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Graphene: a revolutionary nanomaterial

Where can I start introducing graphene? We could say that graphene has started many revolutions thanks to its extraordinary properties. The electronic band structure of graphene was first predicted as far back as 1947 [1] and without being a new material, as graphene is defined as one of the individual layers that forms graphite, it was discovered in 2004 when it was extracted from graphite [2]. Graphene was discovered using adhesive tape on graphite when a single layer of graphene was deposited on top of a silicon substrate and its electronic properties measured. This is when the graphene revolution began. The scientists that did this discovery got awarded the Nobel Prize in physics in 2010. Graphene was the first two dimensional material to be discovered, however, since then many other 2D materials have been found.

Graphene is composed of carbon atoms and it is only one atom thick. These carbon atoms are arranged in a hexagonal honeycomb lattice structure and exhibit sp^2 hybridisation. This hybridisation together with the atomic thickness (0.345 nm), give this unique material extraordinary properties, such as: extremely high electron and hole mobility values ($>10^5$ $cm^2V^{-1}s^{-1}$) even at room temperature [3]; very high thermal conductivity ($>$4,000 $Wm^{-1}K^{-1}$) at room temperature [4]; high transparency (2.3% of light absorbance over a wide range of the visible spectrum) [5] and high mechanical strength with a Young's modulus of 1 TPa [6].

Graphene is a semi metal and the electron hole symmetry is unique to graphene, at the Fermi level or Dirac point both electrons and holes co-exist and these charge carriers can have a very high speed 10^6 m/s. That is why the particles in graphene behave as massless (energy momentum dispersion relation is linear) and they are described using the Dirac equation. Graphene has enabled the experimental study of many high energy and condensed matter physics phenomena that had been predicted theoretically [7]. Even superconductivity has been observed in graphene when two layers of graphene were stacked with a certain angle [8], this could pave the way for exotic new physics still to be discovered.

Due to this unique linear energy momentum dispersion relation, electrons in graphene interact strongly with photons across a wide range of the spectrum, theoretically covering the frequency from ultraviolet to infrared, and extending into terahertz or even radio frequency. Such broadband responsivity can be effectively controlled by the Fermi level of graphene through either electrostatic gating or optical pumping and make it an ideal material for optoelectronics.

The term graphene covers a family of materials since depending on the method used to manufacture it, it will have different properties and in turn will be used in different applications. In this short article, I will focus on the graphene that will be applied in electronics, optoelectronics, photonics, sensors and biosensor applications.

It is now established that the technology to produce graphene for these applications is based on chemical vapour deposition (CVD). At close to 1,000 °C methane (or a carbon source) is introduced in the CVD reactor to form a continuous one atom thick graphene layer on top of a catalyst surface such as copper. This graphene is typically polycrystalline (it is formed by coalescing grains of different size) and can be produced at 200 mm wafer scale or even larger scales, although research is moving towards large single crystal graphene growth [9, 10]. After the growth step, graphene is transferred onto application substrates for integrating it into different components. This transfer process has many advantages but also certain disadvantages. Graphene can in principle be transferred onto any substrate, allowing the monolithic integration of graphene with other materials, thus reducing considerably manufacturing costs and paving the way for a relatively pain free industrial integration with silicon technology which is the backbone for the current semiconductor industry. As one of the main disadvantages, we should point out that this transfer process can induce defects and residues on the graphene layer that could lead to a reduction of the electronic properties. Graphene offers unprecedented advances in device performance that could pave the way for applications in photodetectors and modulators for image sensors, light detection and ranging (LiDAR) and data communications, radio-frequency devices, magnetic devices, Hall sensors, and all sorts of gas, chemical and biological sensors. These applications could be realized on an integrated CMOS (complementary metal oxide semiconductor) chip where silicon (Si) devices provide the driver, read-out and peripheral circuitry necessary to form a complete system [12, 13].

The road to commercialization of new advanced materials is very complex and requires many years (> 30 years) and large investments to generate substantial market impact. Graphene is no different in this perspective. Soon after the Nobel Prize was awarded to the discovery of graphene, the European Commission decided to invest 1 billion € over 10 years into the research of graphene and 2D materials. This Graphene Flagship [11] project started in 2013 and it has enabled building an ecosystem of diverse start-up companies within Europe that

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will form the basis for the future graphene industry. Some of these start-up companies have been created with the mission to exploit CVD graphene's potential in optoelectronics to enable next-level machine vision and safer driving cars in adverse weather conditions (Qurv Technologies, Emberion), in biomedical applications such as brain implants (InBrain Neuroelectronics) and data communications (CamGraPhIC, Black Semiconductor) just to mention a few.

Another interesting application worth mentioning for CVD graphene is that of biosensors. Graphene field effect transistors exhibit very high sensitivity and they could detect the presence of different biomolecules or bioreceptors (pathogens such as viruses, cancer or diverse disease biomarkers) at very low detection levels, revolutionising point of care applications. Graphene transistors present this extreme sensitivity due to the high surface to volume ratio (2D nature) and high sensitivity of the Fermi level to the presence of charged biomolecules near the surface, making them ideal for diagnostics [14, 15].

Graphene has demonstrated performance benefits over existing technologies at device level and an easy integration with silicon CMOS technology, this will pave the way for introducing graphene into future commercial products.

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Amaia graduated in polymer chemistry (MSc equivalent) from the University of the Basque Country (San Sebastian, Spain) and got a BSc (Hons.) degree in applied chemistry from the University of Strathclyde (Glasgow, UK). She received her Ph.D. degree in polymer chemistry from the University of Strathclyde in 2002. From 2001 to 2003, she was a Postdoctoral Research Fellow working in two European projects related to molecularly imprinted polymers. In 2004, she joined Ferring Pharmaceuticals (previously Controlled Therapeutics) where she worked in the research of new controlled drug delivery systems as a Senior Polymer Scientist. Her contribution led to the granting of three patents in novel biodegradable and biostable polymers for the controlled release of active compounds. In 2010, she became the Scientific Director of Graphenea. At Graphenea, she leads the research and development activities on graphene-based materials. Since joining Graphenea, she has so far filed for fifteen patents and published more than 86 publications in peer reviewed journals, including *Nature* and *Science*. She has been the Principal Investigator in 27 EU FP7/H2020 funded research projects, 24 collaborative projects including the Graphene Flagship and 3 people training network projects. In the Graphene Flagship, she is a member of the executive board and world package leader in the wafer scale integration workpackage as well as deputy leader in the wafer scale growth workpackage of the 2D-Experimental Pilot Line. In addition, she has also given more than 66 invited talks in international conferences. Her research interests include the synthesis, characterization, integration and future industrial applications of graphene.

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