



Maximising the Impact of Graphene Research in Science and Innovation (EuroGRAPHENE)

EuroGRAPHENE Review Panel

Final Consensus Report

The EuroGRAPHENE programme can be rated overall as highly successful. Seven Collaborative Research Projects (CRPs) were funded covering most of the current developments in the field: fabrication and characterization (including epitaxially grown graphene, nanoribbons, nanostructures, and interfaces with metals), electrical and optical measurements, and theoretical modelling. EuroGRAPHENE has created and helped in shaping a closely collaborating community of researchers in graphene science and technology in Europe. This community has grown about ten times since the start of the programme. In this respect, EuroGRAPHENE can be considered as an enabler of the Graphene Flagship programme funded by the European Commission in 2013.

1. Progress in the Collaborative Research Projects (CRPs)

All of the projects have been successfully completed and most of them have fully achieved their goals. In some cases (ENTS, GOSPEL, ELOGRAPH), goals were adapted with respect to the initial proposal and CRPs have seized opportunities to start new, previously unforeseen activities which have led to interesting discoveries.

Significant progress was achieved in terms of fabrication of **high quality graphene material**. The EPIGRAT CRP produced graphene by Chemical Vapour Deposition (CVD) on SiC substrates achieving electron mobility of up to $4000 \text{ cm}^2/(\text{Vs})$ for hydrogen intercalated graphene. The project GOSPEL focused on the fabrication of graphene-organic hybrids by combining small polyaromatic molecules or nano-graphenes. By using original bottom-up solution-based self-assembly approaches, the team produced exfoliated graphene and nanoribbons and achieved excellent results.

Innovative devices were demonstrated within the ENTS CRPs which explored graphene-based spintronics. Notable is the work on high-mobility suspended graphene samples and the observation of quantum Hall states in 50 nm wide nanoribbon devices.

Progress towards the fabrication of high-quality graphene transistors for electronics applications was rather marginal and has achieved less impact. Although at the beginning of this programme this seemed to be a promising direction, the potential of graphene-based

devices for digital and RF electronic applications has not been proven to be competitive with respect to silicon or other traditional semiconductor technologies.

Projects benefitted from the complimentary expertise of partners in different countries and from interactions between theory and experiments. The optimal size of a CRPs being somewhere between 4-5 partners, collaborations have been most effective and fruitful in such cases. Five out of seven CRPs listed at least five joint publications that include two or more nodes. Concerning this joint output, though not all CRPs present the same level of interactions, a significant improvement was achieved with respect to the mid-term stage. Indeed, during the second half, all the CRPs have shown a clear intention to promote and increase the collaborative aspect.

Overall, the total number of publications, around 300, is impressive. The number of high-end scientific papers is however low as only few Science and Nature publications emerged with partial support from this programme, despite the large number of high-end publications in this field globally. Some results appeared in highly ranked chemistry and physics journals (Nature Materials, Nature Chemistry, Journal of the American Chemical Society, etc.) Patenting activity has been limited (9 reported patents), which can, in part, be explained by the exploratory and fundamental focus of this programme.

EuroGRAPHENE has also had an impact on national programs, and has, for example, enabled Polish teams involved in EPIGRAT to create a base for the establishment of a national Graphene Engineering Programme in Poland which is currently running. Another example of good practice is the interaction between EuroGRAPHENE and the German Priority Program on graphene funded by the German Research Foundation (DFG).

Noteworthy is the creation of the spin-off company GraphenSiC by Linköping University (involved in GRAPHIC-RF).

2. Programme Integration

EuroGRAPHENE has brought together projects addressing different aspects of graphene research and it was not clear from the beginning which degree of interactions could be expected between the CRPs. Critical mass and different expertise congregating in the CRPs are however the strong point of this programme that has produced excellent results in many cases. Almost all CRPs have exploited this possibility for cross-fertilization, at least to some extent.

The two projects addressing growth of graphene on SiC (EPIGRAT and GRAPHIC-RF) had several common areas of interest and have organized a joint workshop (December 2012, Catania). Their collaboration will continue within the Graphene Flagship. Both projects have provided their samples to other CRPs for specific measurements (ENTS and SpinGraph, respectively).

ENTS, SpinGraph, CONGRAN have interacted and exchanged on the topics of spin filters (SpinGraph and ENTS joint meeting in September 2011 in Konstanz), quantum dots (ENTS and CONGRAN) and nanoflakes (SpinGraph and CONGRAN). Some of these collaborations resulted in joint cross-CRP publications.

3. Networking, Training and Dissemination

CRPs were very active in networking, training and dissemination. All of them were active in general graphene activities which took place in and outside Europe, and have used these opportunities for initiating collaborations and discussing results. Research visits were used for this purpose as well. Several dozens of PhD students and postdoctoral researchers were involved and trained within the program and a significant fraction of them (over 40) was funded directly through EuroGRAPHENE.

Dissemination occurred mainly using standard avenues for academic research – publications in scientific journals and talks at international conferences. Most of the CRPs also made important outreach efforts which included articles in national newspapers aimed at general audience, TV interviews and websites.

EuroGRAPHENE networking and dissemination activities extended far beyond the consortia of its CRPs. The conference Graphene Week, which was run by EuroGRAPHENE in 2012 and 2013, has become the main annual event of graphene community in Europe and will be the main official conference of the European Graphene Flagship programme in 2014.

4. General comments and other feedback

As pointed out by several CRPs, the limitation of the programme funding for a duration of 3 years hampers the full funding of PhDs in some countries where PhD programmes run for 4 years. The synchronization in the starting dates of different projects in the CRPs was also problematic as funding was not made available to all partners at the same time. Finally, the participation as full partners of researchers from other larger European countries (France, UK, Spain) would have been beneficial for the overall programme and its impact.