Scanning the Issue

Flexible Electronics Technology, Part II: Materials and Devices

Flexible electronics is entering an exciting phase in the technology development cycle. After a decade of fundamental materials and device research, we are now witnessing the first major push toward commercialization. Productization requires device architectures and materials processes that are reliable and suitably qualified for high volume manufacturing. While the focus of the July issue of the PROCEEDINGS OF THE IEEE was on electronic systems and applications, the theme of the current issue is on materials and device technology, process development, and manufacturing technology. We believe the fifteen papers in this issue provide a good overview of the status of flexible electronic materials and manufacturing technology.

Replacing the rigid substrate enables a number of unique applications in displays, imaging, and macroelectronic systems. In the first paper, "Reel to Real: Prospects for Flexible Displays," Allen describes the technical, manufacturing, and market issues pertinent to the flexible display industry, along with the business and strategic challenges faced by the industry. While displays represent a very large market space, application of flexible electronics in smart tags, energy storage, photovoltaics, and embedded microelectromechanical systems (MEMS) present opportunities that cannot be easily addressed with traditional microelectronics. Thin flexible components and semiconductors are essential for the realization of highly integrated flexible systems. While bulk silicon has dominated the electronics industry for over fifty years, polymeric/organic materials present opportunities for large area manufacturing. In "Flexible Electronics Systems—Polytronics," Bock describes inline manufacturing processes for polymer electronics using commercial high-volume production tools. One of the most interesting aspects of flexible polymeric electronics is the opportunity to integrate fluidic, mechanical, optical, and electrical components on large area substrates.

An often-mentioned application for flexible electronics is in electronic textiles and wearable electronics. These are fabrics that have electronics and interconnections woven into them. The large areas and the physical flexibility of the fabric do not allow for electronic integration using traditional methods, and new integration concepts are starting to emerge. Tanaka and Kuniyoshi, in "The Electronic Circuit Composition and Structure of Thread for a Novel Braid Electronics System by Kumihimo Structure," present a braid integrated system based on textile fibers. Here, circuits are integrated using the Kumihimo structure by weaving threads on which FETs, photoelectric transducers, contact electrode pads, and wiring patterns are mounted periodically.

The next two papers review advances in semiconducting materials for flexible electronics. Recent developments in organic semiconductor materials and micro/nanocrystalline Si could lead to higher speed flexible electronic circuits. In "Design of High-Performance Regioregular Polythiophenes for Organic Thin-Film Transistors," Ong *et al.* report on structural design of solution processed polythiophenes for transistor fabrication. The use of organic materials in flexible electronics offers fundamental economic advantages but comes with a unique set of challenges. Organic materials are generally insoluble and low in performance. More critically, they are sensitive to moisture and oxygen, which requires manufacturing in an inert atmosphere adding to fabrication costs. Ong *et al.* discuss the material design challenges for self-organization from solution and stability against p-type doping by oxygen. While the work of the Xerox team presents advances in organic electronic materials, there is a lot of activity at developing silicon deposition processes that are compatible with plastic substrates. For compatibility with plastic substrates, the fabrication processes have to be modified and process temperatures have to be lowered, while maintaining the transport properties of the silicon film. Sazonov *et al.*, in "Low-Temperature Materials and Thin-Film Transistors for Flexible Electronics," discuss the adaptation of low-temperature processes using standard industrial-compatible tools for the growth of micro/nanocrystalline silicon and associated dielectrics at low temperatures. They demonstrate thin-film transistors with device mobilities comparable to those achieved with amorphous silicon deposition at higher temperatures.

Developing efficient and flexible energy storage and portable power sources is essential for flexible micro- and macroelectronics to become a viable technology. Recent advances in organic light-sensitive materials have triggered renewed interest in photovoltaics. Organic solar cells are attractive because of the versatility of engineering organic light sensitive molecules and the potential for high speed roll-to-roll manufacturing. In "Flexible Conjugated

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Polymer-Based Plastic Solar Cells: From Basics to Applications," Dennler and Sariciftci review the semiconducting properties of organic conjugated macromolecules and the application of these materials to enable high-efficiency solar cells. While flexible organic photovoltaics present an excellent means to harvest solar energy, integration of thin-film batteries with photovoltaics could be useful for application in space-based macroelectronics.

Technology for making flexible displays is not yet fully developed. There are several areas where currently no technical solutions exist. These include inadequate properties of the substrates, difficulties of packaging, and additional difficulties in driver integration and getting adequate power into these displays. If we overcome these difficulties at a reasonable cost, then a large number of applications can be enabled using flexible displays. The two papers that follow relate to the flexible organic LED (OLED) displays. In "Toward Novel Flexible Displays—Design and Fabrication of OLEDs on Plastic Substrates," Zhu *et al.* discuss a flexible top emitting OLED display using an aluminum-laminated polyethylene terephthalate substrate. This aluminum layer acts as barrier to permeation of oxygen and moisture. In the next paper, "Transparent Flexible Substrates Based on Polyimides with Aluminum Doped Zinc Oxide (AZO) Thin Films," Park *et al.* discuss the electrical and optical transmission properties of these films and the influence of deposition temperature on these properties.

