challenges for all these applications, he said, lie in trying to achieve the required performance. As an example, he cited the Hemispherical Area Detector for Imaging program, which seeks to mimic the function and simplicity of the human eye. The traditional camera has many drawbacks in concept, including the need for several lenses, which are complex, expensive, and heavy. Achieving a 114-degree field of view requires 14 lenses, 2 of them aspherical. "What if we could mimic the human eye?" he asked. "It has a single lens and a curved retina, and a much wider spectral range than cameras. The challenge has been to develop these curved focal planes, because the manufacturing technologies were all developed for flat surfaces. If you could have a single camera with a very wide point of view," he said, "think about the military applications you can enable."

DARPA and partners are now developing technologies that address that challenge. Sea Bright, a company co-founded by Nobel Laureate Alan Heeger, had demonstrated a 128-by-128 photodetector array on a curved surface with a very small radius of curvature, which is the "real challenge." He said that Lincoln Laboratories and others had achieved curved surfaces in the past, but the challenge is to achieve the 1-centimeter range and still have enough pixels. He said that his lab had demonstrated this with pixels of 50 microns. They had processed the signals using metal oxide TFTs on a curved surface, using new maskless laser-write lithography. "It has been a huge success," he said, "to demonstrate we can go beyond conventional electronics and enable some new applications."

Higher Resolution for Printing

In the area of printable electronics, he said, the challenges were more obvious than the solutions. The objective is to create printing technologies that can enable custom electronics without lithography. Considerable investment has gone into displays and lighting, but less into the necessary work on sensors. For printing, he said, the performance of printing technology must improve from a resolution of 20 microns to about 1 micron, which would allow "a huge leap ahead in terms of the performance of transistors and other components." Also needed is to significantly improve the transconductance of the transistors. "You have to talk about these numbers," he said, "and then ask whether you can really achieve something that's much better than what we have today."

Other building blocks for printable electronics include operational amplifiers, which have been used for many years in conventional electronics. The current research question, he said, is whether this performance can be improved using printable electronics technologies, which would enable sensors that are flexible, can be distributed, and have other advances of flexible electronics. "The other building blocks are also very important," he said, "including batteries that are printable. The challenge is really to improve the technology by developing the specific components, assigning performance metrics to them, and showing that we can actually achieve those metrics."

The final example he mentioned was the vision of the flexible x-ray imager, an improvement over conventional x-ray in terms of size, weight, and performance. The portable medical radiography devices in use today are very heavy, and transporting an injured warfighter from the field to the nearest medical facility takes an average of half an hour. A goal is the ability to perform instant x-ray imaging as soon as a warfighter is wounded, which is a high priority for DoD. "In principle," he said, "we can actually scan the entire body in minutes and be able to locate the shrapnel from an IED blast, for example. This would have a huge impact on the DoD's ability to enable new missions."

Dr. Shenoy ended by stepping back from specific technologies, which he called "absolutely important," to offer a broader and more personal view of the issue. "I think that for the industry to get excited about it," he said, "and see where the opportunity is, you've got to show how you can reduce cost. In other words, the challenge for all of us is not so much on the technology side now, or on competing with conventional electronics. It's more on creating new applications and markets, developing low-cost manufacturing, and making clear what the business model will be based on those markets. This is where the real opportunity lies."

NIST AND THE TECHNOLOGY INNOVATION PROGRAM: AN EARLY INVESTOR IN FLEXIBLE ELECTRONICS

Michael A. Schen
Technology Innovation Program (TIP)
National Institute of Standards and Technology (NIST)

Dr. Schen, senior scientist and advisor to the director of the Technology Innovation Program (TIP), said he would review the "innovation infrastructure" that is necessary not only for the flexible electronics technology, but for any "embryonic, transformational" technology confronting American business. He began with a summary of the mission of NIST: to use a variety of technical tools to promote innovation and industrial competitiveness. Those tools, he said, are found within the major programs of NIST, including its laboratories, the Manufacturing Extension Partnership (MEP) program, TIP, and the Baldrige Quality Program.

The tools of NIST that are designed to strengthen the innovation infrastructure include a combination of research tools for wholly new areas of science and technology and measurement, and standards tools for maturing technologies. These tools allow for accurate comparisons not only of performance and function, but also for the frameworks required by international trade. NIST also takes part in various PPPs that are designed to address and accelerate critical aspects of the innovation infrastructure.

NIST is interested in flexible electronics, he said, for several reasons. First, as a part of the Department of Commerce, NIST plays a role in advancing leadership on the part of every industrial community, and in the case of flexible electronics, "that leadership is apparent." In addition, in both the technology as a whole and in the subtechnologies required to support it, NIST is charged with building and strengthening the metrology by which new materials and devices are improved and integrated. A good example, he said, is the need to better measure and analyze the complex nanostructures within the device elements of flexible electronics.

In addition, Dr. Schen said, the technologies of flexible electronics demand manufacturing innovations of high technical risk, which means that sources of private capital may not be willing to invest. NIST has a role in advancing promising technologies that face such a combination of business and technical risk. One reason that flexible electronics is promising in a national context, he said, is its potential to generate jobs, improve the nation's international competitiveness, and address a variety of other critical national needs, such as the need for the best defense-related technologies.

What, he asked, is flexible or printable electronics? "From our point of view," he said, "I'd like to suggest that it is not only a way of manufacturing, but also a potential new set or family of goods. It's not only the what, but the how, and it's important that resources be made available to address both aspects of the problem."

To address the "how" questions, Dr. Schen said that NIST's laboratory programs were focused on both materials processing and electronics aspects of flexible electronic devices. To date, TIP had funded a scale-up in advanced materials competitions for 2009 and 2010, and for critical processes in 2010. To address the "why," he said, industry was providing to TIP its vision of the key gaps that public-private partnerships can address.

Helping Technologies Advance

Dr. Schen summarized the ways NIST tried to apply elements of its toolkit to help technologies advance. The process begins with the discovery, or proof of principle, in which the NIST laboratories and perhaps the newly established construction grant program can help. As the technology begins to mature, NIST may become part of a consortium, such as the FlexTech Alliance, that helps to nurture the technology. This can both strengthen leadership of a new firm and also clarify the objective of the technology and gaps that must be addressed. NIST responds to this process both by assisting individual firms and by partnering with the International Electronics Manufacturing Initiative (iNEMI). He said that NIST used the concept of TRLs to evaluate progress, in much the same way as DoD, ARPA-E, and other organizations.

As a technology continues to emerge, he said, NIST laboratory programs continue their involvement, as does TIP. There is also the opportunity for MEP to help facilitate linkage between users and providers of technology. This program specifically helps to lower business risk and promote the confidence of small firms as they move forward.

Dr. Schen predicted that flexible and printable electronics were poised to have a "global, disruptive, and transformational impact." Citing results from a leading market research firm,[5] he said that the market for printed and thin-film electronics is projected to grow from $1.9 billion in revenues in 2010 to $55.1 billion in 2020, "which would represent a doubling every 18 to 20 months."

Historically, he noted, the Advanced Technology Program (ATP) of NIST had been an early funder of this effort, from which he drew several lessons. Individual projects, he said, were primarily vertical consortia that had a focus on manufacturing, emphasizing prototyping and a systems approach to integration. TIP, which superseded ATP, had begun to offer competitions in 2008 and to focus on manufacturing in 2009 and 2010. This was done not only to accelerate availability of advanced materials at scaled-up quantities and

[5] IDTechEx Ltd. is a global firm that specializes in consulting and market research on radio-frequency identification (RFID) labels, smart packaging, and printed electronics.

improve reliability for device and systems manufacturers, but also to tackle critical process advances embodied in new visions of manufacturing.

Emphasis on Manufacturing, Supply Chain, and Teamwork

The dialogue about manufacturing, he said, started in 1998 and 1999 with industry's vision of both functionality and potential applications. Emerging from that vision, he said, was a set of manufacturing rules. Since then, the problems had become more complex and the insertion points more broad. "This is a continuously evolving landscape," he said. "I would suggest that the frontiers in technology will continue to drive these concepts that were delivered 10 years ago: the emphases on manufacturing, the supply chain, and teamwork, especially on teams that are vertically aligned."

He said that ATP did make key contributions in this development, first by bringing together players in an embryonic industry. It also helped forge a vision of where the industry needed to go. Since then, he said, the industry had moved rapidly and was now on "the cusp of a rapid explosion." This heightens the need for consortia that play a leadership role, he said, pointing to iNEMI as a good example. "That will continue to be necessary," he said, "along with demonstration of manufacturing capabilities and integrating manufacturing with processing and materials." He said that value of the partnership, beyond raising technical capabilities, was to strengthen domestic capacity to participate in the global marketplace.

Dr. Schen said that TIP was distinctly different from the predecessor ATP in its orientation toward translational research that addressed critical national needs. It seeks to do this by providing early-stage money on a cost-shared basis, which mitigates the high technical risk of new technologies. The program allows for the early-stage translation of ideas, he said, and is oriented toward the needs of industry.

He said that printable electronics represented a "solution pathway" that would affect many sectors of civil infrastructure, including energy and health care, as well as defense. During the first year of funding for manufacturing, he said, NIST had been oriented toward scaling up production from research quantities of electronic materials, including printable inks, to producing quantities that device manufacturers could depend on for precommercial work. They were also helping to leverage early-stage investments in nanotechnology.

A Need for Broader Dialogue to Expand Industry Leadership

Dr. Schen then turned to the need for a broader dialogue to expand the industry leadership and the role that NIST programs can play in this regard. He touched on nanomanufacturing and suggested that the pathway to higher performance, new applications, and new market opportunities would depend on demonstrating both the integration of functionality and the capacity of the functionality in any given case. "You're seeing that investment in nanotechnology," he said. "The National Nanotechnology Initiative has reached a point in flexible electronics and printable electronics where nano-enabled inks are on the horizon. That represents a whole new toolkit."

He said that the supply chain was dominated by small and medium-sized enterprises, including the startups from universities, federal labs, and other sources. These startups had the vision to move ahead but were still fragile financially. He said that programs such as TIP and NIST, and consortia with industry, were important in nurturing new enterprises so they can compete globally. At early stages of firm growth, NIST measurement tools helped the firms expand and export.

A challenge ahead of NIST, he said, was how best to align the overall priorities of the institute with those of industry. NIST priorities include strengthening its laboratories and facilities according to critical national priorities. It also plans to promote extramural programs that link it more closely with industry and academia, and to emphasize partnerships with state and regional leadership.

Dr. Schen concluded by summarizing what the new field of flexible electronics means to the nation. The field, he said, represents not only a technology of interest to existing enterprises—some of which are large—but also a growth arena for new firms. The entry of new firms brings the potential for job growth, and a potential laboratory for studying how stronger collaboration among the sectors can improve results. "Improving the efficiency of that innovation and of translational research," he said, "whether between private-sector entities or between public and private sector, is going to be necessary if we are to be successful in a global way."

ONE STATE'S INITIATIVE: ADVANCING FLEXIBLE ELECTRONICS IN OHIO

Byron Clayton
NorTech

Dr. Clayton said that the state of Ohio had introduced its own flexible electronics initiative, called NorTech, and that he had noticed four trends. The first reflected the remarks of many other speakers about the need for government investment. In Ohio, he said, his organization viewed investment in flexible electronics as a larger enterprise involving the state, federal government, and private firms. "We think it's part of the state's job to help spur that private investment." Second, he said that the trend of cultivating collaboration across sectors, also mentioned by other speakers, was an emphasis in Ohio. A third trend was the broad effort to help firms scale up their roll-to-roll manufacturing capability. The fourth trend, not yet begun, would reflect the need for northeastern Ohio and for the state as a whole to stimulate market pull.

He said that NorTech was a technology-based economic development organization, based in Cleveland, which covered 21 counties. Its specific role is to focus on emerging technology industries, with a current emphasis on advanced energy and flexible electronics. He said that the strategy of NorTech was not simply to raise money from the state, but to use that money to leverage federal and private funding as well. As examples of this, he said that the region had recently been awarded an i6 Challenge,[6] as well as a Small Business Administration (SBA) award specifically to help grow the existing flexible electronics cluster.

Building Relationships Across Sectors

At NorTech, he said, the first objective was to build relationships across sectors, for example, with funders who work with universities, small medium and large businesses, and the federal and state governments. Another objective was to draw the activities of industry together in the form of roadmaps. He had just completed one for the flexible electronics industry, in partnership with Dr. Gamota, another speaker at the symposium. "The roadmap we've developed is a strategic roadmap," he said. "We know there are technology roadmaps already developed, so we focused on what do we need to do to grow the industry. This includes collaboration, investment, scaling up manufacturing, and focusing on market pull."

Dr. Clayton discussed a model that he said had worked for NorTech. Technology commercialization was imagined as a continuum of five stages: imagining, integrating, demonstrating, market entry, and growth. The program is structured to allow the infusion of money at the most appropriate point of this technology commercialization continuum.

To do so, he said, the model had been subdivided into several program levels. The largest was the Ohio Third Frontier Investment, a $2.3 billion program designed to focus on the first three phases: doing the basic research, incubating the new firm, and developing the products to the proof-of-concept stage. The Third Frontier program had begun as a $1.6 billion program in 2002. It was placed before the voters in a referendum that failed to pass. NorTech succeeded in placing it as a bipartisan bond issue a second time, when it passed with about 52 percent of voters in favor of it. In 2010, the issue was presented again as a bond issue, to extend the investment by $700 million for three more

[6]The i6 Challenge is a $12 million innovation competition sponsored by the Economic Development Administration.

years, and this time 62 percent of voters approved it. "If you think about what Ohio has gone through during the last recession," said Dr. Clayton, "and the number of manufacturing jobs we've lost, it's refreshing to know that people understand that we need to invest in technology."

