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Graphene-Driven Revolutions in ICT and Beyond

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Abstract

This session described the FET Flagship Pilot on graphene and related two-dimensional materials. The flagship targets a revolution in information and communication technology, with impacts reaching into other areas of the society. The session featured four talks on the scientific and technological potential and open research challenges within the scope of the proposed flagship, industrial view on possibilities and challenges posed by graphene and related materials, and presentation on the implementation and structure of the flagship pilot.

Keywords: graphene; FET flagship

1. Graphene – the material with most superlatives

Graphene is single layer of carbon atoms arranged in a hexagonal lattice with a host of properties ideal for applications, see Fig. 1. One of the commonly occurring forms of carbon, graphite, is a stack of graphene layers, and has been used in a number of applications for hundreds of years, while monolayer graphene is still mainly confined to academia. The overall goal of the FET Flagship is to change this and harness the potential of graphene and related materials to revolutionize information and communication technology (ICT) and find new applications in other areas.

The current focus on graphene followed the ground-breaking experiments by A.K. Geim and K. Novoselov in 2004 that were acknowledged with the Nobel Prize in Physics in 2010 [1]. The huge interest in graphene is driven by the considerable and tantalizing potential that this material offers in conventional as well as radically new fields of ICT applications [2,3]. The electronic structure of graphene is very unusual – the electrons behave more like massless, relativistic particles than like the charge carriers in everyday electronics – which leads to higher device speeds and potential for electronics that is much faster than what we have today [4,5]. Graphene is almost transparent, absorbing only 2.3% of incident light [6], and very well suited for photovoltaic applications in optoelectronics, touch screens and solar cells [3]. Due to its ultimate thinness, graphene is very flexible, but at the same time graphene is the strongest material we know (about 300 stronger than steel with the same weight) [7] as well as the best conductor of heat [8], which enables not only flexible electronics but many applications outside ICT as, *e.g.*, strong lightweight composites. Some of graphene's superlative properties are given in Fig. 1.

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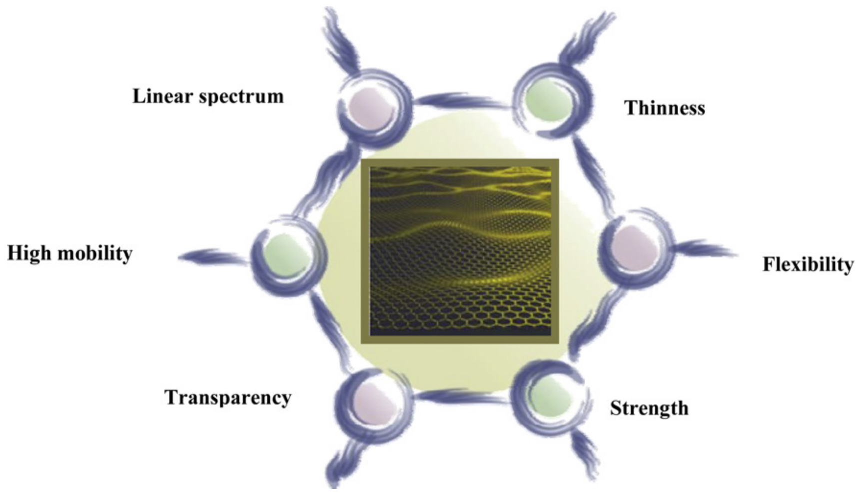

Figure 1. The unique properties of graphene can be utilized, either separately or in combination, to create novel applications such as flexible transparent electronics, conducting light and strong composites, and many more.

2. Research challenges technological potential associated with graphene and related materials

Since the start of the graphene revolution in 2004, numerous application concepts based on graphene have been demonstrated. In just a few years, high-frequency graphene transistors have reached performance that rivals that of the best semiconductor devices that have over sixty years research effort behind them; graphene electronics is still very much at its infancy and, extrapolating from recent progress, we expect graphene devices to break the 1 THz barrier in a matter of a few years [1–5].

In optoelectronics, the first graphene-based touch screen was recently demonstrated in a collaboration between SKK University and Samsung in Korea [9]. The touch screen application is expected to be one of the first to be commercialized, partly because the materials choice is quite limited: the screens must exhibit both electrical and optical functionalities, and very few materials conduct both electricity (like metals) and light (like window glass) [3,9]. Presently, touch screens rely on limited resources such as indium that is only available from a few sources, predominantly in China, while graphene is essentially an unlimited resource – carbon is one of the most common elements on Earth.

Graphene has been used to produce tunable lasers by exploiting the material's unusual electronic structure that guarantees a wide tunability range [3,10]. Graphene's properties also imply that the percentage of light absorbed decreases when the incoming light intensity increases, which can be exploited to fabricate very fast pulsed lasers that have great potential in optical communication [3,10].

However, despite the great progress in graphene science and technology during the past six years, the field is still very young and many challenges remain. Some of the challenges are fundamental: due to the unique structure of graphene, many of the possibilities it offers are still poorly understood, and their analysis requires highly sophisticated methods; to quote the Nobel Laureate Frank Wilczek from the Nobel Symposium on graphene held in Stockholm in May 2010, "*graphene is probably the only system where ideas from quantum field theory can lead to patentable innovations*". Among these fundamental challenges are a detailed understanding of the properties of finite graphene structures and graphene multilayers and the role that edges play in them, and magnetic properties of graphene and the possibility to use spin rather than charge as the information carrier.

