Special Issue on Advanced Flexible Electronics for Sensing Applications

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I. INTRODUCTION

Flexible hybrid electronics. Sounds like it might be interesting, but what exactly does it mean? Unfortunately, it depends on who you ask and the context being discussed. So, let's start with "flexible." It could mean adaptable for multiple applications, but, here the term refers to mechanical properties, although not necessarily precisely defined. Mechanically flexible might mean anything from conformable (nonlinear shape) to bendable or rollable (around a defined radius of curvature), or even foldable and stretchable. Although not well defined, the intent is to differentiate from the rectangular, rigid form factor of conventional semiconductor electronics.

This special issue on flexible hybrid electronics provides insight into the technical problems that must be overcome as well as the new capabilities they could provide.

Hybrid means heterogeneous integration of conventional electronics with other electronic components (passive devices, sensors, etc.) that could be fabricated using conventional thin-film transistor (TFT) process technology by additive printing (ink jet, gravure, etc.). The purpose is to provide an electronics solution that has adequate performance, but in a low cost, novel form factor because printing offers the ability to inexpensively fabricate structures over large areas on mechanically flexible substrates (plastics, metal sheets, bendable glass). However, integration with conventional electronics such as silicon CMOS is necessary to achieve required performance because TFT and printed devices are significantly inferior to conventionally fabricated devices.

Finally, just what kind of electronics might be of interest in this context? The original intent was driven by the growth of displays and photovoltaics, and later by area lighting. All are based on electronics distributed over a large surface area and can provide excellent electrical performance. However, when fabricated on glass, they are heavy, breakable, and restricted as to placement. Thus, fabrication on substrates such as plastic would overcome those limitations while delivering a quality product in a variety of interesting form factors at lower manufacturing cost. At the same time, organic thin-film transistors (OFETs) and light emitting diodes were being developed for these electrooptic products. These organic materials can be relatively easily developed into inks that can be printed at room temperature on plastic substrates. Thus, the concept of printed, flexible TFT-based electronics was initiated in the 1990s time frame.

While attractive in concept, printed, flexible displays, photovoltaics,

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and lighting have had many challenges to overcome and are only now seeing significant market penetration. Simultaneously, a different direction was explored that aimed at exploiting the concepts of printing TFTs on flexible substrates to address the needs for lightweight, conformable, large area, and low-cost sensor systems. It is this category of applications that we cover in this special edition. We focus on this topic because in many ways, it is a more complex problem because active electronics must be incorporated into the sensor system to provide control, computation, and communication functions. What might these systems be? They can range from the low end wireless sensor tags for the Internet of Things (primary driver low cost) to wearable electronics (driver is comfortable form factor for health and safety monitoring) to embedded sensors (driver is large area, distributed structural and environmental monitoring). Although the original goal was to use printed TFTs for the electronics, subsequent work demonstrated that this was feasible for only a segment of the market. Where higher electronics performance was required, a hybrid approach would be needed.

The interest in this area is not new, but is only now becoming feasible. The famous Dick Tracy wrist-worn radio goes back to 1946 (The Road to Wrist-Wearable Electronics from Radio to Computer, by Alexander Magoun, Ph.D., IEEE History Center). In 1965, flexible circuitry was credited with providing 25% more room inside a telephone to allow more functionality in the same package. But, it is only recently that the ability to fabricate active electronic components, not just wiring interconnect on flexible substrates that has created both tremendous opportunities and challenges. For additional insights and information, we refer the reader to several references. Information Display is available from the Society for Information Display. The Jan./Feb. 2015 issue has several articles on flexible and wearable devices. The Materials Research Society is also a good source for information on novel electronic applications and materials. For example, the *MRS Bulletin* of April 2013 (vol. 38, no. 4) covered the topic of electronics on paper. Similarly, the March 2012 edition of the *MRS Bulletin* (vol. 37, no. 3) addressed the materials and approaches to enable stretchable electronics. For perspective on the thinking and technology for flexible electronics a decade ago, the reader is referred to the Proceedings of the IEEE (vol. 93, nos. 7 and 8, July and August, 2005). We hope that this special edition provides insight into the technical problems that must be overcome as well as the new capabilities that flexible hybrid electronics could provide.

