Editorial[1]

Reflections on Graphene: Horses for courses

THOUGHTS ON GRAPHENE: Professor Adarsh Sandhu, Electronics-Inspired Interdisciplinary Research Institute, Toyohashi University of Technology, Japan.

The Nobel Prize in Physics for 2010 was awarded 'for groundbreaking experiments regarding the two-dimensional material graphene', and notably, not for the applications of this material that has sparked the imagination of researchers worldwide.

As Andre Geim is quoted as saying in an interview [1] "….the citation, was given for the properties of graphene; it wasn't given for expectations……Ernest Rutherford's 1908 Nobel Prize in Chemistry wasn't given for the nuclear power station….."

Will the new found properties of graphene and its derivatives yield the definitive applications that spawn new industries and create employment opportunities on the scale associated with the semiconductor industry 21st century? Only time will tell. But what are the issues and trends that will determine its destiny? What do we know now may give us a glimpse into the future. First, Graphene is a single layer of carbon with a honeycomb structure. It is inexpensive and easy to produce: mechanical exfoliation, chemical synthesis or vapour phase deposition [2]. It is ambipolar, namely, the charge carrier concentration can be tuned from electrons to holes. It has remarkably high carrier mobility, with charges travelling 10–100 times faster than silicon at room temperature, and exhibits the quantum Hall effect at room temperature, a signature of its 2D nature [3]. The electrical conduction can be switched on and off in bilayers of graphene, thereby, offering possibilities for electron devices similar to field effect transistors. It is transparent, flexible, and has a high thermal conductivity and high Young's modulus, and for the thinnest material known, it has a strong propensity to absorb light, making it an ultra-thin optical quencher [4]. The surface of graphene can be functionalized with a wide range of biochemical species for potential biosensing applications [5].

But the future of graphene is still difficult to predict. For example, as in the early days of the development of silicon and compound semi-conductors, there is still not a consensus about the most useful method for synthesizing graphene. Mechanical exfoliation yields pristine single layered graphene with excellent transport properties, but this approach is not suited for large scale production.

Chemically derived graphene is a promising alternative, not requiring elaborate and expensive gas handling systems or deposition reactors. The quality and size of the resulting graphene flakes, however, are issues, and the search continues for efficient methods to transfer the reduced-graphene oxide to appropriate substrates. With a view to contributing to this and doping aspects of this particular topic of research, my group at the Electronics-Research Interdisciplinary Research Institute (EIIRIS) at Toyohashi University of Technology recently demonstrated exploiting the charged nature of graphene oxide (GO) to self-assemble GO-flakes at specifically defined regions on patterned substrates followed by reduction with hydrazine to produce r-GO with the necessity to 'hunt' for flakes on substrates [6,7].

Chemical vapour deposition on metal substrates such as copper, nickel, and iron is a front runner for the production of large areas and large volumes of graphene as exemplified by the report by industrial researchers in Korea on large area stretchable transparent electrodes [8]. In spite of this and related reports, however, transferring graphene to useful substrates is proving a challenge. And, intriguingly, substrate-less or suspended graphene shows much better electrical characteristics, but entails a complicated device fabrication process.

Recently, a two groups reported on an economic and environmentally friendly approach that does not require toxic chemicals, where microbials were used to reduce graphene oxide into graphene [9,10]. Inspired by these reports, in 2012 my group at Toyohashi reported on the use of benign microbials extracted from a local riverside for the reduction of GO into high quality graphene [11]. These results are notable as a means of biologically mediated synthesis of graphene for the development of industrial applications of graphene and related compounds.

In addition to industrial applications such as transparent electrodes for touch screens and displays, bio-chemical sensors and ultra-strong light weight composites, more novel applications in the report of boring nanoholes in graphene, then electrostatically pulling biomolecules such as DNA through the tiny hole, and importantly, monitoring fluctuations of the electrical conductivity of the graphene as the DNA goes through for point of measurement DNA sequencing.

But ultimately, the future of graphene related compounds will be determined by a combination of practical applications with water tight intellectual property rights protecting the 2D world. Compared with the silicon and compound semi-conductor industry, the initial investment in research and development of graphene devices is low, which has resulted in huge number of papers from researchers in Asia-Pacific, where funding and infrastructure for research involving expensive vacuum systems and is not as plentiful as their Western counterparts.

