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MEETING DAY 3, Wednesday, June 29

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Plenary speakers are typically approached after their talk by a small group of audience members wishing to ask questions. But when Nobel Laureate Andre Geim, the discoverer of graphene, finished his lecture on the third day of the Sixth International Conference on Materials for Advanced Technologies (ICMAT) in Singapore, he was swamped by a group of admirers mostly interested in autographs and photos. An unsuspecting passerby might have thought a movie star or a music idol was in the middle of the crowd. Instead it was Dr. Geim, who seemed reluctant to be the focus of such attention, but was gracious about it all the same.

Geim wasn't the only big name in science who spoke yesterday. Another Nobel Laureate, Ada Yonath of the Weizmann Institute in Israel, gave a fascinating talk about ribosomes that explored their pre-biotic nature as evidenced by a proto-ribosome that has been around for millions of years and still functions in cells today. Charles Lieber of Harvard University gave a great talk on the wide range of applications of semiconductor nanowires, including *in vivo* recording of the internal signals of living cells; Qi-Kun Xue of Tsinghua University in China introduced a new class of materials called "topological insulators" that could have a major effect on computer chip technology; and Jean M.J. Frechet of the King Abdullah University of Science and Technology in Saudi Arabia introduced a new type of functional molecule that can convert sunlight directly into work. Not bad for one day at the ICMAT in Singapore!

Andre Geim (in profile on left, in white shirt) signs autographs for his scientific admirers

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Singapore by night

Fourth Plenary Lecture: Andre Geim

Graphene: Status and Prospects

Andre Geim of the University of Manchester, United Kingdom, discovered graphene in 2004, for which he was awarded the Nobel Prize in 2010. For someone whose work involves a single layer of carbon atoms, he went out of his way early in the lecture to say that all natural objects are three-dimensional, and that the emphasis on terms like quasi-2D,-1d, and -0D materials should be placed on “quasi.” “If nature creates something it uses all three dimensions, instead of limiting itself,” Geim said.

So what about graphene? This, Geim said, is a case of 3d

growth followed by the extraction of one atomic plane, so it does not violate the previous rule. “Graphene has an extremely simple structure, so you might not expect much from it,” he said. Geim then went on to detail a long list of graphene’s extraordinary properties, including that it is the thinnest imaginable material; it has the largest surface area of any material at approximately 3,000 m^2/g; it is the strongest material “ever measured”; it is the stiffest material known (stiffer than diamond); and it is the most stretchable and pliable material. Electronically, it can accept homogenous doping from 10^8 to 10^{14} cm^{-2}, has the astonishing quality of ballistic electronic transport on sub-micron scales, and has a carrier mobility at 300 K that routinely reaches approximately 15,000 cm^2/Vs. And this is just a partial list of its properties.

Turning to graphene’s current status, Geim said that during the last two years the quality has improved greatly. Low temperature mobilities of a few million cm^2/Vs have been demonstrated. Also, the search for substrate other than silicon has located hBN, which supports an ultrahigh mobility of 500,000 cm^2/Vs.

Geim then gave several examples of the remarkable physical properties of graphene. Using the example of a car crashing into a wall, he noted that in the real world the car would simply be smashed, and in the quantum world the smashed car would be accompanied by a “ghost car” that would tunnel through the wall. If the wall was made of graphene, the car would go undisturbed through any wall thickness due to Klein tunneling. Visually, Geim said, a one-atom-thick single crystal of graphene is visble by the naked eye as a gray material. Finally, when exposed to fluorine graphene becomes a wide-gap semiconductor; fluorographene also acts as “2D Teflon,” according to Geim.

Eventually, manufacturers will have thae ability to make graphene in ton quantities and kilometer lengths, he said. Applications could include ultrahigh frequency “ballistic” transistors; ultrafast photodetectors, with graphene acting as a transparent metal; and a much needed substitute for indium tin oxide (ITO). A transparent, flexible, rectangular sheet of graphene with a diagonal of 30 inches has already been made by one company, and the costs are coming down. Geim ended with a take-away message: “After five years, applications for graphene are no longer wishful thinking. Only the extent remains unclear.”

