Graphene Electronics

Carbon, the basis of all known life on earth, has surprised the scientific community once again with its exotic properties. Graphene is a form of carbon and as a material it is completely new — not only the thinnest ever but also the strongest. Graphene is one atom thick, which makes it the thinnest material ever discovered. Graphene is a one-atom-thick planar sheet of sp²-bonded carbon atoms that are densely packed in a honeycomb crystal lattice.

The carbon bond length in graphene is about 0.142 nm. Graphene is the basic structural element of some carbon allotropes including graphite, charcoal, carbon and nano tubes. It can also be considered as an infinitely large aromatic molecule, the limiting case of the family of flat polycyclic aromatic hydrocarbons called graphenes. At an atomic scale, it looks a bit like chicken wire made of carbon atoms and their bonds.

Graphene is highly conductive, conducting both heat and electricity better than any other material, including copper, and it is also stronger than diamond. It is almost completely transparent, yet so dense that not even helium, the smallest gas atom, can pass through it. With graphene, physicists can now study a new class of two-
dimensional materials with unique properties. Graphene makes experiments possible that give new twists to the phenomena in quantum physics. Also a vast variety of practical applications now appear possible including the creation of new materials and the manufacture of innovative electronics. Graphene electronic devices are predicted to be substantially faster, thinner and efficient.

Two Russian-born scientists based at the University of Manchester in the UK shared the 2010 Nobel Prize for Physics for their "groundbreaking" work on graphene: a material with amazing properties. The two experts have shown that carbon in such a flat form has exceptional properties that originate from the remarkable world of quantum physics, a release from the Nobel committee said.

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Silicon to Graphene Carbon
Carbon nano sheets are considered the future of smaller, faster and cheaper electronics. High on the list is graphene—planar sheets of honeycomb carbon rings just one atom thick. This nano material sports a range of properties—including ultra-strength, transparency (because of its thinness) and blisteringly fast electron conductivity—that make it promising for flexible displays and super speedy electronics. The theoretical mobility of electrons in pure graphene is 200 times that of silicon. This will make it extremely interesting material for future high speed electronics and sensors.
Silicon is the master base material of present-day electronics involving the transport of electrons and holes across the junction. However, there are growing complications related with the transport of these current carriers along with the increasing cost involved with miniaturization of silicon based electronics. Hence, efforts are to look for other base materials which are cheap with advantages similar to silicon as well as nano-electronics making use of the wave nature of particles to generate electronic waves due to electron diffraction instead of electrons diffusion, where particles need not to move and the energy will be transferred in the form of waves.

P.A.M. Dirac has established and highlighted the particle’s wave nature at quantum level and Dirac’s equation explains the unique phenomena concerning the motion of the electron at nano level. It is found that an electron which seems to be moving slowly must actually have a very high frequency oscillatory motion of small amplitude superposed on the regular motion. As a result of this oscillatory motion, the velocity of the electron at any time equals the velocity of light.

Carbon being available in plenty in its different forms like diamond and graphite is under investigation as a base material for electronics for a long time. Diamond is very costly and hard but graphite, the material that gives pencils their marking ability, is cheap and flexible and could be the basis for a new class of nanometer-scale carbon based electronic devices which will make use of the attractive properties of carbon nano tubes which can be produced using established microelectronics manufacturing techniques.

Recently, researchers have developed foundation for circuitry and devices based on graphite. Graphene (electronic name given to graphite) is a condensed matter realisation of the Dirac electron relativistic wave equation at quantum level in two dimensions. Many of the unusual properties of relativistic fermions in quantum electrodynamics (QED) reappear in graphene. The discovery of graphene, followed by observation of an anomalous quantum electronic transport phenomena in it has triggered intense focus of research in this one atomic thin two-dimensional system. The unique electronic band structure of graphene lattice provides a linear dispersion relation where the Fermi velocity replaces the role of the speed of light in usual Dirac’s equation. Because of its high electronic mobility, structural flexibility, and
capability of being tuned from p-type to n-type doping by the application of a gate voltage, graphene is considered a potential breakthrough in terms of carbon-based nano-electronics. Using thin layers of graphite, researchers at the Georgia Institute of Technology in the United States, in collaboration with the Centre National de la Recherche Scientifique (CNRS) in France, have produced proof-of-principle transistors, loop devices and circuitry. Ultimately, the researchers hope to use graphene layers less than 10 atoms thick as the basis for revolutionary electronic systems that would manipulate electrons as waves rather than particles, much like photonic systems control light waves.

Graphene nano ribbons (GNR) band zig-zag type structure can be semiconducting or metallic depending on width. Graphene differs from most conventional three-dimensional materials. Intrinsic graphene is a semi-metal or zero-gap semiconductor. Understanding the electronic structure of graphene is the starting point for finding the band structure of graphite. It was realized early on that the E-k relation is linear for low energies near the six corners of the two-dimensional hexagonal Brillouin zone, leading to zero effective mass for electrons and holes. Due to this linear (or “conical”) dispersion relation at low energies, electrons and holes near these six points, two of which are inequivalent, behave like relativistic particles described by the Dirac equation for spin 1/2 particles. Hence, the electrons and holes are called Dirac fermions, and the six corners of the Brillouin zone are called the Dirac points.

