Macroelectronics

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Jae-Geun Park, Guest Editors

Abstract

As revolutionary as microelectronics has been as a technology, there are functions that it does not address. Microelectronics focuses on ever-smaller integrated circuits (ICs) in ever-fewer square millimeters of space to increase clock speeds and decrease the power required for computer processing functions. However, applications requiring control, communications, computing, and sensing over a large area are difficult or cost-prohibitive to achieve because of the material incompatibilities of traditional ICs with structures, materials, and manufacturing technology. Macroelectronics addresses these applications with the aim of providing active control circuitry *in situ* over areas of many square meters for displays, solar panels, x-ray imagers, surface measurements, structural shape control, vehicle health monitoring, and other large-system applications. The materials challenges of macroelectronics integrated circuits (MEICs) reviewed in this issue include lightweight flexible substrates, thin-film transistors (TFTs) with IC or near-IC performance, modeling, and manufacturing technology. Compatible component materials, flexible substrates, processing conditions, host system composition, and functionality provide grand challenges that are just beginning to be addressed by researchers.

Keywords: *electronic material, lithography, sensor.*

Electronic devices have become increasingly pervasive over the last 50 years. Advances have been driven primarily by microelectronics, based on the well-known Moore's law that describes the increasing complexity (and therefore performance) as feature size decreases over time. While there are many issues to be addressed, as described by ITRS roadmap,[1] the mainstream microelectronics industry continues to provide ever-increasing performance and functionality. However, other forms of electronics have also become important, as they address problems that conventional microelectronics cannot. The most significant of these is the display industry, which now rivals the integrated-circuit (IC) industry in terms of revenue. The technical drivers for these two major industries are essentially opposite. While the IC industry strives to make the smallest possible devices in the smallest possible area, the display industry is interested in large devices over the largest possible area. This drive to distribute the devices over large areas can be considered "macroelectronics," because neither the active devices nor the area they cover needs to be "micro" in scale.

Commercially viable macroelectronics began in 1988 with thin-film-transistor–based liquid-crystal displays (TFT-LCDs). Direct-view active-matrix liquid-crystal displays (AMLCDs) based on inorganic TFTs on glass substrates represent the first commercial success of macroelectronics. Sales of AMLCDs have superseded the cathode-ray tube in both revenue (2002) and units (2004) to become the dominant display technology on the planet.[2] Examples include the demonstration by Samsung in 2005 of an 82-in.-diagonal screen with six million TFTs controlling the brightness of each of two million color pixels (see Figure 1); a 100-in. AMLCD, announced by LG.Philips LCD Co. in January 2006; and an IBM monitor product introduced in 2002 with a 22.2-in.-diagonal screen, 27 million TFTs controlling 9.1 million (3840 × 2400) color pixels, and a TFT vertical/horizontal pitch of 124.5/41.5 μm. These TFT pitches are about a thousand times larger than those found in ICs. This difference in transistor density may be used as one way to distinguish macroelectronics ICs (MEICs) from classical metal oxide semiconductor field-effect transistor ICs.

Beyond the dominant AMLCD technology, several niche display technologies also use TFT backplanes to drive pixels over large areas and thus are considered examples of macroelectronics. Examples include displays based on organic light-emitting devices, electroluminescent electrophoretic ink, and field-emission mechanisms. Other large-area display technologies are not macroelectronics, as they do not have MEICs built into them. Examples include inorganic light-emitting diodes (LEDs), vacuum cathode-ray tubes (CRTs), and most plasma technologies. The LEDs now popular for jumbo-size outdoor displays in stadiums, billboards, and building facades are not macroelectronics, because they are driven externally by personal computers, not internally by TFT MEICs. The CRT vacuum technologies are driven by analog electronics (e-guns and deflection coils) and are not even digital, let alone macroelectronic. Drive voltages and power are also a distinguishing factor: TFT technologies typically operate at 3–5 V, drawing 1–10 W, compared with 1–20 keV and 1–10 kW, variously, for plasma, CRT, and LED displays. The pixel size in LEDs and plasma are also issues: millions of LEDs are separately packaged and hand-mounted with 10-mm pitch in arrays meant for viewing at hundreds of feet.

Some potential future application areas for macroelectronics are illustrated in Figure 2. These areas include displays (top left and top right), sensors (top right and bottom right), energy harvesting (top right and bottom left), electronics embedded into gear (radios, range finders, computers) and clothing (bottom left), and structural health monitoring of vehicles or humans (bottom right). Structural health monitoring involves a range of sensors, processors, and transmitters built with flexible MEICs within vehicle composite materials to actively sense and report faults, or mounted on/in human biomaterials (skin/tissues) to continuously sense and transmit physiological and cognitive status. The weight and materials integration issues with ICs make these applications impossible or unlikely with a purely microelectronics approach and thus require macroelectronics.