II. WHAT IS THIS SPECIAL EDITION ABOUT?

Displays and PV as we have noted have been very influential in the emergence of printed and flexible electronics. That said, over the last decade or so the fields have diverged although some of the underlying fabrication technologies remain common. The differentiation has come to involve the desire to provide intelligence (the now ubiquitous "smart") to novel products. Displays and PV pioneered manufacture of large area or conformal/flexible formats. However, the ability to manufacture in novel formats leads to the question of what other electronic systems might be manufactured and what capabilities are needed for success. Displays and PV are relatively electronically simple. Their functionality is achieved via diodes and transistor switches with no logic, memory, or analog functions except those supplied by conventional packaged electronic parts. Thus, novel form factor electronics for applications such as sensor and actuator systems need more complex electronics to control, compute, and communicate. Conventional electronics, of course, are very capable of all such functions, but not necessarily with the desired mechanical features. Where the electronics systems are intended to be disposable, wearable, fit conformably into structures, or be unobtrusive, then the various components need to be low cost, thin, lightweight, and bendable. Ideally, this goal could be accomplished with the same materials and manufacturing methods used for displays and PV. However, with few exceptions, this approach is not possible and significant research has been directed towards manufacture of more complex electronic functions with advanced printing technologies. More recently, even printing technologies have proven inadequate as electronic requirements have become more demanding. It is this opportunity to create special purpose electronic systems in novel form factors that we focus on here. These devices have features and requirements in common with those of displays and PV, but with much more demanding required capabilities and manufacturing tolerances. While there have been many reviews on conventional TFT electronics based on materials such as amorphous silicon, organics, and oxide-based compound semiconductors, in this proceedings we emphasize the possibility of integrating printed electronics with conventional electronics.

III. OVERVIEW OF PAPERS

Flexible hybrid electronics for sensor systems has many important aspects. All of them cannot be addressed in this special edition. For example, the question of what substrate to use for what applications is diverse enough to almost be a special issue in itself (various plastics, flexible glass, paper, thin-metal sheets). There are also many options for conductors ranging from the well-established copper and indium tin oxide to various nanoparticle metallic inks and more recently carbon nanotubes and graphene. Similarly, materials possibly suitable for fabrication of TFTs could require multiple special issues. Here, we focus on key enabling technologies for system integration to include manufacturing methods, component design considerations, and exemplar applications that demonstrate the advantages of the thin, lightweight, flexible format, especially for sensor applications.

A. Manufacturing Technology

While displays and photovoltaics have been in large scale manufacturing for years, other printed, flexible, or large area electronics are just beginning to reach the commercialization stage. Specific products and manufacturing methods are still TBD, but there are several technologies that will be essential to the commercialization of flexible printed and hybrid electronics. As with conventional electronics, the ability to cost effectively pattern materials to define and interconnect electronic devices is perhaps the foremost consideration. Thus, in the first paper in this special edition, Kahn describes why patterning functional materials is one of the key technologies to enable flexible electronics. Successful approaches depend upon the ability to construct layers of materials having precisely defined architectures and relationships on flexible supports. The paper reviews the major patterning techniques that have been used for flexible electronics, and discusses the unique features, advantages, and disadvantages of each.

A second key and enabling technology is the ability to deposit and remove materials required for printed electronics. Therefore, the next paper by Morrison *et al.* describes tools and methods for Roll-to-Roll (R2R) production, which combines the advantages of inexpensive, lightweight & flexible substrates with high throughput. A variety of web handling and coating technologies/platforms enables high volume R2R manufacture of thin-film silicon solar cells and TFT active matrix backplanes. The work presented describes the latest advances and principal challenges inherent in moving from lab and pilot scale manufacturing to high volume manufacturing.

The power required to operate the hybrid flexible devices is both a manufacturing issue, and also a system design issue. Thus, we include a discussion of this topic by MacKenzie and Ho here because it is a necessary consideration when planning commercialization of a flexible or printed product. If flexible electronics are to become a commercial reality for wearable electronics, medical devices, and internet of things devices, energy storage technologies that safely and robustly match the mechanical flexibility of the overall system are required. The essential requirements for energy storage for feature-driven applications in flexible electronics are addressed with the goal of finding the most compelling fit between product needs, consumer safety, and technology capabilities.

B. Device Manufacturing Issues

With the above as background to baseline technology applicable to fabrication of flexible and hybrid systems, we then include several papers that describe the challenges involved in adopting these technologies for practical applications. These are presented from the perspective of increasingly difficult application requirements.

Noh *et al.* outline a specific example of why hybrid printing processes for fabricating flexible organic thin-film transistors are not readily transferrable to scalable, fully printed processes because of threshold voltage (Vth) variation. The underlying causes are discussed by considering effects of misalignment, rheology of electronic inks, and external additives. By addressing these issues, fully gravure printed RF sensors are realized with 26 printed CNT TFTs achievable with acceptable *Vt* variation.

