
Graphene and Perovskite Solar Cells: A Review on Recent Emerging Revolutionary Technologies in Chemistry

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Abstract:

If the 20th century was the age of plastics, the 21st century seems set to become the age of graphene—a recently discovered material made from honeycomb sheets of carbon just one atom thick. Science journals have been running out of superlatives for this wondrous stuff: it's just about the lightest, strongest, thinnest, best heat- and electricity-conducting material ever discovered. And if we're to believe the hype, it promises to revolutionize everything from computing to car tires and solar cells to smoke detectors. Similarly, the hunt is on to find a cheap and safe solar-cell technology. Crystalline silicon is the basis for 90% of commercial photovoltaic devices, which use semiconductors to convert light into electricity. But silicon photovoltaics are still expensive to process, their manufacture produces toxic by-products and they are cumbersome to install. Perovskites could be a game-changer. These materials have crystal structures that are based on pyramid-like tetrahedral arrangements of atoms or molecules. Long explored as potential semiconductors, superconductors and for their optical and magnetic properties, perovskites are also efficient at absorbing light and transporting charges — ideal properties for capturing solar power. In this paper, we will discuss the structure, properties, applications and future scope of graphene and perovskite solar cells.

Keywords: Graphene and perovskite solar cells

Introduction:

21st century have been marked by the rise of a global economy by advances in science and technology. While science is concerned with understanding how and why things happen, technology deals with making things happen. Development is closely related with technology Technology has without doubt transformed our lives into something much better. Recently the technologies that have revolutionised the world includes Nanosensors and the Internet of Nanothings, Tiny sensors that can connect to the web, Next Generation Batteries Making large-scale power storage possible based on sodium, aluminium or zinc, The Blockchain A revolutionary decentralized trust system, Two-Dimensional Materials graphene “Wonder materials” are becoming increasingly affordable, Autonomous Vehicles Self-driving cars coming sooner than expected, Organs-on-chips using chips instead of organs for medical testing purposes, Perovskite Solar Cells making progress towards ubiquitous solar power generation, Open AI Ecosystem from artificial to contextual intelligence, Optogenetics using light to control genetically modified neurons, Systems Metabolic Engineering Chemicals from renewable sources viz. microorganisms. This paper is a review of the structure, properties, applications and future scope of graphene and perovskite solar cells.

Discovery of graphene:

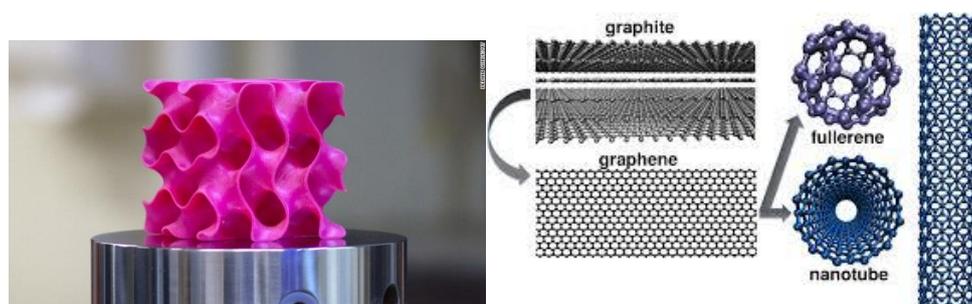
In 2004, a group of physicists from Manchester University, UK, led by Andre Geim and Kostya Novoselov, used a very different and, at first glance, even naive approach to obtain graphene and lead a revolution in the field. They started with three-dimensional graphite and extracted a single sheet (a monolayer of atoms) using a technique called micromechanical cleavage. Graphite is a layered material and can be viewed as a number of two-dimensional graphene crystals weakly coupled together – exactly the property used by the Manchester team. By using this top-down approach and starting with large, three-dimensional crystals, the researchers avoided all the issues with the stability of small crystallites. Furthermore, the same technique has been used by

the group to obtain two-dimensional crystals of other materials, including boron nitride, some dichalcogenides, and

the high-temperature superconductor Bi-Sr-Ca-Cu-O. This astonishing finding sends an important message: two-dimensional crystals do exist and they are stable under ambient conditions.