The biggest challenge for macroelectronics technology is to enable applications beyond displays that involve large areas and volumes that cannot be cost-effectively achieved through traditional packaged-chip fabrication followed by pick-and-place assembly and that nonetheless require sophisticated, high-performance circuits. The large scale of macrosystems gives rise to the requirement for properties heretofore not associated with IC applications, such as thinness, ductility, and elasticity of electronic components, even during operation. Depending on specific applications, some design rules for traditional ICs must be maintained (e.g., length of transistor channels) and others relaxed (e.g., area of circuit layout).

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Figure 1. Samsung 82-in. 2-megapixel (Mpx) active-matrix liquid-crystal display (AMLCD) next to a 102-in. 2-Mpx plasma display panel at the Society for Information Display Exhibition in May 2005. The AMLCD has 6 million thin-film transistors in its subpixels and is an example of the state of the art in macroelectronics manufacturing technology for full high-definition (HD) digital television displays. A 100-in. 2-Mpx AMLCD was announced in January 2006 by LG.Philips LCD Co. (Photograph courtesy of D.G. Hopper.)

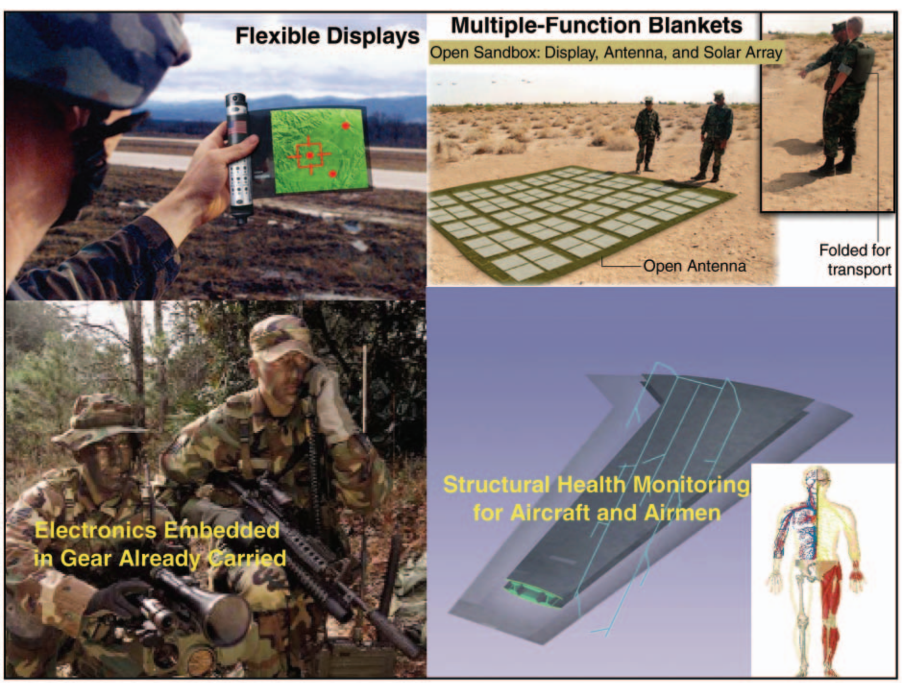

Figure 2. Examples of conceptual future applications envisioned for macroelectronics. (Photograph courtesy of D.G. Hopper.)

While displays have already become a dominant force in electronics over the last few years, other trends have emerged that do not have the same success criteria as conventional electronics. One such area is new materials and devices for radio-frequency identification (RFID) tags. Here, the interest is not in performance, but in the lowest possible price, so that "disposable" electronics becomes possible. There is growing interest in other nontraditional product drivers, including light weight for portability, distribution over large surface areas for measurement and control functions, and flexibility to allow the electronics to be conformed to a 3D surface or folded for ease of transport. All of these desirable qualities are characterized by attributes that are significantly different than the number of transistors/cm^2 that drives classic microelectronics.