Next, Subramanian *et al.* provide a detailed study of how printing technology can be successfully adopted for manufacture of TFTs. To make printed electronics a reality, it is necessary to deliver high resolution, good reproducibility, excellent pattern fidelity, high process throughput, and compatibility with the requisite semiconductor, dielectric, and conductor inks. The paper reviews the physics of pattern formation to show how control of drop merging and drying can be used to produce high-fidelity shapes. The authors discuss gravure and inkjet printing to produce sub-2 micron features at printing speeds of $\sim$1 m/s for high-performance fully printed transistors on plastic over large areas.

There is a need for more than just TFTs for printed electronic systems, and the next paper by Hester *et al.* provides examples of one of the directions the technology may take. Inkjet printing and additive manufacturing technologies (AMT) are introduced for the fabrication of flexible RF/microwave electronics and sensors. The paper covers examples of state-of-the-art printed passives, sensors, microfluidics, and antennas that could set the foundation for wireless sensor ad-hoc networks with enhanced cognitive intelligence and "zero-power" (energy harvesting). The paper also discusses the major challenges for the realization of inkjet-printed/3D-printed high-complexity flexible modules.

Finally, Street *et al.* provide a prospective on where printing of electronics has been and where it might go in the future. Printing as a manufacturing technique is a promising approach to fabricate low-cost, flexible and large area electronics. Over the last two decades a wide range of applications have been explored, although some turned out to be challenging to commercialize. However, progress in terms of material science, device- and process technology now makes it possible to target some realistic applications such as printed sensor labels. When needed, higher performance can be achieved with printed hybrid electronics, opening up further applications. For the future, they describe a prototype sense-and-transmit system, focusing on integration, interconnection of the chips, compatible interface electronics, and providing power.

As mentioned in several of the papers, as interesting and adaptable as printing might be for flexible electronic systems, there are also major impediments to fabrication of higher performance devices necessary for many applications. The basic reason for this is that the strength of printing, the ability to deposit materials at ambient temperatures over large areas rapidly, is also its weakness. For fabrication of high-performance devices what is needed is small feature size and ordered crystalline structure. Both are difficult, if not impossible, to achieve via conventional printing technologies. As described in the above mentioned papers, this is not an issue where the system of interest does not require higher performance than what printing methods can provide. But, many systems of interest require higher performance circuits to be effective for demanding applications (computation and communication especially). To address this issue, we include two papers to demonstrate how more complex and higher performance systems are possible by merging printing and conventional electronics into a hybrid approach.

Integration of rigid materials, such as inorganic crystalline materials that are the fundamental materials responsible for the explosion of technology and products in electronics and photonics, has become of increasing importance as interest in higher performance flexible systems has grown. Means for doing so have been developed in several research groups. One of the most prolific in terms of possible applications and breadth of exploited technologies has been the Rogers group at University of Illinois. In the next paper they provide an overview of their approach to the problem and demonstrate many of the advantages and applications. They report important progress in developing design strategies, materials, and associated assembly techniques that provide approaches to electronics with unconventional formats: light weight, large area, high-performance electronics, systems with curvilinear shapes and demanding forms of mechanical flexure, and functional bioresponsive electronics. They also highlight advances that are enabling such capabilities—specifically, the fabrication of device elements using high-performance inorganic electronic materials joined with printing and transfer methods to affect their integration within functional modules.

In a similar fashion, exploiting the strengths of microelectronics technology can facilitate the advance of flexible electronics as described by Hackler *et al.* Their premise is that while the potential benefits of printed and flexible electronics are well known, major gaps exist. They then discuss the benefits and challenges of taking a hybrid manufacturing approach that integrates traditional, yet flexible, electronic devices (system on polymer) with printed components to meet performance requirements. This yields a physically flexible integrated circuit (IC) chipset that can easily migrate into smart, wearable consumer devices, flexible and conformal industrial applications, and smart sensor structures.

C. System Demonstrators

With both pure printing and hybrid integration of conventional chips and printing methods available for fabrication of flexible systems, an obvious question is what kinds of applications are envisioned to build on the success of products such as flexible displays and photovoltaic modules. To provide a sense of where these technologies might go, the final set of papers offers some perspective on what flexible systems may be of interest and how they might be brought about.

The contribution from Cambridge University presents a concept for a future interactive display. Thin-film transistors and sensors constitute fundamental building blocks for a new generation of applications ranging from interactive displays and imaging to future electronic systems. This paper reviews the current status of the ubiquitous amorphous oxide semiconductor technology for flexible and transparent interactive displays to conceptualize a TFT-based fully heterogeneously integrated and autonomous system that can be realized using a combination of oxide TFT and other technological routes.

Next, we present an effort from a national research center known as ASSIST that considers the challenges of developing a truly wearable and viable physical health monitor. The paper focuses on addressing the key challenges in wearable health and environmental systems that enable ultra-long battery lifetime, user comfort and wearability, and validated sensor data. This paper presents the latest advances in use of nanotechnology to build miniature, self-powered, wearable and wireless sensing devices, high-efficiency nanostructured energy harvesters and storage capacitors, new sensing modalities, low-power computation, and novel flexible materials.