Structure of graphene:

Carbon plays a unique role in nature. The formation of carbon in stars as a result of the merging of three particles is a crucial process that leads to the existence of all the relatively heavy elements in the universe. The capability of carbon atoms to form complicated networks is fundamental to organic chemistry and the basis for the existence of life, at least in its known forms. Only three-dimensional (diamond, graphite), one-dimensional (nanotubes), and zero-dimensional (fullerenes) allotropes of carbon were known. The two-dimensional form was conspicuously missing, resisting any attempt at experimental observation – until recently. Graphene is comprised of honeycomb-like two-dimensional sheet of planar and one-atom thick sp^2 -hybridized carbon has gained particular interest. More interestingly, graphene can be treated as the basic building block of other important carbon allotropes: 2D graphite by stacking of individual graphene sheets, 1D nanotube by rolling of a graphene sheet and 3D fullerene by wrapping of a graphene sheet.^[1,2] Further, graphene bears extraordinary thermal, mechanical and electrical properties owing to its long-range π -conjugation, which have long been an exciting area of research, and thus are being exploited for their technological application^[3,4,5]. The other properties which make graphene unique are its large surface area (2,630 m²g⁻¹), high conductivity (10⁶ Scm⁻¹) and excellent chemical stability^[1,6,7]. Owing to its unique physical and chemical properties, graphene and its derivatives have attracted tremendous interest in many different fields in recent years^[7,8]. Further, its composites with various nanoparticles like metal and metal oxide have produced a new class of material with much improved properties^[8-12]. Therefore, the study of graphene and its composites have been the subject of immense research interest. Although the band structure of graphite was first proposed theoretically and calculated by P. R. Wallace in 1947, its existence in the real world was thought impossible at that time^[13]. But, in 2004, Andre Geim and Konstantin Novoselov established that a single layer of carbon atoms could be isolated, which bestowed upon them the Nobel Prize for Physics in 2010. Above all, graphene has been touted as the “miracle material” of the 21st Century, which implies its potential impact in future nanotechnology.



Honeycomb structure of graphene Different allotropes of carbon

Applications of graphene:

Graphene is considered to be the world's thinnest, strongest and most conductive material - to both electricity and heat. All these properties are exciting researchers and businesses around the world - as graphene has the potential to revolutionize entire industries - in the fields of electricity, conductivity, energy generation, batteries, sensors and more. Graphene has been used as a reinforcing agent to improve the mechanical properties of biodegradable polymeric nanocomposites for engineering bone tissue applications.^[14] Functionalized and surfactant dispersed graphene solutions have been designed as blood pool MRI contrast agents.^[15] Further,

iodine and manganese incorporating graphene nanoparticles have served as multimodal MRI-computerized tomograph (CT) contrast agents.^[16]

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.^[17] Graphene is so thin water has near-perfect wetting transparency which is an important property particularly in developing bio-sensor applications.^[18] Researchers demonstrated a nanoscale biomicro-robot (or cybot) made by cladding a living endospore cell with graphene quantum dots. The device acted as a humidity sensor.^[19]

Graphene has a high carrier mobility, and low noise, allowing it to be used as the channel in a field-effect transistor.^[20] Graphene allows water to pass through, however it is almost impervious to liquids and gases. Graphene can be used as an ultrafiltration medium to behave as a barrier between two substances. As graphene offers high electrical conductivity, thinness, strength and high electrical conductivity it may help develop quick and efficient bioelectric sensory devices, with the ability to monitor such things as glucose levels, haemoglobin levels, cholesterol and even DNA sequencing. Graphene is stiff, strong and very light. Presently aerospace engineers are incorporating carbon fibre into the production of aircraft as it is also very strong and light. It is anticipated that graphene will be used to create a material that can replace steel in the structure of aircraft, improving fuel efficiency, range and reducing weight. Since it has good electrical conductivity, it will be used to coat aircraft surface material to prevent electrical damage resulting from lightning strikes.

