Graphene Nano-, Micro- and Macro-Photonics

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ABSTRACT

Graphene has already become an established medium for novel photonic devices and their applications. In some cases, *e.g.* the use of graphene as a non-linear medium with saturable absorption properties, it is experimentally convenient to use the readily available form that is known as graphene oxide. Moreover, technological and scientific developments that are advancing control of the properties of graphene for electronic applications are also likely to be applicable in photonic and optoelectronic devices.

This presentation will review research in the field of graphene photonics across the world. It will address, in particular, its application as a saturable absorber, *e.g.* for pulsed operation of fibre lasers – as well as work on materials characterisation of deposited graphene films. Patterning of graphene films with precision at the micro- and nano-scales will be an important requirement – and will be considered in this presentation.

Keywords: graphene, macro-photonics, micro-photonics, nano-photonics, non-linear optics.

1. INTRODUCTION

The extraordinary properties of the material graphene – a single atomic-layer thick arrangement of strongly bonded and regularly located carbon atoms – have commanded a massive upsurge of activity in the research domain. The award of the Nobel prize to Geim and Novoselov, in 2010, has highlighted the importance of this material – and it is likely that graphene will be used extensively in a wide variety of applications. It is already plausible that graphene will replace silicon for some purposes in electronics – and novel photonic and optoelectronic device capabilities have already been demonstrated. This presentation will be concerned with some of the basic properties of graphene that are relevant to the domains of photonics and optoelectronics, where there is considerable potential for its exploitation in a variety of existing and novel applications.

The title for this presentation has been chosen, in part, because it is our intention to highlight some of the already demonstrated photonic capabilities of graphene. Use is made of the word *macro-photonic* to convey the idea that graphene may be exploited photonically without the need to define the area coverage by the graphene layer(s) or impose any form of patterning on the graphene layer(s). Considerable scope exists for future research that can build on the development of technologies for area-controlled deposition and embedding of single or multiple layers of graphene – together with a number of possible alternative approaches to the patterning of graphene at the micrometre and nanometre size scales. The development of such patterning techniques will lead to the creation of domains of research activity that can legitimately be described as *graphene micro-photonics* or *graphene nano-photonics*.

2. LITERATURE REVIEW

The Nobel prize winners, Geim and Novoselov have reviewed, in reference [1], the early years of research that followed their discovery of a simple technique for its production. The excellence of its properties and the intellectual excitement associated with graphene are well captured in the review in Nature Photonics by Bonaccorso and co-workers [2]. This review highlights much of the potential of graphene as a photonic and optoelectronic material. An already extensive research literature provides more detail on the various important properties of graphene. As graphene oxide, it is for instance possible to generate useful levels of short wavelength visible light from graphene [3].

The fact that stable graphene layers can be produced by elevated temperature processing of single-crystal silicon carbide (SiC) [4] implies the additional possibility of using electrical current injection, in SiC-based LEDs, to pump graphene (oxide) photoluminescence, thereby effectively providing *electroluminescence*. The same paper and others in the literature describe the realisation of field-effect transistor-like device structures, with the crucial 'gate oxide' formed by the now well-established process of atomic layer deposition (ALD). Evidence for a significant quantum Hall effect in graphene [4] leads to the conclusion that device-useful magneto-optic effects should be obtainable, *e.g.* for controlled magneto-optical polarisation rotation, in very compact structures. Similar structures, as an 'add-on' to silicon photonic waveguides, could also provide either magneto-optic or enhanced electro-optic modulation effects.

Graphene can already be produced with the scale of large-area coverage that is required for exploitation as high-quality transparent (and flexible) conducting films in photovoltaic or display device applications [5]. The strong non-linear optical properties of graphene [6], such as saturable absorption for mode-locked laser

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operation, Q-switched laser operation and four-wave mixing (FWM) for controlled multi-mode laser operation, have been illustrated for the specific case of fibre lasers [7-10]. But the same non-linear optical properties should also be readily applicable in other types of laser, including semiconductor lasers. The creation and potential application of graphene nanostructures for terahertz photonics purposes are clearly illustrated by the work of Wright and co-workers [11].

The potential impact of graphene oxide for biological and biomedical research, *e.g.* for cellular imaging and for drug delivery, is well illustrated by the paper of Sun and co-workers [12]. This brief literature view could be extended considerably further, but what has been covered above clearly indicates the extensive scope and potential of graphene photonics.

3. GRAPHENE BASED PHOTONIC DEVICES AND TECHNOLOGY

There will be a sustained need to develop a base of technology and analysis that will ensure that graphene with the desired properties can be deposited or grown in the exact locations desired . The technology base will still include the classical 'scotch-tape' method for extracting graphene from graphite – as well as the form known as graphene oxide (as flakes in solution) - and the in-situ formation of graphene chloride from graphene layers that have been extracted from graphite. The controlled deposition or formation of single or multiple layers of graphene by processes such as chemical vapour deposition and the high temperature sublimation of silicon from silicon carbide will also be required. Tuning of the electronic bandgap of graphene from zero to typically quite small finite values (on the order of one tenth of an electron volt), by controlling the deposition process (or otherwise) is an important further technique that has already been developed. We have already mentioned the use of deposited graphene layers for enhancement of short-pulse generation in fibre-laser devices – and take the opportunity to cite our own recent work [13]. Simple deposition processes for graphene can be exploited, for instance, for the introduction of graphene into fibre-optical devices – notably in fibre-lasers, where including graphene as an ingredient in the laser cavity can lead to – or enhance – Q-switching and mode-locking behaviour. For either of these techniques for the creation of short – or very short – pulses of light, the graphene acts as a strongly saturable absorber.

