SCANNING THE ISSUE

Emerging Graphene-Based Electronic & Photonic Devices, Circuits, and Systems

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Carbon is a very ancient element that has been studied extensively for over a century. This Special Issue on Emerging Graphene-Based Electronic & Photonic Devices, Circuits, and Systems focuses on the amazing electronics and photonics applications of 2-D carbon, graphene. The first recorded attempt to study few-layer graphite—as it was known then—in a form recognizable today as graphene appears to have been in 1859 [1]. Much is now known about the chemistry and physics of graphene, and emerging engineering applications are being reported routinely. A decade since Noveselov *et al.* published their results on field-effect transport in few-layer graphene [2], [3], the field is now ready for serious consideration of graphene as an electronic material. This Special Issue aims to highlight some of the different devices and applications currently being pursued.

This special issue provides a snapshot of the emerging graphene-based devices and circuits that are now possible and addresses the challenges that still remain.

This volume of the Special Issue has 19 papers that roughly cover five subareas that are important for future applications of graphene in electronic and photonic devices, circuits, and systems. The subareas are: 1) epitaxial growth of graphene; 2) single field-effect transistors, high-frequency RF mixer circuits, frequency multipliers, and oscillators; 3) multiscale modeling of graphene-based transistors; 4) graphene photonics, including plasmonic applications, graphene-based terahertz devices, and graphene-based photodetectors; and 5) other graphene-based devices and applications such as resistive memory, on-chip interconnects, microelectromechanical systems, and graphene bioelectronics.

The volume begins with a historical perspective of carbon-based nanometer-scale materials by Dresselhaus and Terrones. These authors trace the arc of the early work in the 1950s and 1960s, with much of the work motivated by technological applications of carbon fibers. In the 1970s, it was recognized that intercalation was a way to separate individual layers of graphene and thus modify their properties. The discussion continues with the history of the discovery of fullerenes, carbon nanotubes, culminating in the work of Noveselov *et al.* on the first study of the electronic properties of single-layer graphene [2], [3].

The first subarea discussed in the issue is epitaxial growth of graphene and its subsequent integration with other materials necessary for production of devices. Colombo *et al.* describe one of the emerging methods for growing graphene—the chemical

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vapor deposition method—which is based on a catalytic reaction between a carbon precursor and a metal substrate such Ni, Cu, and Ru, to name a few. Another approach for growing graphene is described by Fukidome *et al.* This approach, which produces graphene-on-silicon, begins with a gas-source molecular beam epitaxy process that results in deposition of a thin film of SiC on a silicon substrate. The SiC layer is then heated to high temperatures ($> 900\ ^\circ$C) so that the silicon in the SiC layer sublimates, leaving behind a layer of graphene on a much thinner layer of SiC on the initial silicon substrate. This approach is intriguing in that it could potentially lead to the integration of traditional Si-CMOS devices with graphene-based devices on the same base substrate platform.

The next series of papers, constituting the second subarea of the volume, discuss graphene-based transistors and circuits. The first paper in this series by Schwierz sketches an overview of the status and challenges in graphene-based transistors. It discusses the types of graphene-based transistors that have been reported to date and compares their performance metrics to those of transistors made from other materials systems. The following paper by Jena discusses graphene-based tunneling transistors, and how these compare to 2-D transistors made from the GaAs/AlGaAs materials systems. In the paper by Jung *et al.*, self-aligned field-effect transistors with extremely small access lengths are discussed. Finding suitable gate-dielectric materials for graphene remains a problem since most traditional dielectrics introduce undesirable impurities and disorder in the graphene. The paper by Meric *et al.* addresses this problem by using boron nitride as a dielectric material. These authors show that the performance of graphene-based transistors with boron nitride as the dielectric can be improved considerably compared to those that use conventional dielectrics. It is believed that the hexagon structure of boron nitride is more compatible with graphene than that of other dielectric materials, hence leading to device performance improvements. Two papers in this subarea discuss the potential of graphene-based transistors in the design of high-frequency circuits. The paper by Wu *et al.*, for example, demonstrates the use of graphene transistors in a four-port RF mixer. This mixer is capable of operating at frequencies up to 10 GHz. The paper by Hsu *et al.*, on the other hand, uses the graphene transistors to design and demonstrate the operation of a frequency multiplier circuit in the gigahertz frequency range. These two demonstrations clearly point the way for future applications of graphene-based transistors in circuits. Finally, the last two papers in the second subarea are concerned with modeling and simulation issues in graphene transistors. Unlike transistors based on conventional 3-D materials, graphene introduces a complication in that the nanometer-scale nature of the material confronts one with quantum mechanical issues that cannot be ignored. A paper by Fiori and Iannaccone addresses this issue by using multiscale modeling of graphene transistors. It discusses incorporation of quantum effects in the models that describe transport and field effects in the devices. The paper considers *ab initio* methods for modeling of graphene and graphene nanoribbon-based transistors. The paper by Xu *et al.*, on the other hand, considers issues connected with variability in the devices. It attempts to identify the source of the variabilities, and how these contribute to fluctuations and noise in the devices.