Graphene on photon absorption generates multiple electrons. Also graphene can work on all wavelengths unlike silicon. Graphene-based photovoltaic cells are flexible and thin and can be used in clothing to help recharge the mobile phone or even used as retro-fitted photovoltaic window screens or curtains to help power the home. Spintronics is used in disk drives for data storage and in magnetic random-access memory. Electronic spin is generally short-lived and fragile, but the spin-based information in current devices needs to travel only a few nanometers. However, in processors, the information must cross several tens of micrometers with aligned spins. Graphene is the only known candidate for such behavior.^[21] Appropriately perforated graphene (and hexagonal boron nitride hBN) can allow protons to pass through it, offering the potential for using graphene monolayers as a barrier that blocks hydrogen atoms but not protons/ionized hydrogen (hydrogen atoms with their electrons stripped off). They could even be used to extract hydrogen gas out of the atmosphere that could power electric generators with ambient air.

Due to graphene's high surface area to mass ratio, one potential application is in the conductive plates of supercapacitors.^[22] Graphene oxide is non-toxic and biodegradable. Its surface is covered with epoxy, hydroxyl, and carboxyl groups that interact with cations and anions. It is soluble in water and forms stable colloid suspensions in other liquids because it is amphiphilic (able to mix with water or oil). Dispersed in liquids it shows excellent sorption capacities. It can remove copper, cobalt, cadmium, arsenate, and organic solvents.^[23] Graphene accommodates a plasmonic surface mode,^[24] observed recently via near field infrared optical microscopy techniques^{[25][26]} and infrared spectroscopy^[27] Potential applications are in the terahertz to mid-infrared frequencies,^[28] such as terahertz and midinfrared light modulators, passive terahertz filters, mid-infrared photodetectors and biosensors.^[29] Scientists discovered using graphene as a lubricant works better than traditionally used graphite. A one atom thick layer of graphene in between a steel ball and steel disc lasted for 6,500 cycles. Conventional lubricants lasted 1,000 cycles.^[30]

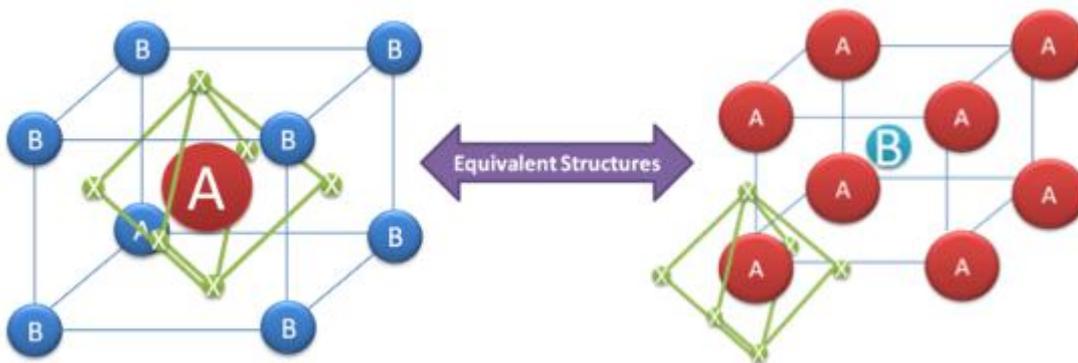
A graphene-based plasmonic nano-antenna (GPN) can operate efficiently at millimeter radio wavelengths. The wavelength of surface plasmon polaritons for a given frequency is several hundred times smaller than the wavelength of freely propagating electromagnetic waves of the same frequency. These speed and size differences enable efficient graphene-based antennas to be far smaller than conventional alternatives. The latter operate at frequencies 100-1000 times larger than GPNs, producing .01-.001 as many photons.^[31] Graphene's high thermal conductivity suggests that it could be used as an additive in coolants. Preliminary research work showed that 5% graphene by volume can enhance the thermal conductivity of a base fluid by 86%.^[32] Graphene's strength, stiffness and lightness suggested it for use with carbon fiber.

Graphene has been used as a reinforcing agent to improve the mechanical properties of biodegradable polymeric nanocomposites for engineering bone tissue.