But what about patents? Geim did not patent the initial discovery because of insufficient concrete applications and lack of industrial support [1]. Intriguingly, the Manchester group has been surpassed by other inventors in the submission of patents, with surprisingly groups Asian researchers from Kumoh National Institute of Technology, Samsung, and Sungkyunkwan University leading the league of top 10 university inventors [12].

In my view, the future of graphene will be determined by imaginative ideas, innovation, and the resonance of both these boundary conditions with market needs; a classic scenario of horses for courses.

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Adarsh Sandhu, Ph.D
Presidential Advisor on Internationalization
Deputy Director
Electronics-Inspired Interdisciplinary Research Institute (EIIRIS)
Toyohashi University of Technology

Tel/Fax: +81-532-81-5142
E-mail: sandhu@eiiris.tut.ac.jp

1-1 Hibarigaoka Tempaku-cho, Toyohashi City, Aichi Prefecture 441-8580
EIIRIS: http://www.eiiris.tut.ac.jp/
Lab website: http://www.eiiris.tut.ac.jp/sandhulab/

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Professor Dr Adarsh Sandhu is Deputy Director of the Electronics-Inspired Interdisciplinary Research Institute (EIIRIS), Toyohashi University of Technology. Other responsibilities at Toyohashi include advisor to the president and head of international public relations. He came to Japan in 1985 after receiving a Monbusho Scholarship to study at the Tokyo Institute of Technology and University of Tokyo. Then, in 1986 after completing his doctoral thesis at the University of Manchester, England, he joined Fujitsu Laboratories Ltd., Atsugi, as their first foreign researcher with a permanent position. At Fujitsu, he developed molecular beam epitaxy systems for the growth of III-V compound semi-conductor heterostructures and quantum effect electron devices. Major breakthroughs included the fabrication of the world's first carbon doped base heterojunction bipolar transistor using gas source MBE and ultra-high resolution magnetic field sensors based on HEMT heterostructures.

In 1992, Dr Sandhu took a sabbatical as a visiting scholar at the Cavendish Laboratory, Cambridge University, where he conducted experiments on the transport properties of semiconductor and superconductor interfaces. In April 1995, he left Fujitsu to take up a tenured faculty position at a private university, where he continued to work on condensed matter physics and initiated research on magnetic imaging of ferromagnetic domains by scanning Hall probe microscopy (SHPM). In August 2002, Dr Sandhu accepted a tenured position at the Quantum Nanoelectronics Research Centre, Tokyo Institute of Technology, where his research activities included nano-scanning Hall probe microscopy and development of biosensors based on magnetic labels for rapid medical diagnosis.

Dr Sandhu is a regular visitor at universities in Asia-Pacific, including Tsinghua University and IIT Delhi, and has collaborative projects with several major Japanese corporations. He is also a member of several important Japanese academic societies including the 162 and 175 committee's the Japan Society for the Promotion of Science (JSPS); Japan Society of Applied Physics (JSAP); and Magnetic Society of Japan (MSJ). Dr Sandhu is the founder of the 'JSAP International' newsletter and has authored numerous articles on science and education for Japanese journals. He has the rare distinction of being a member of the Foreign Correspondents Club of Japan (FCCJ), and FCCJ Toastmasters.

Among his research interests are nanomagnetics, with emphasis on two dimensional electron gas heterostructures for the fabrication of high sensitivity Hall sensors and scanning Hall probe microscopy, and exploitation of magnetically induced self-assembly of magnetic nanoparticles for biomolecular recognition and point of care medical diagnostics.

Dr Sandhu is fluent in Japanese—spoken and written, giving lectures on solid-state physics and electromagnetism in the Japanese. He enjoys most sports and outdoor activities and writing about scientific developments in the Asia Pacific region. Dr Sandhu's travels in Asia and observations of the impact of science and technology in this part of the world form a backdrop to his first novel—scheduled for completion in 2012—set in Beijing, Delhi, and Tokyo. Dr Sandhu has served as Editorial Consultant for *Nature Nanotechnology* and *Nature Photonics,* and editor of research highlights for NPG Asia Materials. He is currently the editor of *IOP Asia-Pacific* website - a platform dedicated to highlighting scientific developments in Asia Pacific.

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