A garphene bilayer channel transistor with a very high Ion/Ioff ratio, graphene single electron devices and graphene nano-mechanical structures for NEMS

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Introduction

Graphene has ignited tremendous interest since its discovery in 2004[1]. The observation of field effect in graphene has particularly attracted the attention of the electron devices community resulting in a large volume of work on graphene field effect transistors (GFET). Indeed graphene is one of the possible materials for the neo silicon era, according to the 2009 International Technology Roadmap for Semiconductors . One outstanding property of graphene is its high carrier mobility at room temperature. In exfoliated supported graphene, mobility as high as 70000 $cm^2 V^{-1} s^{-1}$ has been reported [2]. However, large area monolayer or bilayer graphene suffers from the absence of a band gap, which results in poor switching capability of GFETs. Despite the intense work to improve the Ion/off ratio, only values less than 400 were achieved. The largest band gap values were achieved with dual gated GFETs which are controlled using a top gate and a back gate. Values of I_{on}/I_{off} ratios of around 400 have been demonstrated [3].

Single electron transport in graphene quantum dots is still not fully understood despite efforts by several researchers investigating graphene single electron transistor (GSET)[4]. Our group is engaged in the development of such devices with the aim of building tunable, well controlled GFETs.

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 in general, is far from being explored. Owing its extraordinary electronic, mechanical and thermal properties, extremely enhanced micro and nanosystems can be built, that surpass their silicon counterpart. By combining graphene's electronic and mechanical properties, monolithic sensors can be developed with superior sensitivity.

Device fabrication

U-shaped Graphene bilayer channel transistor

All fabrication was carried out using a dual focused ion beam/scanning electron microscope system (Zeiss NVision40 FIB/FEGSEM) equipped with a gas injection system (GIS). A bilayer graphene flake on a 300 nm layer of SiO_2 on Si (sample purchased from Graphene Industries Ltd.) was used. Electron beam- induced tungsten deposition was then used to deposit thin protective layers across the edges of the graphene flake in areas where contact formation would take place. Square contact pads, 50 µm x 50 µm, and smaller rectangular strips to connect the pads to the graphene were deposited using gallium ion beam-induced tungsten deposition in the same system. The ion beam current was adjusted in the range 0.08 – 13 nA for maximum deposition rate depending on the areas over which the deposition was occurring. The Gallium ion beam was then used to mill the contact wires and graphene flake to form and isolate the device. A beam current of 150 pA was used when milling the tungsten and 80 pA when milling the graphene. The samples were annealed at 400 °C for 10 minutes prior to their characterisation.

Graphene single electron devices

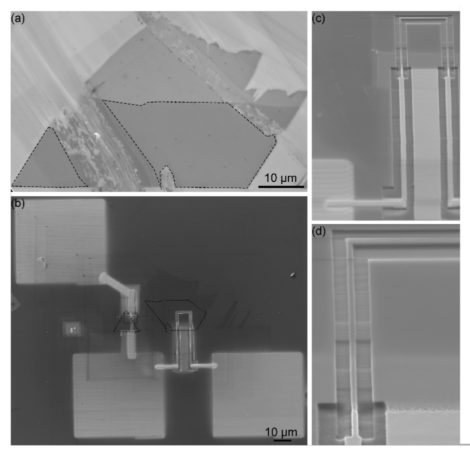
A variety of quantum structures were fabricated using mono and bilayer graphene. The devices were fabricated in two steps: coarse patterning using e-beam lithography and fine patterning using the helium ion microscope. The coarse patterning is used to define contact leads and to isolate an area of 1 um x 1 um where helium ion direct write will take place to define the quantum dots. For the fine patterning we used the helium ion microscope (HIM) which 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 0.5 nm in combination with smaller proximity effect compared to ebeam lithography. This allows a much localized writing on materials as we will show here. Our tool integrates a 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 an uploaded bitmap file. The helium ion beam can carve extremely sharp structures in graphene thanks to it small spot size.

