GUEST EDITORIAL

Next-Generation Nanopackaging

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I AM DELIGHTED TO INtroduce this special issue on nanopackaging to realize next-generation three-dimensional (3-D) and flexible electronics with heterogeneous functional integration. *Nanopackaging* is defined as the packaging of devices and systems with nanoscale materials and processes for improved performance, functionality, miniaturization, reliability, and cost. It seeks to bridge the gap between integrated circuits (ICs), which are at the nanoscale, and the rest of the system components that are typically at milliscale or microscale.

Nanopackaging plays a key role in all the major aspects of system integration: improved functional density, higher power densities and power efficiency, higher bandwidth with lower power, improved thermal management, and better reliability. These are illustrated in Figure 1 with two examples of systems: one as a 3-D computing and communication module and the other as a flexible electronics module for wearables and the Internet of Things (IoT). The role of nanopackaging is briefly described in the five subsequent sections. All of the major nanopackaging technologies are highlighted in this special issue.

POWER SUPPLY AND CONVERSION

Nanostructured electrodes improve the volumetric power densities because of their higher surface area, conformal ultrathin dielectrics or electrolytes, and counter electrodes, and thus, they lead to thinner power components. These can be embedded into the package or on wafers, instead of mounting them as discrete surface-assembled bulky components. Because of their proximity to the actives, they also lower the effective inductance parasitics. This leads to improved power distribution and granularity, with improved efficiency. The article by Ninad Shahane, P. Markondeya Raj, Chandrasekharan Nair, Vanessa Smet, Chintan Buch, and Rao Tummala reviews nanopackaging for power sources, energy harvesting, and power conversion using several categories of examples for batteries, supercapacitors, generators, capacitors, and inductors.

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THERMAL MANAGEMENT

Nanoscale materials and interfaces improve the heat rejection and spreading from the chip to the heatpipe or coldplates, from where the heat is rejected to the ambience. Two-dimensional (2-D) nanomaterials made of graphene and boron nitride (BN) can improve the film's thermal conductivity, while also allowing for better phonon transfer across the interfaces, when fabricated as thin conducting or insulating films. They can also play a strong role in the design and fabrication of the heatpipes and coldplates themselves. The article by Mustafa Akbulut and Ethan A. Scholar describes 2-D nanocomposites of graphene and BN in polymers for thin high-thermal-conductivity insulating films that are used in the thermal management of power modules in applications such as automotive drivetrain.

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FUNCTIONAL COMPONENTS

Nanomaterials can provide unique radio frequency, sensing, and digital packaging functions. Also, nanopackaging encompasses packaging of nanoscale devices using both top-down nanostructuring processes and bottom-up self-assembly processes. As one such example, ferromagnetic nanowires are emerging as suitable candidates for integrated nonreciprocal components for millimeter-wave (mm-wave) communication functions. They can be used to create Faraday rotation and extend to applications such as circulators and isolators. Nitin Parsa and Ryan C. Toonen describe the design, fabrication, and characterization of ferromagnetic nanowires for generating quasi-optical Faraday rotation.

FLEXIBLE ELECTRONICS

Flexible electronics are emerging to address the large market need for the IoT, structural monitoring, health care, and monitoring through wearable and implantable electronics. Nanomaterials play a role in the low-temperature deposition of conductors with printed or additive manufacturing approaches. Nanocomposites can be engineered to enable soft or deformable interconnections that can resist bending and deformation, scalability to fine pitch, and provide options for reworkability or remateability for device assembly and flex-to-flex connectors. The aforementioned article by Ninad Shahane, P. Markondeya Raj, Chandrasekharan Nair, Vanessa Smet, Chintan Buch, and Rao Tummala reviews the interconnections and assembly approaches with nanoscale materials.

