The University of Toronto's **Professor Chandra Veer Singh** provides a detailed look into Canada's investment in graphene, highlighting the need for greater funding and international collaboration

Canada's graphene story

IN 1947, Professor P R Wallace of McGill University, Montréal, Canada, wrote a seminal paper on the electronic band structure of graphite. Fast forward 68 years, and a monolayer of this material, popularly known as graphene, forms the trendiest material system for materials science research at the international level.

Graphene is no more an overhyped material – not only will it live up to its promises, but it has a real potential to provide important applications in the electronics, sustainable energy, healthcare, structural and sports sectors. Since the isolation of graphene, multiple 2D materials have been synthesised experimentally. Many more have been theorised, with intriguing chemical, electronic, and mechanical properties that expand the boundaries of existing structure-property space. It is also now possible to create heterostructures of 2D materials to suit a wider array of applications. In this article, we provide an academic's perspective on the opportunities and challenges of graphene-related research in Canada.

Professor Chandra Veer Singh

Mechanical properties

Pristine graphene has a tensile strength of 130 gigapascals, about 200 times that of steel. Consequently, it has promising applications as a strengthening constituent in polymer nanocomposites for wear-resistant coatings and bulletproof armours. Exciting developments have taken place at the University of Toronto, Ontario, in the past three years on the mechanical properties of graphene and related materials. The nanomechanics and materials laboratory, led by Professor Tobin Filleter, utilises atomic force microscopy techniques to probe the strength and wear resistance of graphene and related thin materials. Together with Professor Yu Sun, who leads the advanced micro and nanosystems lab at the same university, it has also developed *in situ* electron microscopy devices to measure the tensile stress-strain behaviour and directly visualise fracture.

In Canada, the University of Toronto is dedicating particular efforts to graphene and computational modelling research

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At Toronto, our computational materials engineering lab has combined with these two groups to take our individual graphene research to the next level. Our collaborative work has shown that the intrinsic strength of monolayer graphene oxide is approximately 50% of the 2D intrinsic strength of pristine graphene; it was well supported by our first principles theoretical calculations. This is a promising result considering that graphene oxide can be manufactured at much lower cost from bulk graphite and has excellent dispersibility in many solvents, permitting low cost engineering applications. Such synergistic collaboration of experimental and computational groups can accelerate the discovery and design of innovative novel materials and devices.

Energy and nanoelectronics

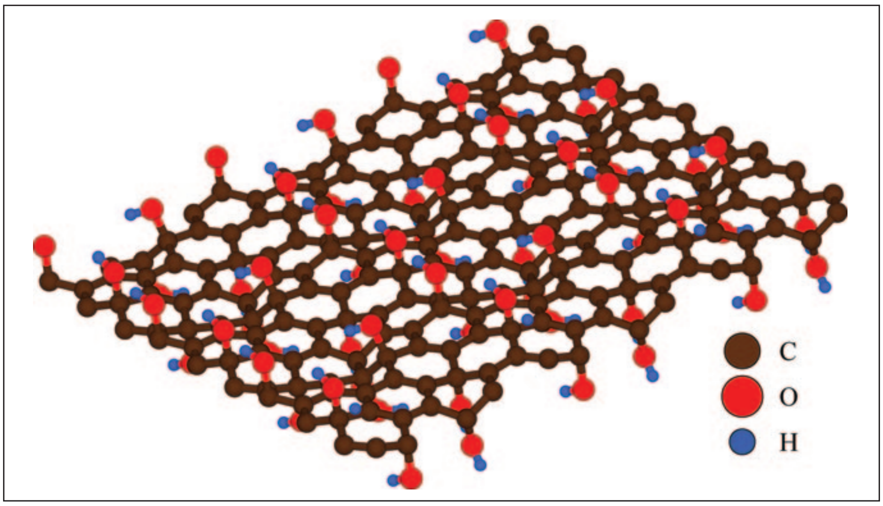
Excellent research is being conducted in Canadian universities on graphene and related materials for sustainable energy applications. Research groups led by Professor Andy (Xueliang) Sun at the University of Western Ontario and Professor Aiping Yu at the University of Waterloo, Ontario, have developed graphene-based devices for Li-ion battery and supercapacitor applications. Meanwhile, at the University of Toronto, Professor Keryn Lian's laboratory has focused on alternative carbon nanomaterials for developing high performance supercapacitors, and Professor Hani Naguib's group has developed nanocomposites with graphene nanoplatelets for multifunctional applications. At the same university, a multidisciplinary 'Solar Fuels' team, led by Professor G A Ozin, has been assembled to discover and develop novel nanostructured catalysts for converting carbon dioxide into useful chemicals such as methanol using sunlight.

In the field of nanoelectronics, the research groups led by Professor Thomas Szkopek at McGill University, and Professor Joshua Folk and Professor Peyman Servati at the University of British Columbia, are exploiting 2D materials to create tuneable electronic devices. Not cited here are groups working on healthcare, but for sure the number of research groups focusing their efforts on these material systems is growing quickly. Within a few years, it is anticipated that Canada will be an important player in this research field.

Computational modelling

The traditional materials design process is based on extensive laboratory testing, which is time-consuming and expensive. For understanding the fundamental structure-property relationships in nanomaterials, computer-assisted modelling is proving to be a valuable scientific tool as it allows atomic scale understanding with high precision, without conducting very expensive and time-consuming experimental testing.