The next level was the Edison Programs, which had two divisions. One was for business incubators—specifically technology incubators—of which the state had about 13. The other was for Edison Technology Centers, of which there were six distributed around the state. These were designed primarily to help existing businesses commercialize their products and grow.

The third level was designed to attract investors, featuring a 25 percent state tax credit offered to people who invest in technology. A part of this incentive package was the Ohio Venture Capital Fund, a fund of funds that provided funding to firms that channel at least 50 percent of their investments into technology firms in Ohio.

Within these broad programs, he said, were a number of subprograms that apply money to different areas, including small business, universities, entrepreneurs, and economic development organizations. The strategy is to approach investment simultaneously from multiple directions.

The Need for Clusters

Dr. Clayton said that Ohio had seven programs specifically to foster cluster development, but it had not supported one for flexible electronics. Even without that support, he said, a flexible electronics cluster emerged on its own. "That shows the power of what can happen as an industry emerges," he said. He estimated that while flexible electronics was relatively new to Ohio as an area of investment, several programs had invested about $8 million in the field since 2008. He said that he expected additional investment soon from the Ohio Third Frontier program, which had spent only $1 billion of its $2.3 billion, all of which must be spent within five years.

He discussed where the Third Frontier money had actually been invested in relation to the five phases. Although it had followed the plan's objective of supporting the first three phases of imaging, incubating, and demonstrating, it had invested almost nothing in the last two phases, especially stimulating market pull. He said that NorTech would probably request state support to help stimulate demand and connect the cluster members to that demand.

His final point was to compare the two existing clusters, one for photovoltaics and the other for flexible display and electronics. The PV cluster was in northwestern Ohio, the flexible display cluster in northeastern Ohio. A report by SRI International, completed around the beginning of 2010, attributed about 5,000 to 6,000 jobs to the first and about 1,000 jobs to the second. "The encouraging fact," he said, "was that both continue to grow even in the economic times we're in."

Dr. Clayton summarized some lessons NorTech had learned from its technology investments in Ohio. A key was to develop a shared agenda among cluster members that included pursuit of not only state funding, but federal and private funding as well. A second point was to connect competencies across the state. The northeast and northwest had now connected, he said, and a near-term focus would be to strengthen that connection and add others to develop a more widely shared agenda and greater numbers. A third lesson was the importance of a cluster development program, which was now a current focus. A final point was the importance of encouraging the state to provide funding for market pull. NorTech was planning to do that by using an SBA grant to create a pilot project and show that stimulating market pull does work.

In conclusion, Dr. Clayton stated that Ohio had done a good deal for flexible electronics in the state. "We have one of the best state programs," he said, "and continue to receive some kudos for what we've done. However, there is a lot of work to do." Specifically, he reiterated that the end goal is not to gather state money, but to use state money to raise funding from federal and private sources. He said that the Third Frontier program had leveraged its state money by eight or nine to one, as indicated by the STI study, and that NorTech had created about 54,000 jobs across the state, including a portion for flexible electronics. "So this strategy can be very successful."

DISCUSSION

A questioner asked panel members how much money they had invested in flexible electronics and how much in flexible displays and lighting. Dr. Schen of NIST said that within the last year, its first award cycle had focused on manufacturing. "We're not funding any individual device or systems work, but so far we've been supporting research on inks." He said that the amount invested had been roughly $15 million to $20 million over the three- to five-year life of the awards.

Dr. Pellegrino of the Army said that, "in very round numbers," the Army was spending about $2 million a year on the Flexible Display Center, much of which supported research related to flexible electronics. In addition, several million dollars went into related activities, such as infrastructure, developing tool sets, and early applications of materials devices, an amount that holds relatively steady from year to year. This amount was increased by matching dollars from industry, which, in the case of the FlexTech Alliance, was a 60-40 match.

Dr. Shenoy of DARPA said that the size of any program would depend on the objective. As an example, the Micro-Systems Technology Office may invest "something like $10 million per program per year." A curved focal plane program he was managing received $25 million for four to five years. The work of his office was also accompanied by other related programs, such as a flexible electronics program recently initiated by the Defense Sciences Office.

Dr. Clayton added that in the roadmapping process, he asks cluster partners how much money is needed. He said the cluster had estimated a need for $100 million to accomplish the region's goals over the next seven years.

Dr. Wessner said that the spending environment being described was a familiar one, with DARPA having access to ample funding, TIP having less money, and the states struggling to participate. "We don't do enough in that transitions area, or in the standards area," he said, "neither of which is trivial. We tend to underplay the challenge of exporting to other markets, and more the question of how American firms can make these products and sell them profitably."

Dr. Taussig asked a question about the change from ATP to TIP, by which large companies seemed to be excluded under some circumstances. Dr. Schen said that indeed the legislation only allows for SMEs, as well as universities and other entities, to receive federal money. But he said that large companies can still participate, both to nurture the technology and also to have access to it should it be successful. In this sense, he said the paradigm for large-business participation had shifted in that business could now participate in the role of a venture investor. "They pay their own way, which helps lower technical and business risk by stimulating the supply chain as well as cultivating potential clients or customers. Thus TIP is stimulating at not only the front end but also the back end of a large enterprise. But that message is not well understood yet."

A questioner followed up, asking, "How much coordination has been going on in the federal agencies in funding the flexible electronics effort?"

Dr. Shenoy of DARPA said that this depends on what each agency and office is trying to do. As an example, he said that no other agency was doing just what his program was doing. "That's the first thing we do at DARPA—we spend the first year or more holding meetings or workshops to make sure we are not duplicating someone else's effort. Then we operate in a certain way. We work to a technology readiness level (TRL) of 2 to 4, and then hand it over to the services. That's the DARPA model. We don't stay in this for too long. Once we review the risks, we hand it over and help them transition it to specific platforms."

Dr. Schen of NIST added that the work of NIST is enhanced by the strong contributions from the NIST laboratories and partners in other agencies, in addition to some of their contractors.

A questioner from the audience asked about coordination among agencies and others working in this area.

Dr. Andrews of L-3 said that the investment was still very small, with the largest appearing to be from the Army at $15 million or so per year. He also noted Dr. Pellegrino's comment that the largest challenge is to improve manufacturing technology. But he said it would be useful to think about what a major coordinated effort would cost.

Dr. Pellegrino said that extra funding for flexible displays would certainly accelerate the current progress being made and integrated with the commercial sector. The same might hold true for more general flexible electronics, he said. With funding on the order of $10 million to $15 million per year, "you could make great inroads into the applications and manufacturing." If $100 million a year were matched and continued over five years, one might expect "a couple of different applications spaces," and assurance of real progress in at least one of them.

Dr. Clayton said that one of his cluster member companies had taken a different approach. After receiving both state and federal funding, the company had hit upon a product that seemed to have commercial appeal and took it directly to market. The idea was a flexible, rewritable display on a writing pad, which they called a boogie board. To the surprise of many, it became a fast-selling item on Amazon, and the company quickly added employees, shifts, and revenue. They also learned more quickly than most companies about scaling up their manufacturing, "because they had real customers banging on their door." In the cluster, other companies were now saying they might like to look out for applications of their own that they could commercialize. "Maybe it's not the sexiest product," he said, "but it's out there, it's working, and the company is scaling up and learning how to manufacture."

Panel III:

What Is the Rest of the World Doing?

Moderator:
Pradeep Fulay
National Science Foundation

Dr. Fulay, program director of Electronic, Photonic, and Magnetic Devices at NSF, said he would briefly review how NSF had been involved in supporting flexible electronics research. He said that flexible electronics itself was funded primarily through the Division of Electrical, Communications, and Cyber Systems, and that the Small Business Innovation Research (SBIR) program had funded many of the companies working in the area. NSF also covered many areas of basic research of relevance to flexible electronics, as well as technology transfer and translational research.

As illustrations, he listed some "hybrid devices" supported by NSF that find application in key fields:

- Energy: organic photovoltaics, solid-state lighting, and batteries;
- Electronics: displays, e-paper, sensors, and actuators;
- Biomedical and health care: sensors, system on a foil;
- Communications: RFID; and
- Defense: various applications.

He also reported that NSF supports a wide variety of flexible hybrid electronics research, including the following:

- Organic and polymer electronics and optoelectronics: OLEDS, organic field-effect transistors (OFETs), solar cells, and sensors/actuators;
- Inorganic thin-film devices: transistors and circuits, light emission, PV, displays, and batteries;
- Hybrid devices: both organic and inorganic; and
- Hybrid circuits and systems: hybrid organic/inorganic complementary metal oxide semiconductors (CMOSs), etc.

So the central challenges for each of these areas of research were fabrication and manufacturing. The pressing issues in these areas include the need to achieve low cost, high throughput, and print compatibility.

In addition to hybrid devices, he said, NSF provides research support and opportunities, including programs that encourage university-industrial partnerships. Depending on definitions, he said, the foundation supported about 200 projects in flexible electronics, including work on transistors, OLEDs, zinc oxide, and flexibly printed electronics research. "Typically, these are small, single-investigator projects, though the NSF does support an Engineering Research Center in solid-state lighting and a lot of instrumentation through the Materials Research Initiative. The foundation also encourages strong industrial interaction, including a number of programs directed at SBIR/STTR programs and GOALI programs."

In Europe, a Spirit of Sharing

From an international perspective, he said that he and a colleague had funded a study in May 2009 to assess the state of the art in flexible electronics, primarily in Europe. They visited leading laboratories in industrial, university, and other research settings to learn more about successful strategies. He had many discussions about how industry has to collaborate and work with universities, and vice versa. He said he saw some outstanding examples of this, especially in Europe, where barriers between academia and industry are very porous, with "professors going back and forth." There are effective mechanisms for dealing with intellectual property (IP) issues, notably at the Fraunhofer institutes in Germany and IMEC in Belgium. He described dynamic interdisciplinary teams that had developed effective ways of working together.

Dr. Fulay cited strong research groups that had existed for many years, and close public-private partnerships working in precompetitive research. A key, he said, were mechanisms to promote sharing of specialized fabrication and prototyping facilities and multiorganization centers.

During his survey he had queried European scientists about perceived U.S. strengths in this field of research. Those scientists commented on the following:

- Strong research universities with well-regarded Ph.D. programs;
- A well-developed venture capital infrastructure more advanced than that of most countries;
- Practical knowledge about how to create startup companies;
- Ability to attract talent from everywhere; and

- Strong public support from organizations such as NSF, DoD (e.g., ARL-Flex Display Center at Arizona State University), DoE, and others.

He summarized his talk in the form of suggestions from the panels of experts created during the survey. These suggests were offered in three groups, as follows:[7]

Suggestions (1):

- Establish NSF-National Nanofabrication Infrastructure Network (NNIN)-like facilities dedicated to flexible hybrid electronics.
- Allow universities greater access to federal fabrication equipment and expertise.
- Provide incubation facilities for small companies.
- Replicate successful NSF models for microelectronics and nanotechnology.

Suggestions (2):

- Establish a SEMATECH-like organization for hybrid flexible electronics to support precompetitive research involving multiple companies and universities.
- Nurture technologies until they are ripe for commercialization.
- Create support models linking government agencies and industry.

Suggestions (3):

- Establish new funding streams that support research from multiple organizations.
- Create focused R&D centers that perform the full range of research, from fundamental to applied.
- Enhance funding mechanisms that would help groups of companies to develop high-risk technologies.[8]

Despite funding and time limitations, he said, his study "was an eye-opener. I would like to see this happen at a higher level in the U.S. We also need to have more agencies working together and try to leverage these partnerships the way they do in Europe. This has been an EU-level priority for about a decade, where they take a long-term view of the field."

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[7]See World Technology Evaluation Center website, where a free 25-Mb file containing the full report is available.
[8]Report is available at <*http://www.wtec.org/flex/HybridFlexibleElectronics-final-July2010.pdf*>.

THE GLOBAL VIEW OF PRINTED ELECTRONICS AND WHAT IT COULD MEAN TO THE UNITED STATES

Andrew W. Hannah
Plextronics
Pittsburgh, Pennsylvania

Mr. Hannah, CEO of Plextronics and vice chair of the Organic Electronics Association, began with a description of his company, an eight-year-old spin-out from Carnegie Mellon University, based in Pittsburgh. Plextronics had 70 employees, about 22 of whom were Ph.D.s from around the world. The company's objective was to develop polymer-based inks that were either semiconductive or conductive. They were sold for three primary applications: printed light, printed power, and printed circuitry.

He defined printed electronics as "organic electronics plus flexible electronics." In the case of Plextronics, the company makes printable inks for customers to use on substrates. When the inks are printed, they become thin, functional films that can be used to create many next-generation electronic devices, such as thin displays, organic solar films, or potentially RFID tags. One advantage is low cost, he said, and another is flexibility. Using such inks, customers are able to place the electronics on any surface they can print them—one of the visions of the industry.

In visualizing the developing industry of printable electronics, he suggested, it was helpful to "think from a Lego perspective." The industry begins with a set of basic building blocks that are assembled to produce more complex and useful integrated products. In the case of printable electronics, the building blocks include lights in the form of OLEDs or small area flat-panel displays for white-light panels of cell phones and other existing products; organic photovoltaics (OPV); building-integrated photovoltaics, for which early products are already on the market; and OFETs, for which demonstrator products include RFID tags for baggage handling by airlines.

