GUEST EDITORIAL

Nanopackaging Pervades Future Electronic and Bioelectronic Systems

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SEAMLESS HETEROGENEOUS device and component copackaging technologies are the key to future electronic and bioelectronic systems. Such systems will be pervasive and include mobile and high-performance computing, high-bandwidth 5G communications with enhanced mobile broadband and massive Internet of Things (IoT) connectivity, implantables and wearables for health monitoring and therapy, and advanced driver assistance systems, among other features. To realize such systems, necessary packaging technology building blocks are needed. These include high-bandwidth interconnections with power and signal integrity between devices; high-efficiency granular power delivery to different voltage domains within the devices; seamless RF front-end module integration with antennas, passives, and the beamforming devices; compact 3D power converters; and active microelectrode arrays with integrated power and signal conditioning in bioelectronics. Higher component densities with heterogeneous integration are required to realize any of these building blocks and systems, which are enabled by nanopackaging.

As described in the December 2018 special issue of *IEEE Nanotechnology Magazine*, nanopackaging enables better performance, miniaturization, and processing of all the functional building blocks in a typical system, such as high-density and high-efficiency power storage and delivery; RF front-end module integration; high reliability with miniaturization; and low-cost, large-area, and high-volume additive manufacturing techniques. Figure 1 summarizes the impact of nanomaterials in power, RF, and bioelectronic functional integration through some prominent, though not exhaustive, examples. This special issue selectively highlights three key examples of nanopackaging advances that manufacturers use to realize these building blocks. These advances include power delivery, low-cost additive manufacturing of flexible wireless sensing systems, and high-reliability miniaturized electronics.

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POWER DELIVERY

Researchers are realizing that power supply is a major challenge to future computing systems for mobile processors, due to size restrictions, and for data processing-intensive applications such as servers or data centers, due to their need for high efficiency and performance. Power supply includes power conversion, power delivery, and power management. Current approaches create several limitations in each of these subsystems, including the following:

1) power conversion far from the load, limiting the response time
2) multiple stages of conversion, reducing efficiency
3) low-density inductors and capacitors leading to large size
4) large losses due to long interconnections through the board.

This special issue selectively highlights three key examples of nanopackaging advances that manufacturers use to realize these building blocks.

Researchers are developing advanced substrate-compatible thin-film and thick-film processes to achieve higher power handling with thinner form factors. Traditional power conversion is based on switching regulators with inductors or transformers as the main storage components. However, capacitor-based power conversion with switch capacitor networks or hybrid resonant converters is emerging as an alternative to address the size, electromagnetic interference, and integration limitations of thick magnetic components.

Multilayered ceramic capacitors, innovative high-surface-area tantalum or aluminum electrode capacitors, polymer film capacitors, and silicon trench capacitors are key options for capacitors efficiently filtering the power supply noise. All of these approaches are used at different levels of the power delivery chain, based on the current and voltage rating, equivalent series resistance, frequency stability, capacitance density, thickness, and integration options.

Irrespective of the approaches, advanced high-permittivity dielectrics that manufacturers can synthesize with scalable polymer thick-film and printing approaches can bring key paradigm changes in the capacitor integration. Such high-permittivity dielectrics with nanocomposites are traditionally synthesized by ceramic or metal-filled polymers. However, innovative nanocomposite or hybrid dielectrics are emerging to address the limitations of these approaches. Such nanocomposite dielectrics can achieve permittivities of above 20 and still retain the benefits of low-temperature polymer-processing approaches such as spin coating and additive manufacturing. "Nanocomposite Capacitors in Power Electronics and Multiferroics,"

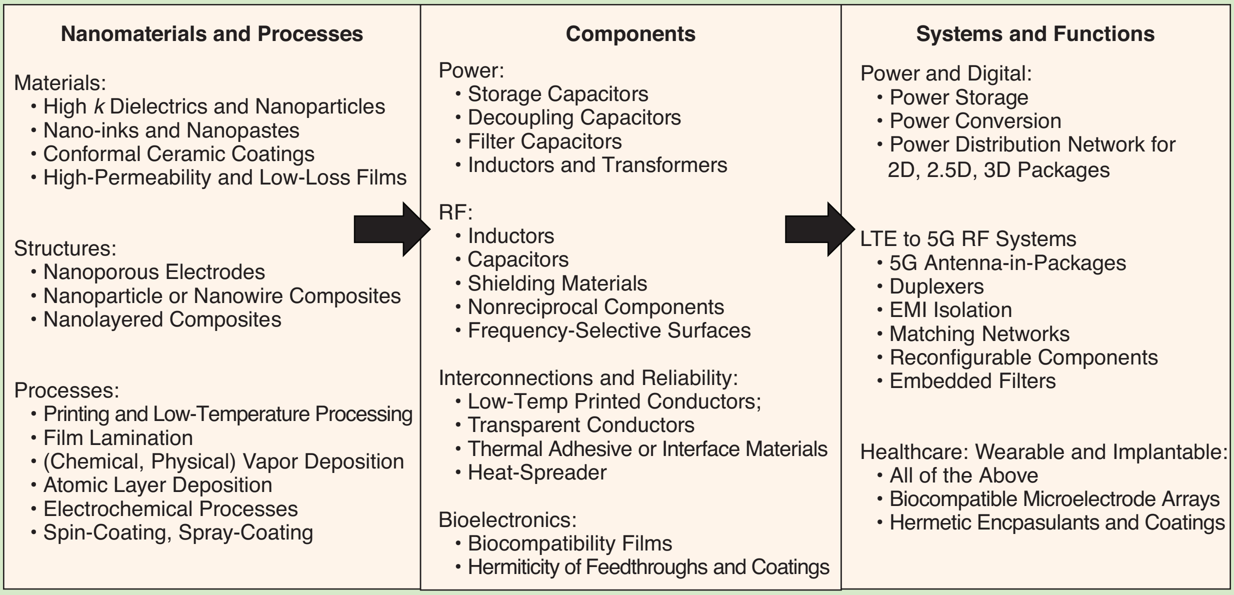

FIGURE 1 Nanoscale materials, structures and processes leading to advanced components and functions.

