GRAPHENE FOR NANO-ELECTRO-MECHANICAL SYSTEMS

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***Abstract* — We discuss the prospect of graphene as a material for nano-electro-mechanical-systems. A comparison between SOI silicon and graphene fabrication technologies is presented as well new ideas for integrated new electromechanical devices combining novel electronic and mechanical properties of graphene. We also present new results of graphene nanostructuring with the helium ion microscope as an emerging technology for fabrication of electromechanical devices..**

***Keywords :* Graphene, Helium ion microscope, NEMS, MEMS**

I - Introduction

Recent years have seen a growing interest in graphene material. This material,, has attracted such interest thanks to its remarkable electrical properties. Graphene is only one to a few atomic layers thick and yet it is the strongest known material. Electrons in graphene exhibit very high mobility, with zero effective mass and mean free path of a few micrometers, even at room temperature [1]. It can sustain current densities five order of magnitude larger than ordinary metals, and exhibits very large thermal conductivity [2] and strength [3]. It also exhibits large negative thermal expansion coefficient which is up to 10 times that of graphite [4].

To date, only electronic properties of graphene are widely explored. These studies revealed novel electronic properties by fabricating structures such as p-n junctions [5], nano-ribbons [6], quantum point contact [7], single electron transistors [8], and quantum dots [9],etc. Research progress in this direction will make graphene a "neo-silicon" material of choice for future electronic components.

Other graphene attributes such as mechanical or thermal properties have not been so widely investigated. A few studies reported values of room-temperature thermal conductivity of ~ 5000 Wm^{-1}K^{-1} [2] and breaking strength of 42 N/m [3]. Values of Young's modulus were reported to be close to 1 TPa [3]. Studies also showed that graphene is a very flexible material and impermeable to gases making it ideal for many applications in life science [10].

Despite the significant amount of work on graphene electronic devices such as the field effect transistor, its use in sensors, actuators or micro and nano-electro-mechanical systems (MEMS/NEMS) in general, is as yet little explored. Bunch et al. have demonstrated graphene electromechanical resonators exhibiting charge sensitivities down to 8×10^{-4} electrons per root Hz at room temperature, highlighting the potential of graphene for NEMS applications [11]. By combining graphene's electronic and mechanical properties, monolithic sensors can be developed with superior sensitivity.

Despite the fact that silicon technology remains dominant in NEMS and MEMS areas, the growing interest in graphene is slowly building up, which could pave the way to new devices. For example mono or bilayer graphene has been tipped as a new channel material of choice for transistors to compete with the latest silicon innovations such as the development of extremely thin silicon SOI material with only a few atomic layers of silicon [12]. In spite of the enhanced carrier mobility of ultrathin SOI MOSFET (i.e. in channel thicknesses of around 3~4 nm, the mobility enhancement is due to subband energy modulation), mono and bilayer graphene show even higher values of the carries mobility, which can exceed 15,000 cm^2 V^{-1} s^{-1} [13], enabling fast electronics as demonstrated by IBM on their 100 GHz graphene FET [14].

From the mechanical point of view, graphene is one of the strongest materials ever discovered with a breaking strength of over 200 times that of steel [3]. It is thus logical to consider thick graphene[*] as a material for micro and nano mechanical devices, e.g. accelerometers, pressure sensors, membranes, resonators, etc. Recent progress in epitaxial growth of graphene led to the development of very high quality "thick graphene" made of a stack of single atomic layers [15], on a wafer scale, by Fujitsu Ltd. The mechanical properties of this high quality material remain to be investigated. This development will open possibilities for the development of new technologies based on thick graphene.