The integration stage begins when innovators place these building blocks on any surface of a device and then imagine the different applications. In the early stages of the industry, the focus was restricted to achieving low cost or performing some function better than an existing technology at a minimal level. For the industry to emerge, he said, it needs to break out of this restricted thinking to realize the much greater potential applications. "It's what can you do creatively with these technologies when you combine them."

Power New Uses in Advertising

Mr. Hannah mentioned the example of advertising, which today uses primarily electrophoretic, electrochromic technology in which OPV powers electrophoretic displays under indoor lighting. But several marketing studies indicate the potential for much more powerful uses, he said. Customers who see a sign with a product will buy it 40 percent more often than if there were no sign. If the sign moves, they will buy the product 80 percent more often than if there were no sign. "So motion drives purchasing behavior," he said. "It is only a matter of time before you walk into a retail establishment and see these things blinking. You can see that printable lighting represents the next generation of advertising, product packaging, or shelving labels."

These new forms of lighting will need power, he continued, and they will not all be connected to the grid. He said that OPV was a good example of a new energy harvesting technology that will become more useful. The use of price tags will also change, he said, to connect them electronically with inventory control. "You'll completely change the way you manage the inventory," he said, "because you can then introduce dynamic pricing. For example, when supply goes down in a retail environment, the price should go up. In an integrated world when these things talk to each other, that becomes a reality. It is also an example of how business models can change."

Today, he said, printable electronics represents a $2 billion market, with OLED lighting accounting for about half and other forms dividing the rest. At current rates of growth, the various components of the industry, including lighting, power, and circuitry, are projected to become a $60 billion industry by 2019. "That is a big number," he said. "Is it possible? I have venture investors, so I have to answer that question quarterly, and will try to show you why I think that it is possible."

The Technology is "Leaking Out of the Country"

Around the world, Mr. Hannah said, some 3,000 organizations are developing printed electronics, according to trade organizations. Of those, about 850 are in the United States, 875 in the European Union, and 650 in East Asia. So the customers are divided fairly evenly throughout the world. In terms of Plextronics customers, he finds that, of his 50 largest customers, about half are in Asia, a third in Europe, and only six in the United States. In addition, an analysis of patents shows that about 5,000 patents in organic electronics have been awarded in the United States, 4,000 in Europe, and 25,000 in Asia. "So where's the activity? he asked. "In Asia."

He also presented an analysis indicating that U.S.-based printable electronics companies are becoming scarce—even though "technology creation is a U.S. strength." He reported that U.S. companies are being bought by non-U.S. firms, and non-U.S. venture capitalists are investing directly in U.S. firms. For example, E Ink was acquired by PVI (Taiwan), Kodak's OLED business by

LG (Korea), Artificial Muscle by Bayer Material Science (Germany), and Dow's Business Unit by CDT (United Kingdom). U.S. firms receiving foreign direct investment include Add-Vision from CDT, Alps Electric, and Toppan Forms (all from Japan); Polyera from Solvay (Belgium); Plextronics from Solvay (Belgium); and Konarka from Total (France) and Konica Minolta (Japan). "I'm in the venture community a lot," he said, "and I see more activity from a foreign investment and acquisition perspective in this technology than I've seen in any other industry. This is another indicator that the technology is actually leaking out of this country.

Government Backing is a Strength Abroad and a Weakness in the United States

Continuing with his industry analysis, he discussed expenditures being made by governments. "Government backing is identified as a strength in Asia and Europe," he said, "and a weakness in the U.S." Using data from IDTechEx, a research and consulting service, he said that the U.S. government spent about $50 million in 2009 on printable electronics. In Europe, governments had spent a total of half a billion dollars, and have planned to spend an additional half a billion dollars, mostly on government-industry consortia. Much of the spending is clustered around specific topics, he said, such as "a strategy to develop a next-generation material for organic field-effect transistors so we can own the printed transistor market." Another target may be organic light-emitting technology and how to integrate it with other technologies. "What comes out of this spending is consortia of companies," he said. The requirement is real demonstrations of market pull, which is needed to support the development of the supply chain and the technology and materials for the specific application. Data on government spending in Asia, he continued, is very difficult to gather. For Taiwan, he said, the government intends to invest about $200 million in printed electronics from 2006 to 2013. He had no data for Korea, but spending there was estimated to be greater than for Taiwan. He had no data for Japan, but spending there was estimated to be greater than for Korea.

A Missed Opportunity?

Mr. Hannah said that the OEA, the largest global trade organization for printed electronics (PE), keeps a detailed roadmap to track how government spending is allocated. The roadmap is refreshed regularly, using nine specific applications, including such detail as material requirements, roadblocks, and which groups are working on various aspects of the technology. "This is a very powerful way to drive an industry," he said.

He said that the current conclusions about the global PE market included the following points:

1. Asia leads the world in developing intellectual property.
2. Foreign purchases and/or investments in U.S. businesses are large and accelerating.
3. The United States is being outspent in PE by other governments.

In considering whether the United States has missed the opportunity for leadership in PE, he cited the LCD industry as a "cautionary tale." Referring to a chart of LCD industry growth over time, he said that the first operating LCD had been developed in 1968—by an American company, RCA. This was followed by the first demonstration of amorphous silicon-based, active-matrix LCD in 1988. By six or seven years after that, LCDs had grown to a $10 billion industry, largely because of demand for laptop computers. The industry then went through "period of boom and bust," with the introduction of cell phones driving the next generation of growth, followed by a pause, and now the popularity of LCD televisions driving the current phase of growth. "This is a cautionary tale," he said. "In 1968 RCA developed the first operating LCD, but today 90 percent of the production of LCDs is in Asia." In addition, he said, the LCD experiences also demonstrate how fast growth can begin—once it begins.

The Power of the High-Tech Science Park

"It's not too late to do what the U.S. should be doing," he said. What worked for advanced electronics industries, he said, was the high-tech science park. He noted that in Taiwan, a "whole corridor of high-tech science parks generate[s] critical technology for the OLED space." As other models he cited the Holst Centre in the Netherlands, focused on a vertical approach to the OLED industry, as well as the Fraunhofer and ITRI facilities. In the United Kingdom, he said, PETEC was an interesting model—a design, development, and prototyping facility competing for position in the next generation of lighting technology.

"One policy strategy I find very interesting," he said, "is the U.K. action to ban incandescent bulbs, which is going to drive the next generation of lighting technology there. So you don't need just money to drive technology and policy change, you need to figure out what will drive behavior."

As an industry, he said that he estimated an R&D need for $100 million a year. But the priority must be a focus on the end users: "The applications are what's going to drive this business." Second, applications will have little impact without advancing every step in manufacture, including testing, validating, and improving technology through prototypes and demonstrators.

"We have technologies in OLED and some OPV that could move into the market tomorrow," he said. "There's no doubt about it." He said that one customer was ready to buy 100,000 units of his firm's technology, an integration of OPV and lighting technology. If it could be manufactured at a low enough price, he continued, the customer would take two million pieces immediately. However, his firm does not have any partners that can manufacture at such high volume, so he has to reach out to an Asian company and a German company for help. "So the applications are here," he said. "We just need really smart people to develop the applications and the manufacturing infrastructure."

The essential steps for building the industry in the United States, he said, are to focus on the applications, focus on the industry, and provide incentives to companies that will use U.S.-made components and build a U.S.-based supply chain. To establish state-of-the-art manufacturing, he said, the industry needs to share infrastructure, especially for the prototyping stage of development.

Mr. Hannah closed by advising firms to take a patient view of their investment in this new field. "It's like trying to change the energy industry overnight," he said. "This isn't like developing software, where you can deliver products tomorrow."

ORGANIC AND FLEXIBLE ELECTRONICS IN GERMANY —A SNAPSHOT

Christian May
Fraunhofer Institute for Photonic Microsystems
Dresden

Dr. May said he would give an overview of the development of flexible electronics in Germany, and more broadly in Europe. He said that although the activities and projects of his Fraunhofer Institute for Photonic Microsystems was funded by several levels of government—the German federal government, the local government of the Free State of Saxony, and the European Commission—he considered himself "a user" who developed technologies, not a government scientist.

He said that across the European technology landscape, it was difficult to distinguish the various kinds of photonics by attribute—flexible, organic, printable, and so on—because they are all closely related. His institute in Dresden, he said, focused primarily on "small-molecule materials which had not been printable in the past." In Europe, he said, this category is called organic or large-area electronics. The attributes of this technology category that are valued in Europe include robustness and flexibility, which allow for ubiquitous electronics, and its many "green" features, which include low carbon footprint, low materials consumption, low-impact manufacturing, and a substantial contribution to reducing energy consumption. He called the goal of low-cost manufacturing "a vision of the future," which was needed to bring the promise of low-cost substitutes for CMOS technology. Aspects of the technology that have been demonstrated to date are expensive, he said, so a primary goal is to achieve mass production and reduce costs.

The current space that includes organic and large-area electronics, he said, could be better understood by a glance backward into the past. Through the 1990s, he said, the industry emphasized inorganic semiconductors, including flat-panel displays. Beginning around 2005 this emphasis shifted to LCD panels and was moving to organic and printed electronics, with growth predicted to increase from 2015 to 2020.

In Europe, a Lack of Startups and Entrepreneurs

In Europe, Dr. May said, there was good strength in research and development on OLEDs, printed RFIDs, and transistors. He also said that the European market was "huge," as the field of applications grew steadily. He cited a very good supply chain, especially in materials and production machinery. A notable lack, however, was a sufficient number of startups and entrepreneurs "with a clear view from research to manufacturing. Committed giants," he said, "are needed. We have to bridge this gap from basic research to industry." He said there was some risk that the European market would be taken over by foreign manufacturers, and external companies would benefit from the research and investment already being done in Europe.

A strategic research agenda of Photonics21, which is the European Technology Platform for Photonics and a synchronized strategic research agenda for the Organic Large Area Electronics (OLAE) were handed over to the European Commission during the Photonics21 Annual Meeting in Brussels in January 2010. He noted that the details of the agendas were public and could be downloaded. He said that a key recommendation of the merged groups was to develop more pilot production centers in technology clusters to help close the gap between R&D and products. In addition, it recommended more nurturing of the emergence of a European OLAE industry, partly through new approaches to creating lead markets.[9]

Other recommendations included the following:

- Establish an OLAE platform with the participation of all stakeholders.
- Coordinate existing OLAE networks and platforms.
- Coordinate EU and national member state R&D programs.
- Develop an approach for R&D cooperation in and beyond Europe.
- Establish standards early in the development of a new product.

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[9] *<http://www.photonics21.org/>.*

- Establish new training schemes suited to the heterogeneous OLAE field.
- Increase the EU R&D funding budget for OLAE in response to huge market expectations.
- Establish new ways to access capital.

All such activities, he said, would have to be coordinated; this was even more important than funding levels.

Dr. May turned to the organic electronics situation in Germany, where most of the funding for the past 10 years had come from the German Federal Ministry of Education and Research. At first, the funding was targeted at various single projects, but later was given to coordinated actions, such as Polymer Electronics, the funding topic for 2001. To date, the ministry had furnished about €30 million in funding for organic electronics.

Innovation Alliances

A new instrument for Germany was the Innovation Alliance, which had two major projects.

The first was the OLED Alliance, which received €120 million from the government, starting in 2006 and continuing with Phase 2 in 2009. By that model, industry commits to investing five times what it has received during the public funding phase if it is successful at commercialization. This alliance focused on OLEDs for lighting applications and organic photovoltaics. The three large private partners were the dominant German lighting companies, Osram and Philips, and Applied Materials. One emphasis of the Innovation Alliance was machinery, led by Applied Materials, and another focused on special organic lighting applications, such as lighting applications, displays, illumination, signage, and automobiles.

The second German instrument was the Innovation Alliance OPV (organic photovoltaics), which had received funding of €60 million, starting in 2008. Phase 2 was planned for 2011.This alliance used the same basic partnership model as the first alliance.

A third instrument organized by the government was the Cluster of Excellence approach for organic electronics. Candidates were invited to compete for nomination as Clusters of Excellence, and each cluster would consist of a consortium of universities, R&D organizations linked to universities, and companies. Applicants could represent any fields in engineering. A cluster in Dresden had been selected to work on silicon-based high-efficiency devices for computing. A second cluster under installation in Heidelberg was designed to emphasize organic electronics, for which it receives €40 million in funding, matched by industry contributions, for the period 2008-2013.[10]

Dr. May then turned to the German research landscape, describing a general division of labor by which the universities typically perform fundamental research while industry performs applied research and development. Funding for internal and external investments in research by industry totaled €55.4 billion, while the budget for universities was €9.2 billion and for the state (Länder) institutes €0.9 billion. Other research organizations include the Max Planck Gesellschaft, which focuses on basic research; industrial research labs; and the special model of the Fraunhofer Gesellschaft, which tries to bridge the gap between basic research and the developmental work of industry. Typically, he said, Fraunhofer works closely with university, with institute directors holding academic chairs. The objective is to "use results of basic research and transfer such results to processes which are of use to industry. Therefore we are more or less working on industrial-related equipment." He also gave a more formal description of the Fraunhofer objective as the effort to "undertake applied research of direct utility to private and public enterprise and of wide benefit to society."

