Optical Materials 72 (2017) 496–500

Contents lists available at ScienceDirect

Optical Materials

journal homepage: www.elsevier.com/locate/optmat

Influence of electron beam and ultraviolet irradiations on graphene field effect transistors

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ARTICLE INFO

Article history:
Received 17 April 2017
Received in revised form
19 June 2017
Accepted 21 June 2017

Keywords:
Graphene
Chemical vapor deposition
Field effect transistor
Electron beam irradiations
Ultraviolet irradiations

ABSTRACT

Electrical transport properties of graphene can be modulated by different controlled doping methods in order to make it useful for practical applications. Here we report a comparative study of electron-beam (e-beam) irradiated and ultraviolet (UV) irradiated graphene field effect transistors (FETs) for different doses and exposure times. We observed red shift in Raman spectra of graphene under e-beam irradiation which represents n-type doping while a divergent trend has been identified for UV irradiations which signify p-type doping. These results are further confirmed by the electrical transport measurements where the Dirac point shifts towards negative backgate voltage (i.e. n-type doping) upon e-beam exposure and shifted towards positive backgate voltage (i.e. p-type doping) under ultraviolet irradiation. Our approach reveals the dual characteristics of graphene FETs under these irradiation environments.
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1. Introduction

Emerging graphene-based electronic, photonic and spintronic devices have found interesting applications in photodetectors, solar cells, gas sensors, field effect transistors, heterojunctions, flame detection, environmental monitoring, magnetic sensors, chemical and biological analysis [1–20]. Graphene's outstanding character can be optimized by tuning the doping concentration to make it useful for various applications. Various methods can be used to modify the electrical properties of graphene such as hydrogenation [21], interstitial doping [22] and chemical functionalization [23]. Apart from the above mention methods, the charge carrier density of graphene can be modulated by ultraviolet light and e-beam irradiations [24,25]. I. Childres and A.A balandin et al. demonstrated the influence of e-beam irradiations on electrical properties of graphene and its degree of degradation. They also concluded that e-beam induces n-type doping in graphene [26,27]. M.Z. Iqbal et al. also reported that e-beam irradiations induces defects in graphene and transform the crystalline structure to amorphous at higher e-beam doses [28,29]. Similarly the influence of UV irradiations on CVD graphene is reported by Zhengtang et al. and M.Z. Iqbal et al. have investigated that UV irradiations modify the doping level (i.e. p-doping) in CVD grown graphene with minimal change in charge carrier mobility [24,30–33]. Such studies put forward a new strategy to fabricate radiation hard devices which remains stable at extreme conditions.

In this work, we study comparatively the influence of UV and e-beam irradiations on the graphene structural and electrical properties. Raman spectroscopy is utilized to study the modulation of structural properties and the doping level of graphene. Furthermore, we have also investigated the doping tunability for both UV light and electron beam irradiations by electrical transport measurements. Our findings enable us to study the effect of different irradiation sources on the electrical properties of graphene thus paving a way to fabricate graphene based homo junctions that could be beneficial for future electronic and photonic applications of graphene.

2. Experimental

Large area single layer graphene samples were synthesized on 25 μm thick Cu foil from Alfa Aesar (99.8% pure) using chemical vapor deposition (CVD). A copper foil were introduced into a thermal CVD furnace. The pressure of furnace was kept at ~10^{-4} Torr, and heated upto 1010 °C with inflow of H_2 gas (~10^{-2} Torr). After the temperature reaches to 1010 °C both CH_4:H_2

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http://dx.doi.org/10.1016/j.optmat.2017.06.039
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(20 standard cubic centimeters per minute (sccm): H_2 (5 sccm)) were introduced into the furnace for 8 min for graphene synthesis. After growth, the graphene sample was cooled to room temperature. The CVD grown graphene film on Cu foil was transferred on the silicon substrate (p-doped) after spin coating (850 rpm: 2500 rpm for 10 s: 60 s) a thin layer of polymethylmethacrylate (PMMA). Then, the bottom Cu foil was etched by dipping it in solution of ammonium persulphate (APS, $(NH_4)_2S_2O_8$). The deionized water was used to wash the PMMA layer. Then the CVD graphene with top PMMA coating was transferred onto p-doped silicon substrate having 300 nm thick SiO_2 top layer. Graphene/SiO_2/Si was kept in acetone for 24 h to dissolve completely the PMMA coating. Then, methanol was used to rinse and dried with nitrogen gas. The metallic electrodes patterning were made after removing PMMA layer. Initially the patterning on graphene was done by photolithography and after developing the metallic electrodes (Cr/Au: 5 nm/30 nm)) were made using thermal evaporation system. In the next step Hall bar pattern is made by simultaneous process of photolithography using mask aligner and oxygen plasma treatment. Then the inner patterning were made by e-beam lithography and inner electrodes (Cr/Au: 5 nm/55 nm) were deposited using thermal evaporation system. The 220 nm wavelength ultraviolet light (UV) of 11 $mWcm^{-2}$ average intensity was exposed for doping of graphene. The Raith GmbH lithography system was used to expose graphene to e-beam irradiation. The graphene devices were exposed with 500 μCcm^{-2} e-beam intensity as the function of time. Raman spectra measurement was performed with Renishaw microspectrometer with a wave number ranges from 1100 cm^{-1} to 3200 cm^{-1} having laser power of 1 mW and wavelength is 514 nm at room temperature.