**Graphene Electronics**

From graphene based nano electronics, scientists expect to make electronic devices of a kind that don’t really have an analog as in silicon-based electronics, so this is an entirely different way of looking at electronics. The ultimate goal is integrated electronic structures that work on diffraction of electrons rather than diffusion of electrons. This will allow the production of very small devices with very high efficiencies and low power consumption. The graphene circuitry demonstrates high electron mobility – up to 25,000 square centimeters per volt-second, showing that electrons move with little scattering. The researchers have shown electronic coherence at near room temperature, and evidence of quantum interference effects.
Potential applications

Single molecule gas detection

Graphene makes an excellent sensor due to its 2D structure. The fact that its entire volume is exposed to its surrounding makes it very efficient to detect adsorbed molecules. Molecule detection is indirect: as a gas molecule adsorbs to the surface of graphene, the location of adsorption experiences a local change in electrical resistance. While this effect occurs in other materials, graphene is superior due to its high electrical conductivity (even when few carriers are present) and low noise which makes this change in resistance detectable.

Graphene transistors

*Due* to its high electronic quality, graphene has also attracted the interest of technologists who see them as a way of constructing ballistic transistors. Graphene exhibits a pronounced response to perpendicular external electric fields, allowing one to build FETs (field-effect transistors). Facing the fact that current graphene transistors show a very poor on-off ratio, researchers are trying to find ways for improvement. Researchers had demonstrated four different types of logic gates, each composed of a single graphene transistor and built an experimental graphene chip known as a frequency multiplier. It is capable of taking an incoming electrical signal of a certain frequency and producing an output signal that is a multiple of that frequency.

Although these graphene chips open up a range of new applications, their practical use is limited by a very small voltage gain (typically, the amplitude of the output signal is about 40 times less than that of the input signal). Moreover, none of these circuits was still demonstrated to operate at frequencies higher than 25 kHz. Recently, researchers have been able to create graphene transistors with an on and
off rate of 100 gigahertz, far exceeding the rates of previous attempts, and exceeding
the speed of silicon. The 240 nm graphene transistors were made using extant
silicon-manufacturing equipment, meaning that for the first time graphene transistors
are a conceivable—though still fanciful—replacement for silicon.

**Integrated circuits**

Graphene has the ideal properties to be an excellent component of integrated
circuits. Graphene has a high carrier mobility, as well as low noise, allowing it to be
used as the channel in a FET. The issue is that single sheets of graphene are hard to
produce, and even harder to make on top of an appropriate substrate. Researchers
are looking into methods of transferring single graphene sheets from their source of
origin onto a target substrate of interest. The smallest transistor so far, one atom
thick, 10 atoms wide was made of graphene.

Researchers have fabricated and characterized graphene transistors operating at GHz
frequencies. They have also announced to have created an n-type transistor, which
means that both n and p-type transistors have now been created with graphene. At
the same time, the researchers demonstrated the first functional graphene integrated
circuit – a complementary inverter consisting of one p- and one n-type graphene
transistor. However, this inverter also suffered from a very low voltage gain.

**Transparent conducting electrodes**

Graphene’s high electrical conductivity and high optical transparency make it a
candidate for transparent conducting electrodes, required for such applications as
touch screens, liquid crystal displays, organic photovoltaic cells, and organic light-
emitting diodes. In particular, graphene’s mechanical strength and flexibility are
advantageous compared to indium tin oxide, which is brittle, and graphene films may
be deposited from solution over large areas. Large-area, continuous, transparent, and
highly conducting few-layered graphene films were produced by chemical vapor
deposition and used as anodes for application in photovoltaic devices. One layer of
graphene absorbs 2.3 % of white light and this property was used to define the
Conductivity of Transparency that combines the sheet resistance and the
transparency. This parameter was used to compare different materials without the use of two independent parameters.

If graphene sheets are made thin enough, they basically become transparent, which has led some experts to suggest that the material could be used in a new generation of low-cost, crack-resistant display screens for televisions and laptops. This year, researchers reported that they created a working touch-screen display using graphene. Maybe the stuff will be ready for the market by the time that future iPhone 9 is ready to pop.

*Ultra capacitors*

Due to the incredibly high surface area to mass ratio of graphene, one potential application is in the conductive plates of ultra capacitors. It is believed that graphene could be used to produce ultra capacitors with a greater energy storage density than is currently available.

*Graphene biodevices*

Graphene’s modifiable chemistry, large surface area, atomic thickness and molecularly-gatable structure make antibody-functionalized graphene sheets excellent candidates for mammalian and microbial detection and diagnosis devices. The most ambitious biological application of graphene is for rapid, inexpensive electronic DNA sequencing. Integration of graphene (thickness of 0.34 nm) layers as nano electrodes into a nanopore can solve one of the bottleneck issues of nanopore-based single-molecule DNA sequencing.

