GRAPHENE-CA

Coordination Action for Graphene-Driven Revolutions in ICT and Beyond

Coordination and support action

WP5 Outreach, Dissemination and Visibility

Deliverable 5.5 “Final Graphene Research Report”

Main Author(s):

Jari Kinaret, Vladimir Falko, Andrea Ferrari, Jani Kivioja, Tomas Löfwander, Daniel Neumaier, Konstantin Novoselov, Vincenzo Palermo, and Stephan Roche

Nature of deliverable: R

Dissemination level: PU

Due date of deliverable: M12

Actual submission date: M12

Project funded by the European Commission under grant agreement n°284558

LIST OF CONTRIBUTORS

Partner	Acronym	Laboratory Name	Name of the contact
1(coordinator)	CUT	Chalmers tekniska hoegskola	Jari Kinaret
2	UNIMAN	The University of Manchester	Andre Geim
3	UNILAN	Lancaster University	Vladimir Falko
4	UCAM _DENG	The Chancellor, Masters, and Scholars of the University of Cambridge	Andrea Ferrari
5	AMO	Gesellschaft fuer angewandte Mikro- und Optoelektronik mit beschraenkter Haftung AMO GmbH	Daniel Neumaier
6	ICN	Catalan institute of nanotechnology	Stephan Roche
7	CNR	Consiglio nazionale delle ricerche	Vincenzo Palermo
8	NOKIA	Nokia OYJ	Jani Kivioja
9	ESF	Fondation Européenne de la Science	Ana Helman

TABLE OF CONTENTS

Deliverable Summary

This deliverable gives a concise research roadmap for the flagship targeting graphene-based revolutions in ICT and beyond. The research program will not be able to address all the directions outlined in the comprehensive scientific and technological roadmap (Deliverable D3.1) but will initially focus on information and communication technology and a few areas closely linked to it. In the long term, the research agenda can be expanded depending on the level of resources available.

Deliverable

The scientific and technological roadmap for graphene and related two-dimensional materials has been developed during the pilot phase. It is based on inputs from the international academic and industrial research community collected through workshops, conferences, and reading of supplied and open-source documents. The vast amount of information has been collected in a 200 page document. This document forms the base for the Flagship work-plan for the ramp-up phase and beyond.

In constructing the roadmap and the work-plan it became increasingly clear that graphene has a realistic chance to become the next disruptive technology. For a disruptive technology, a roadmap will necessarily take a quite different form compared with a roadmap for an evolutionary technology, as for instance the ITRS for semiconductors. In order to become disruptive, a technology needs to offer not incremental, but dramatic, order of magnitude, improvements over the existing state of the art. The more universal the technology, the better chances it has for broad base success. Consider plastics, they are being used everywhere, from automotive industry and health to packaging and electronics. In terms of its properties graphene certainly has the potential. Many of its characteristics are unique and superior to those of other materials. More importantly, graphene offers an extensive combination of the “super”-properties. So, it is really a question of how many applications graphene can be used for and how pervasive it can become. Are the properties of graphene indeed so unique that they will overshadow inconveniences of the switching to a new technology, a process usually accompanied by large R&D and capital investments?

One of the reasons for the incredibly fast progress of graphene research is the multitude of very special properties observed in this 2D crystal: it possesses a number of characteristics which are unique or superior to those of other materials. Graphene holds the leading position in many parameters, including mechanical stiffness, strength and elasticity, electrical and thermal conductivity, it is optically active, chemically inert, impermeable to gases, and so on… These properties allow graphene to earn its place in current technologies as a replacement for other materials in existing applications. For instance, in principle, graphene with its high electrical and thermal conductivities could be used for interconnects in integrated circuits in place of copper and its high mechanical stiffness would allow its use for ultrastrong composite materials.

However, what makes this 2D crystal really special and what gives it a chance to become disruptive is that all these properties are combined in one material. The combination of transparency-conductivity- elasticity will find uses in flexible electronics; high mobility-ultimate thinness in efficient transistors for RF applications, transparency-impermeability-conductivity for transparent protective coatings and barrier films. The list of such combinations is endless and grows day by day. The most important combinations are probably those which have not been explored yet, as they would lead to new, revolutionary applications, which were unthinkable prior to the isolation of graphene in 2004.