3. Results and discussion

Fig. 1(a) and (b) show the schematic view of graphene based FET fabricated on SiO_2/Si under e-beam and UV light exposure, respectively. The irradiation treatment process was carried out in such a way that only graphene channel was exposed to e-beam irradiations [28,29]. While in the case of UV illumination the graphene channel as well as the metallic contacts were exposed to UV irradiations. The calculated value of R_c in case of UV irradiation is approximately 260 Ω. Thus R_c is not much effected by UV irradiations [34,35]. Scanning electron micrograph of our device is shown in Fig. 1(c); the red color shows graphene with gold electrodes designated by grey color. Raman spectra of graphene device upon exposure to e-beam and UV irradiations is carefully examined after each radiation step. These treatments have shown contrasting effect of doping upon exposure as confirmed by Raman spectroscopy and transport measurements. Raman spectra of untreated and e-beam irradiated graphene samples are illustrated in Fig. 2(a). The G and 2D characteristics peaks for untreated graphene appear at 1587 cm^{-1} and 2690 cm^{-1}. The G and 2D peak positions of untreated graphene before and after e-beam irradiations are shown in Fig. 2(a). This indicates that G and 2D peaks are shifted towards lower wave number upon exposure to e-beam irradiations. The intensity of D peak increases with increase of e-beam irradiation for a certain range of dose and then it decreases with further increase of irradiations as presented in Fig. 2(a). This indicates the transformation of graphene from crystalline to nano-crystalline and then amorphous form [29,36]. Fig. 2(b) shows Raman spectra of graphene under UV illumination for different exposure times. The shifting of G and 2D peaks towards higher wave number indicates p-type doping in graphene [24,33,37,38]. Moreover, the shifting of positions for G and 2D peaks are summarized for both treatments as shown in Fig. 2(c) and (d), respectively. The shifting of the peaks positions towards lower wavenumber signifies n-type doping for graphene in case of e-beam treatment [29], while their shift towards higher wavenumber corresponds to p-type doping in graphene for UV illumination. The shifting of G and 2D peaks toward lower and higher wavenumber indicates n- and p-type doping as previously reported [33]. This shift in wavenumber for both cases may be attributed to change in the carrier density and shifting of fermi level. Resistivity as a function of backgate voltages is demonstrated in Fig. 3 (a) and (b), respectively. Dirac point position for untreated graphene lies at $V_{CNP} = +15$ V, which shows that it was initially p-doped. The charge neutrality point (CNP) gradually shifts to negative backgate voltage and reaches upto $V_{CNP} = -36$ V when exposed to different doses of e-beam irradiations showing n-type doping in graphene. However, the Dirac point is observed to move towards higher value of positive backgate voltage i.e. $V_{CNP} = +34$ V indicating p-type doping in graphene upon the exposure to UV irradiation for different duration of times [32,33]. The comparative study of this behaviour under e-beam and UV irradiations is also shown in Fig. 3 (c) and (d), respectively. Mobility of holes and electrons before and after exposing to e-beam irradiation doses and UV illumination for different time periods is calculated by taking the slope of conductivity versus backgate voltage using the following relation (1) [26].

$$\mu = (1/C_g)(\delta\sigma/\delta V_g) \quad (1)$$

where σ is the conductivity of graphene, C_g is gate capacitance. Electron-hole mobility in graphene decreases from 1000 cm^2/V.s to

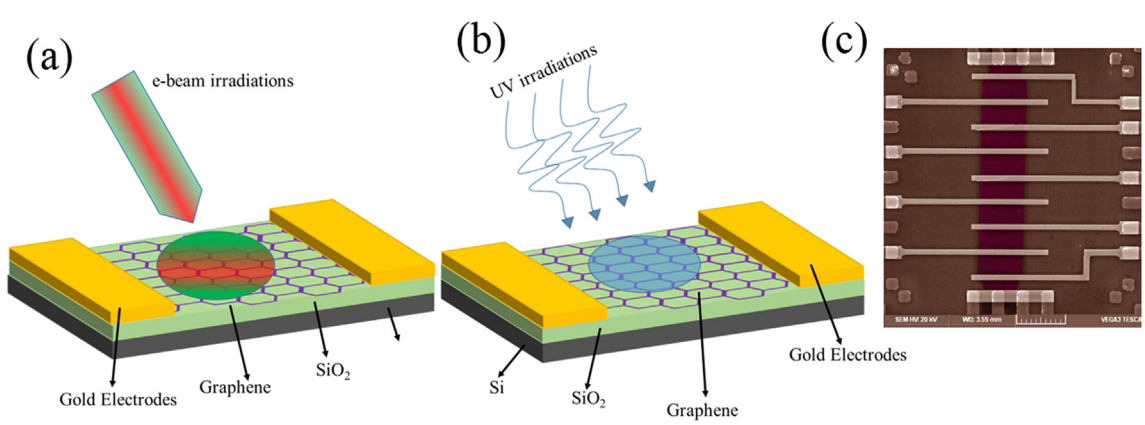

Fig. 1. (a) Schematic view of graphene based field effect transistor (GFET) fabricated on SiO_2/Si substrate exposed to electron beam irradiations. (b) While upon exposure to ultraviolet (UV) illuminations. (c) Scanning electron micrograph of GFET with red color representing graphene layer and metallic electrodes designated by grey color pattern.

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