■ Fifth Plenary Lecture: Charles Lieber

Semiconductor Nanowires: A Platform for Nanoscience and Nanotechnology

Charles Lieber of Harvard University tried to answer the question of “what makes a platform in science and technology?” using the many varieties of semiconductor nanowires as his basis. He defined nanowire technology as one based on well defined, tunable building blocks that could be used in the bottom-up assembly of hybrid, multicomponent functional nanomaterials in novel environments. Lieber then reviewed the key advances in nanowire structures over the years—from straight, single material nanowires to coaxial ones made of two materials, and from branching nanowires to kinked structures resulting from topological changes. Most recently, his team has extended synthesis capabilities to include the introduction of stereocenters to control the topology of nanowires.

In *p-i-n* core/shell radial nanowires, the focus is on open circuit voltage (V_{oc}). By varying the relative thickness of the layers in hexagonal core/shell nanowires, a V_{oc} of 0.5 V has been demonstrated in a 200-nm diameter nanowire, showing that controlled growth can be used to tailor voltage properties. By varying the thickness of the layers in both core/shell and stacked geometries, Lieber said, we can absorb a higher percentage of the solar spectrum, with obvious benefits to photovoltaic devices.

Lieber seems to be most excited about nano-electronic/biological interfaces to create new tools for biophysics and healthcare. Nanowire dimensions are on the same scale as nerve synapses (sub-100-nm) and ion channels in cells (several nm), making nanoelectronic transducers perfect for interfacing with the brain and other tissues. To date, his group has demonstrated a bio-nanowire FET device capable of detecting the binding and unbinding of a single molecule; a system capable of detecting disease-marker proteins in a multiplexed, real-time manner; and selective, real-time detection of a single virus particle. Remarkably, they have also developed a nanowire-biological FET capable of a 100-billion-fold increase in the discrimination of components of blood serum.

But this is all extracellular science, which, while remarkable, is not good enough for Lieber. “We’ve been working on going inside the cell *in vivo*,” he said. He and his group are developing “kinked” nanowires based on *cis* (as in the chemical conformations *cis-trans*) junctions with acute angle bends. The kink tips are less than 50 nm in diameter, which is smaller than a virus. If viruses can penetrate cell walls, these devices should be able to, also. In practice, unmodified nano-FET probes could not enter the cell, but when they coated the probe with a compatible phospholipid, they were able to enter the cell. This represents the first report of *in vivo*, intracellular recording of cellular signals using nano-FET devices, according to Lieber. The next step is to incorporate nanowire devices into living tissue to produce “cyborg tissue.” “We are trying to blur the distinction,” Lieber concluded, “between electronic devices, living cells, and tissues.”

Third Theme Lecture: Qi-Kun Xue

Novel Properties of Topological Insulator Thin Films of Bi_2Te_3 and Bi_2Se_3 Prepared by Molecular Beam Epitaxy

Very strong spin-orbital coupling can combine electronics and magnetics, according to Qi-Kun Xue of Tsinghua University, China. The topology of conductors and insulators is of primary importance in his research. He showed a slide with gold bars representing conductors and a ceramic bowl representing insulators. In between, there is another state called a “topological insulator,” which Xue said is a new class of material. The topological insulators are produced when strong spin-orbital coupling “twists” the valence and conduction bands of an ordinary insulator to form a Dirac cone-like band structure. These new materials could have uses in spintronics and quantum computing.

Xue’s group is investigating Bi_2Te_3 and Bi_2Se_3 single crytals grown by molecular beam epitaxy using an MBE-STM-ARPES system. They have achieved layer-by-layer growth of both crystals on Si with excellent surface morphology. The Bi_2Te_3 film was atomically flat with very few defects. Another approach has been to deposit Bi_2Se_3 on a graphene/Si substrate, with similar results. The Fermi levels of these materials reside within the conduction band, so doping is necessary to move the Fermi level into the Dirac cone-like ”twisted” bandgap. When this is achieved, these topological insulators could possibly be used to replace Si in future generations of electronic chips. Xue ended with a slide showing a traffic jam inside today’s Si chips, while the topological insulator-based chip was represented as the “information highway for chips of the future.”