The next three papers in the volume fall in the subarea of graphene photonics. The first paper, by Jablan *et al.*, discusses plasmonics in graphene. Plasmons in graphene differ in a substantial way from surface plasmons in metal-dielectric interfaces. They are, for example, excited in the frequency range from the visible through the infrared to the terahertz. In graphene, plasmons are expected to provide valuable insights into many-body effects that include electron–phonon, electron–electron, and plasmon–phonon interactions. A paper by Sensale-Rodriguez *et al.* addresses the potential to design reconfigurable terahertz devices using electrically tunable optical properties in modulators and switches that are based on graphene. The last of the three papers on graphene photonics, by Xia *et al.*, addresses fundamental light-graphene interactions within a single-electron framework. It discusses experimental measurements of the dynamic conductivity and its relationship to light transmission. The paper also provides the design and experimental results of a graphene-based photodetector in a metal–graphene–metal configuration. This is similar but different in its principle of operation to a conventional metal–semiconductor–metal detector. Several other optoelectronic devices that include a waveguide modulator, tunable infrared plasmonic filters, and polarizers are described.

The fifth, and last, group of papers in this volume is on various other applications of graphene. A paper by Yang *et al.*, for example, addresses the use of graphene in a transparent resistive memory element. The device described is a ZnO-based transparent resistive random access memory that employs graphene as a transparent and stable resistive element with switching characteristics usable in memory applications. The paper by Rahkeja *et al.* discusses the prospects of using graphene as an interconnect material that could replace copper in future Si microchips. Graphene has desirable electron transport properties at the nanometer-scale which conventional interconnect materials do not possess. This paper introduces signal transport mechanisms and models for graphene and compares these to transport in copper. It further discusses the possibility of electron spin injection in graphene wires. In yet another application area, a paper by Chen and Hone discusses the unique mechanical properties of graphene and their suitability for nanoelectromechanical systems. The specific properties that make it suitable for this application include high stiffness, ultrahigh strength, and its well-known electronic properties. This paper presents state-of-the-art graphene-based nanoelectromechanical devices and the signal transduction schemes required for these devices. The last paper in this category, by Hess *et al.*, addresses use of graphene transistors in biosensing applications. Because graphene is composed of carbon, it is intrinsically biocompatible. This paper discusses how to fabricate solution-gated transistors from graphene. It describes the fabrication process for such devices and presents experimental results that demonstrate the suitability of graphene for biological applications. Experiments with electrogenic cells to confirm that graphene-based transistors can be used to record electrical activity in cells are reported.

Finally, the last paper of the volume, by Alcalde *et al.*, assesses the commercial potential of graphene in large volume applications. The applications considered in this paper are different from those discussed in the majority of the papers of the volume. Specifically, the paper focuses on applications where comparisons can be made with other existing materials that currently dominate particular market segments. The market segments include displays, where transparent electrodes (indium tin oxide) play a key role, carbon-based nanofillers, and conductive materials (copper, aluminum, graphite, activated carbon).

Although much progress has been made in our understanding of the electronic structure and properties of graphene during the last decade, much still remains to be done in bridging the gap between laboratory demonstrations and the engineering prototypes necessary as precursors for commercial scaleup for production. We hope the papers in this volume will provide readers with a snapshot of the emerging graphene-based devices and circuits that are now possible, as well as the challenges that still remain. ■

REFERENCES

[1] B. C. Brode, "On the atomic weight of graphite," *Phil. Trans. R. Soc. Lond.*, vol. 149, pp. 249–259, 1859.

[2] K. S. Noveselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, "Electric field effect in atomically thin carbon films," *Science*, vol. 306, pp. 666–669, 2004.

[3] K. S. Noveselov, D. Jiang, F. Schedin, T. J. Booth, V. V. Khotkevich, S. V. Morozov, and A. K. Geim, "Two-dimensional atomic crystals," *Proc. Nat. Acad. Sci.*, vol. 102, pp. 10451–10453, 2005.

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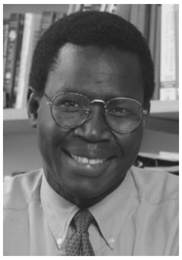

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