by Eli S. Leland, Peter R. Kinget, Ioannis Kymissis, Daniel Steingart, Seth R. Sanders, and Stephen O'Brien, highlights an innovative approach for realizing high-permittivity nanocomposites in 3D-printed high-density capacitors for integrated power convertors or voltage regulators.

LOW-COST ADDITIVE MANUFACTURING OF WIRELESS SYSTEMS

Nanopackaging technologies have been impacting additive manufacturing of flexible systems with scalable and low-cost roll-to-roll processing. Driven by IoT market needs, these technologies are projected to create a massive global economy in the next 4–7 years. Nanomaterials not only provide passive functions such as low-loss device-to-package printed interconnections and transmission lines and antenna arrays, but they can also off-load the active circuits from rigid silicon chips and integrate them into the flex substrates with printing and other technologies.

Printed active diodes and field-effect transistors can also provide sensing functions and integrate them with wireless interfaces directly on flexible substrates. "Nanotechnology-Empowered Flexible Printed Wireless Electronics," by Aline Eid, Jimmy Hester, Yunnan Fang, Bijan Tehrani, Syed Abdullah Nauroze, Ryan Bahr, and Manos M. Tentzeris, reviews the role of nanotechnology in flexible printed wireless and sensing electronics, and details the printed ramp interconnections. This article highlights key nanopackaging innovations in flexible electronics including chemical surface modifications for better metal-polymer adhesion leading to superior reliability and metal-semiconductor Schottky contacts for improved sensitivity.

The primary role of electronic packaging is to seamlessly interconnect actives to passives without generating interconnected parasitics. With the trends toward high-frequency systems, the device–package interconnection losses from wirebonding and flip-chip tend to dominate the total system loss. They also limit the flexibility and miniaturization of the system. Die-embedding systems with printed direct interconnections between the chips and the system components can address this challenge. Nanoinks for printed interconnections are commercially available from several suppliers and can be processed at a temperature of approximately 80 °C. Low-temperature accelerated photo-sintering of these printed inks are also developed by high-throughput processing.

HIGH-RELIABILITY MINIATURIZED ELECTRONICS

Functional integration is achieved with advanced designs that are enabled with new materials. Manufacturers commonly use traditional polymer and polymer composites in packaging applications as dielectrics, encapsulants, and underfills for reliability, thermal interface materials, and mold compounds for fan-out packaging. Since fan-out packaging is emerging as the mainstream technology for application processors in mobile electronic products, their properties play a key role. Mold compounds are being widely investigated for better thermal-mechanical (low CTE of 4–5 ppm/C and high interfacial fracture

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toughness of 30 J/m^2), thermal (high thermal conductivity of more than 5 W/mK), and electrical (low dielectric loss of less than 0.005 for supporting high-speed digital or high-frequency interconnections) characteristics.

Other commercialization examples of nanopackaging materials are in the area of off-chip interconnections and thermal adhesive (interface) materials based on silver and copper nanopastes. However, for high-power applications, the residual porosity and microstructural instabilities have created reliability concerns in high-power die-attach applications. Nanocomposites of copper or silver with additives to control stress are being developed by material suppliers. In a recent key innovation by Namics Inc., they incorporate additives into the nanopaste to fill the pores and to stabilize the microstructure while also enhancing the toughness of the thermal adhesive materials. On the other hand, direct copper-to-copper interconnections with nanostructured copper interfaces are promising to overcome the pitch and reliability limitations of solder-based assembly technologies. Such nanostructured copper interconnections are developed by presynthesized inks or pastes that are transferred to the interconnection, or by innovative nanocopper foams formed in situ on the tip of the copper pillar.

With the trend toward low-cost flexible electronics for wearable IoT, display, and implantable electronics, organic functional materials and their packaging in polymer films is becoming extremely important. Since polymers are not inherently hermetic, they are prone to a diffusion of moisture, oxygen, and other reactive ions. For long-term reliability, it is important to protect the systems with inorganic hermetic coatings. “Ultrabarrier Films for Packaging Flexible Electronics,” by Ankit Kumar Singh and Samuel Graham, describes the advances in multilayered nanoscale coatings to provide near-hermitic performance. Researchers are widely investigating this technology for the reliability of flexible organic semiconductors in display applications, but it can also be applied to bioelectronic implants. Nanoscale barriers can be deposited as ultrathin conformal coatings and can replace bulky ceramic cases and hermetic cans that are brazed onto the chip carrier substrate in bioelectronics implants. This process can eliminate the extra volume in the hermetic package, and can also lead to better flexibility and fewer constraints during implantation.