Fraunhofer is the biggest nonprofit R&D organization in the world, he said, with about 17,000 employees and annual budget of €1.4 billion. It consists of 59 institutes that are involved in virtually all fields of engineering; each institute is largely independent administratively. About 33 percent of operating funds come from government, while another third comes from publicly funded projects awarded to Fraunhofer on a competitive basis. The most important portion, he said, was the final third, which is generated from direct contracts with industry. "This number," he said, "shows how attractive the work we are doing for industry is, which is to bridge the gap between basic research and the work done by industry."

Dr. May has worked at the Fraunhofer Institute for Photonic Microsystems (IPMS) since 2003. Its permanent staff of 207 is led by directors Prof. Dr. Hubert Lakner and Prof. Dr. Karl Leo. The total budget is €23 million. Most of this budget is dedicated to research on MEMS devices for photonic applications and on organic electronics. Dr. May, along with Prof. Leo, is responsible for activities in organic electronics. It is one of several business units and includes lighting, photovoltaics OLED microdisplays, and sensors.

The Challenge of Cost

In 2008, IPMS created a "trademark" for its activities called the Center for Organic Materials and Electronic Devices (COMEDD) to market its own

[10] *<http://www.optischetechnologien.de/>*.

work more effectively. Under COMEDD, three fab lines are being installed. The first is a pilot line to produce a Gen2 substrate for work in OLED lighting. The second will be for roll-to-roll manufacturing, "because we will only succeed if we decrease costs very, very much," including the cost of materials. A third line would handle such technologies as signage, OLED on CMOS, lighting, and organic photovoltaics, which he called "technically very similar." These pilot fabrication lines would be designed to produce "medium" volume for companies that want to be active in OLED lighting and signage, but which lack sufficient funding to invest in their own lines.

IPMS has a large number of research and industrial partners, he said, both in Dresden and in the surrounding area. This network consists of collaborators who support the "full value chain" of activities "from materials and modeling to organic technology to tools to products." The network receives some "minor" funding from local government to help with management.

His own project, named R2FLEX, is developing roll-to-roll fabrication of small-molecule OLEDs for lighting applications and organic solar cells on flexible substrates. The project had introduced tools, he said, enabling the production technology for lighting, but the project still had to decrease material costs and process manufacturing costs. It was attempting to do this by using metal strips as cheap substrates and establishing a small-molecular roll-to-roll deposition process. This project, begun in 2007 and now in its second phase, had 11 partners from industry. Of total funding of €11 million, 58 percent came from the German Federal Ministry of Education and Research, the rest from industrial partners themselves. The project was now developing its first R&D production line to make the change from sheet-to-sheet to roll-to-roll processing. Its objective would be to provide monochrome OLEDs for lighting and signage, and to adapt this process for organic solar cells as well.[11]

Dr. May summarized by saying that organic electronics were strong in Europe at the research and developmental levels, but that this technology still faced challenges in moving to industrial products at industrial scale. A significant catalyst for this challenge was the German funding model, which included a blend of government assistance and industry matching.

[11]The system, he said, was a batch-type R&D vacuum coater for metal strips and polymer webs up to 300 mm with up to 14 linear organic evaporators. The substrate patterning and coating were done by wet processes with some lamination available under an inert atmosphere and the possibility of inert transfer between systems.

TAIWAN'S FLEXIBLE ELECTRONICS PROGRAM

Janglin (John) Chen
Display Technology Center
Taiwan

Dr. Chen brought to his presentation an unusual perspective, having spent 24 years with Eastman Kodak in the United States before moving back to his native Taiwan to become a leader in developing the flexible electronics industry. He was chief technical officer for the Kodak LCD Polarizer Films Business until 2005, when he took a position as vice president and general director of the new Display Technology Center in Taiwan. He also became chairman of the Taiwan Flat Panel Display Materials and Devices Association.

He began by saying it was a pleasure to be back in the United States, and to have the opportunity to discuss some lessons learned in Taiwan that might be helpful to those developing flexible electronics in the United States. "It may be some advantage to be able to see both sides of the fence," he said.

Dr. Chen said that his perspective would be informed by his position at ITRI, the Industrial Technology Research Institute. ITRI is located in Hsinchu Science and Technology Industrial Park, the leading science park of Taiwan, where some 360 high-tech firms are located. ITRI was founded in 1973, and ITRI South was added in 2004. As of January 2010, it had 5,852 employees, 1,126 of whom had Ph.D.s. The institute had spawned 10,132 patents and 158 startup firms, and had opened flexible electronics pilot labs to develop the areas of printed circuits, paper-like speakers, touch sensors, printed sensors, flexible lightings, and flexible PV films. A major objective of Hsinchu Park, and of ITRI, is to facilitate technology transfer from the research labs to private firms.

Dr. Chen commented on the current high standing of Taiwan in the world of electronics. Taiwan is a tiny country, he noted, about the size of Rhode Island, with a population of about 24 million. Yet this small island, with a gross domestic product of about $418 billion, has made a "significant and remarkable achievement in the last 20 or 30 years" by assuming a global leadership role in manufacturing ICT-related products. Today, he said, one strategy is "basically trying to leverage Taiwan's fast integration capability and to add value to ICT products by introducing this new feature called flexible."

R&D Driven by the Federal Government

The R&D effort in Taiwan, he said, is primarily driven by the federal government through the Ministry of Economic Affairs (MOEA). ITRI, a not-for-profit organization, plays the leading role in identifying and developing promising new technologies, along with the major research universities. "At a certain point in technology development," he said, "they invite industry to participate and invest, and then the government will come in with matching funds. That's how the industry is gradually built up."

In the area of flexible electronics, investments for 2010 were made as follows: $30 million from MOEA to research institutes, $2.5 million from MOEA to universities, $6.1 million from MOEA to industry, and $7.5 million invested by industry. This followed a decision made in 2006 that MOEA would begin to fund R&D projects in flexible displays, electronics, lighting, PV, and related material, process, and equipment development.

Dr. Chen then delineated the process by which a technology is actually supported and encouraged toward full commercialization by industry. The key, he said, was to get industry involved through joint development programs. As an illustration, he diagramed the key elements of support for the electrophoretic display industry, in which he was personally involved. "To build an industry," he said, "you have to build a complete supply chain, all the way from the upstream R&D to the market. This has five elements: first materials, then equipment, then the panel maker, then a system, and finally the application or market. For the materials stage we recruited and invited four companies to join this joint development program. On the equipment side, we recruited five companies, and so on. This model for the electrophoretic supply chain is the same model we used for the LCD supply chain. This model has worked pretty well and it's been proven year after year to be capable to gradually build up the complete supply chain."

A Strategy Focused on Lifestyle

Dr. Chen said that an emphasis on flexible electronics had formally begun in Taiwan in 2006, the same year he returned to take a job with ITRI. In that same year, he moved into the new Flexible Display Center as director. In the five years since then, the Taiwanese government has invested close to $200 million in this technology. "So the government is really behind the whole incentive," he said. "We believe this the first significant opportunity in flexible electronics. Basically, our strategy focuses on two main themes that have to do with lifestyle. One is the mobile lifestyle, and the other is green energy-saving display."

He displayed some of the product areas in his technology portfolio, such as printed circuits, touch sensors, and printed sensors, but most importantly, he said, they all made use of the transition from rigid substrate to flexible substrate. This work was carried out in the well-equipped Flexible Electronics Pilot Lab. In addition to roll-to-roll (R2R) sputter technology, it also had an R2R exposure unit and equipment for many printed or flexible applications. "When you transition from rigid to flexible substrate," he said, "it is very important how you enable it. Much of our effort and achievement have been realized through the so-called flex substrate material and how to build flexible devices on a rigid substrate. I negotiated to acquire this technology from

Eastman Kodak, and it's a very elegant design, and truly roll-to-roll." The process, called Bi-Chrome Cholesteric Display, uses a series of patterning, coating, layering, and cutting processes.

Reads and Writes Just Like Paper—"and It's Rewriteable"

"As a result, the kind of flex display or device we generated reads and writes just like paper. Even more beautiful, it's rewriteable. You basically erase the image and then it's ready to be rewritten again. We're trying to open up or explore different applications." As an illustration, Dr. Chen showed this e-paper being used to copy or duplicate landscape paintings by Chinese artists from the Song Dynasty, in particular the famous "Pure and Remote View of Streams and Mountains" by Xia Gui. For this purpose, the e-paper was made very long and narrow, 300 cm by 24 cm. He also showed examples of e-signage and a "soft clock" using this technology.

One of the products generated by this center was the "paper-like speaker" that won the 2009 *Wall Street Journal* Technology Innovation Award, he said. Formally called the paper-thin fleXpeaker, it covers a large area, 2.2 meters by 50 centimeters, and consumes only a fifth to a tenth the power of a traditional speaker. It is designed for autos, ICT products, home theaters, and other uses.

He also elaborated on the process of using a new material, polyimide (PI), as a substrate. His center knew that when a plastic material is used as a substrate and glued to the glass substrate holder, it results in poor alignment, residual glue, and low tolerance for high temperatures. When PI is applied in solution to make a transparent film on the glass substrate, it gives a large coating with good alignment, no residue, and high-process-temperature tolerance. "And this process lets us utilize a huge infrastructure of current Taiwan flat-panel display manufacturing," he said. "We could use a capacity that's not being utilized, to make a new product." It has been given the name FlexUP, or Flexible Universal Plane, which has "higher transparency, higher electrical conductivity, and it's flexible."

Dr. Chen touched on some current events that had shifted the global balance of firms in the flexible electronics field. The recent financial crisis, he said, had put great pressure on some innovative but small Western companies, which have been forced to seek additional funding or even buyouts. The best-known example was the absorption of E Ink into the large Taiwanese firm PVI, the combination of which is now known as E Ink Holdings, Inc. E Ink Holdings now supplies e-paper modules to Amazon, Sony, Barnes & Noble, and many other firms. In another case, the giant Taiwanese firm AU Optronics Corp (AUO) bought another American company called SiPix, which had developed a microscale e-paper that is imprinted with minute holders for nanoquantities of fluid or particles and can be produced in sheets by roll-to-roll technology. In summary, he said, "one firms' demise happened to be the other firm's fortune."

Suddenly, much of the world's e-reader technology is now concentrated in Taiwan.

He closed by summarizing some of his major points:

- Leveraging the experience and sound infrastructure of ICT manufacturing, Taiwan is well positioned for developing next-generation flexible electronics.
- Development activity in Taiwan is propelled by the government's seed funding. ITRI, the government-owned institute, then develops, along with research universities, the fundamental technologies and subsequently transfers them to industries as it forms a complete supply chain.
- Presently, flex display is the most promising market opportunity for flexible electronics. Large-area, flexible sensors could be the next.
- Recent financial difficulty had driven a wave of Western startup firms to seek funding or manufacturing partners in Asia. This trend had helped to bring to Taiwan important new technologies in flexible electronics.

FLEXIBLE AND PRINTED ELECTRONICS—A KOREAN INITIATIVE

Changhee Lee
Seoul National University

Dr. Lee, professor of electrical engineering and computer science at Seoul National University (SNU), began with a brief discussion of the origins of printing. He graciously noted the beauty of the Gutenberg process of the 1400s, but proudly displayed an even earlier Korean effort. This was a Korean Buddhist document known as the Jikji, the world's oldest product of moveable metal type, printed in Korea in 1377.

Korea is a small country, he noted, so it had to focus its development efforts on specific areas that were relevant to existing industry. He said that display technology and some of the applications fit well with earlier technologies in terms of infrastructure and human skills. "We believe that everything that can benefit from being flexible will be flexible, and printed," he said.

He added that for a resource-poor country, flexible electronics had special appeal in their low cost and ability to reduce material waste and energy consumption. He also noted that a paradigm shift is under way that "may be a threat to our existing industries" if Korea does not adapt quickly enough. In doing so, he said, Korea would take a slightly different path than Taiwan. Because its own government was more conservative than that of Taiwan in matters of technology funding, the shift would have to be led by Korean industry, which, he said, was "very aggressive" and is led by global giants Samsung Electronics and LG Electronics.

Korean Universities and Research Institutes

Dr. Lee offered a detailed view of Korean universities and research institutes, which are located primarily in Seoul, Daejeon City, Jeonbuk Province, and Jeonju City. The initiatives in printed electronics were in five main locations, the largest in Seoul. They were coordinated by the Korean Display Industry Association (KDIA), whose focus was mainly on flexible electronics. The other major association is KoPEA, the Korea Printed Electronics Association; both are headquartered in Seoul. The two associations, he noted, did not work closely together, even though their interests overlap. Another broad organization, the 21st Century Frontier Program, supported research in next-generation displays, and Seoul National University supported an Inter-University Semiconductor Research Center Display Center and an OLED Center.

In Daejeon City, the Electronics Telecommunications Research Center (ETRI) is one of largest such centers in Korea, focusing on flex and OLED lighting. Also located there is the Korean Research Institute of Chemical Technology, conducting research on printing technologies; the Korean Institute in Machinery and Mechanics, for research on printing machines and technology; and the Korean Advanced Institute for Science and Technology, a largely theoretical research institute.

In Jeonbuk Province and Jeonju City, he said, were held International Workshops on Flexible and Printed Electronics at Mooju. In addition, there is the Jenoju City branch of KETI, and the Korean Printed Electronics Center, supported by the Ministry of the Knowledge Economy.

In Sunchon City is the Regional Innovation Center and the World-Class University Program, supported by the Ministry of Education, Science, and Technology. The university has a printed electronics department with both undergraduate and graduate students that is "quite unique," he said.