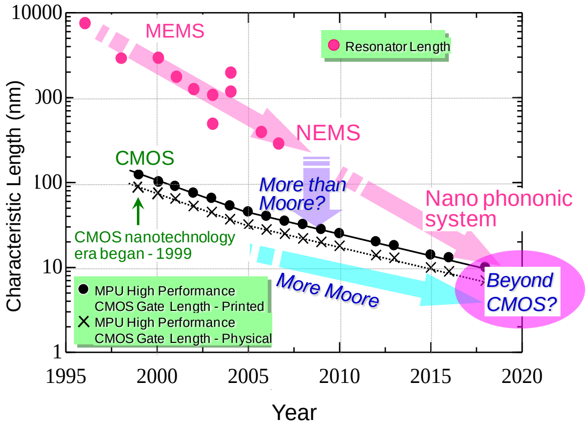

Figure 1: Graphic representation of NEMS down-scaling trend.

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[*] Here we mean by "thick graphene" more than 3 atomic layers.

Material	Young Modulus TPa	Mobility cm^2V^{-1} $s^1(300^oK)$	Thermal conductivity $Wm^{-1}K^{-1}$	Poisson ratio
Graphene(mono-bilayer)	~ 1 [3]	>15000 [1]	~ 5000 [2]	0.165 [3]
silicon	~0.13[16]	≤1400[17]	~1500[18]	~0.28 [18]

Table 1: Materials properties of graphene and bulk silicon.

One can envisage a hybrid thin-thick graphene structures, using thin graphene (less than 4 atomic monolayers) for electronics and thick graphene for mechanical structures.

In figure 1 we show the silicon NEMS downscaling trend. Graphene NEMS (GNEMS) would join the trend later on during the -SiNEMS era. One foresees two possibilities; graphene for more Moore or graphene for more than Moore by combining GNEMS with graphene transistor.

II – Material properties and technology

NEMS technology has recently emerged as a viable route towards the production of novel, high speed devices, offering high density integration and devices with low power consumption. These devices are a result of a hybrid approach, combining NEMS with conventional CMOS electronics ("More than Moore"). Such hybrid devices find applications in logic [19], non-volatile memory [20] and ultrasensitive mass detectors [21]. An example of a non-volatile memory NEMS device is the suspended gate field effect transistor (SGFET) [22], consisting of a moveable beam (the gate) and a MOS channel. This device exhibits a higher switching speed compared to the conventional silicon MOSFET. The remarkable mechanical and electronic properties of graphene, suggest that it is possible to develop such hybrid structures using this material instead of silicon. However, to manufacture reliable graphene NEMS/MEMS, will require the maturity of graphene growth technologies on the wafer scale and low cost production. Such technologies are still in their infancy despite recent development by research groups and industries [15].

Thin body SOI has been the material of choice to develop integrated NEMS. in which mechanical as well as electronic structures can be fabricated, allowing low power and high frequency operation . The technologies used here are mature MEMS and IC manufacturing processes combining material deposition, dry and wet etching technologies, etc. To be able to manufacture (GNEMS) devices, various technologies need to be developed including wet and dry etching of graphene as well as selectivity with regard to various mask materials e.g. photoresist, silicon oxide, silicon nitride, etc.

It is useful to draw a comparison between silicon and graphene although bulk properties of silicon may differ from thin SOI silicon, but good approximations can be made with the available data. Table 1 shows different material parameters for graphene and bulk silicon.

One notices for instance, graphene's higher value of the Young modulus compared to that of silicon. This higher value will allow the fabrication of high frequency resonators from graphene. For example a nano-beam made of multilayer graphene would have a resonant frequency roughly three times larger than a beam of silicon having the same dimensions based on the values in Table 1. The remarkably higher thermal conductivity and high current carrying capacity will allow the use of graphene as interconnects in electronic ‘chips’ as a replacement for copper. The high values of graphene mobility will provide a good material to be used as a channel in MOSFETs.