In this issue of *MRS Bulletin*, we provide a snapshot of some of the major trends in macroelectronics. Primarily, our overview is from the perspective of active devices, which are the key enablers of this emerging technology. Additional technology challenge areas for macroelectronics include substrates, dielectrics, and sealing. These issues are addressed to some extent within the articles in this issue, but the reader is also referred to the many articles on these topics published by the Society for Information Display, and to the U.S. Army flexible display initiative described by Pellegrino et al.[3]

Macroelectronics often involves co-fabrication of electronics and structures. An MEIC is typically built directly onto or within the structure it controls, senses, or communicates with. The ultimate MEIC is inseparable from and synergistic with the system in which it resides—like the nervous system within a human body. The opposite is true for traditional microelectronics, in which passive devices, packaged chips, boards, and boxes are each fabricated separately and only later are integrated into the structure to be operated or interfaced with. This difference in systems engineering approach has profound implications for the materials, electronic design, and manufacturing techniques required. The TFT MEICs in active-matrix displays must be built in during the manufacturing process of the display for it to work—you cannot just append an IC later. The TFT MEICs used in aircraft structural health monitoring must be built into the composite materials. The weight, volume, and materials compatibility (e.g., flexibility) of packaged ICs preclude their use for this application.

One very desirable feature is to apply integrated electronics to flexible substrates in the anticipation that this achievement would dramatically increase applications that could be addressed. Envisioned macroelectronics applications include covering exposed surfaces (e.g., airframes, walls), integration into mechanical structural elements to conserve space and weight (buildings, airships, unmanned aerial vehicles, clothing), and control/sensor applications. Furthermore, with a flexible substrate, the electronics package could be folded or rolled up for storage when not in operation.

Organic TFTs (OTFTs) may have better compatibility, in terms of coefficients of expansion, with composite materials in which they may be embedded for applications such as structural health monitoring in aircraft. In this *MRS Bulletin* issue, Lee et al. from Samsung discuss OTFTs, with a particular emphasis on display applications. The authors review OTFTs for large-size displays and demonstrate that their unique solution-processable gate dielectric materials form uniform films over large areas and exhibit excellent insulating properties and reduced contact resistance. A 15-in. full-color AMLCD and 192 × 64 pixel active-matrix organic LEDs driven by pentacene-based OTFTs have been demonstrated for the first time. Optimization of these materials for organic semiconductor patterning creates an opportunity to develop commercially viable flexible MEICs.

Transistors for macroelectronics cannot be made with the thick-film designs and high-temperature processes used to make traditional small (10 mm × 10 mm) IC chips on small (300 mm) rigid substrates in an expensive fabrication facility; TFT designs must be used instead. The TFT was invented by Weimer[4] in 1962 at the RCA Laboratories (now Sarnoff Corp.) for the purpose of implementing the IC concept, but its main application has been as a pixel switch and driver circuitry running at kilohertz speeds for active-matrix flat-panel displays based on liquid-crystal light modulation. These applications have not forced TFT research to produce the higher device performance in speed (megahertz, gigahertz), scale, or cost that will often be needed for MEICs. Thus, producing TFTs with IC-quality performance is a technical challenge that macroelectronics must address. Near-IC performance at a throw-away low cost is another.

Recent work by Brotherton et al.[5] at Philips in the United Kingdom has shown that TFTs with channel lengths similar to ICs are possible; the Philips goal is to move all electronics into the display. Furthermore, these high-performance TFTs must be compatible with all other MEIC properties (e.g., flexible substrate) or have other novel characteristics (e.g., transparency). The group led by Wager[6] has invented transparent TFTs (TTFTs) based on a novel new class of semiconductors known as amorphous multicomponent heavy-metal cation (a-MHMC) oxides (see Figure 3).

However, it has proven very difficult to achieve high-performance TFTs and macroelectronics on plastic substrates. In this issue, van der Wilt et al. from Columbia University and Sarnoff Corp. discuss poly-Si TFT circuit fabrication directly on a plastic substrate, which is the most advanced and highest-performance technology achieved to date, as measured by unity gain frequencies f_t of 250 MHz and 185 MHz for *n*-type and *p*-type metal oxide semiconductor TFTs and by CMOS ring oscillators above 100 MHz.[8]

The challenges for fabricating high-quality, poly-Si TFTs, especially on low-temperature substrates, are daunting. For that reason, alternative methods such as the OFETs are of considerable interest. But the difficulty of obtaining organic-based TFTs with adequate device characteristics has led to the search for new ways to fabricate crystalline, inorganic semiconductors on lightweight and low-cost substrates. Examples of this approach include carbon nanotubes and silicon nanowires. As these devices have novel compositions and structures, yet are analogous to classical transistors, theory, modeling, and circuit simulation tools need to be adapted from the IC and flat-panel display industries and expanded to address the peculiarities of macroelectronics circuits. In their article, Alam et al. from Purdue University address the issue of modeling these new device structures such that the rapidly expanding experimental results can be used to predict and develop future macroelectronics materials, structures, and devices.