Perovskite SolarCells:

The terms "perovskite" and "perovskite structure" are often used interchangeably. Technically, a perovskite is a type of mineral that was first found in the Ural Mountains and named after Lev Perovski who was the founder of the Russian Geographical Society. A perovskite structure is any compound that has the same structure as the perovskite mineral. True perovskite (the mineral) is composed of calcium, titanium and oxygen in the form CaTiO_3 . Meanwhile, a perovskite structure is anything that has the generic form ABX_3 and the same crystallographic structure as perovskite (the mineral). However, since most people in the solar cell world aren't involved with minerals and geology, perovskite and perovskite structure are used interchangeably.

The perovskite lattice arrangement is demonstrated below. As with many structures in crystallography, it can be represented in multiple ways. The simplest way to think about a perovskite is as a large atomic or molecular cation (positively-charged) of type A in the centre of a cube. The corners of the cube are then occupied by atoms B (also positively-charged cations) and the faces of the cube are occupied by a smaller atom X with negative charge (anion).



A generic perovskite crystal structure of the form ABX_3 . Note however that the two structures are equivalent – the left hand structure is drawn so that atom B is at the $\langle 0,0,0 \rangle$ position while the right hand structure is drawn so that atom (or molecule) A is at the $\langle 0,0,0 \rangle$ position. Also note that the lines are a guide to represent crystal orientation rather than bonding patterns.

Depending on which atoms/molecules are used in the structure, perovskites can have an impressive array of interesting properties including superconductivity, giant magnetoresistance, spin-dependent transport (spintronics) and catalytic properties. Perovskites therefore represent an exciting playground for physicists, chemists and material scientists. In the case of perovskite solar cells, the most efficient devices so far have been produced with the following combination of materials in the usual perovskite form ABX_3 :

- A = An organic cation - methylammonium (CH_3NH_3)⁺
- B = A big inorganic cation - usually lead(II) (Pb^{2+})
- X_3 = A slightly smaller halogen anion – usually chloride (Cl^-) or iodide (I^-)

Since this is a relatively general structure, these perovskite-based devices can also be given a number of different names, which can either refer to a more general class of materials or a specific combination. As an example of this, we've created the below table to highlight how many names can be formed from one basic structure.

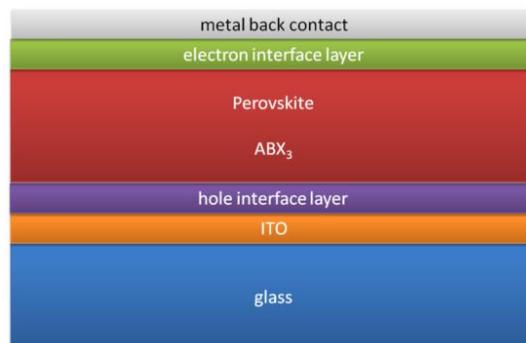
Fabrication and Measurement of Perovskite Solar Cells

Although perovskites come from a seemingly different world of crystallography, they can be incorporated very easily into a standard OPV (or other thin film) architecture. While the best perovskite structures have

been vacuum deposited to give better, more uniform film qualities, this process requires the co-evaporation of the organic (methylammonium) component at the same time as the inorganic (lead halide) components. The accurate co-evaporation of these materials to form the perovskite therefore requires specialist evaporation chambers that are not available to many researchers. This may also cause the practical issues of calibration and cross-contamination between organic and non-organic sources which would be difficult to clean.

However, the development of low-temperature solution deposition routes offer a much simpler method to incorporate perovskites, and can even be used with existing materials sets. Although perovskite solar cells originally came out of DSSC research, the fact that they no longer require an oxide scaffold means the field is branching out, and that many device architectures now look very similar to thin-film photovoltaics (except with the active layers substituted with the perovskite). The key to enabling this is by ensuring that the perovskite precursor materials use relatively polar solvents for deposition. Therefore, orthogonal solvent systems for the different layers can be easily developed.