One of the biggest challenges in flexible electronics design lies with the reliability and lifetime of the devices. Thermal stresses arising from fabrication and mechanical stresses induced from mechanical flexing of the substrate, coupled with electrical stressing of the system, can lead to rapid degradation of system performance, thus undermining the overall reliability of the system. Various aspects of the electromechanical reliability of flexible substrates and conductors are discussed in the following two papers. Cairns and Crawford, in "Electromechanical Properties of Transparent Conducting Substrates for Flexible Electronic Displays," discuss the electromechanical and optical characteristics of flexible transparent anodes using indium–tin–oxide and conducting polymers under cyclic loading conditions. While transparent conductors pose unique challenges due to the optical requirements, in the case of flexible electronics, interconnects can be engineered to provide the desired performance. In "Stretchable Interconnects for Elastic Electronic Surfaces," Lacour *et al.* describe a technique to integrate electronics on compliant substrates by distributing rigid-subcircuit islands. Specifically, they examine the electrical and mechanical integrity of metal lines interconnecting these islands when the elastic electronic surface is stretched up to tens of percent strain.

Substrate and encapsulation technology is a critical enabler of flexible electronics. Substrate materials must meet a number of different requirements including optical transparency, oxygen and water impermeability, high-temperature capability, chemical ruggedness, dimensional stability, and compatibility to roll-to-roll fabrication. We have three papers that review various aspects of substrate technology and engineering. First, in "A Transparent, High Barrier, and High Heat Substrate for Organic Electronics" Yan *et al.* describe the development of high-performance plastic substrates. In the following paper, "Method of Measuring Ultralow Water Vapor Permeation for OLED Display," Dunkel describes a new permeation measurement method deploying tritium-containing water as tracing materials to measure the rate of water and oxygen permeation through barrier coatings and perimeter sealing. Finally, in "Vacuum Web Coating—State of the Art and Potential for Electronics," Ludwig addresses the production aspects of flexible electronics with emphasis on cost reduction using roll-to-roll processing.

Despite the advantages of flexible electronics technology and its application potential, expansion into high-volume applications dictates the need for suitable manufacturing processes for high-volume and high-throughput production processes. For device fabrication on flexible large area electronics, lithographic patterning is a major challenge. There are several factors that need to be taken into account in low-cost high-throughput lithography. These include resolution, frame size, dimensional stability associated with the substrate, roll/frame handling, and yield. The two papers on patterning that follow address entirely different lithographic approaches. First, in "Printing Methods and Materials for Large Area Electronic Devices," Chabinyc *et al.* describe a digital printing method for thin-film transistor backplanes. Because this method employs printed photoresist layers, which they refer to as digital lithography, it can be used for creating patterns of both organic as well as inorganic materials. They demonstrate fabrication of thin-film transistors using a combination of digital lithography, for patterning metals, and ink-jet printing, for creating polymer semiconductor layers. In the subsequent paper, "Flexible Electronics and Displays: High Resolution, Roll-to-Roll, Projection Lithography and Photoablation Processing Technologies for High-Throughput Production" Jain *et al.* describe a new class of roll-to-roll lithography systems that provides high-resolution projection imaging over large exposure areas on flexible substrates. By projection imaging and image scaling, they demonstrate high-precision alignment to deal with processing-induced dimensional instability of the substrate as well as simultaneous patterning of millions of pixels.

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He is a Member of the American Physical Society, the Electrochemical Society, the Materials Research Society, the Society for Information Displays, the International Society for Optical Engineering, and the Institute of Electrical Engineers (U.K.). He served as chair of the EDS-SSC society in the IEEE K-W Local Chapter, IEEE Newsletter Editor for Region 7, and received the IEEE/EDS Distinguished Lecturer Award in 2004. He is a member of the IEEE EDS Publications Committee and the IEEE EDS Sub-Committee on Organic and Polymer Devices. He chairs the 2005 IEEE Lasers and Electro-Optics Society Technical Committee on Displays, and the Displays Subcommittee in 2004 and 2005. He is an Editorial Board Member of IEEE TRANSACTIONS ON DEVICE AND MATERIALS RELIABILITY and the newly created IEEE/OSA JOURNAL OF DISPLAY TECHNOLOGY. He serves as Cochair of the Fall 2005 Materials Research Society Symposium M: Flexible and Printed Electronics, Photonics, and Biomaterials.

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