Currently several record high characteristics have been achieved with graphene, with some reaching theoretically predicted limits: room temperature electron mobility of 2.5×10^5 $cm^2/V\cdot s$ (theoretical limit $\sim2\times10^5$ $cm^2/V\cdot s$); a Young modulus of 1TPa and intrinsic strength of 130GPa (very close to that obtained in theory); complete impermeability to any gases and so on. It has also been documented to have a record high thermal conductivity and can sustain extremely high densities of electric current (million times higher than copper).

Graphene's many superior properties demonstrate that it may indeed be a miracle material. However, some of these characteristics have been achieved only for the highest quality samples, mechanically exfoliated graphene, and for graphene deposited on special substrates like hexagonal boron nitride. As yet, equivalent characteristics have not been observed on graphene prepared by other techniques, though these methods are improving day by day. The area will receive even greater attention from industry when it will be proven that mass-produced graphene can have the same outstanding performance as the best samples obtained in research laboratories.

Below, in Figures 1 and 2, we summarize the graphene roadmap. The illustrations intend to show how we can exploit the unique graphene material platform for a wide range of applications in ICT, energy, materials, health and beyond, as well as the currently expected timelines for realizing competitive components and taking them to market.

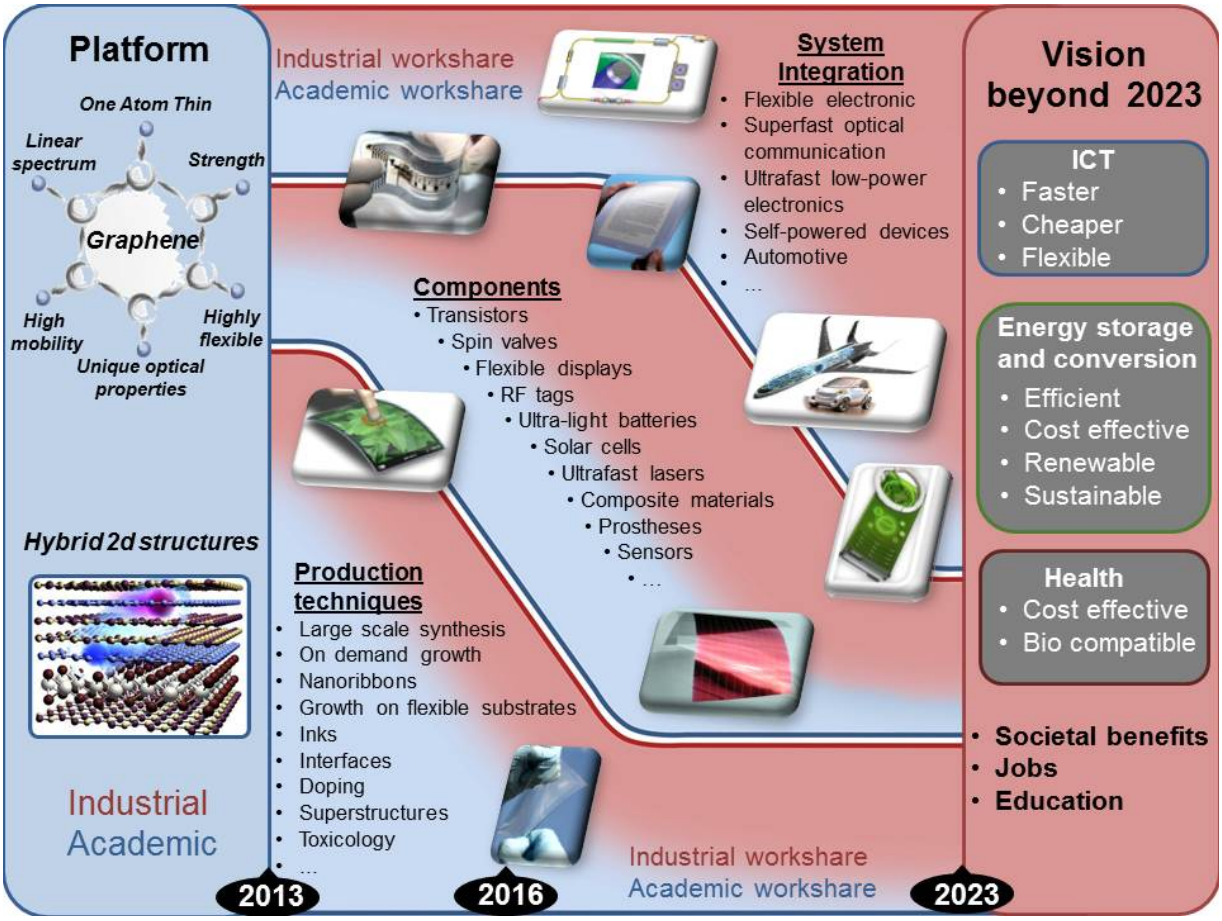

Figure 1*: Illustration of the European graphene roadmap for the period of 2013-2023 and beyond for exploitation of the unique graphene material platform for a wide range of applications in ICT, energy, materials and beyond.*

