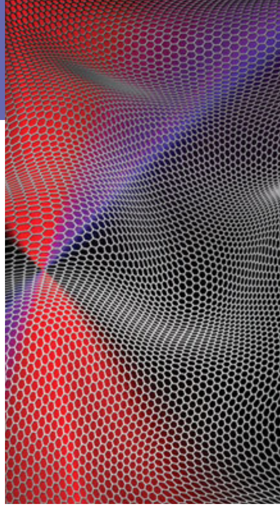

Graphene: A journey through carbon nanoscience

Mildred Dresselhaus

The modern era of materials science started about 25 years ago. Departments of metallurgy changed their names to departments of materials science and engineering, and physics departments, which had been highly focused on high energy and particle physics, showed increased interest in condensed matter and applied physics.

The 1980s brought us fullerenes and major advances with carbon fibers. These two research directions merged through multiwall carbon nanotubes, which were known from work in the 1970s and 1980s but had no specific nomenclature and had earlier roots in the Russian literature going back to the 1950s. Before 1980, there was not much international air travel and therefore little interaction between researchers in Europe, North America, and Asia. An important event in nanocarbon history was the First International Conference on Intercalation Compounds in La Napoule, France, in 1977, which brought researchers on carbon nanostructures together for the first time. It was not much later in the early 1980s that Materials Research Society (MRS) meetings and other conferences started including carbon nanostructure sessions.

In 1990, various funding agencies launched nanoscience and nanotechnology initiatives, creating increased research opportunities, in particular for young people to enter these research areas and to find employment upon completing their studies.

This was also a time of intellectual ferment. For me, the emerging interest in nanoscience led to a nanoscience and nanotechnology conference in Washington in 1990, where Richard Smalley and I, who were both invited speakers, had a public conversation about the possibilities of studying single-wall carbon nanotubes. These conversations were soon followed by theoretical work carried out independently by three groups, predicting that single-wall nanotubes would be especially interesting nanostructures because they could be either semiconducting or metallic, depending on their chirality. In physical terms, nanotube chirality means that the electron structure of a nanotube is sensitively dependent on the particular orientation of the symmetry axis of the hexagons in the nanotube crystal structure relative to the nanotube axis.

Almost at the same time as the prediction of nanotube chirality was presented, the synthesis of single-wall carbon nanotubes was reported by Iijima at NEC in Japan and Bethune at IBM in the United States, and these studies showed this prediction to be correct. With single-wall carbon nanotubes having a diameter of 1 nm, nanoscale research really took off. Encouragement of nanoscale research by funding agencies accelerated the entry of young people into the field, thereby introducing many new ideas. The complexity of the chirality dependence of the many interesting nanotube properties resulted in attracting many people to this research field. MRS actively contributed to these developments by convening relevant symposia and workshops on these and other topics of nanoscience and nanotechnology. Such encouragement was strongly influential in the development of a large scientific community knowledgeable in this research field.

Thus, in late 2004, when Geim and Novoselov published their seminal paper on the synthesis of monolayer graphene, a large number of highly knowledgeable people were available to appreciate the significance of graphene and to start contributing quickly and actively to this rapidly evolving field. For the next five years, graphene research was featured at many conferences and workshops, and these activities correspondingly contributed to advancing the field. The multidisciplinary approach of MRS meetings closely matched the needs for growth in this field and the desire of researchers as well as industrial and governmental research funders to seek practical applications.

With rapid growth of the field and its high activity level for nearly a decade, researchers in the past two years have started to look at the more general topic of two-dimensional and layered materials, including the creation of superlattices of different layered materials, and of superlattices of gapless constituents alternating with semiconductors with normal bandgaps such as graphene and BN superlattices. Materials such as MoS_2 and WS_2, which have been known for some time as lubricants, and Bi_2Te_3, known as a thermoelectric material, have recently escalated in importance as two-dimensional materials beyond graphene.

Emerging interest in carbon-based nanostructures and related materials is clearly a worldwide phenomenon, with the emergence of the large-scale European flagship proposal for support by both individual European countries and by the European Union as a whole. Other large programs are also being launched in Korea and Singapore. Interest in nanocarbon continues to be strong in Japan as well. The finding that carbon nanostructures can be effectively used to sequester ^{137}Cs coming from the radioactive accident at the Fukushima-Daiichi nuclear plant is having a practical impact, providing evidence for the value of scientific progress to address critical society needs.

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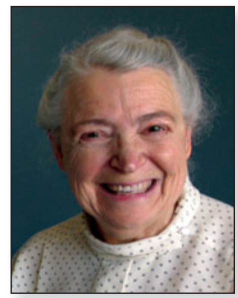
Considering historical perspectives like this brief review going back to nanocarbon developments since 1990 is important to remind us how poor we are in predicting the future and how important resiliency and flexibility are in advancing the scientific enterprise. From this 20-year history we can see how a topic with deep intellectual content, but not yet appreciated by many unfamiliar with the unique structure and properties of graphene, gathered momentum through the discovery by Geim and Novoselov of a simple way to fabricate interesting laboratory samples. The sharing of this knowledge with an interested interdisciplinary community captured their attention, creating an explosion of enthusiasm and promise for practical applications. Graphene research and development is expected to have longer-term impact, which is hard to predict. I remember well the first announcement of the laser in 1960 when I started my independent research career at the MIT Lincoln Labs. It was difficult at that time to predict that LASERS would become ubiquitous and used at the checkout counter of every supermarket. It was difficult to predict that nuclear magnetic resonance (NMR) discovered in the 1950s would revolutionize chemistry and medicine. Materials research has in recent years been responsible for the appearance of many unique and interesting materials. Some of these emerging materials, when compounded with the information technology revolution, are likely to change daily life in unknown ways for the next generation.



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