Pohang City is home to the premier Korean research facility for nanotechnology, the Pohang Science and Technology University, a small research university and cluster.

Dr. Lee also briefly discussed the Korean Printed Electronics Center, most of which is located in Jeonju City. The government gave support of $70 million from 2004 to 2009, and the local government contributed as well. Some 59 universities, small companies, and other participating organizations work at the center.

Of the major technology companies in Korea investing in flexible electronics, Samsung maintains most of its facilities at a large complex in Suwon City/Kiheung, including Samsung Electronics (R&D on semiconductors, LCDs, and Si-solar cells) and Samsung SMD (OLED R&D). The second

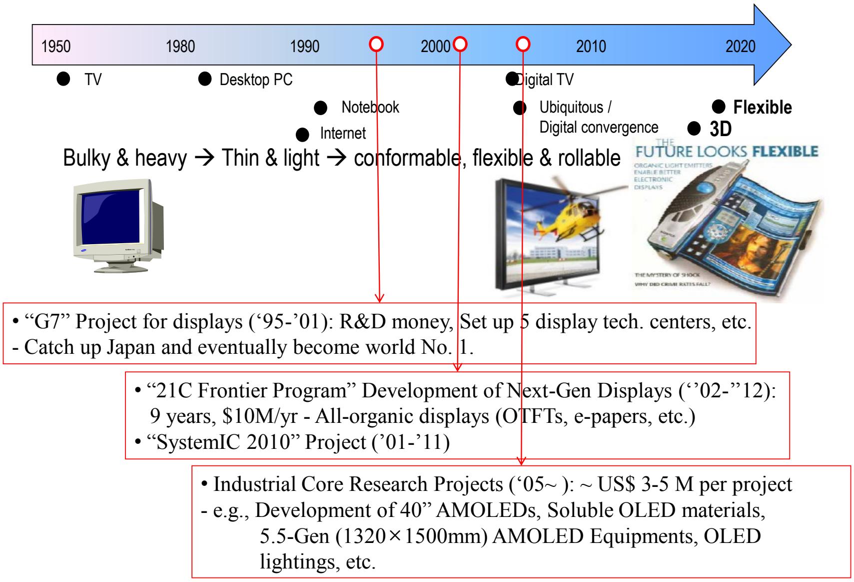


FIGURE 2 Roadmap of displays and government support.
SOURCE: Changhee Lee, Presentation at September 24, 2010, National Academies Symposium on "Flexible Electronics for Security, Manufacturing, and Growth in the United States."

corporate giant, LG, supported LG Display in Kumi City (LCDs and OLEDS) and LG Display in Paju City (LCDs, OLEDs). He said that LG would invest more than $1 billion in 2010 and 2011 to build up OLED products.

Finally, he said, several small companies were located in Sunchon city, making roll-to-roll RFIDs.

"Catch Japan"

Dr. Lee showed a summary roadmap of the Korean display industry and government support. "In 1950 we had had nothing," he said, "all destroyed by Korean war." The electronics industry emerged rapidly in the late 1960s and 1970s, beginning with black-and-white television sets. This was followed in the 1980s by the desktop PC industry, followed again by Internet technology and computer notebooks in the early 1990s. Investments in the display area began in the 1990s with the licensing of technology from Japanese firms. As Korean firms quickly learned to make displays on their own, said Dr. Lee, the government created an "ambitious" G7 program for displays (named pointedly after the world's seven leading economic nations). The G7 provided R&D money for the period 1995 to 2001. Five display technology centers were set up under the informal slogan "catch Japan" (a member of the G7), and by 2004, Korea had done just that, becoming the largest producer of LCDs. Korea then set up another program, the 21st Century Frontier Program, to develop next-generation displays from 2002 to 2012, with a budget of $10 million per year. These included all-organic displays, organic thin-film transistors, and e-papers. This project was accompanied by the SystemIC 2010 Project, from 2001 to 2011, focused mostly on memory. It had no technology-on-system IC, so the government invested in research on these systems. "This was really a big project," Dr. Lee said.

Dr. Lee praised both KDIA and KoPEA for their role in moving the industry forward, saying they had "allowed the display industry to become strong." In addition, the government helped by asking industry, especially Samsung and LG, to support the Korean research institutes, while investing about $5 million per year in public funds. Most of the funding went for active-matrix OLEDs, OLED lighting, and related technologies. The associations also urged Samsung and LG to start developing facilities to produce large-area

		1st Phase	2nd Phase	3rd Phase
Year		'11 '12 '13 '14	'15 '16 '17	'18 '19 '20
Applications	All-printed, large-area OLEDs	Development of core tech. for printable OLEDs • Soluble OLED materials • Printable OLED backplanes	Long-lifetime printable OLEDs • Large-area OLED printing • Uniformity, Stability	All-printed AMOLED • Gen 11 • Flexible R2R AMOLED
	Green Display Tech. & Process	Development of core tech. for printable LCDs/PDPs • Pritable Color Filters • Pritable Cell Barriers, etc	Eco – Display tech. • Printable TFTs • New materials & Processes	All-printed LCD/PDP
	Disposable Displays	Low-cost e-papers	Large-area e-paper	All-printed Disposable E-paper
	Interactive Smart Displays	Printable Touch and haptic sensors	Printable Touch Panels	All-Printable Touch and haptic Displays

KDIA, Vison and strategy for the development of Korean display industry (2010. 6)

FIGURE 3 Printed Electronics roadmap.
SOURCE: Changhee Lee, Presentation at September 24, 2010, National Academies Symposium on "Flexible Electronics for Security, Manufacturing, and Growth in the United States."

OLEDs, which the country did not yet have. Each company is forming a consortium to develop this technology and will compete for a contract to develop it. Funding will also go to ETRI and to research universities.

In discussing the two competing associations, he noted that each sponsors an international conference on its own specialty—one on display, one on printed electronics. KoPEA did not have as much power as KDIA, he said, which has a longer history and more support from both Samsung and LG. KDIA also has a Printed Electronics Roadmap for both printed and flexible electronics.

SNU itself has a long history as a display technology research center, he said, which was initiated by the government during the days of the G7 Project. The university does fundamental research in display technology, educates graduate students in display areas, and exchanges personnel and technology with the display industry.

In closing, Dr. Lee offered a summary of Korea's standing and rapid progress in this technology:

- Korea is very active in developing printing technology for displays, especially large-area, low-cost, ecodisplays, and flexible displays. The development of other PE technologies is in its infancy.
- Korea's main advantages in flexible electronics are strong manufacturers (Samsung, LG) and good supply chains.
- Korea's weaknesses include a lack of fundamental research, core IPs, and advanced materials.
- The strategy of the Korean government has four primary components:
    - Support research on core technologies (printing technologies and materials) and strategic applications (LCSs, OLEDs, e-papers, touch panels, flexible PCBs, organic solar cells, and RFIDs).
    - Strengthen the equipment and materials industries through next-generation display testbeds, R&D tax exemptions, support for small companies, and other policies.
    - Build infrastructure, enhance international collaboration, and support international conferences and R&D programs.
    - Educate more R&D manpower through research centers, Build Korea 21, and World Class University programs.

"We have many opportunities," he said in closing. "There is a paradigm shift under way, and we are very active."

DISCUSSION

A questioner asked whether the United States has any technology clusters to support flexible electronics at the level supported by Korea. One participant joked that on a tiny island like Taiwan, everything is a cluster. Mr. Hannah said that the Flexible Display Center in Arizona is the closest to such a cluster, and that university technology cluster near Albany, New York, is planning a cluster on flexible printing technology. "But there is really no cluster in the U.S. beyond that."

Dr. Kota asked whether the United States has come "too late to the party." He also asked about offshoring. If the United States supports good companies, he asked, how do we keep other big companies from taking them over?

Mr. Hannah said that the LCD platform display industry moved to the Far East "because a lot of the drivers and backplane technology required to manufacture the devices were there." He said that he believed flexible electronics would have "a much simplified device structure" and could be manufactured and distributed locally. This would bring an advantage in transportation and lower overall costs of ownership. He used the analogy of newspapers, which are printed and distributed locally. "If you can get your costs down for manufacturing and materials, why can't you print your electronics locally and distribute locally? I think a new model can exist, especially when there's not a lot of low-cost labor associated with the manufacturing process. I think you can build that industry in the U.S. and you can keep it here." He added that Europe seems to be betting on this outcome in its efforts to bring the manufacturing base back to Europe. "That's why all these initiatives are happening in the U.K. and Germany, for example. They want the next-generation manufacturing industry to happen in their back yard. We should be feeling the same."

Zakya Kafafi from NSF asked how much activity in flexible electronics is there in Middle Eastern countries. She said that these countries seemed to be interested mostly in photovoltaics. She also asked why there were "no women" in this field. Dr. Lee responded that in Korea about five of the engineers and other researchers in his department, electrical engineering, were women, and that the ratio increases steadily.

A participant from George Mason University asked how Korea could be successful with its lack of IP rights. Dr. Lee replied that Korea does not have a long enough research history to have built up IP on the fundamental technologies. "We get licenses, or buy startup companies in America or Europe," he said. Recently the country has focused on filing patents, he said, and the number of awards has increased significantly. "I think we are number four in the world, after Japan, Germany, and the USA. Eventually we won't have such serious problems. Now we need collaboration with small companies. In addition, the government has encouraged filing patents and gave incentives to researchers in universities and research institutes. So when government funding results in a patent, it should be owned by the university or research institute, but the incentive should go to the inventors, the portion depending on the agreement, typically 10 to 70 percent, depending on each license. "Another challenge is that we don't have a good financial system to support startups, based on IP, so this is quite different from the EU and America. It is really difficult to initiate startup companies."

Mr. Hannah confirmed the importance of IP, saying that it was fundamentally a value driver for the company. "We focus on patenting, both core molecules and uses. Even with a company of just 70 people, we have our own in-house patent attorney and a legal assistant, and one of the best outside legal firms in the country."

Byron repeated the question about whether "we were indeed late to the party," asking "our guests from outside the U.S." for a candid response. Dr. Chen replied, with some humor, "Why do you want to get manufacturing back? It's a dirty and sweaty job. [Laughter.] In Taiwan, we're trying to climb up the value chain. We need either more IP, or the key material. Actually, manufacturing requires a very high investment, and low return. I know it's a campaign here. But think more about it. Do you really want to do that? This country is still great, in terms of technology, in terms of innovation. But we have lost a little of the manufacturing mentality. In the United States, we no longer have that discipline, or that spirit of working. So think about it. It doesn't mean we cannot do it, or too late to the party, just a matter of finding where we want to be in the right position."

Mr. Hannah responded that the healthiest economy has a balance. "You have to have manufacturing, service, and all types of jobs. At some point, we have to bring some portion of manufacturing back, and regrow the manufacturing base. This is an opportunity where we can grow from virtually nothing in this industry to potentially a $300 billion industry over the next 20 years. In an industry of that size, you have to have your piece of manufacturing."

Panel IV:

What Is Needed? Opportunities for Collaborative Activity

Moderator:
Nick Colaneri
Arizona State University

ROADMAPPING FOR FLEXIBLE ELECTRONICS

Daniel Gamota
International Electronics Manufacturing Initiative (iNEMI)

Dr. Gamota offered a brief history of the International Electronics Manufacturing Initiative (iNEMI), which evolved from a joint effort between the electronics manufacturing industry, led by Mr. Mauro Walker, then of Motorola, and the federal government, led by Dr. Lance Glasser, who was the director of the Electronics Technology Office at DARPA. Driving their actions in 1994 was the belief that manufacturing was an important core competency in the United States. Although the manufacturing landscape in the United States has changed significantly since 1994, the belief in manufacturing has not changed. "We believe that in flexible electronics today, there's still an opportunity for us to be a very strong player in this emerging field," he said.

iNEMI's focus is on advancing electronics manufacturing technology, which he described as "establishing the infrastructure, and making sure that you're ready to go to market today with product." The essence of manufacturing, he said, is having a strong supply chain—the right people to not only design and provide the technologies and raw materials, but also to carry out production. An essential component in remaining competitive, he said, is the ability to predict emerging and innovative manufacturing technology.

Companies were active in iNEMI, he said, in part because of its grassroots nature and access to the state of the art in electronics manufacturing innovation. The cost of membership was small, he said, and the benefits were sufficient to attract a significant population of firms. Specifically, the Flexible Electronics Technical Working Group (TWG) had grown from about 25 members when it was founded in 2005 to about 50 in 2010. (By April 2012, iNEMI had approximately 100 members.)

"We've actually gone through our third iteration of the flexible electronics roadmap chapter," he said, "creating a new iteration every two years." The roadmap process of gap analysis followed by establishing research priorities is carried out by the TWG and requires two years. The most recent flexible electronics roadmap, for 2011, had been submitted a month earlier. One strategic purpose of the roadmap was to stimulate the development of industry standards. He had learned in his 15 years at Motorola, he said, that without rigorous standards, it was impossible to achieve high yielding manufacturing operations.