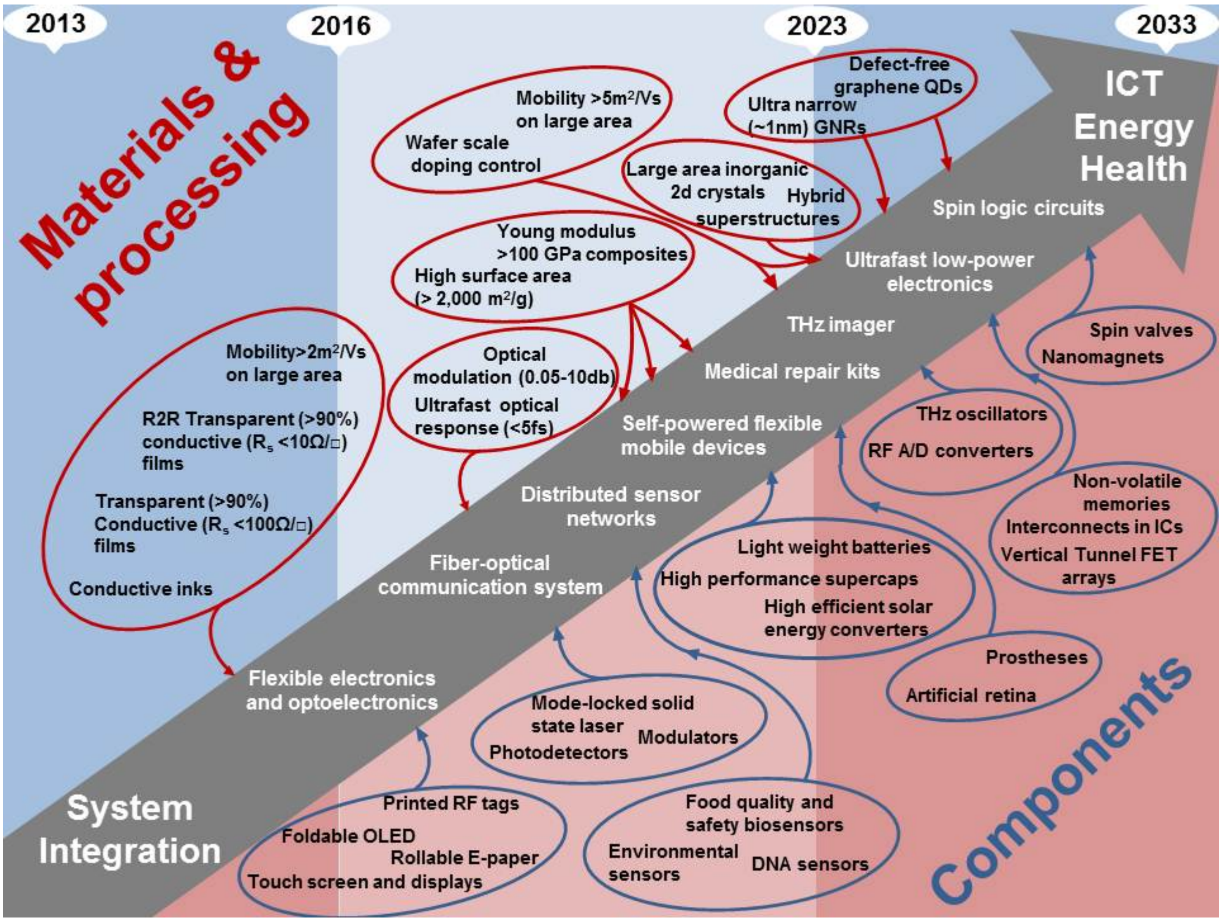

***Figure 2**: Illustration of the European graphene roadmap for the period of 2013-2023 and beyond for the development of materials and processes needed for a wide range of components and applications, and the vision to bring these components to market.*

The **research agenda** for the Flagship is based upon the graphene scientific and technological roadmap outlined above. The research agenda has been defined in broad terms with long-term goals for the full 10-year period and in more detail in the form work plans for the first 30-month period, where the latter period coincides with the foreseen CP-CSA project in the 7th framework programme. The research has been divided into 11 scientific work packages. These can be grouped into topics of increasing levels of maturity with regards to closeness to industrial applications, see Figure 3 below. Naturally, for the first 30-month period of the flagship, industry will be more involved in the work packages covering more mature topics while academia will be involved in more fundamental studies. As time progresses, we foresee that several topics will mature and move from tier 1 into tier 2 and further into tier 3, with increasing industrial participation.