In addition to the research cited above, accurate atomistic simulations conducted by our lab at the University of Toronto have shown that the strength of a polycrystalline graphene sheet is highly dependent on the grain character, temperature and loading rate, providing a reasonable explanation of the large experimental scatter reported by other researchers. We have also shown that it is theoretically possible to store more than 7.0wt% hydrogen on the graphene's surface by careful defect engineering, briefly surpassing the target set by the United States Department of Energy. The high performance computing infrastructure required for such theoretical research is attributed to Compute Canada, which performs the critical role of providing state-of-the-art computational facilities, data storage, and valuable support to the Canadian researchers, mainly through the resource allocation grants.



Two-dimensional structure of graphene oxide: ultra-strong and ultra-thin

In another case, we have shown that the edges of another 2D material, MoS_2 monolayer, are highly reactive for photocatalysis for purposes of water splitting for hydrogen production. The United States has led the way by injecting \$250m (~€222m) of funding and resources through the Materials Genome Initiative, which has the aim "to discover, manufacture, and deploy advanced materials twice as fast, at a fraction of the cost". Canada, a past manufacturing hub, especially the province of Ontario, needs such a concentrated push to rediscover its past competitiveness.

Ongoing challenges

Overall, the growth of graphene research in Canada is more of a 'natural' outcome, rather than 'designed' growth. Unlike the UK, other European countries, China and the United States, the foremost reason for this is that there is no dedicated funding initiative from the Government of Canada as of yet that is solely focused on graphene. Invariably, graphene research forms just part of ongoing research programmes; hence, there is an urgent need for the Natural Science and Engineering Research Council of Canada and other funding agencies to fill this gap with financial support for this extremely important research field.

A significant quantity of the research cited above has been possible due to important infrastructural funding through the Canada Foundation for Innovation, in co-ordination with provincial agency funds such as the Ontario Research Fund. These funds allow researchers to build state-of-the-art experimental facilities such as the recently unveiled Ontario Centre for the Characterization of Advanced Materials at the University of Toronto. This centre will allow the study of forces at the atomic level, which will be the key to developing innovative new materials. The centre, co-led by Professor Charles Mims and Professor Doug Perovic, houses a collection of cutting-edge analytical instruments for surface and structural studies that are arguably the best in Canada.

Overall, infrastructural funding in Canada can be rated as 'good'. Yet ongoing support for running this infrastructure in the form of funding for long term technicians and research associates for user facilities is poor. There are no programmes to fund these ongoing technical support needs, and there are also limited opportunities for jobs for highly skilled

personnel in Canada compared to similar positions in the United States and elsewhere.

Montréal will host the country's first major conference on graphene later this year

The financial support for operating grants is severely limited for such fundamental research and cash-strapped governments have no patience with research that is not almost immediately commercial. The Government of Canada provides excellent opportunities to partner with industries; however, private companies are currently cash-strapped too and hence are not looking at the long term technologies. The funding support for graphene-related research can be best described as 'difficult' in Canada.

Centre development

The second challenge facing graphene research in Canada is that it lacks large scale collaboration, which is required to bring the exciting opportunities provided by graphene and other 2D materials to fruition in the form of commercial technologies. The research accomplishments made by graphene scientists in Canada have so far been mostly from individual research groups.

Other nations are dedicating resources in the form of new graphene and 2D materials centres; for instance, the UK has led by developing the National Graphene Institute at the University of Manchester and the Cambridge Graphene Centre at the University of Cambridge, and Singapore has developed its own Graphene Research Centre at the National University of Singapore. However, no such centre exists in Canada that can bring together an array of excellent researchers with multitudes of skillsets to tackle challenging issues in the development of graphene-related technologies.

Industry participation

Canada's large graphite deposits provide a unique opportunity for industry traditionally involved in graphite mining. Seizing this opportunity, multiple companies have started focusing on graphene. Lomiko Metals, which owns graphite deposits in northern Québec, partnered with Graphene Laboratories of New York and was able to manufacture graphene from Canadian graphite for the first time.

In order to overcome scalability and cost issues in graphene manufacturing, Grafoid Inc, incorporated in 2011 in Ottawa, Ontario, has developed MesoGraf™ technology that claims to manufacture low cost, environmentally sustainable, high-quality graphene with a minimal environmental footprint. In this regard, they have just been awarded an 8.1 million Canadian dollar (~€5.8m) grant by Sustainable Development Technology Canada, a programme focusing on funding innovative industry solutions for sustainable development. Other industry leaders which are seizing this opportunity to produce graphene in Canada include Carbon Canada and Northern Graphite. If successful, the low cost manufacturing of high-quality graphene at large scale will make Canada a graphene powerhouse.

International collaboration

One aspect missing from this picture has been the lack of fruitful industry-academia collaboration on graphene-related technologies. Since Canadian industry is a late entrant to the race for graphene technologies, such partnerships will take some time to evolve and become visible. The inaugural edition of the 'Graphene & 2D Materials International Conference and Exhibition', to be held in Montréal in October 2015, will certainly enhance Canada's visibility on graphene research.

The three-day conference is expected to include nearly 30 keynote speakers, including representatives from major universities and businesses in both North America and Europe; Professor Andrea Ferrari of the University of Cambridge, UK, is also expected to attend. Grafoid has been confirmed as the conference's main sponsor and the event is poised to attract global players on graphene-related technologies, and provide a unique platform for information exchange for graphene research.

Momentum is now building in Canada for graphene research and different pieces are falling into place. Time is ripe for building a unified network of government, academia and industrial partners engaged in graphene-related technologies like the Graphene Flagship consortium initiated by the EU. Furthermore, given the EU's leadership in this area, Canada needs to develop new multilateral co-operations with the Union's member states, providing international collaborative opportunities to Canadian researchers.

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