A Roadmap to See the "Gaps and Needs"

It also provided the members who were entrepreneurs an opportunity to see the most significant "gaps and needs" of the industry. With this perspective, gained from the view of the supply-chain landscape from customers, competitors, and suppliers, firms had a better chance of producing a product that could meet real needs and generate significant markets with robust sales. Some of those needs, such as high-performance materials, had begun to emerge at the very beginning of the roadmapping process. The first flexible electronics roadmap was published in 2007 and stressed the need for high-performance materials, but work for that version began in 2005 to identify a portfolio of critical needs, and actually the first discussions to assess existing and future needs began as early as 2003. This roadmapping process was already providing a comprehensive and strategic view of development for flexible electronics for nearly eight years. "Those needs identified in 2003 have been coming up consistently on this roadmap," he said, "and we've been waiting and waiting for solutions to be commercialized addressing those needs. Finally we're starting to see people provide the products and technologies that are going to fill those gaps and needs."

Dr. Gamota noted also the special nature of manufacturing, which, unlike R&D, requires skills that engineers gain when working in industry supporting production operations. "There's a difference when you get into manufacturing. It is a unique discipline, and it isn't for everyone. When I joined Motorola from academia, my problem-solving skills were rewired to accommodate the manufacturing operations environment. You may have graduated as an electrical engineer, but a manufacturing engineer is what you ultimately become when joining a company whose core competency is manufacturing. It's the same with materials science, or any other field. Those individuals participating in iNEMI appreciate the value of a roadmap to a manufacturing company. I didn't have to go to iNEMI and convince them to put a roadmap together for flexible electronics. They came to me and asked for a roadmap because they appreciate its value." The information in the roadmap is critical for the manufacturing engineer, he said, "because if they can't reproduce what they're assembling in the R&D environment during process scale-up, they're not going to succeed in high volume manufacturing."

He said that because of the roadmap, people had been working to provide technologies to address needs since 2003, trying to find valuable market niches for their own firms to introduce products. "So these technology needs had been on enough people's radar screens that I believe we're starting to see the fruits of our labor. Success in delivering manufacturing-compatible solutions becomes apparent when almost everybody in the room is racing to deliver new applications built on a common manufacturing platform to diverse markets—aerospace, automotive, health care."

Dr. Gamota summarized the process for gathering the knowledge needed to create and produce new products, especially at the early stages. R&D activities are also supported by the roadmapping process, he said, when participating members meet to pool their experiences about what knowledge is needed to develop a technology and the gaps that are needed to be filled. The gap analysis helps the industry make its case to funding agencies likely to support this kind of critical and sometimes high-risk R&D, especially NIST, DARPA, ARPA-E, and the Department of Homeland Security. The appropriated funding can then be funneled to the researchers, who can carry out the basic and applied research. In the past, iNEMI has established groups to perform research that it deemed critical; as an example, a project to investigate lead-free solder alloys was performed by iNEMI members when that topic was identified as a potential future industry barrier.

The iNEMI roadmapping process has been growing consistently since 1994, he said. For the 2009 iNEMI Roadmap, there were more than 550 participants, including more than 250 companies or organizations from 18 countries. The 20 TWGs and 5 product emulator groups produced more than 1,400 pages of information, along with roadmaps for the needs anticipated during 2009-2019 for a variety of electronics related technologies—solar, lighting, printed wiring board, microelectronics packaging, and flexible electronics.

Showing the Way to High-Volume Manufacturing

The 2011 flexible electronics roadmap highlights products having potential applications in six product emulator groups: portable/consumer, office/large systems, defense and aerospace, medical products, automotive, and network communications. "So now you're starting to see the flexible electronics ecosystem evolve. Adopters of flexible electronics are beginning to design future products that will integrate this technology which is being developed." This represents a market pull for flexible electronics, he said, and therefore a basic manufacturing infrastructure must be established to enable customers to

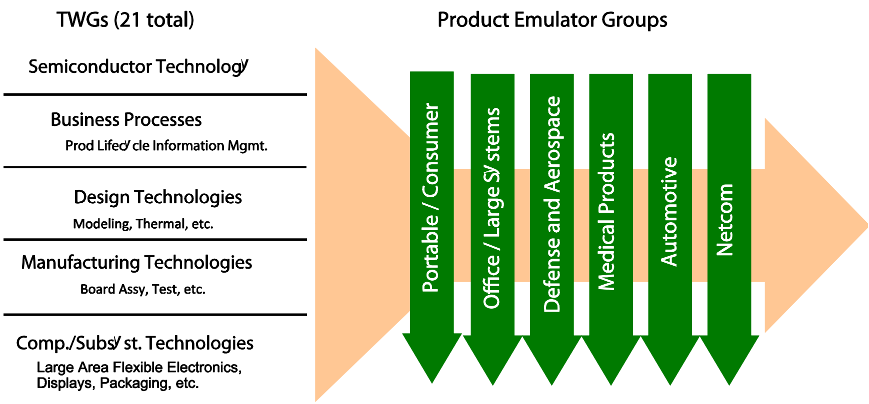
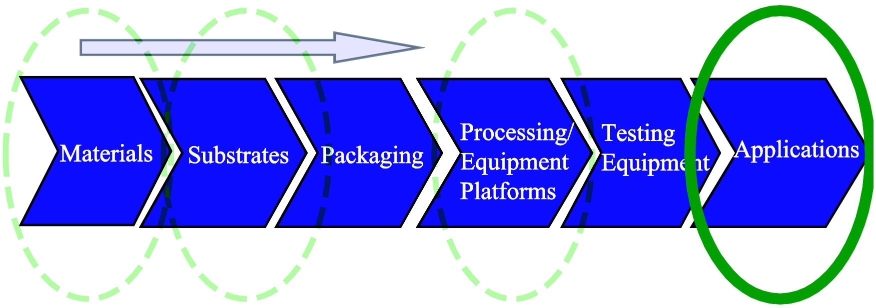


FIGURE 4 Roadmap development: Product sector needs versus technology evolution.
SOURCE: Daniel Gamota, Presentation at September 24, 2010, National Academies Symposium on "Flexible Electronics for Security, Manufacturing, and Growth in the United States."

plan for easy and efficient use of the technology. "A roadmap is, if anything, a great strategic exercise, because it shows you exactly how you need to prepare for going to high-volume manufacturing. Plus it lists specific technologies and their developers and, in many cases, the supply chain members who can help your company launch flexible electronics based products."

Dr. Gamota described a shift he had seen in roadmap topic participation. In 2007, the greatest need described by participants was higher-performance materials. "We heard, 'If we can't have better materials, we can't succeed in developing item-level RFID tags. For RFID devices that track cargo on ships and inventory in retail stores, we need devices that operate at a higher frequency, or we're not going to be able to offer desirable products to the market'." In the 2009 roadmap, however, the focus shifted to a concern over substrates and processing equipment. "No more high-performance-materials complaints. The RFID customer had become a little more accommodating in terms of what design methodology they would use for the product, and they were more accepting in terms of what products they could produce based on the available materials."

For the 2011 roadmap, he continued, the concern had shifted once again—to processing equipment, "high-volume manufacturing platforms," and near-term applications. "As we went through the different iterations of the roadmap," he said, "we started populating each of the different value chain segments within the roadmap; we were able to observe the flexible electronics industry focus shifting as solutions to needs became available. You could see the



2007 Roadmap greatest participation -"Materials"
2009 Roadmap greatest participation shifted "Substrates" and "Processing Equipment"
2011 Roadmap greatest participation shifted "Processing Equipment" and "Applications"

FIGURE 5 Shift in roadmap topic participation—Movement along supply chain.
SOURCE: Daniel Gamota, Presentation at September 24, 2010, National Academies Symposium on "Flexible Electronics for Security, Manufacturing, and Growth in the United States."

market go from an emerging market to a market that today is ready to launch a suite of different products."

The SEMATECH Roadmap as a Model

Dr. Gamota noted that the iNEMI roadmapping process methodology was different from the roadmap introduced earlier by Dr. Clayton of NorTech, which was developed to establish a strategy to capture maximum value from the high density of companies in northeastern Ohio that participate or could participate in the flexible electronics industry. He mentioned that the iNEMI roadmap was more like the International Technology Roadmap of Semiconductors created by SEMATECH, which served as a model. The iNEMI flexible electronics roadmap contained a situation analysis of technologies and products, such as substrates and their quantified key needs, gaps, and "showstoppers." The roadmap has tables listing the attributes of flexible electronics enabling technologies for today, those that are midterm goals five years from now, and those that are goals 10 years from now.

Next he turned to discuss the roadmap topic of functional inks, and the critical attributes and issues associated with them. He mentioned that the purpose of this exercise for functional inks was to ask the TWG members what attributes are needed to reach the 2016 and 2021 goals. The TWG identified a list of attributes that included higher performance, longer shelf and pot life, solution processability, compatibility with other functional inks, robust synthesis and formulating routes, and others. An important topic mentioned several times during TWG meetings, he said, was improved manufacturing platforms. "I think what's happening is that to address this topic we're seeing the reuse and integration of processing equipment used by different industries to design new manufacturing platforms. First, the flexible electronics industry adapted a manufacturing platform that was developed for another use—graphic arts printing. Then it took another platform, developed for another industry, microelectronics assembly, and combined the two. "So I think that manufacturing of flexible electronics, large-area electronics, and organic electronics is really a reuse phenomenon whereby manufacturing platforms are being designed and built by leveraging existing hardware and integrating it with advanced manufacturing technologies."

In finding the best functional inks, he said, it was sometimes necessary to innovate, but often the most practical approach was to design product based on existing materials and equipment, which saved time to launch products and capture value. This he called a "very big issue" that had been highlighted several times by different groups stressing the importance to design product and qualify processes based on the best available materials instead of waiting for the "perfect" high-performance material. The main reason, he said, was that once a scalable manufacturing process is qualified, it is no longer viewed as an unproven prototype process or R&D study. It is now considered a moderate-volume or high-volume product line that can be improved when higher-performing functional material becomes available. "At the end of the day," he said, "it is more important to have a stable manufacturing process operating at high yield versus running a line that sometimes assembles 2,000 products that have to be reworked." Such issues were all becoming significant topics for discussion at TWG meetings and "bubbling up to the surface" as companies reached the stage of development where manufacturing readiness was the central issue.

Dr. Gamota emphasized the importance of both reliability testing for manufactured products, which depend on what kind of use and handling a product will need to endure, and standards, which are being developed under the auspices of various standards bodies (e.g., IEC, IEEE, and IPC).

He summarized the "top four needs and gaps" for flexible electronics manufacturing as follows:

- In-line inspection and testing equipment: He said that every manufacturer of flexible electronics was requesting either a roll-to-roll line or a hybrid line with integrated inspection tooling. "This is really the most common request they've had from companies: 'We want this today, and we want the design guidelines and materials to go with it.' That tells me they're convinced that flexible electronics technology is ready to offer products to the market and that they will be able to

expand their product portfolio later once their manufacturing operations are up and running. Addressing this need in the near-term is very important."
- Higher-performance semiconducting inks (including semiconducting, OLED, and PV active).
- Simulation and design tools: "These are nice to have, but I think companies are most concerned about the first two. The technology may miss its opportunity for market entrance if the first two needs are not addressed quickly."
- Robust manufacturing platforms: "Flexible electronics manufacturers are reusing and modifying manufacturing platforms, as necessary, that have been developed for other industries; for the most part this is going quite well but a commercially available flexible electronics manufacturing platform would help accelerate the diffusion of products into the market and adoption of the technology by more companies."

Dr. Gamota closed by reminding his audience that the third roadmap was due out in January 2011, and that the next updating would begin promptly six months after that. "It's a very robust and exciting field," he said. "The product emulator groups that support iNEMI are very much interested in flexible electronics technology as a new product differentiator, and making a contribution to facilitate in its adoption by their companies."

CONSORTIA IN FLEXIBLE ELECTRONICS FOR SECURITY, MANUFACTURING, AND ECONOMIC GROWTH IN THE UNITED STATES

Malcolm J. Thompson
RPO, Inc.

Dr. Thompson, the chair and CEO of RPO, Inc., said that his talk would focus on consortia, and that he would mention his company only briefly. RPO, he said, produces polymer optical waveguides designed to improve the performance of touch-screen technologies. He added that the company, headquartered in California with manufacturing facilities in Australia, was about to announce a manufacturing acquisition in the United States that is intended to produce about 2 million optical components a month for optical touch systems on a plastic flexible substrate.

He said that he would try to describe the value and structure of consortia for this new industry in various environments. He noted that he had had a variety of experiences in electronics, both as a researcher, a venture capitalist, and company founder, and that both his experiences and the "mistakes" he had made had contributed to what he would say about flexible electronics. He said that the electronics industry had started in the United States and was in many ways still flourishing here. "Moore's law continues to drive toward smaller features, higher density, and more complexity," he said. "But instead of building a facility that used to cost $100 million 20 years ago, it may cost today over $2 billion to make a large manufacturing facility." Many of them, he added, have been built in other countries.

Dr. Thompson said that about 166,000 people are employed in the U.S. electronics industry, and about 1.6 billion are employed in that industry in Southeast Asia. "For every 25,000 employees at Apple designing those great gadgets that they turn out today," he said, "there are 250,000 people in Shenzen Fulong Electronics in China manufacturing those products. It's a ratio of 10 to one."

However, he said, the future opportunities for flexible printed electronics were likely to be different and to allow for more diverse manufacturing opportunities. One reason for this is that the products will be "on the human scale." This, he said, would hold true for products in energy, health care, consumer products, the battlefield, security, training and education, and communications.

A Trend Toward Custom Manufacturing

"Manufacturing is going to be customizable, and diversified products are going to be manufactured closer to the end user," he said. He offered the "simplistic" example of printing, which 20 or 30 years ago would be done at a print shop, which "manufactured" the print for the customer. Today, he said, we each have printer in our home, which means that each person is the manufacturer of printed documents. He said that the new paradigm would feature much smaller manufacturing facilities located much closer to the point of use. Most importantly, he said, "you're going to turn around a product very quickly, in a matter of a few days. I think that's a really important difference."