Manufacturing advanced MEICs requires a new fabrication industry based on techniques that are currently alien to microelectronics processing. Roll-to-roll substrate handling replaces wafer batches; material deposition via printing replaces vacuum evaporation; material removal by stamping replaces etching, and self-assembly replaces deterministic, submicrometer-scale placement of components. The capital required to build a microelectronics state-of-the-art 300-mm wafer fabrication facility is $3 billion; macroelectronics facilities are anticipated to cost an order of magnitude less. Furthermore, the cost pure unit area of product is expected to drop from the order of $10,000 per sq ft for microelectronics to $100 per sq ft for macroelectronics. An initial approach to this alternative means of manufacture is presented by Chason et al. from Motorola in their description of adopting printing techniques and circuit board technologies for large-area, low-cost macroelectronics for applications such as telecommunications products.

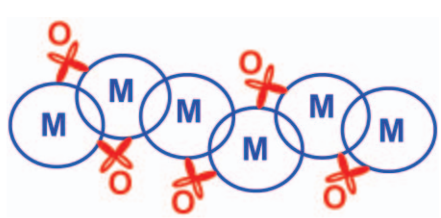

Figure 3. Schematic illustration of an amorphous multicomponent heavy-metal cation oxide.[7]

To achieve both the technical and cost goals for high-performance macroelectronics, patterning techniques are needed for MEICs that include dynamic self-alignment to 1 μm or less over more than 300 mm of stretchable/shrinkable substrate, rather than 100 nm or less over 0.3 m of rigid substrate in ICs. While the design rule tolerance may be relaxed 10× in many cases for an MEIC compared with a traditional IC, the substrate scale grows by 1000×. Also, macroelectronics substrates may not be rectilinear flat. These capabilities are expected to be significant enablers of future macroelectronics products.

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2. *Report of the Department of Defense Advisory Group on Electron Devices Special Technology Area Review on Displays* (Office of the Under Secretary of Defense for Acquisition, Technology & Logistics, Washington, DC, June 2004). Available to the public from the National Technical Information Service, Springfield, VA.

3. J.M. Pellegrino, G.L. Wood, D.C. Morton, and E.W. Forsythe, in *Proc. SPIE* **5080** (SPIE, Bellingham, WA, 2003) p. 1.

4. P.K. Weimer, in *Proc. IRE* **50** (1962) p. 1462. Working at the RCA Laboratories (now Sarnoff Corp.), Weimer fabricated integrated thin-film circuits incorporating passive elements and hundreds of thin-film transistors (TFTs) operating in enhancement, with the first semiconductor films for TFTs being CdS. Weimer's experience with *n*- and *p*-type TFTs led him to the invention of the low-power complementary invertor and the flip-flop circuit, both now widely used in CMOS silicon memories. Although the TFT approach to integrated circuits was displaced by x-Si for most applications, the advantage of the TFT for large-area circuits was apparent. Also, Weimer thought it fun to challenge the silicon establishment with an alternative approach.

5. S.D. Brotherton, C. Glasse, C. Glaister, P. Green, F. Rohlfing, and J.R. Ayres, *Appl. Phys. Lett.* **84** (2) (2004) p. 293. Working at the Philips

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Research Laboratories in the United Kingdom, Brotherton et al. have focused on increasing circuit integration in active-matrix liquid-crystal displays (AMLCDs) with the ultimate goal of system-on-panel displays. Achievement of this goal requires the replacement of metal oxide silicon field-effect transistor (MOSFET) circuits with poly-Si thin-film transistor (TFT) circuits. The key difference between MOSFETs and TFTs is the channel length: production MOSFET channels are submicrometer in size, while TFT channels are 4–6 μm. Brotherton et al. demonstrated 0.5-μm channel-length TFTs with a 20-nm-thick gate oxide with high mobilities (μ_p = 60 cm^2/V s, μ_n = 80 cm^2/V s) and with gigahertz potential (~0.1 ns delay/stage at 3 V supply for a 15-stage complementary-pair MOSFET ring oscillator).

6. J. Wager's group at Oregon State University and Hewlett Packard in Corvallis, Oregon, have begun to investigate amorphous multicomponent heavy-metal cation (a-MHMC) oxides for transparent thin-film transistor (TTFT) applications. Initial results are reported in Dehuff et al., *J. Appl. Phys.* **97** 064505 (2005) and Chaing et al., *Appl. Phys. Lett.* **86** 013503 (2005). For example, 85% transmission of visible light was obtained for zinc indium oxide (ZIO) TTFTs made at 300°C having a mobility μ of 10–30 cm^2/V s and an on/off ratio of 106.

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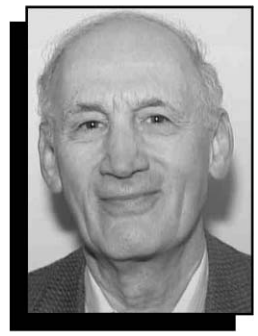
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