The WPs are strongly interlinked, both in terms of facilities and methods used in the studies, researchers involved and practical outcomes. Inter-WP coordination is a priority of the flagship, and will be addressed specifically in flagship organization and internal dissemination procedures.

Graphene research is still undergoing explosive growth. As a result, we expect a number of unpredicted discoveries in the field, and will in the flagship continuously monitor and assess scientific developments that may open new technological opportunities. We expect that these opportunities will lead to new work packages once the evolving fields have reached sufficient scope and maturity, and the necessary funds become available.

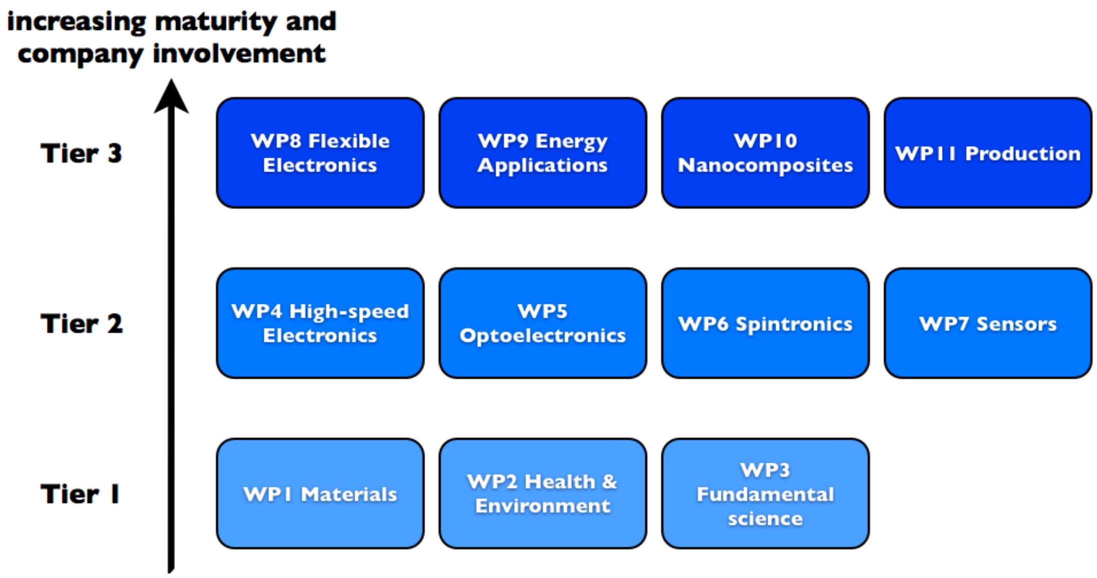

Figure 3: *The eleven scientific and technological work packages of the GRAPHENE flagship grouped according to increasing maturity and closeness to application. There are more partners from industry in the WPs covering more mature topics.*