Other future electronics opportunities, he said, would emerge in the category of flexible and potentially printed electronics at human scales. These were likely to include conformable and portable photovoltaics, wearable health monitors, sensors, and flexible displays and e-books.

Dr. Thompson turned to some comparative global trends in flexible electronics, saying that the United States had made a lukewarm and slow response to the opportunities. He said that in East Asia, both Japan and Korea were moving rapidly, with strong government backing and "many giants involved." In Europe, he said the primary effort was made by Germany, with strong activity also in Holland, the U.K., and Sweden. The industry in Europe had the "strongest government backing in more aspects, especially in Germany, with many large and small companies involved; he added that there were few startups in Europe. "Compared with Asia and with Europe," he said, "the U.S. response has been anemic at best."

FIGURE 6 "Why flexible electronics?"
SOURCE: Malcolm Thompson, Presentation at September 24, 2010, National Academies Symposium on "Flexible Electronics for Security, Manufacturing, and Growth in the United States."

In looking to the future of flexible electronics, he reiterated the prediction made earlier that the industry was moving along a growth path similar to those of semiconductors in the 1990s, and then flat-panel displays in the 2000s. He warned, however, that it was impossible to predict the future of any technology with confidence. He recalled participating in a panel discussion in 1991 when experts from around the world were asked to predict the largest LCD screen that would be manufactured; the unanimous answer was about 30 inches.

Given that caution, he asked why the future of flexible electronics did look bright. He said that previous speakers had done an excellent job in describing what the new industry would probably offer, including new forms of power, lighting, sensors, and communications. He said that instead of dwelling on those topics he would look more closely at the value of a consortium to combine the multiple interests of government, industry, and academia, and to mitigate the challenges to each of them.

The Need for Partners

Government, he said, is very much interested in job creation, national security, national competitiveness, economic growth, and the cost of government services. At the same time, it does not like to "pick winners or losers," which he called very difficult to do. Government also wants support for precompetitive R&D and tended to work in silos without sufficient collaboration.

The interests of industry, he said, focused on profit, revenue, market dominance, and intellectual property, which he called "a big, big issue" when forming a consortium. "How do you get people to collaborate when you have to deal with intellectual property?" He said that the overriding concern for industry, however, is partners and infrastructure. "You can't exist on your own," he said. "You have to have an equipment and materials supply chain, along with customers like Hewlett-Packard, Dell, and others producing the products. You need to have a giant infrastructure established in order for you to be successful, however big your company is." He noted the disadvantage of not having the big R&D centers like Bell Labs, Xerox PARC, and others. "They basically don't exist anymore, so these big projects are not taken on by industry."

For academia, he said, the main interests would remain educating and training, innovative R&D, and new materials and processes, but all of these were pressured by the decrease in funding for universities. In addition, academic research was seldom well aligned with the needs of industry.

Viewing the different interests and strengths of the three sectors, he said, clarified the need for a flexible electronics consortium. "And someone needs to verbalize that and bring it together, because they won't do it individually themselves."

Why should this be done in flexible electronics? he asked. For one thing, materials, equipment, and processes cut across many research areas, which are beyond the reach of any single company. A consortium would allow collaboration to overcome challenges that are common to all sectors and companies. For example, all of them need expensive research that is precompetitive, reaches across applications, and is capable of broad adoption. "What the consortium essentially does is to make sure the picture is complete and allow identification of technology gaps." This can be done through roadmapping and by ensuring that everybody is working together in a coordinated way, with not too many people working on the same thing.

Consortia for Increased Efficiency

"In the end, this is all about increased efficiency," he said, "to get us from the start to the finish line. I think a national consortium is needed to orchestrate all of these players. We need to galvanize industry and government interests, we need to promote cooperation and collaboration." He added that the pressure of poor economic times raises the urgency of collaboration, allowing the industry to pool resources, address the most pressing needs, ensure product integrity, and lower energy costs. A consortium would also help the industry adapt to the changes in manufacturing, where the printing industry must address the rise of e-books, printed photovoltaics, and low-cost medical sensors.

Dr. Thompson turned to some lessons learned from past consortia that could be applied to future consortia. He spoke of his role in founding the U.S. Display Consortium (USDC) in 1993, an industry-government consortium comprising 140 companies.[12] His first act was to learn more about SEMATECH, the consortium to help strengthen the U.S. semiconductor industry. He called SEMATECH a "defensive organization" whose mission was to "save the equipment and materials semiconductor industry." He learned that the USDC mission would have to be similar in taking a defensive position. But then he learned that, after SEMATECH was founded, it took three years to complete its first contract. The reason, he was told, was that each member firm was concerned about losing its intellectual property, and unwilling to reveal secrets. Eventually, he said, the companies discovered that they were all using similar processes, and they began to collaborate on mutual equipment and materials needs.

Another lesson, he said, was revealed more recently as the display industry developed. It turned out that the most profitable company in the display industry today is not Samsung, which is a global leader in selling the displays themselves, but Corning, which makes the glass. "You cannot predict where the value will be in the value chain," he said. "You have to embrace it all." Some other lessons he learned about consortia were that timing is crucial, constant rethinking is required, and funding must be sufficient.

The Consortium as a Champion

Among the objectives of a consortium, he said, is to provide leadership, synergy, and collaboration. It must also address dual-use requirements, and create an IP policy that encourages innovation and commercialization. Finally, it must focus on U.S.-based companies and the creation of state-of-the-art manufacturing jobs. He emphasized that manufacturing is no longer a dirty industry, but a job that requires much more training, intelligence, focus, and fast turnaround. Creating such an organization, he emphasized, requires a champion, and the consortium itself must be one "that we can trust, because that's what we need."

Another reason to support a consortium, he said, was that the interests of the electronics industry and government are intertwined. For example, defense and homeland security are dependent on the leadership of the U.S. electronics industry.[13] Within that need, he said, are some specific goals that

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[12]The primary mission of the USDC was to help develop a U.S.-based manufacturing infrastructure for flat-panel displays. USDC has now become the FlexTech Alliance, shifting its emphasis from flat-panel displays to flexible displays.

[13]He cited an article from *The Economist:* "… industrial policy works best when a government is dealing with areas where it has natural interest and competence, such as military technology or energy supply." August 5, 2010.

must be pursued by the United States. One is the updating of DoD's procurement and legacy systems. Another is the realization that the electronics industry has the potential for powerful job creation. He said that USDC and FlexTech Alliance had done well in coordinating the interests of the government and the industry.

Dr. Thompson closed with the opinion that a national consortium could have a powerful and positive impact on the industry. He suggested that it would not be the largest part of the industry, but the most critical part. A primary task, he said, would be to oversee the development of the supply chain, which would be very complex and dynamic. He also suggested sponsorship of academic and industry R&D, a traditional strength, to maintain a flow of new manufacturing materials and equipment. He estimated that U.S. government funding of $350 million to $650 million over five years, with a 60 percent industry cost share, would attract "significant industry participation. So you double the amount of the government investment. And that could be orchestrated—it's been done before. This is all about changing the economy and creating very new jobs."

COOPERATING ON THE MANUFACTURING CHALLENGE

Thomas Edman
Applied Materials

Mr. Edman, vice president of Applied Materials for corporate business development and global corporate affairs and marketing, began by professing his support for consortia and partnerships. In addition to his position at Applied Materials, he was also chairman of the Flex-Tech Alliance, and his former company, Applied Films Corporation, had received one of the first grants from USDC, the predecessor of Flex-Tech. "It was a grant that was very important to us in establishing the company," he said, "and building a company around the display industry."

Applied Materials, he said, is a world leader in nanomanufacturing solutions, and the number one equipment supplier of semiconductors, LCD displays, and photovoltaic solar technology, and is moving in additional markets in energy and environmental solutions. The company also has strong roll-to-roll manufacturing capability in Germany. Company revenue was about $5 billion "in a down cycle," he said, referring to 2009, and about $10 billion in an up cycle, which he estimated to be the case in 2010. The most important corporate figure, he said, was the budget for R&D, which had remained constant at about $1 billion since 2000, "in bad times and good times." The company had a presence in 93 countries, with manufacturing facilities in China, Germany, Israel, Italy, Singapore, Switzerland, Taiwan, and the United States.

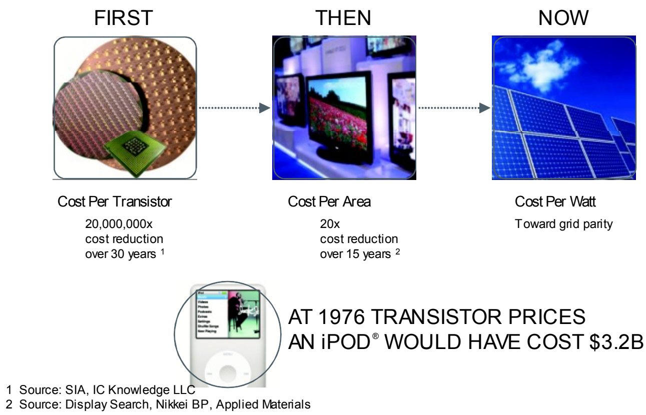

FIGURE 7 Delivering manufacturing scale drives low costs.
SOURCE: Thomas Edman, Presentation at September 24, 2010, National Academies Symposium on "Flexible Electronics for Security, Manufacturing, and Growth in the United States."

A Focus on Cost and Commercialization

In producing equipment products, he said, the focus of the company was on costs and commercialization. The industry as a whole had succeeded in lowering costs sharply since the 1970s. He noted that transistor prices had been reduced by a factor of 20 million; at 1976 transistor prices, he said, an iPod would cost $3.2 billion. "And I hesitate to tell you how large the device would be."

Since then, he said, the company has focused on taking a similar approach to other industries. For example, the cost per area of displays had been reduced by a factor of 20 over the past 15 years. The effort today is to do the same for solar PV, driving the cost per watt downward toward grid parity.

Applied also has a full line of roll-to-roll platforms, which he said were well suited to flexible electronics. From their very large area tool that made transparent and metalized packaging materials, they had developed a smaller modular tool called the SmartWeb, which is focused on flexible electronics. "We define the target market today as being PV, touch panels, and flex display applications, which are growing." The company also makes barrier films for the battery industry and other sectors.

In roll-to-roll processing. the company has focused on lowering costs per area and has been reasonably successful at increasing width and producing uniform films. The challenge comes on the functional side—materials innovation.

Where Partnerships Have a Role

Here, he said, is where partnerships could have a role. "Our customers' customers are very cost-conscious," he said. "They care about cost, and they also care about quality. That's been driving them toward lowering capital intensity and maximizing the efficiency of their production lines." This, said Mr. Edman, creates a challenge for an equipment manufacturer. The firm is being asked to meet a very intense competitive environment while its chief end markets have slowed in growth. It is also being asked to do more in film process development. While the R&D demands have not slowed in any of the industries served, Applied is being pushed to maintain leadership in those markets.

In the 1990s, the company could do a lot of the work be itself, but it cannot afford to do that today. "That, to us, means partnerships," he said. "That means looking outside of Applied Materials."

One place the company looks is to its vendors, its customers, and companies in adjacent spaces. Here it can develop processes or link processes that meet customer demand. At its Maydan Technology Center, for example, an advanced semiconductor processing facility in Sunnyvale, the company has invited partners to work side by side with Applied's engineers. "They place their equipment next to ours, we run the full process for our customers, and we develop on that process. This is very important to us in speeding our time to market."

Working with Companies in Adjacent Spaces

A second area of focus for partnerships is venture investments. The company is trying to encourage innovation in new end markets, in some cases working with companies in adjacent spaces. Applied has invested about $100 million in its ventures portfolio, which he called a very important part of the company's future growth in new applications. He highlighted several companies, including Infinite Power Solutions, a flex battery company; Plextronics, which he called "an excellent company in the materials space," also involved in flex; and Tera-Barrier, a company in Singapore that had developed encapsulation technology.

Another area, Mr. Edman said, was global partnerships, of which he showed a partial list. "We believe our markets are growing in Asia," he said, "so we have established R&D infrastructure in Zhejiang for solar, as well as a manufacturing infrastructure in Taiwan and in Singapore." Partners in Germany include Fraunhofer Institute, whose structure was much admired by Applied. "Placing our equipment there has allowed us to learn a lot," he said, "and I think our partners in Germany have benefited as well."

A fourth category is global university investments. "This is another means of leveraging our more fundamental research ideas and bringing them along the path toward commercialization. It's also a great means of attracting students." Examples included partnerships with the Indian Institute of Technology in Bombay, the University of California at Berkeley, and Stanford University.

Partnering with Government

Applied has also created an externally funded RD&E program, which has grown rapidly. We realize it is important for us to partner with the government and to look outside for assistance and for innovation." He said that one driver for this change was the energy business, which is policy driven and "a world where governments play a very important role."

Prime examples, he said, were DARPA and now I-ARPA, which were funding interesting innovations in a number of Applied's areas of focus. "We do have this urgency to commercialize nascent technologies," he said, "and we realize we can't fund it all ourselves." Some of the programs the company has joined in include energy, batteries, and energy storage. These programs take place in a cost-share environment, he emphasized, which "fits very well with our strategic direction."