■ Technical Talks

Symposium A: Nanostructured Oxides, Interfaces, Heterostructures, and Devices

In-situ Synchrotron X-ray Studies for Oxide Materials Design and Discovery

Ferroelectric switching with applied electric fields is the norm, but Stephen Streiffer from Argonne National Laboratory, USA, showed that it can also be achieved by chemical means. His presentation this morning focused on the common ferroelectric $PbTiO_3$, grown on $SrTiO_3$ substrates such that the polarization is normal to the film plane. The resulting films have a large depolarizing field, which must be compensated by some means, such as domain formation, accumulation of free charges or, in this case, by adsorbed oxygen ions on the surface. As Streiffer quipped, nature abhors a polar catastrophe. He demonstrated that by varying the oxygen partial pressure, they can switch the polarization of their $PbTiO_3$ films by changing the extent of charge compensation.

Using the advanced photon source at Argonne, Streiffer extracts extremely precise information about the films via grazing incidence spectroscopy in-situ, varying the oxygen pressure and detecting changes in the film polarization from changes in crystal structure. He showed the resulting phase diagrams, in which regions of monodomain ferroelectric phases are separated by a narrow region with 180-degree stripe domains at critical oxygen pressures and temperatures. Surprisingly, they find that these intermediate oxygen pressures suppress the ferroelectric ordering temperature, a result that they shed some light on with Landau theory calculations.

Standing room only at Wednesday's plenary session

Nanoscale Chemical, Structural and Electromechanical Properties of Rare-earth Doped $BiFeO_3$ Epitaxial Thin Films

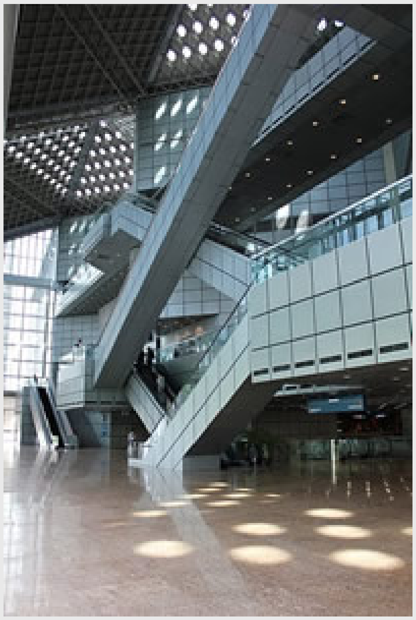
The afternoon session of Symposium A proved that $BiFeO_3$, the much-studied darling of multiferroics research, still has a few tricks up its sleeve. Ching-Jung Cheng, of Nanyang Technological University, Singapore, and an international team of collaborators are examining rare-earth doping as a route to inducing the morphotropic phase boundary in $BiFeO_3$ previously stabilized with epitaxial strain. In his presentation today, Cheng showed how the chemical pressure induced by Sm, Dy, and Gd dopants favor a paraelectric, orthorhombic phase of $BiFeO_3$, unlike the rhombohedral, ferroelectric parent phase. Monitoring the development of the orthorhombic phase with XRD, Cheng demonstrated that the effect is tunable, showing how the 1/2 peaks of the rhombohedral phase gradually give way to the 1/4 peaks of the orthorhombic phase as dopant levels are increased. Ferroelectric hysteresis measurements of the doped systems show an evolution from the square loops of a robust ferroelectric to weakly hysteretic, antiferroelectric double-loops. He compared this to La-doped films, where the chemical pressure is smaller but the disruption of Bi lone-pair ordering is presumably the same. The La-doped films they studied remain ferroelectric at all doping concentrations, which Cheng sees as evidence that the effect seen with the other dopants is entirely due to chemical pressure. The work was presented as way to desirably enhance the properties of $BiFeO_3$ by accessing a morphotropic phase boundary region.

