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RESEARCH ARTICLE

NANOSCALE BASED GRAPHENE: A REVIEW OF ITS PROPERTIES FOR ELECTRONIC AND PHOTONIC APPLICATIONS

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ABSTRACT

The discovery of a new material brings the most exciting and fruitful periods of scientific and technological research. With a new material creates new opportunities to reexamine old problems as well as pose new ones. One of the most interesting features of graphene is the rich physics set up by the various nanostructures it may adopt. The planar structure of graphene makes this material ideal for patterning at the nanoscale. This review article presents recent progress in graphene research and in the production methods, and subsequently describes various graphene applications.

INTRODUCTION

Carbon has various hybridized states (sp, sp^2, sp^3) and can form diverse bonding, with the ability to bind to itself and to nearly all elements. As a consequence, carbon has numerous allotropes [1,2] such as graphene,[3,4] fullerenes,[5] carbon nanotubes,[6] nanorings,[7] and nanobuds figure-1.[8] Synthesis and discovery of new carbon phases with high stability, novel bonding characteristics, unique properties, and applications will be an ongoing effort for theoretical, synthetic, and material scientists.[9-11] Ever since graphene was first created in 2004,9 many claim that it can be used in a host of device applications, carbon-based electronics, even rivaling silicon as the electronics material of choice for the future.

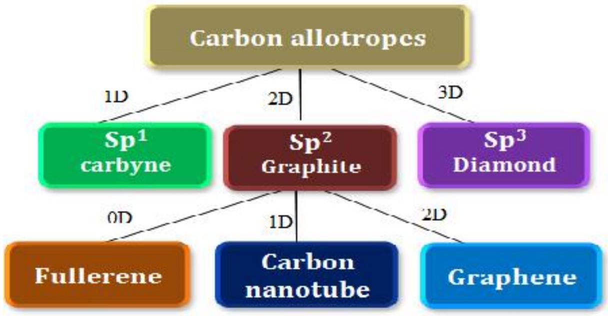

Figure 1 carbon Different numerous allotropes

Graphyne and graphdiyne are two-dimensional carbon allotropes of graphene with honeycomb structures. Graphone and graphane are hydrogenated derivatives of graphene .[12-14] The advanced and unique properties of these new materials make them highly promising for applications in next generation nanoelectronics. Graphyne is better than graphene in directional electronic properties and charge carriers. Graphene is the first example of a close-packed two dimensional (2D) crystalline material isolated in nature; and it is currently receiving unusual growth in research attention [15]. The hexagonal arrangement of the carbon atoms in graphene can be reduced into two interpenetrating sub-lattices of carbon atoms with inversion symmetry between them (Figure 2) .

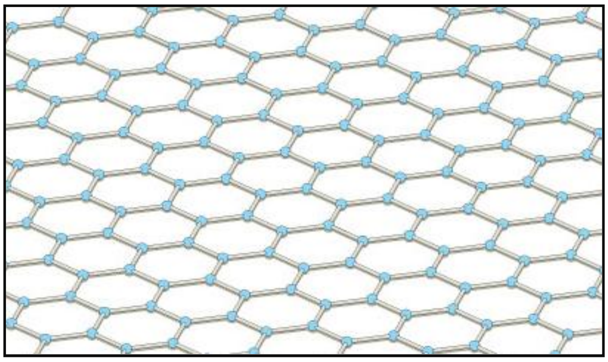

Figure 2 Graphene: A Two Dimensional Form of Carbon with Unusual Band Structure

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With a chacterstic band gap and magnetism, graphone and graphane show important applications in nanoelectronics and spintronics. Because these materials are close to graphene and will play important roles in carbon-based electronic devices, they deserve further, careful, and thorough investigations for a diverse range of nanotechnology applications [16-21] as illustrated in figure- 3.

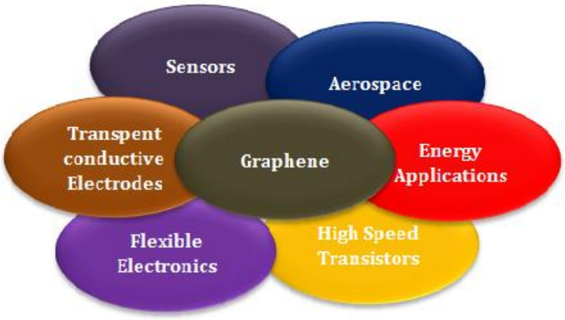

Figure 3 Applications of Graphene

Graphene: atomic and electronic structure

Carbon is an extremely versatile element, not only in the form of organic compounds, but also in inorganic (nano)materials. The two well-known allotropes of crystalline carbon, graphite with sp^2 hybridization (black, good electric conductor, soft) and diamond with sp^3 hybridization (transparent, insulator, hard), have very different physical properties. The large variety of sp^2 nanocarbons while others are still hypothetical—obtained by various ways of stacking graphitic elements and/or by incorporating defects in the graphitic network have an even wider range of physical properties depending on their particular structure or, in other words, on the way their constituting atoms are linked together [22-24].