The development of technologies for area-controlled deposition and embedding of single or multiple layers of graphene – together with a number of alternative approaches to patterning of graphene at the micrometre and nanometre size scale [14, 15] – forms an essential requirement for the creation of novel photonic devices based on graphene. Photonic devices that will require – or are likely to require – controlled definition of graphene layers include electro-optic modulators [16], switches and deflectors and, more generally, devices based on optical waveguides in which graphene is added into a planar (or other geometry/topology) waveguide structure to add functionality. The word 'electro-optic' should be understood to mean, in general, devices in which the optical behaviour and properties are controlled by changes in electric field strength, potential bias, current flow or charge state. The specific electronic properties of single- and multi-layer assemblies of graphene – which can, for example, be radically different from the electronic properties of bulk semiconductors – will need to be understood and incorporated into the design of the electrooptic devices based on graphene.

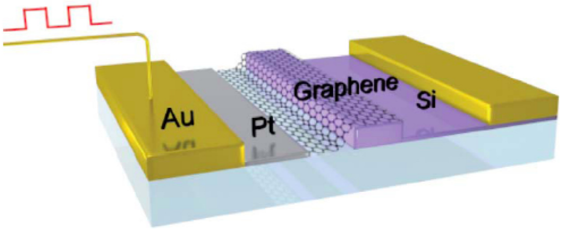

Figure 1(a). Schematic general representation of a graphene-based electrooptic waveguide modulator device.

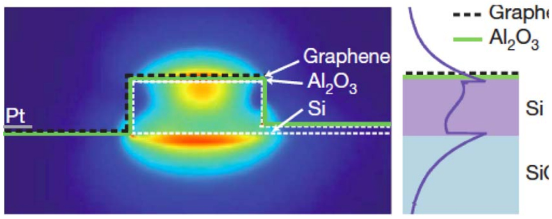

Figure 1(b). Cross-section of the graphene-silicon electrooptic modulator device.

Figure 1 shows schematically an example of a graphene electrooptic device based on a silicon ridge waveguide [16]. The patterned graphene layer is separated electrically from the silicon waveguide by a thin insulating layer of aluminium oxide. Electroabsorption type modulation is obtained by application of an electric potential between the two gold electrodes, extended by the Pt layer that is located below one gold electrode and above part of the graphene layer. The physical effect that is exploited in this device is tuning of the position of the Fermi level of the graphene.

Figure 2(a) shows the 'static' experimental performance of the device. Operating voltages on the order of 4 V produce changes in transmission equivalent to approximately 10 dB for a device length of 100 µm. Figure 2(b) shows that the device modulation bandwidth is on the order of 1 GHz, limited by the RC time constant of the structure.

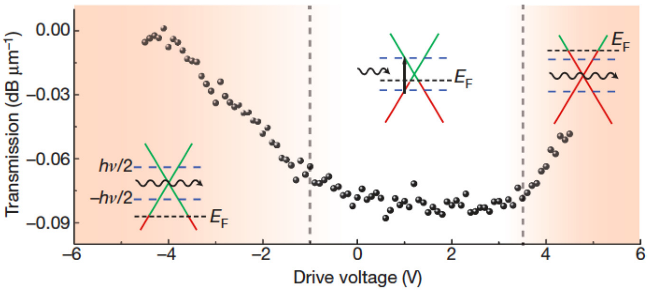

Figure 2(a). Experimental device transmission versus applied voltage.

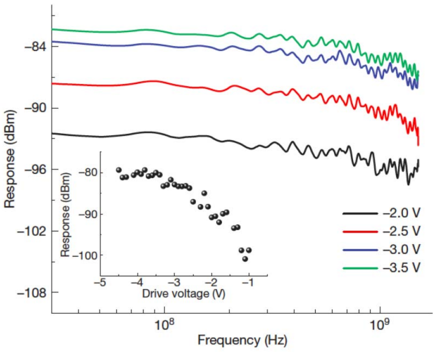

Figure 2(b). Modulation response of the device.

There is also scope for the development of a range of what may be described, in a broad sense, as *doping* techniques. The use of doping processes will make it possible to modify, down to regions defined by a few atomic lattice periods, the electrical and optical properties of graphene layers, in various ways. Doping with appropriate 'ingredients' will enable control and modification of the optical transparency, the electrical conductivity and the type of conductivity. Doping will enable localised and aggregate changes in the electrical and optical properties of graphene that are relevant for photonic device applications, including various forms of photonic sensors and, in particular, biosensors. It is already clear that the combination, with the appropriate preparation processes, of high transparency (*i.e.* low optical absorption) and large electrical conductivity could be useful for both light-emitting devices and light-detecting devices. Predictions of a high value (~3) for the real part and a significant imaginary part for the refractive index of graphene [17] are particularly relevant to the incorporation of graphene into planar optical waveguide device structures, as well as possible insertion of graphene into the voids of photonic crystal fibres.

4. CONCLUSIONS

Fundamental understanding of the properties of graphene will be vital for prediction of the behaviour that can be exploited in experimental device structures. Experimental work is required on graphene formation, deposition and patterning processes – and it should be guided, in substantial measure, by theoretical analysis and numerical computation. The exact nature and properties of the edge-region of patterned graphene structures can vary substantially, depending on the way in which the pattern is generated. The reliable exploitation of patterned graphene in photonics applications will require both a large volume of experimental research and a corresponding body of theoretical work.

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