Another category of major research institutes, he said, "is where the real value lies, where we are able to commercialize our capabilities and assist our customers to commercialize entire processes." He cited IMEC in Belgium as "a great example of this in semiconductors," along with the Fraunhofer Institutes and the Maydan Technology Center, which he said is increasingly becoming "a wonderful platform for commercialization of new technologies in semiconductors."

Finally, Mr. Edman said, the Web Group was developing flex-related collaborations with major institutions. He mentioned again the historical involvement with the Fraunhofer system, placing roll-to-roll coaters in Fraunhofer facilities. The company also worked with the University of Cambridge on longer-term development programs, and with the Center for Advanced Microelectronics Manufacturing (CAMM) in Binghamton, New York, "which I would call our attempt to reach out to a potential full processing facility and our desire to be part of an innovative process line as flex commercializes."

In conclusion, Mr. Edman stated that Applied Materials was well positioned as a potential partner to the flex industry. Government-industry partnerships had become more important to the company, along with the ability to leverage R&D dollars and commercialize more quickly. "We are seeing applications emerge at an incredible pace in the flex area, and yet we have a relatively small business unit in flex. I think most of the equipment companies are in this position, with a relatively small business trying to service multiple applications. So the need to have an integrated platform I think is immense, and represents a terrific opportunity for the U.S."

Panel V:

Roundtable—Key Issues and Steps Forward

Moderator:
Donald Siegel
University at Albany, SUNY

Ananth Dodabalapur, University of Texas at Austin
Stephen Forrest, University of Michigan
Robert Trew, National Science Foundation
James Turner, Association of Public and Land-grant Universities

Dr. Forrest began the discussion by asking about Dr. Gamota's emphasis on inks. He observed that in the existing organic electronic infrastructure, products had been based on an evaporation, spray-on technique, rather than a liquid process. He asked why inks were chosen above other methods for making inexpensive and potentially high-performance devices.

Dr. Gamota acknowledged the point, noting that between iterations 1 and 2 of the roadmap, iNEMI had become "agnostic" in terms of solution processing or vacuum deposition. "We listened to what our constituencies said. For the second edition of the roadmap, we had a large contingent of people from Arizona State, the CAMM center, and others who brought in small-molecule and evaporative technology." In the end, he said, they had to balance the two, concluding that systems requiring higher performance might go to evaporative systems. "But what we see now is that solution processing applications are very close to commercialization. And the commercialization path they've selected is based on products that don't require the high performance achieved by materials processed using vacuum-deposition technologies. Historically, if you're looking for higher performance, you rely on vacuum deposition, although today there are some solution-processed small-molecule materials that are demonstrating higher performance. Material selection is often driven by product cost and the performance of the final product."

Ananth Dodabalapur said that he wanted to recommend two points to the symposium. One stemmed from the successful NSF-sponsored program called the National Nanofabrication Infrastructure Network. This program was started in the days of the semiconductors and expanded with the advent of nanoelectronics, and was still "very functional." He said that it was based on a network of host universities throughout the country. Each host university maintains a set of fabrication equipment, which was used by students and postdocs of that university, as well as by startup companies and larger companies that pay a certain fee. He said that one such facility, focusing on conventional microelectronics, was located in Texas. Many startups, including one or two that he had created, benefited from the infrastructure. "So it's an equal-access system where I see a lot of value and a lot of creative intellectual property generated—not just by university researchers, but also by startup people." He proposed the creation of a similar network of infrastructure facilities for flexible electronics, "some kind of national flexible electronics research infrastructure network to be used by university researchers and industry, which includes both startup companies as well as larger companies." He noted that something similar already functioned well in Arizona, facilitating interactions. "I think that could be a powerful way of keeping our innovation engine running smoothly, and also helping to make the important transition to commercialization."

A questioner from NIST raised the topic of the supply chain, and strategies employed to cultivate and nurture the supply chain. He asked the views from the panel about whether a vibrant and sustainable supply chain within the United States might actually become a target for organizations that might want to move it offshore, purchase it, or otherwise place a controlling interest elsewhere. "If the government is asked to do things to help stimulate a U.S. supply chain, what strategies might you recommend for helping to retain and maintain that supply chain on-shore?"

CREATING THE RIGHT DEMAND

Mr. Edman of Applied Materials said that from his perspective, one of the critical areas to focus on was the markets companies are trying to serve. He mentioned the example of low-emissivity windows and coated-glass applications, and said that the demand for these products in the United States had been encouraged through incentives. California had mandated low-e window usage, which led to further regulation and energy-efficiency improvements, "which was the goal." In that case, he said, the government played a role, and now the coated-glass industry was very strong in the United States. He said there were probably many examples where the government could play a similar role in encouraging demand and encouraging infrastructure to remain in the United States. He said that making sure that members of the consortium keep the jobs in the United States could be more problematic, and that the Fraunhofer model and others did not operate that way. "They understand that this is a free global market, and that the challenge is how to create the right infrastructure and demand."

Dr. Forrest added that, once a supply chain is created, the industry has to be very clear about what is to be supplied. This should begin with a few tested or proven technologies for which a demand already exists. "There has to be a demand pull," he said. "Low cost can never be a driver of anything. The driver has to be a new application or an application that can't be served by a different technology. Once you do that, you create capacity, and it's the excess capacity which then grows the new industries off that supply chain." He said this pattern had been demonstrated by the history of CMOS development and other technologies. "If you say that products in flexible electronics are just going to be cheaper than products in regular electronics, I would say that is wishful thinking." The key, he said, is that the product does something differently that people need. "It may a long time to get to the right price points," he said, "maybe not in my lifetime. The issue is really what you're trying to make, and what that does that other technologies can't."

A questioner asked Mr. Edman about the platform modes discussed earlier, and which of certain technologies that are well known now were likely to develop into flex. Mr. Edman referred to his company's venture portfolio, and the atmospheric techniques for depositing films. The company was also aware of other areas that it viewed as potentially disruptive to its existing technology base, but areas that they should, as an equipment supplier, be interested in. From that perspective, he said, the company certainly could not stop the development of those technologies. Instead, Applied had to learn, as a company, how to exploit that development and how to embrace it. "That's what we are trying to look forward to in our investment portfolio," he said, "and also how we partner. We need to understand where these industries are going."

A participant noted that materials was "absolutely critical to moving forward" as well. Already the industry's progress was closely tied to the equipment, he said, but in a number of markets it would be the driver, which raised the importance of understanding what materials are being developed.

Michael Ciesinski, representing the FlexTech Alliance, asked if anyone had a reaction to Dr. Thompson's strong call for a consortium. He noted a great deal of activity in the United States in some areas, including the Flexible Display Center and several universities, and asked "how the industry could reach critical mass."

PARTNERING AS A MATTER OF SURVIVAL

Dr. Forrest agreed that Dr. Thompson had made a strong case for partnerships, partly because many of the technologies needed to bring this industry to maturity "are just too broad for a single company. If you don't have materials scientists," he said, "you have to go out and find them. If you don't have people who know how to make equipment, you have to find them." He said he saw the point of Dr. Thompson's arguments that consortia were an important element. "Again," he said, "it's always going to be pulled by some application. It can't be just random alliances. But once you know that, I think the industries and the universities are finding ways to work more productively together—not because they want to, but because it's a matter of survival."

Jim Turner, of the National Association of Land-grant Universities, agreed with Dr. Thompson about the "fear factor" that drove the adoption of SEMATECH, noting that the Science Committee in the House of Representatives was actually competing with the Defense Committees in the House of Representatives for the role of authorizing the money to get this thing started. This indicated that SEMATECH was an important model, he said. "But I think that when we talk about SEMATECH today, what we really are talking about is SEMI-SEMATECH, or SEMATECH 2.0, when we were trying hard to get the next generation of DRAMs going. We fell on our face, but eventually we understood that the whole game was the supply chain and strength in the suppliers, and once we did understand, things went well." He added that the drive does not absolutely have to be fear, but that it could be. "It has to be something really powerful that pulls a lot of people together. We may need to look at getting the White House engaged, as well as getting a SEMATECH-like consortium running."

Donald Siegel commented that, being an academic economist, he was not very practical, and said that the proceedings had been a revelation in allowing him to learn about the flexible electronics industry. He said he had learned several things. First of all, it was an industry that was difficult to define; "in fact, it's not clear whether it's flexible or organic. But regardless of how you define it, there appear to be several key facts about this industry." First, he said, there were very broad and diverse applications of the technology. This was not surprising to an economist, he continued, because electronics is thought of as a general-purpose technology. It has broad applications across sectors and can in fact transform the production process in many of those sectors. Second, there may be an important quality of sustainability to this industry, such as green jobs and green technology, which the foreign speakers in particular discussed. Third, global competition in this industry is very strong, and the United States is behind the curve. "In fact," he said, "our charge was to study research consortia around the globe, and a combination of government investment and university-industry partnerships appear to be drivers of success abroad. But I think the critical limiting fact in this sector is that there's very little data. In order to quantify the potential economic impact of this industry in terms of job creation, we have to do what Dr. Shenoy of DARPA said: You have to make the business case for this industry. Until we do that, we're not going to see more investment, either public or private."

Dr. Thompson closed the discussion with a response about using a business plan. "I started working on photovoltaics in 1982 because of the global oil crisis," he said. "There was a wonderful case to be made. But then, the price of oil went back down, and the business plan disappeared. It's very difficult to know what's about to happen. We must say to the Congress, stop talking only about job creation, and do the investments where don't want to lose out completely—in this area of the future."

III

APPENDIXES

Appendix A

Agenda

Flexible Electronics for Security, Manufacturing, and Growth in the United States

September 24, 2010

The Keck Center of the National Academies
500 Fifth Street, NW
Room 100
Washington, DC

9:00 AM	**Welcome** ***Charles Wessner, The National Academies***
9:05 AM	**Introduction** *Michael Andrews, L3 Communications*
9:15 AM	**Panel I: The Flexible Electronics Opportunity and Industry Challenges: Perspectives from Industry** *Moderator: Sridhar Kota, White House OSTP*
	The Promise and Potential of Flexible Electronics *Ross Bringans, PARC*
	Impact of a Flexible Form Factor for Displays and Lighting *Julia Brown, Universal Display Corporation*

	Roll-to-Roll Fabrication of Transistor Arrays for Sensing and Display Applications *Carl Taussig, Hewlett-Packard*
10:30 AM	**Coffee Break**
10:45 AM	**Panel II: The U.S. Interest: Security, Manufacturing, and Growth** *Moderator: Jon Epstein, Office of Senator Jeff Bingaman*
	Army Applications for Flexible Displays *John Pellegrino, U.S. Army Research Laboratory*
	The DARPA Role *Devanand Shenoy, DARPA*
	The Technology Innovation Program: An Early Investor *Michael Schen, NIST*
	A State's Initiative: Advancing Flexible Electronics in Ohio *Byron Clayton, NorTech*
12:15 PM	**Lunch**
1:15 PM	**Panel III: What Is the Rest of the World Doing?** *Moderator: Pradeep Fulay, National Science Foundation*
	A Global Perspective *Andrew Hannah, Plextronics*
	German Policy Initiatives *Christian May, Fraunhofer Institute, Dresden*
	Taiwan's Flexible Electronics Program *John Chen, Industrial Technology and Research Institute of Taiwan*
	Korea's Initiatives *Changhee Lee, Seoul National University*
3:00 PM	**Coffee Break**

3:15 PM **Panel IV: What is Needed? Opportunities for Collaborative Activity**
Moderator: Nick Colaneri, Arizona State University

Roadmapping for Flexible Electronics
Dan Gamota, iNEMI

The Consortium Opportunity
Malcolm Thompson, RPO

Cooperating on The Manufacturing Challenge
Thomas Edman, Applied Materials

4:15 PM **Panel V: Roundtable—Key Issues and Next Steps Forward**
Moderator: Don Siegel, University at Albany, SUNY

Ananth Dodabalapur, University of Texas at Austin
Stephen Forrest, University of Michigan
James Turner, Association of Public and Land Grant Universities

5:00 PM **Closing Remarks**
Charles Wessner, The National Academies

Appendix B

Participants List

Julia Abrahams

Ray Adomaitis
University of Maryland

Paul Amirtharaj
U.S. Army Research Laboratory

Alan Anderson
The National Academies

Michael Andrews
L-3 Communications

Frank Barros
Department of Homeland Security

Ross Bringans
PARC

Julia Brown
Universal Display Corporation

Miko Cakmak
University of Akron

John Chen
Industrial Technology and
Research Institute of Taiwan

Hemi Chopra
National Institute for Standards
and Technology

Michael Ciesinski
FlexTech

McAlister Clabaugh
The National Academies

Byron Clayton
NorTech

Nick Colaneri
Arizona State University

Khershed Cooper
Naval Research Laboratory

Eve Copeland
U.S.-Israel Science and
Technology Foundation

Carl Dahlof
Delegation of the European Union
to the U.S.A

David Dawson
The National Academies

Romeo del Rosario
U.S. Army Research Laboratory

David Dierksheide
The National Academies

Brian DiNunno
Project Enhancement Corporation

Ananth Dodabalapur
University of Texas at Austin

Michael Dudzik
Lockheed Martin

Michael Durstock
The Air Force Research Lab

Thomas Edman
Applied Materials

Jessica Emond
APCO Worldwide

Pete Engardio
The National Academies

Jon Epstein
Office of Senator Jeff Bingaman

Edward Etzkorn
U.S. Department of Energy

Kevin Ewsuk
Sandia National Laboratories

Dave Eyler
OEM Applications

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