The structure below represents a standard (non-inverted) perovskite solar cell based upon a standard glass/ITO substrates with metal back contact. All that is required to form a working device from the perovskite are two charge-selective interface layers (for the electrons and holes respectively). Many of the standard interface layers from the world of organic photovoltaics work relatively well. For example, PEDOT:PSS and the PTAA-class of polymers work well as hole interface layers, while PCBM, C₆₀, ZnO and TiO₂ makes effective electron interfaces. However, the field is so new that there is a vast archive of possible interface materials to be explored. Understanding and optimising the energy levels and interactions of different materials at these interfaces offers a very exciting area of research.



Generic structure of a standard (non-inverted) perovskite solar cell.

The main issues for practical device fabrication of perovskite solar cells are film quality and thickness. The light-harvesting (active) perovskite layer needs to be several hundred nanometres thick – several times more than for standard organic photovoltaics. Unless the deposition conditions and annealing temperature are optimised, rough surfaces with incomplete coverage will form. Even with good optimisation, there will still be a significant surface roughness remaining. Therefore, thicker interface layers than might normally be used are also required. However, the fact that efficiencies of over 11% have already been achieved for spin coated devices [2] is highly encouraging.

Recent improvements to device processing have led to significant increases in the surface coverage while reducing the surface roughness. One method for improving the surface coverage and the roughness is to add small amounts of acids such as hydriodic, hydrobromic, or hydrochloric acid. These materials are byproducts of the synthesis of methylammonium halides however the presence of these acids have an impact upon the solubility of the lead components. We previously discussed this in a post about the purity of MAI vs lead chloride solubility. Another method is by precise control of the timing of precipitation of the salts, this is done by solvent quenching methods with precise timings of the quench and volumes of the quenching solvents needed to give the optimal performance. To help with our understanding of this we decided to build the new Ossila syringe pump which has allowed us to use this quenching process to push in house power conversion efficiency values over 16%.

Even now there are further improvements being made in all areas of perovskite processing which are of great interest; some of these include mixed phase perovskites, two dimensional perovskite structures, inorganic perovskite. As one of the top ten science breakthroughs of 2013, perovskite solar cells have shown potential both in the rapid efficiency improvement (from 2.2% in 2006 to the latest record 20.1% in 2014) and in cheap material and manufacturing costs. Perovskite solar cells have attracted tremendous attention from the likes of DSSC and OPVs with greater potential. Many companies and research institutes that focused on DSSCs and OPVs now transfer attention to perovskites with few research institutes remaining exclusively committed to OPVs and DSSCs. Perovskite solar cells are a breath of fresh air into the emerging photovoltaic technology landscape. They have amazed with an incredibly fast efficiency improvement, going from just 2% in 2006 to over 20.1% in 2015. Photovoltaic (PV) technologies are basically divided into two big categories: wafer-based PV (also called 1st generation PV) and thin-film cell PV. Traditional crystalline silicon (c-Si) cells (both single crystalline silicon and multi-crystalline silicon) and gallium arsenide (GaAs) cells belong to the wafer-based PVs. Among different single-junction solar technologies, GaAs exhibits the highest efficiency, followed by c-Si cells. The latter dominates the current PV market (about 90% market share). Thin-film cells normally absorb light 10-100 times more efficiently than silicon, allowing the use of films of just a few microns thick. Cadmium telluride (CdTe) technology has been successfully commercialized, with more than 20% cell efficiency and 17.5% module efficiency record. CdTe cells currently take about 5% of the total market.

Other commercial thin-film technologies include hydrogenated amorphous silicon (a-Si:H) and copper indium gallium (di)selenide (CIGS) cells, taking approximately 2% market share each today. Copper zinc tin sulphide technology has been developed for years and it will still require some time for real commercialization. The emerging thin-film PVs are also called 3rd generation PVs, which refer to PVs using technologies that have the potential to overcome Shockley-Queisser limit or are based on novel semiconductors. The 3rd generation PVs include DSSC, organic photovoltaic (OPV), quantum dot (QD) PV and perovskite PV. The cell efficiencies of perovskite are approaching that of commercialized 2nd generation technologies such as CdTe and CIGS. Other emerging PV technologies are still struggling with lab cell efficiencies lower than 15%. High and rapidly improved efficiencies, as well as low potential material & processing costs are not the only advantages of perovskite solar cells. Flexibility, semi-transparency, tailored form factors, thin-film, lightweight are other value propositions of perovskite solar cells. The market forecast is provided based on the following applications: Smart glass BIPV Outdoor furniture Perovskites in tandem solar cells Utility Portable devices Third world/developing countries for off-grid applications.