Thin body SOI production is performed by successive thermal dry oxidation and wet chemical etching of an initial SOI wafer, until the desired silicon thickness is reached. This method has achieved thicknesses of three to four atomic layers [12]. To produce graphene, three methods are used in general: mechanical exfoliation of graphite [25], epitaxial growth on SiC [23] and chemical vapor deposition (CVD) onto metallic surfaces [15]. Thin graphitic layers can be epitaxially grown on 4H-SiC substrate, by the thermal decomposition of either Si-or C-terminated surface [23]. Epitaxial graphene on silicon carbide can be patterned using standard microelectronics processes allowing large integrated electronics on SiC [24]. Exfoliation of graphene sheets remains the only method that produces high quality graphene flakes which are obtained by micromechanical cleavage of bulk graphite [25].

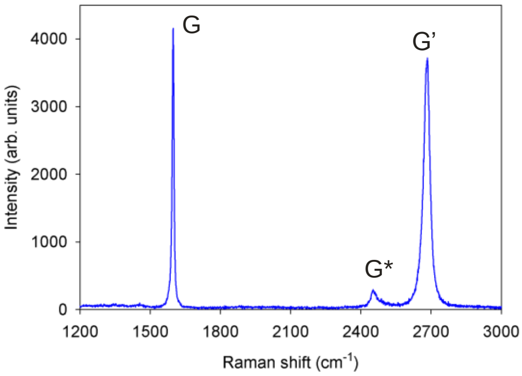

Figure 2: Raman spectra taking on a monolayer graphene showing the G-band peak position at 1600 cm^{-1} and G' band of monolayer graphene at. 2685 cm^{-1}

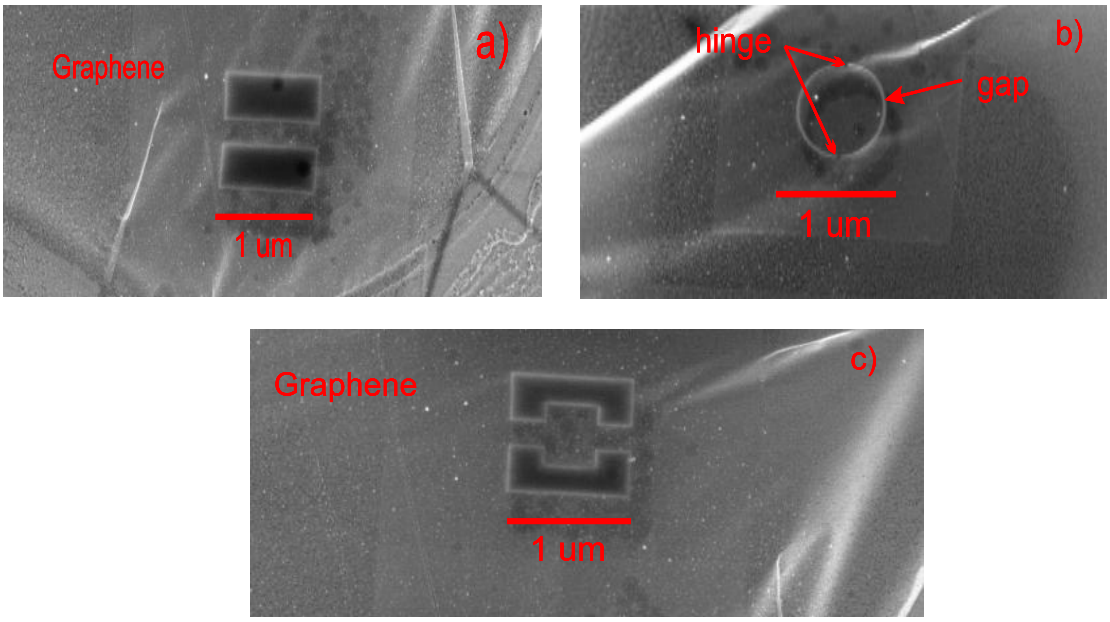

Figure 3. Helium ion patterning of nanostructures on bilayer graphene: a) a nano-beam having a length of 1 um, a width of 200 nm; b) a wine glass disk graphene resonator and C) a resonant torque structure.