Graphene nano-mechanical devices

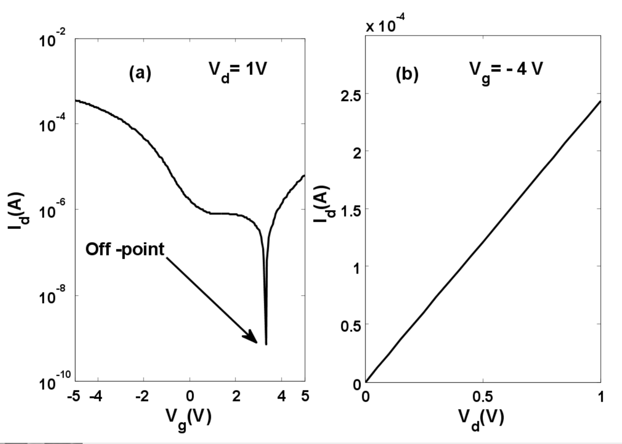
Graphene nano-mechanical structures are fabricated with the helium ion microscope. The sample was loaded into the HIM and the writing was performed under a vaccum of 5 x 10^{-7} Torr. Prior to writing, the HIM chamber was cleaned overnight by an embedded plasma system to avoid contamination of the sample during the writing operation.

Results

U-shaped bilyer graphene transistor[5]



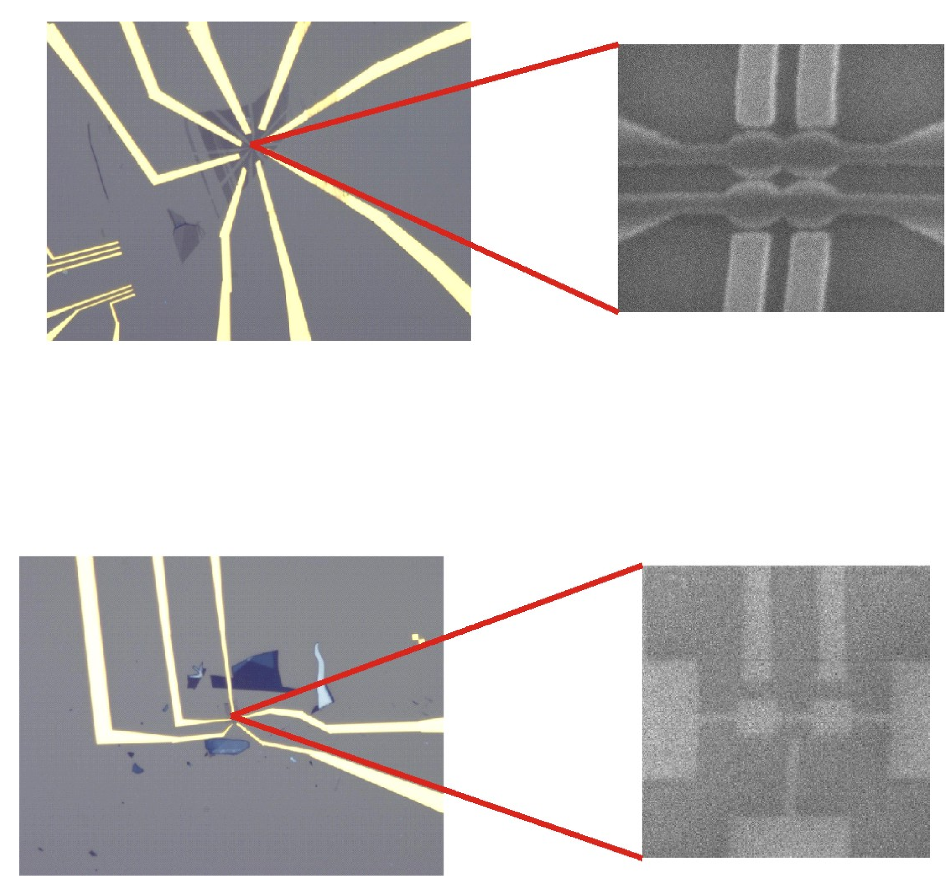
Scanning electron micrographs showing: (a) The graphene flake. The dashed outline marks the areas suitable for formation of the devices; (b) The device and the contact pads, with the dashed outline marking the same area as in (a); (c) the graphene U-shaped device with tungsten contact wires and pads, (d) detail of the graphene U-shaped device.



The I_d-Vg characteristic at V_d = 1 V, showing the off-point of the U-shaped transistor (a), and the Id-Vd characteristic at Vg =-4 V (b).

The results above shows the drain current Id as a function of the back gate voltage, Vg , for a drain voltage of 1V. Figure 2-b shows the drain current as a function of the drain voltage V_d for Vg =4 V. The Id-Vg characteristic shows a marked dip around Vg=V_{off}= 3V, where the GFET channel is switched off. This characteristic is dissimilar to the usual large area graphene I_d-Vg characteristic which shows a smooth evolution of the drain current towards the Dirac point. The I_{on}/I_{off} derived here is around 4.8×10^5 (taking I_d=3.5×10^{-4} A at Vg=-5 V, and I_d=7.25×10^{-10} A at Vg=3.3 V), larger by 3 orders of magnitude than the highest I_{on}/I_{off} obtained in dual gated GFET.