Conclusion:

Graphene is a promising material for new types of systems, circuits and devices where several functionalities can be combined into a single material. Although a lot of effort has already been put together to utilize each and every property of graphene for the development and welfare of mankind still there is much to be done. For example, taking electrochemical sensing into consideration, there is an urgent need in this area to fabricate reliable, reproducible, and low-cost sensors with high detection sensitivity using well-defined graphene. There is still much to be done for the scientific research and technological development of graphene-related theory, materials, and applications. We would like to conclude by stating that opportunities and challenges coexist with regard to the applications of graphene-based nanomaterials.

Organic-inorganic halide perovskites are significant for research and commercialization of solar cells in the next few years due to high efficiency and durability. Advantages of PSC include low processing cost and simple execution of desirable products such as flexible, transparent or all-perovskite tandem cell modules than existing photovoltaics. PSC can show better In modern research silicon solar cell is recorded with efficiency of 25% but it is expensive to manufacture of such high efficiency cells and typical solar cell installations are around 15% efficient. Perovskite solar cells are recorded with 26% efficiency with low processing cost and high stable characteristics whereas, second generation thin film technology results in 12-20% efficient relatively. The perovskite inspired material is quite easy to fabricate and easy to manufacture via printing

process relying on liquid precursor. To capture different portions of light spectrums perovskite materials can be easily tuned and cost of fabrication of such super efficiency solar cells will eventually get reduced.

References:

- [1]. A.K. Geim, and K.S. Novoselov, *Nat. Mater.*, 6, 183, 2007.
- [2]. F. Schedin, A.K. Geim, S.V. Morozov, E.W. Hill, P. Blake, M.I. Katsnelson, and K.S. Novoselov, *Nat. Mater.*, 6, 652, 2007.
- [3] P. Avouris, *NanoLett.*, 10, 4285, 2010.
- [4]. Q. Bao, and K.P. Loh, *ACS Nano*, 5, 3677, 2012.
- [5] K.F. Mak, L. Ju, F. Wang, and T.F. Heinz, *Solid State Commun.*, 152, 1341, 2012.
- [6]. K.S. Novoselov, V.I. Falko, L. Colombo, P.R. Gellert, M.G. Schwab, and K. Kim, *Nature*, 490, 192, 2012.
- [7] M.J. Allen, V.C. Tung, and R.B. Kaner, *Chem. Rev.*, 110, 132, 2010.
- [8] H.Y. Mao, S. Laurent, W. Chen, O. Akhavan, M. Imani, A.A. Ashkarran, and M. Mahmoudi, *Chem. Rev.*, 113, 3407, 2013.
- [9] P.V. Kamat, *J. Phys. Chem. Lett.*, 1, 520, 2010.
- [10]. Z.-S. Wu, G. Zhou, L.-C. Yin, W. Ren, F. Li, and H.-M. Cheng, *Nano Energy*, 1, 107, 2012.
- [11]. C. Xu, X. Wang, and J. Zhu, *J. Phys. Chem. C*, 112, 19841, 2008.
- [12]. Z. Hu, Y. Huang, S. Sun, W. Guan, Y. Yao, P. Tang, and C. Li, *Carbon*, 50, 994, 2012.
- [13] X. Huang, X. Qi, F. Boeyab, and H. Zhang, *Chem. Soc. Rev.*, 41, 666, 2012.
- [14] Mohanty, Nihar; Berry, Vikas (2008). "Graphene-based Single-Bacterium Resolution Biodevice and DNA-Transistor – Interfacing Graphene-Derivatives with Nano and Micro Scale Biocomponents". *Nano Letters*. 8 (12): 4469–76. Bibcode:2008NanoL...8.4469M. doi:10.1021/nl802412n. PMID 19367973.
- [15] Donaldson, L. (2012). "Graphene: Invisible to water". *Materials Today*. 15 (3): 82. doi:10.1016/S1369-7021(12)70037-8.
- [16] Xu, M. S. Xu; Fujita, D.; Hanagata, N. (2009). "Perspectives and Challenges of Emerging Single-Molecule DNA Sequencing Technologies". *Small*. 5 (23): 2638–49.
- [17] Majumder, M; Tkacz, R; Oldenbourg, R; Mehta, S; Miansari, M; Verma, A (2014). "pH dependent isotropic to nematic phase transitions in graphene oxide dispersions reveal droplet liquid crystalline phases". *Chemical Communications. Royal Society of Chemistry*. 50 (50): 6668–6671. doi:10.1039/C4CC00970C. PMID 24828948.
- [18] Press Release (6 January 2015). "Flying Carpet' Technique Uses Graphene to Deliver One-Two Punch of Anticancer Drugs". North Carolina State University.
- [19] Bullis, K. (28 January 2008). "Graphene Transistors". Cambridge: MIT Technology Review, Inc.
- [20] Ponomarenko, L. A.; Schedin, F.; Katsnelson, M. I.; Yang, R.; Hill, E. W.; Novoselov, K. S.; Geim, A. K. (2008). "Chaotic Dirac Billiard in Graphene Quantum Dots". *Science*. 320 (5874): 356–8.
- [21] "High Detectivity Graphene-Silicon Heterojunction Photodetector". *Small*. 12: 595–601. 2016. doi:10.1002/sml.201502336.
- [22] Peng, Zhiwei; Ye, Ruquan; Mann, Jason A.; Zakhidov, Dante; Li, Yilun; Smalley, Preston R.; Lin, Jian; Tour, James M. (2015-06-23). "Flexible Boron-Doped Laser-Induced Graphene Microsupercapacitors". *ACS Nano*. 9 (6): 5868–5875. doi:10.1021/acsnano.5b00436. ISSN 1936-0851.
- [23] Rodrigo, D.; Limaj, O.; Janner, D.; Etezadi, D.; Garcia de Abajo, F.J.; Pruneri, V.; Altug, H. (2015). "Mid-infrared plasmonic biosensing with graphene". *Science*. 349 (6244): 165–168. doi:10.1126/science.aab2051
- [24]. Wu, B.; Tuncer, H. M.; Naem, M.; Yang, B.; Cole, M. T.; Milne, W. I.; Hao, Y. (2014). "Experimental demonstration of a transparent graphene millimetre wave absorber with 28% fractional bandwidth at 140 GHz".
- [25] Ekiz, O.O.; Urel, M; et al. (2011). "Reversible Electrical Reduction and Oxidation of Graphene Oxide". *ACS Nano*. 5 (4): 2475–2482. doi:10.1021/nn1014215. PMID 21391707.
- [26] Ekiz, O.O.; Urel, M; et al. (2011). "Supporting information for Reversible Electrical Reduction and Oxidation of Graphene Oxide". *ACS Nano*. 5 (4): 2475–2482. doi:10.1021/nn1014215. PMID 21391707.
- [27] Dodson, Brian (February 3, 2014). "Graphene-based nano-antennas may enable cooperating smart dust swarms". *Gizmag.com*. Retrieved 2014-04-06.
- [28] "Optical antennas trap and control light with the help of graphene". 23 May 2014.
- [29] Jump up to: ^{ab} "Tuning optical responses of metallic dipole nanoantenna using graphene". *Optics Express*. 21: 31824. doi:10.1364/OE.21.031824
- [30] "World's first graphene speaker already superior to Sennheiser MX400". *Gizmag.com*. 2014-04-16. Retrieved 2014-04-24., full paper on arxiv.org
- [31] Eigler, S. (2009). "A new parameter based on graphene for characterizing transparent, conductive materials". *Carbon*. 47 (12): 2936–2939. doi:10.1016/j.carbon.2009.06.047.
- [32] Galatzer-Levy, Jeanne (2015-06-17). "Graphene heat-transfer riddle unraveled". *R&D*. Retrieved 2015-09-26.