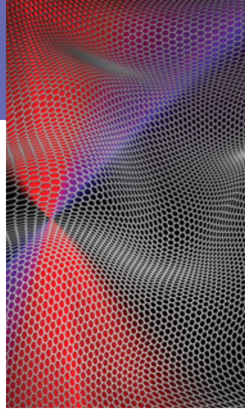

Will graphene be the material of the 21st century?

Patrick Soukiassian

History is replete with materials that have made substantial contributions over the centuries. Carbon as "coal" was definitively the material of the 19th century since it seeded the industrial revolution, triggering the birth of steel and chemical industries, leading to railways and modern naval technology. The rise of electronics was initially based on vacuum tubes with the electron, as a charge carrier, moving in vacuum. Making electrons travel in the solid state, Bardeen, Brattain, and Shockley were the first to successfully create the transistor, initially based on germanium. For this discovery, they were awarded the 1956 Nobel Prize in Physics. Because of the overall excellent properties of its native oxide, SiO_2, an ingredient of central importance in electronics device applications, silicon, a group IV element as is Ge, then became the material of the 20th century. The use of Si propelled the huge development of the electronic and sensor industries, leading to the availability of many high-tech devices and applications that continue to change our lives on a daily basis.

This leads to the question: What could be the material of the 21st century? Silicon continues to see very significant progress and will remain part of the scene, but it is not suitable for many new and emerging applications. The material of the 21st century could be silicon carbide (SiC), which exists in the universe and was indeed found in a meteorite discovered at Diablo Cañyon, Arizona, at the end of the 19th century by Moisan (1906 Chemistry Nobel laureate). Unlike Si, SiC is an especially suitable semiconductor for high-temperature, high-power, high-voltage, and high-frequency electronic devices and sensors. In addition, SiC, which has the same native oxide as Si, is biocompatible, making it a very useful material for interfacing with biology, and is also resistant to radiation damage.

Graphene burst upon the scene in the beginning of this century. Graphene is a single atomic layer of graphite and is made of carbon atoms in a sp^2 bonding configuration. So, it is not a "bulk" material but rather a double-sided "surface." Its existence was predicted theoretically a few decades ago. Experimentally, graphene was initially evidenced at the same time by (1) mechanical exfoliation from a graphite surface using an adhesive tape to pull out one or more atomic layers, and (2) epitaxial growth at the surface of SiC (on both Si- and C-faces) as one of the specific reconstructions of the surface. It could also be grown by chemical vapor deposition on metal or insulator substrates or obtained by chemical exfoliation. Graphene is a zero-bandgap semiconductor, or a semi-metal, and exhibits outstanding and unsurpassed properties, including the largest charge-carrier mobility, potentially scaling to several orders of magnitude above those of well-established semiconductors such as Si. Mechanically, it is the strongest material ever measured. It has the highest thermal conductivity at 10 times higher than copper. Among the unusual and interesting characteristics of graphene, one should mention that electrons move with zero mass and constant velocity in graphene, just like photons, with diffusion lengths reaching the micrometer regime. In addition, graphene is also an excellent light absorber, which is a very useful characteristic in photonics. For their research work on exfoliated graphene, Geim and Novoselov were awarded the 2010 Physics Nobel Prize while, at the same time, for investigating and developing graphene grown epitaxially on wide-bandgap SiC substrates, de Heer received the 2010 MRS Medal. Graphene research and development has exploded in many major institutions around the world, as showcased in this expanded *MRS Bulletin* issue on graphene.

With graphene in hand as a "novel" semiconductor, three issues need to be addressed: (1) growing high-quality, large-area wafers; (2) functionalization of the material; and (3) envisioning possible new advanced applications. While new approaches are still being discovered and developed, high-quality graphene is now available in various forms, due to the very significant progress in the field of material growth. To develop and implement successful and practical technological applications, the next mandatory step is graphene functionalization. This includes (1) bandgap monitoring, since graphene is a zero bandgap semiconductor, (2) doping, (3) metal-graphene interface control to achieve high-quality ohmic contacts, (4) graphene-substrate interface control and passivation, and (5) graphene nano-ribbon engineering. All of these require good control of the graphene surface and interface, as well as advanced nanotechnologies.

While all of these steps are being investigated intensively, achieving significant progress, the most challenging one is certainly to obtain a high-quality metal-graphene ohmic contact, since graphene is just a single atomic layer of carbon atoms. Achieving successful graphene functionalization opens new prospects in many advanced applications in electronics, sensors, photonics, including infrared/THz and lasers, touchscreen technology, micro- and nanoelectromechanical systems (MEMS and NEMS), metrology, and spintronics, with devices potentially having unsurpassed characteristics. In addition, graphene as a carbon-based material is biocompatible and could be very useful in interfacing with biology. New classes of graphene-based sensors are under development. Graphene is also promising for spintronics, initiated by the discovery in the late 1980s of the giant magnetoresistance effect by Fert and Grünberg, who consequently were awarded the 2007 Nobel Prize in Physics. Another extremely interesting and unique aspect of graphene was demonstrated very recently. The spin diffusion lengths in epitaxial graphene were found to exceed 100 μm, paving the road for large-scale spin-based logic circuits beyond CMOS.

One can argue that no other material is likely to possess such a large variety of novel and advanced applications. So maybe we have come full circle from coal, and carbon is back. Indeed, graphene appears to be a very appropriate candidate to become the material of the 21st century. □

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