III – Graphene nano-patterning with the helium ion microscope

Here we present results on nano-patterning of exfoliated graphene using a new tool: the helium ion microscope (HIM)[26]. This tool is a new imaging technology based on a scanning helium ion beam instead of an electron beam. The HIM provides a helium ion probe with a size smaller than 0.7 nm which can be scanned across a sample in a pre-defined pattern to selectively remove areas by direct sputtering of the graphene material [27]. The He ion beam also exhibits low proximity effect compared to Ebeam lithography. This allows a highly localized writing on materials as we will show here. Our tool integrates pattern generator software which offers a user interface allowing the exposure parameters to be adjusted such as the dose, dwell time, writing resolution, etc., as well as the definition of the pattern to be written, either as predefined geometries or a bitmap file. Here, graphene samples are obtained using the exfoliation procedure resulting in monolayer, bilayer and multilayer graphene. The number of atomic layers was determined by Raman spectroscopy. Figure 1 shows an example of a Raman spectrum taking on a monolayer region of the flakes. The characteristic G (~ 1600 cm^{-1}) and G'(~2685 cm^{-1}) peaks are clearly visible and the absence of the D peak at 1345 cm^{-1}, the presence of which is associated with disorder in sp2-hybridized carbon systems, indicates the high quality, defect-free nature of the flake [28].

The sample was loaded into the HIM and the writing was performed under a vacuum of ~5 x 10^{-7} Torr. Prior to writing, the HIM chamber was cleaned overnight by an embedded plasma system to avoid contamination of the sample during the writing operation.

Figure 2-a, 2-b and 2-c show a nano-beam, a wine glass disk resonator nanostructure and a resonant torque nanostructure respectively. These structures were patterned with a resolution of 1 nm/pixel. After patterning, the structures were released buy vapor HF etching of the underlying oxide (300 nm thick). One notices the fine edges of these structures thanks to the very small spot of the beam. This level of accuracy is very hard to achieve with e-beam lithography which is widely used for graphene patterning. The nano-beam has a length of 1 um and the width of about 200 nm, while the resonator has a diameter of 1 um and a gap of less than 30 nm. Gaps less than 10 nm can be achieved. These structures are very familiar MEMS and NEMS structures which are used as sensors or resonators. For instance, as the Young modulus of graphene is close to 1 TPa, very high-frequency resonators (Lame' mode resonators) can be fabricated. The graphene patterning with HIM can achieve a variety of other devices with extremely small dimensions. We are actively working on the functionalisation of these structures by patterning metal electrodes on the structures to allow sensing applications using an integrated gas injection system (GIS) which provides a local metal deposition. This system is used in combination with the He beam to deposit thin metal films and metallic nano-structures by means of chemical vapor deposition (CVD). By taking advantage of graphene enhanced electronic properties, it is possible to develop monolithic schemes for graphene devices which combine movable structures, such as those fabricated here, and a graphene field effect transistor (GFET). Sensing can be achieved through capacitive coupling between the channel of the GFET and the moving graphene structure. One can also take advantage of the fact that

graphene is easily gated (i.e. the resistivity is modulated by the back gate voltage) and in combination of mechanical structures to develop tunable grapheme sensors and actuators.

IV – Conclusion

We have shown that graphene can be used as a material for nano-electro-mechanical-systems. Owing its extraordinary electrical and mechanical properties, enhanced performance devices can be achieved. However, real progress can only be made with the availability of graphene on the wafer scale and the development of new fabrication technologies for graphene. This will allow design and patterning using standard MEMS/NEMS and IC technologies. We have demonstrated the feasibility of graphene nano-patterning using the helium ion microscope. Very fine structures can be obtained thanks to the small beam size and the milling capabilities of the helium ion beam. Future work will focus of the functionalisation of such devices by electrodes deposition on the structures using a gas injection system embedded in the helium ion microscope.

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