Graphene single electron devices[6]

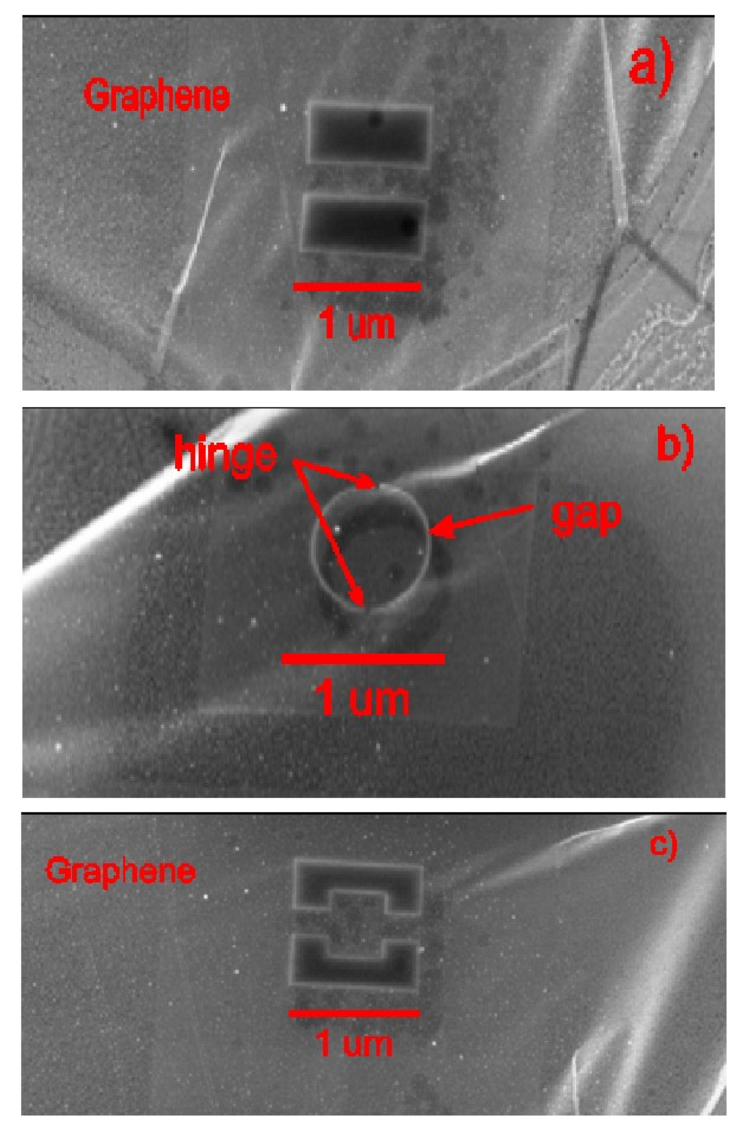


Arrays of fabricated graphene quantum dots. the pictures shows a zoom-in the central area where the helium ion direct write takes place. The contact leads were fabricated using a lift-off process after ebeam exposure. The quantum dots were defined by the helium ion microscope.

We have fabricated two kinds of single electron devices: four coupled quantum dots and two coupled quantum dots fabricated with the helium ion microscope. The four coupled quantum dots can be used as a quantum cellular automaton, allowing a logic operation. The characterisation of these devices is in progress. Notice the fine edges and the squared shape of the double quantum dot. This kind of sharpness is difficult to achieve with ebeam lithography.

Graphene for nano-electromechanical systems[7]

We have fabricated three type of nanostructures: 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 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. Gap values less than 10 nm can be achieved.



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.

Conclusions

In conclusion, we have fabricated a graphene field effect transistor having a U-shape geometry using FIB technology. The achieved Ion/Ioff exceeds 10^5. We have also developed single electron devices using a two step process: coarse structures with e-beam lithography while the very fine structures were fabricated with a helium ion microscope. We have shown that graphene can be used as a material for nano-electro-mechanical-systems. Owing its extraordinary electrical and mechanical properties, enhanced devices can be achieved. Future work will focus of the functionalisation of such devices by electrodes deposition on the structures to characterise their electro-mechanical properties.

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