From wearables, we move to an even more demanding application. Lee *et al.* explore another direction where extreme flexibility as well as sophisticated electronics capability are essential. The large size, planar geometry, and stiff mechanical properties of standard conventional electronics employed in medical devices give rise to important integration challenges with soft biological tissue. The paper presents novel mechanics, materials, and integration strategies for this new class of bioelectronics onboard minimally invasive catheter-based systems. Representative examples highlight the clinical significance of soft biointegrated electronics, along with the mechanics and processes that enable this technology.

The last paper in this special edition examines yet another direction flexible hybrid electronics could take. Specifically, employing the ability to deploy electronics over large areas can lead to novel sensor arrays. The paper by Verma *et al.* describes this approach. By enabling diverse and large-scale transducers, large-area electronics raises the potential for electronic systems to be interactive much more extensively than is possible today. But first, translation into applications requires a base of system functions that cannot be realized by large-area electronics alone. It is necessary to combine large-area electronics with

CMOS, within hybrid systems. To explore platform architectures along with the supporting circuits and devices, they consider, a self-powered sheet for high-resolution structural health monitoring.

IV. SUMMARY AND CONCLUSIONS

Our intention has been to provide the reader with an understanding of what flexible hybrid electronics is about from a description of some of the applicable technologies, to the approaches being taken to overcome performance limitations and provide cost effective solutions, and finally to descriptions of potential future systems. Space precludes coverage of all the areas that are relevant to the subject. We apologize for this and particularly to the many technical contributors whose efforts are moving the technology and the field forward at an increasing pace. We would also be remiss if we did not thank our authors not only for their technical excellence, but for their willingness to sacrifice time and effort to provide the insights contained in this special edition. Further, we must also extend our gratitude to the reviewers who put so much effort into not just technical considerations, but also into ensuring that the material can be understood even by the nonexpert.

In addition to the organizations represented in this Proceedings, to learn more about printed, flexible, or hybrid electronics the reader is directed to FlexTech Alliance (flextech.org) which hosts an annual conference in February as well as workshops throughout the year. Other sources include IdTechEx (http://www.idtechex.com/) and Organic Electronics Association (OE-A,http://www.oe-a.org/home). Of particular interest is that OE-A's roadmap identifies hybrid systems as an important trend.

Of special interest for flexible hybrid electronics systems is the work of electronics manufacturing industry consortia, iNEMI. The iNEMI Roadmap has become recognized as an important tool for defining the state of the art in the electronics industry as well as identifying emerging and disruptive technologies. It also includes keys to developing future iNEMI projects and setting industry R&D priorities over the next ten years.

What is next for flexible electronics? It's hard to know exactly, but certainly some trends are becoming clear. First, regardless of the specific technical approach, there is increasing interest in solutions with novel form factors to include thin, lightweight, conformable, bendable, large area, and disposable. Flexible and printable electronics are consistent with such features. However, where more complex electronic functions are required, it is difficult to see how to achieve the desired capabilities without hybrid integration of conventional electronics in some way as described here. In fact, a reminder is often heard from those active in the development of TFTs—if it can be done in silicon, it will be done in silicon! In fact, current trends in silicon technology are making it easier than ever to include chip technology into flexible designs.

The emergence of 3D chip stacking and leakage power reduction in advanced nodes (ITRS roadmap) has provided infrastructure for both chip thinning and silicon on insulator integrated circuits. Both make thin silicon ($< 50\,\mu$m thick), which is flexible and transparent, readily available in mainstream designs. Thus, flexible electronics can benefit from the massive investment made in IC design and fabrication allowing product designers to focus on system design issues. Further, as described here, printing technology is maturing while directed self-assembly (of chips, not molecules) is being developed. Both offer potential of better controlled and capable systems either independently or as a hybrid approach. Packaging and assembly technology is also moving in a direction that will benefit flexible electronics. Multichip packaging, flexible circuit boards, low-resistivity interconnects, thin-film encapsulation technology all provide enhanced methods for flexible electronics. At the same time, sensors, whether printed or MEMS, are becoming more capable and more diverse, opening up more and more sensor system opportunities. So, although a specific roadmap may not be available, both product requirements and technical capabilities point to a bright future for flexible electronics. ■

ABOUT THE GUEST EDITORS

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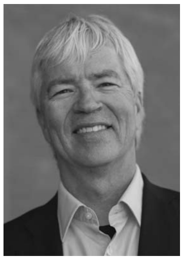

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