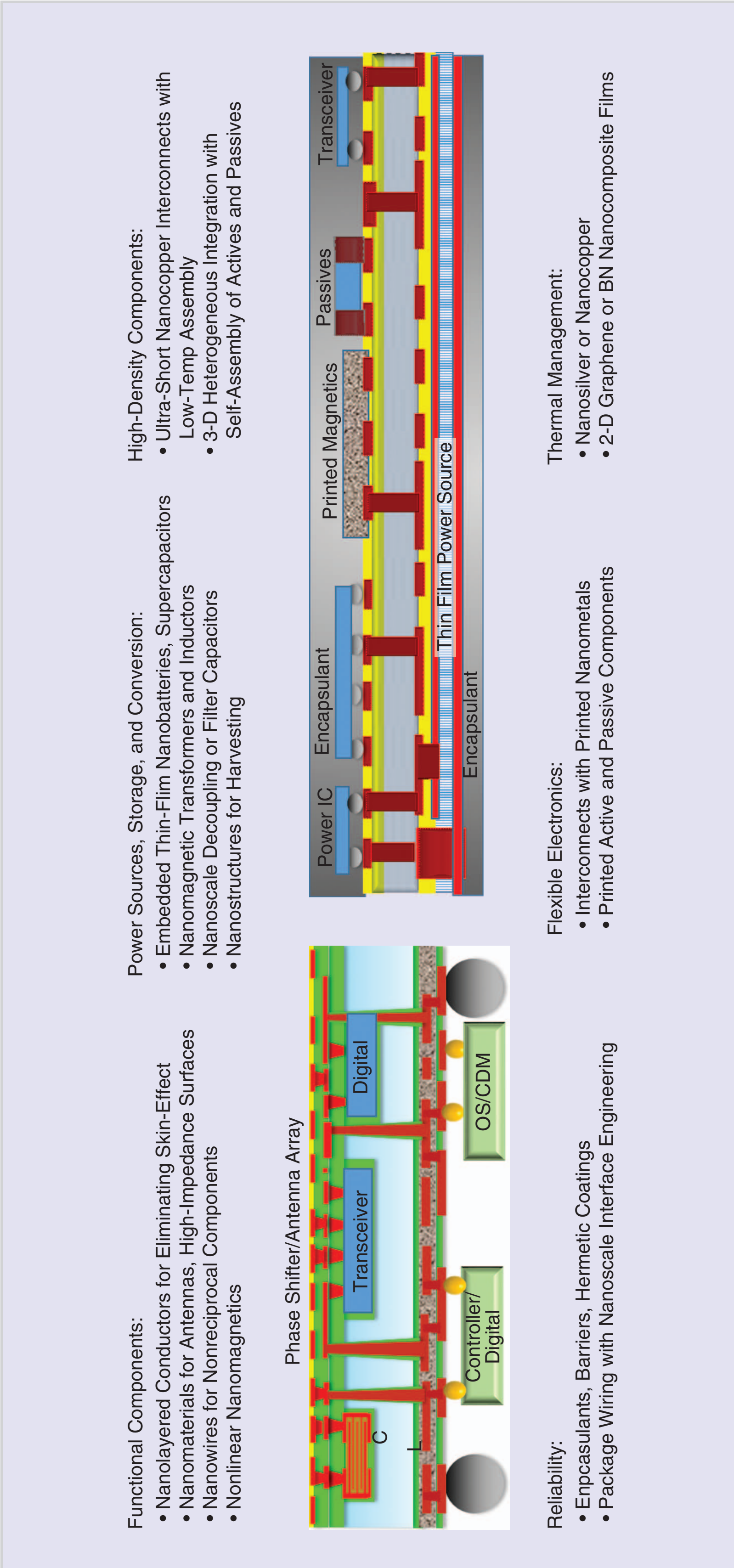

FIGURE 1 Applications of nanopackaging in 3-D modules and flex packaging. OS/CDM: on-site code division multiplexing.

> In the future, nanostructured materials will dominate almost all aspects of electronic packaging.

RELIABILITY

Nanoscale materials can be engineered to attain an unusual and beneficial combination of properties. Nanosilver and nanocopper die-attach materials can lower thermal resistance with high reliability for large power dies, but they also serve as interconnect materials for handling higher current densities without any electromigration or thermomechanical reliability failures. Another primary class of nanopackaging materials is nanocomposite encapsulants and underfills with lower coefficient of thermal expansion, high thermal conductivity, and high glass transition temperature with lower filler content for applications in 3-D IC stacks and packages. Nanoscale barriers can be deposited as ultra-thin conformal coatings and can replace bulky ceramic cases and hermetic cans in flexible electronics and bioelectronics implants.

In the future, nanostructured materials will dominate almost all aspects of electronic packaging. It is the goal of this special issue to describe the importance of this key topic to the IEEE nanotechnology audience. Readers are also encouraged to look for the next *IEEE Nanotechnology Magazine* issue on nanopackaging (appearing in the first half of 2019), which focuses on nanoscale coatings that act as moisture and oxygen barriers, nanointerconnects and functional radio-frequency components with additive manufacturing for flexible electronics, and nanomaterials for encapsulants, flexible and stretchable conductors. N