The solution to your research needs might be just one exhibitor away!

Symposium O: Photovoltaic Materials and Devices

Present and Future of High Efficiency III-V Compound Multi-junction and Concentrator Solar Cells

Following the recent nuclear disaster in Fukushima, Japan's ambitions for increased solar energy generation are redoubled. This is the picture presented by Masafumi Yamaguchi of the Toyota Technological Institute, Japan. The national game plan for photovoltaics in place before the disaster aimed to increase PV power by 13% per year, but there is now interest in shooting for a more aggressive 30% per year, which would bring PV up to nuclear power levels by 2025. Yamaguchi went on to describe Japan's detailed road map for PV. Their mid- to long-term plan slates nearly 30 billion yen to reach a target of 14 yen per kilowatt-hour by 2020, with a module production cost of 75 yen per watt. Target module efficiencies for that period range from 20% for wafer-based Si technologies to 10% for dye-sensitized solar cells. Yamaguchi particularly highlighted the push in multi-junction cells, as demonstrated by his own research group, which seeks to break world records by aiming for efficiencies of 45% for a cell and 35% for a module.

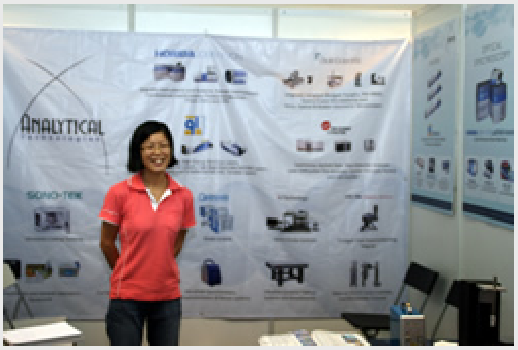


Conference center's inner architecture

Research on III-V-Based Concentrator Solar Cells

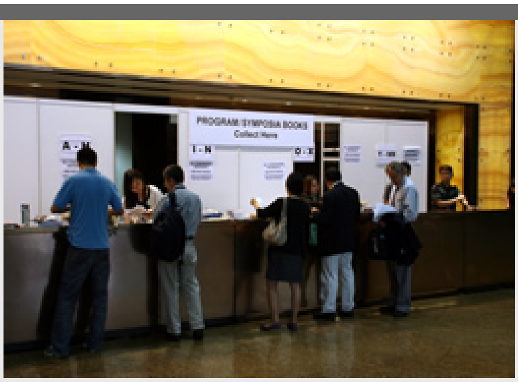
Andreas Bett of the Fraunhofer Institute for Solar Energy Systems, Germany, is also pursuing ambitious goals for photovoltaics. He first showed off the impressive facilities at Fraunhofer for fabrication and testing of solar cells, then made the case for III-V multijunction cells. The high efficiency and low weight (important for space applications) of III-V solar cells make them some of the best around, but their use in large-scale power production is prevented by the high cost of the Ge substrate. However, Bett showed a way around this by shrinking the cells and implementing on-board solar concentrators that provide a 500- to 1000-times concentration. The resulting cells are fabricated at high densities -- 1200 on a single 4-inch Ge wafer -- and have been deployed in centralized power stations in the US. He cited 25% AC efficiencies and an energy payback time of less than 10 months as overwhelming motivators for the technology.

Bett's work on solar cells has two goals: improving efficiency and reducing cost. The industry standard today is 38 to 40% efficiency, in GaInP/GaInAs/Ge multijunction cells. Bett outlined three thrusts of their work at Fraunhofer, aiming to exceed the industry standard. The first is lattice mismatch, in which buffer layers are used to marry layers with differing lattice constants. The second is using more layers to capture more of the solar spectrum, and the third is development of III-V solar cells on Si by direct wafer bonding.



Science at your service!

Scanning the Meeting



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