Why each carbon atom has three nearest neighbors within the graphene sheets. Each p_z orbital overlaps with those of the neighboring carbon atoms to form p-bonds that lead to delocalized electron p bands, much like in the case of benzene, naphthalene, anthracene and other aromatic molecules. In this regard, graphene can be thought of as the extreme size limit of planar aromatic molecules.

The covalent s bonds (shorter than the C–C bonds in diamond) are largely responsible for the mechanical strength of graphene and other sp2 carbon allotropes. The occupied s electronic bands are completely filled and have a large separation in energy from the Fermi level. For that reason, their effects on the electronic properties of grapheme can be neglected, at least to a first approximation [25].

At this level of approximation, the band structure—and therefore the electronic properties—of graphene can be addressed by describing the p bands in a tight binding approximation.[3] Band structure calculations for the honeycomb lattice shown in Fig. 4 yield an unusual electronic structure: the conduction p band and the valence p band of graphene meet exactly at the corners of the hexagonal first Brillouin zone (Fig. 5) and only there. These corners are called the Dirac points. Three of them, labeled as K`, belong to one triangular sublattice in reciprocal space, while the other three, labeled as K0 , form the second sublattice. The valence and conduction bands meet at the K and K` points, but do not overlap, with zero number of states just at these points. Because of this, graphene is called a zero band-gap semiconductor or semimetal. Around the Dirac points, the dispersion relation of the p-- bands is linear with the separation distance, opposite to the other semiconductors, which chiefly exhibit a parabolic dispersion at the Fermi energy. This linear dispersion is at the origin of the unusual electronic properties of graphene [26-29].

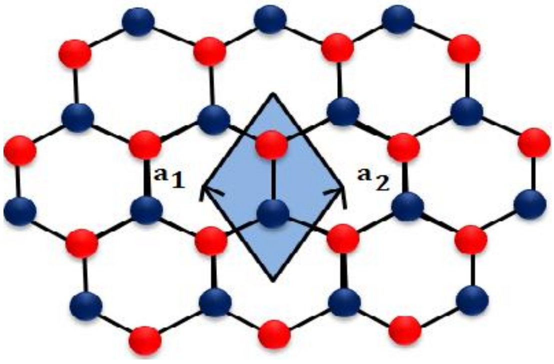

Fig 4 The honeycomb lattice of graphene. The unit cell defined by vectors a_1 and a_2 containing the two atoms belonging to sublattices A (blue) and B (red) is highlighted in light blue.

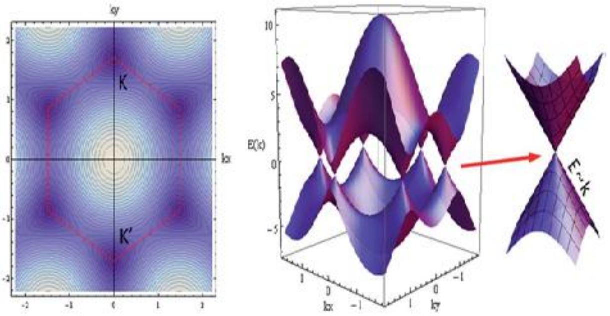

Fig. 5 Contour plot of the energy in the first Brillouin zone of graphene (red hexagon). Plot of the p band structure of graphene, showing the conduction band and the valence band touching at the K points. The zoomed part at the right-hand side shows the linear dispersion in the region of the Dirac point [22].

Table1 Physical & Chemical Properties of Different carbon allotropes

	Diamond	**Graphite**	**C60**	**CNTs**
Color	Colorless	Steel black to Grey	Black solid / Magenta in solution	black
Density (g/cm^3)	3.515	1.9-2.35	1.695	1.33-1.48
Specific Gravity	3.523	2.24	1.7-1.97	***2***
Hardness (Moh's Scale)	101	1-21	**1-2**	**1-2**
Melting Point (ºC)	35505	3652 – 36975	>800 (sublimes)	**Similar to graphite**
Boiling Point (ºC)	48275	42005	n/a	n/a
Electrical Conductivity	Insulator	Conductor	Semiconductor	Conductor toSemiconductor
Hybridization	sp^3 – tetrahedral	sp^2 – trigonal	sp^2 – trigonal planar	sp^2 – trigional planar
Crystal Shape and/or Structure	Cubic	Tabular	Truncated icosahedrons	Cylindrical

It is logical to categorize these by the quality of the resulting grapheme (and thus the possible applications): (1) graphene or reduced grapheme oxide flakes for composite materials, conductive paints, and so on; (2) planar graphene for lower-performance active and non-active devices; and (3) planar graphene for high-performance electronic devices. The properties of a particular grade of graphene (and hence the pool of applications that can utilize it) depend very much on the quality of the material, type of defects, substrate, and so forth, which are strongly affected by the production method; see Table 2.