Many of the major experimental challenges have to do with materials supply. There are several methods to produce graphene – on the laboratory scale, mechanical exfoliation ("Scotch tape method") works well but is difficult to scale-up, while the techniques of chemical exfoliation, chemical vapor deposition and sublimation of silicon carbide are in principle all upscalable and have different strengths and weaknesses [2,3]. Reliable and sufficiently large scale production of graphene with consistent quality is a crucial necessary step before graphene science can evolve into a graphene technology. More recently, a new class of graphene-like two-dimensional materials such as boron nitride and different metal chalcogenides have rapidly emerged as interesting supplements to the new materials palette for electronics [11]. At this point, these materials have not been thoroughly explored, and their full potential has not yet been assessed.

Different application areas have their own research challenges: for instance, the main hurdle that presently blocks the development of digital graphene electronics is the absence of an energy gap, which makes it very difficult to turn transistors off and limit leakage currents, while in analog electronics the related challenge is sufficient power amplification so that several graphene transistors can be connected in series [12]. These engineering challenges spawn new innovative solutions such as the BiSFET that relies on the gapless nature of graphene to create a new type of a transistor, and regard ambipolarity as a new asset rather than a deficiency [13], or the TFET, where the bangap-tunable nature of bilayer graphene can allow efficient switching with no need to manufacture ribbons [14]

3. Industrialization of graphene technology

Graphene research is an example of an emerging *translational nanotechnology* where discoveries in academia are rapidly transferred to applications. The concept translational nanotechnology is typically associated with biomedicine where it is a well-established link between basic research and clinical studies, but the principle can be applied to ICT as well: the most striking example is giant magnetoresistance that moved from an academic discovery to a dominant information storage technology in a matter of a few years. Similarly, *graphene has the potential to make a profound impact in ICT in the short and long term*: Integrating graphene components with silicon-based electronics, and gradually replacing silicon in some applications, allows not only substantial performance improvements but, more importantly, enables completely new applications.

Graphene represents a disruptive technology shift, and, as such, faces great uncertainties and challenges. While we are convinced that graphene will make a revolutionary impact in ICT, it is much harder to pinpoint which applications will emerge first. In consumer electronics the volumes are so large – for instance, 44 mobile telephones are sold worldwide every second – that a reliable supply of materials and components is an absolute requirement. A systems manufacturer will not develop a new technology unless it can be certain of the security of component supply, while the component producer depends similarly on the materials supply and on the demand from the systems manufacturer. A strength of a concentrated effort, such as the flagship, is that it can address all parts of the value chain and catalyze the technology shift that no single player or branch would dare to undertake on their own. The branching of the value chain – usage of same materials or components in different applications – is another strength of such approach. It allows the actors to pursue simultaneously both the low-hanging fruits, the first applications, and the larger strategic goal.

4. Implementation of the FET Flagship pilot

The newly launched pilot project prepares the road for the flagship initiative Graphene-Driven Revolutions in ICT and Beyond. The goal of the flagship is to secure Europe a key role in future ICTs based on graphene and related two-dimensional materials by providing a long term strategy of transferring knowledge and intellectual property to technological applications.

The pilot consortium involves nine academic and industrial partners in seven EU member states as depicted in Fig. 2. They carry the main responsibility for preparing the full flagship, and engaging the large European graphene community in the project. The large flagship consortium is still developing: presently over 300 research groups in over 21 European countries have expressed interest in joining the flagship. The prospective flagship partners represent a wide range of academic and industrial activities that come together to face the challenges of creating a major technology shift in ICT.

Despite being a very young research area, graphene research has already attracted substantial funding both from national and European sources. Combined, the EC and the ERC have funded graphene research with about 50 million Euros and the member states with slightly more, both through national programs and transnational collaborations such as the ESF Eurocores program EuroGraphene. These projects aim at advancing expertise in graphene devices, material characterization, or simulation, and at the development of functionalities such as composite materials and spintronic or photonic applications. However, the existing research effort is fragmentized in sub-critical small projects that end up duplicating each others' efforts, leading to reduced impacts and sub-optimal usage of national and EC resources.

The aim of the Flagship is to improve coordination and create synergy effects that are necessary to realize the impact that we are convinced graphene and related materials will have. We will bring together a focused, interdisciplinary

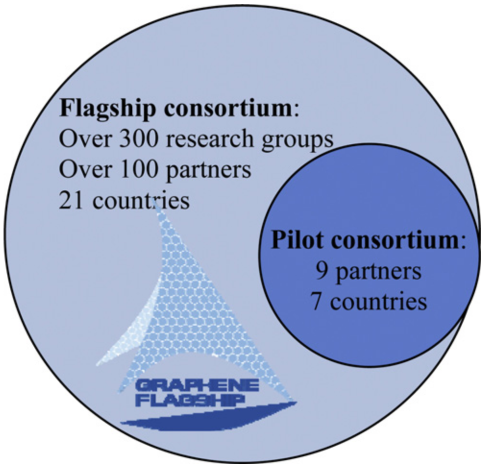

Figure 2. The Graphene-CA consortium.

European research community that aims at a radical technology shift in ICT. We will develop graphene electronics that can sustain ICT devices and technologies evolution beyond the limits achievable with silicon. By exploiting the unique electrical and optical properties of graphene, we will develop novel electronics systems with ultra-high speed of operation and electronic devices with transparent and flexible form factors. We will advance methods to produce cheap graphene materials which combine structural functions with embedded electronics, in an environmentally sustainable manner. The flagship initiative will extend beyond mainstream ICT to incorporate novel sensor applications and composite materials that take advantage of the extraordinary chemical, biological and mechanical properties of graphene.

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