*Anti-bacterial applications*

Scientists have also found that sheets of graphene oxide are highly effective in killing bacteria such as *Escherichia coli*. This means graphene could be useful in applications such as hygiene products or packaging that will help keep food fresh for longer.

**Strength applications**

One atom-thick sheet is not that tough, but when graphene sheets are incorporated into composites, you could come up with a material that’s many times stronger than Kevlar. The Chinese are already working on carbon-nano tube yarn for spacesuits and bulletproof vests. Graphene composites could be produced less expensively than the current generation of carbon-nano tube composites. That opens the way for lighter, cheaper body armor, as well as lighter auto bodies and airplane fuselages as well.

**T-ray scanners**

Terahertz radiation, or T-rays, are particularly well-suited for detecting hidden objects at airport security checkpoints without the health risk posed by X-rays. T-rays could also serve as the basis for medical scanning devices that come even closer to the "Star Trek" tricorder. T-ray scanning is already being used for skin-cancer screening and tooth-cavity detection. The fast frequencies that can be achieved using graphene circuits are the basis for chemical sensors and for generators of terahertz-range light. Maybe graphene will hasten the arrival of those brave new T-ray scanners, for better or worse.

**Heat conducting graphene to cool electronic gadgets**

Overheating in laptops and electronic gadgets isn’t just an annoyance to the end user — it’s a major technological hurdle that puts a hard limit to the speed and energy efficiency of electronics. Heating in electronic components is inevitable and, as processing speeds grow exponentially, a central problem that needs to be dealt with using constantly improving technology. While heat-dissipating fans and the increasingly popular water cooling systems may do the job for now, more portable (and/or quieter) solutions are needed. Silicon, an invaluable material for its unique electronic properties, doesn’t however have good thermal properties, particularly at the nanometer scale. A new, promising approach to controlling the heat problem is therefore to incorporate materials with superior thermal properties into silicon computer chips, to make the heat transfer swifter and more efficient. Knowing that
Graphene behaves as a strong heat conductor can dramatically improve the thermal characteristics, meaning lower temperatures and a concrete possibility for chip manufacturers to reach higher processing speeds with relative ease. Recently, a team of scientists from the University of California (USA) found that multiple layers of graphene show strong heat conducting properties that can be harnessed in removing dissipated heat from electronic devices.

Further developments
Isolated only four years ago, graphene already appears in prototype transistors, memories and other devices. But to go from lab benches to store shelves, engineers need to devise methods to make industrial quantities of large, uniform sheets of pure, single-ply graphene. Researchers are pursuing several processing routes. The initial graphene-making methods worked similarly to pencil writing: researchers would abrade some graphite and then search the debris with a microscope for suitable samples or separate individual flakes with sticky tape.

Although most scientists consider such mechanical “exfoliation” techniques to be suited only for making tiny amounts. Many research groups claim to be able to coat whole silicon wafers with monolayer sheets of graphene cheaply but so far no one has publicly demonstrated it.

Recently the procedure was scaled up to produce as much graphene as you want by using ultrasound to break up graphite into individual layers that are dispersed in a liquid. The suspension can then be dried out on a surface, which leaves a film of overlapping pieces of graphene crystals. Whether these sheets of multiple crystals can work well enough for many applications is uncertain, however, because edge boundaries of individual flakes tend to impede the rapid flow of electrons. Bigger samples might come from chemical exfoliation.

Researchers at the Massachusetts Institute of Technology and elsewhere are looking to make graphene using chemical vapor deposition (CVD), an established process that could be readily integrated into microchip fabrication. In CVD, volatile chemicals react and deposit themselves on a substrate as a thin coating.
The biggest challenge in exploiting graphene’s jack-of-all-trades flexibility in computing applications is getting it to perform as a true semiconductor. While it can be considered a semiconductor like silicon, graphene lacks one crucial property—the ability to act as a switch. Without this, a chip will draw electricity continuously, unable to turn off. But engineers are making headway.

Researchers at the University of Illinois showed that nano ribbons of graphene could be cut in such a way that they could be turned on and off. The most likely applications for graphene will be in analog systems, such as radar, satellite communications, and imaging devices. The first graphene device from DARPA will be for specialized government communications. Researches envision graphene transistors amplifying signals between cell towers and eventually inside cell phones. Even in analog devices, there are still hurdles to overcome—most notably the difficulty of creating large batches of graphene.

Graphene research has discovered hidden interactions that will affect the way components are designed from the super-fast material. Scientists from the Georgia Institute of Technology and the US National Institute of Standards and Technology (NIST) have determined how the orbits of electrons interact with magnetic fields applied to epitaxial graphene. Understanding such interference will be important for bi-layer graphene devices that have been proposed, and may be important for other lattice-matched substrates used to support graphene and graphene devices.

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