Table 2 Properties of graphene obtained by different methods [30]

Method	Crystallite size (mm)	Sample size (mm)	Charge carrier mobility (at ambient temperature) (cm^2 V^{-1} s^{-1})	Applications
Mechanical exfoliation	>1,000	>1	>2 X10^5 and .10^6 (at low temperature)	Research
Chemical exfoliation	≤0.1	Infinite as a layer of overlapping flakes	100 (for a layer of overlapping flakes)	Coatings, paint/ink, composites, transparent conductive layers, energy storage, bioapplications
Chemical exfoliation Via graphene oxide	~100	Infinite as a layer of overlapping flakes	1 (for a layer of overlapping flakes)	Coatings, paint/ink, composites, transparent conductive layers, energy storage, bioapplications
CVD	1,000	~1,000	10,000	Photonics, nanoelectronics, transparent conductive layers, sensors, bioapplications
SiC	50	100	10,000	High-frequency transistors and other electronic devices

Table 3 Electronic applications of graphene [30]

Application	Drivers	Issues to be addressed
Touch screen	Graphene has better endurance than benchmark materials	Requires better control of contact resistance, and the sheet resistance needs to be reduced (possibly by doping)
E-paper	High transmittance of monolayer graphene could provide visibility	Requires better control of contact resistance
Foldable OLED	Graphene of high electronic quality has a bendability of below 5mm, improved efficiency due to graphene's work function tunability, and the atomically flat surface of graphene helps to avoid electrical shorts and leakage current	Requires better control of contact resistance, the sheet resistance needs to be reduced, and conformal coverage of three-dimensional structures is needed
High-frequency transistor	No manufacturable solution for InP high-electron-mobility transistor (low noise) after 2021, according to the 2011 ITRS	Need to achieve current saturation, and fT5850 GHz, fmax51,200 GHz should be achieved
Logic transistor	High mobility	New structures need to resolve the bandgap–mobility trade-off and an on/off ratio larger than 10^6 needs to be achieved

Table 4 Photonic applications of graphene

Application	Drivers	Issues to be addressed
Tunable fibre mode-locked laser	Graphene's wide spectral range	Requires a cost-effective graphene-transferring technology
Solid-state mode-locked laser	Graphene-saturable absorber would be cheaper and easy to integrate into the laser system	Requires a cost-effective graphene-transferring technology
Photodetector	Graphene can supply bandwidth per wavelength of 640 GHz for chip-to-chip or intrachip communications (not possible with IV or III–V detectors)	Need to increase responsivity, which might require a new structure and/or doping control, and the modulator bandwidth must follow suit
Polarization controller	Current polarization controlling devices are bulky or difficult to integrate but graphene is compact and easy to integrate with Si	Need to gain full control of parameters of high-quality graphene
Optical modulator	Graphene could increase operating speed (Si operation bandwidth is currently limited to about 50 GHz), thus avoiding the use of complicated III–V epitaxial growth or bonding on Si	High-quality graphene with low sheet resistance is needed to increase bandwidth to over 100 GHz
Isolator	Graphene can provide both integrated and compact isolators on a Si substrate, dramatically aiding miniaturization	Decreasing magnetic field strength and optimization of process architecture are important for the products
Passively mode-locked semiconductor laser	Core-to-core and core-to-memory bandwidth increase requires a dense wavelength-division-multiplexing optical interconnect(which a graphene-saturable absorber can provide) with over 50 wavelengths, not achievable with a laser array	Competing technologies are actively mode-locked semiconductor lasers or external mode-lock lasers but the graphene market will open in the 2020s; however, interconnect architecture needs to consume low power

Graphene-based photonics and electronic applications

Although numerous challenges remain in developing graphene-based polymer composites, but these materials have already been explored for a range of applications in different fields such as electronic devices, energy storage, sensors, ESD and EMI shielding and biomedical applications [31-34]. It is unlikely that graphene will make it into high-performance integrated logic circuits as a planar channel material within the next decade because of the absence of a bandgap. However, many other, less stringent, graphene electronic applications are being developed, using the available (probably not ideal in terms of quality) material.

Table 2 lists some of the possible applications and the time that it may take for graphene-based prototypes to be demonstrated. Electrons in graphene behave as massless two-dimensional particles, which leads to a significant wavelength-independent absorption (pa52.3%) for normal incident light below about 3 eV. Additionally, mono- and bi-layer graphene become completely transparent when the optical energy is smaller than double the Fermi level, owing to Pauli blocking [30,34-40]. These properties would suit many controllable photonic devices (Table 3).

CONCLUSION

As the current market for graphene applications is driven by the production of this material, there is a clear hierarchy in how soon the applications will reach the user or consumer. The overview of methods for nanoscale patterning clearly shows that, due to the particular electronic structure of graphene, the development of new tools controlling, both the crystallographic orientation of the graphene edges and their atomic scale structure is a cornerstone for future graphene-based nanoelectronics and spintronics.

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