Photoconductive multi-layer graphene photodetectors fabricated on etched silicon-on-insulator substrates*

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Recently, graphene-based photodetectors have been rapidly developed. However, their photoresponsivities are generally low due to the weak optical absorption strength of graphene. In this paper, we fabricate photoconductive multi-layer graphene (MLG) photodetectors on etched silicon-on-insulator substrates. A photoresponsivity exceeding 200 A·W^{-1} is obtained, which enables most optoelectronic application. In addition, according to the analyses of the high photoresponsivity and long photoresponse time, we conclude that the working mechanism of the device is photoconductive effect. The process of photons conversion into conducting electrons is also described in detail. Finally, according to the distinct difference between the photoresponses at 1550 nm and 808 nm, we estimate that the position of the trapping energy is somewhere between 0.4 eV and 0.76 eV, higher than the Fermi energy of MLG. Our work paves a new way for fabricating the graphene photoconductive photodetectors.

Keywords: graphene photodetector, photoconductive effect

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1. Introduction

Graphene, one layer of carbon atoms arranged in honeycomb lattice, has aroused tremendous research interest since it was first realized.[1] Particularly, owing to the high mobilities for electrons and holes,[2–4] and the uniform absorption of light over a wide range of spectrum from ultraviolet to infrared,[5,6] graphene-based photodetectors have been rapidly developed.[7–17] Recently, a number of research studies have focused on graphene field-effect-transistor-structure photodetectors, exploiting photo-voltaic effect and photo-thermoelectric effect.[8–13] However, the photoresponsivity is usually low due to the low absorption coefficient of graphene.[8–13] The enhancement in photoresponsivity of the micro-cavity integrated device is also limited and requires complicated epitaxial technique.[14,15] An alternative way to improve photoresponsivity is to introduce photosensitive nanomaterials such as PbS quantum dots (QDs) into graphene, forming a graphene-quantum-dots (GQDs) hybrid system,[16,17] where one kind of photo-excited charge is trapped in QD while the opposite charged carriers circle in a graphene channel within the lifetime.[16–18] Nevertheless, this requires energy band engineering and complicated graphene modification technique such as colloidal quantum dots decoration.[16]

In this paper, we fabricate multi-layer graphene (MLG) photodetectors on etched silicon-on-insulator (SOI) substrates. A photoresponsivity exceeding 200 A·W^{-1} is obtained which enables most optoelectronic application. The working mechanism of the device is investigated and attributed to the photoconductive effect. We have fabricated half a dozen of devices and all exhibit similar responses.

2. Device fabrication

The substrate of the device is an SOI substrate with 340-nm-thick intrinsic top silicon. We etch 200-nm silicon via inductively coupled plasma (ICP) etching. MLG sample is mechanically exfoliated on a silicon substrate with 300-nm thermal oxide, and then identified by microscope, Raman spectrum and atomic force microscope (AFM). Then a transfer process with a precision of sub-micrometer is performed to transfer MLG microsheet to the SOI substrate. The electrodes are fabricated by a standard electron-beam lithography followed by electron-beam evaporation of 20-nm Ti and 70-nm Au.

3. Results and discussion

Figure 1(a) gives a top-view false-color scanning electron microscope (SEM) image of the device. The length and width of MLG channel are 2 μm and 22 μm, respectively. Raman spectrum at 488 nm is shown in Fig. 1(b). The D peak around 1350 cm^{-1} is negligible, indicating that the transfer process does not introduce any defects into MLG.[19] The ratio of $I(2D)/I(G)$ is 0.69. Both Raman spectrum and AFM

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result (∼ 3 nm, not shown) indicate that the number of layers of MLG is 6–10.[20,21]

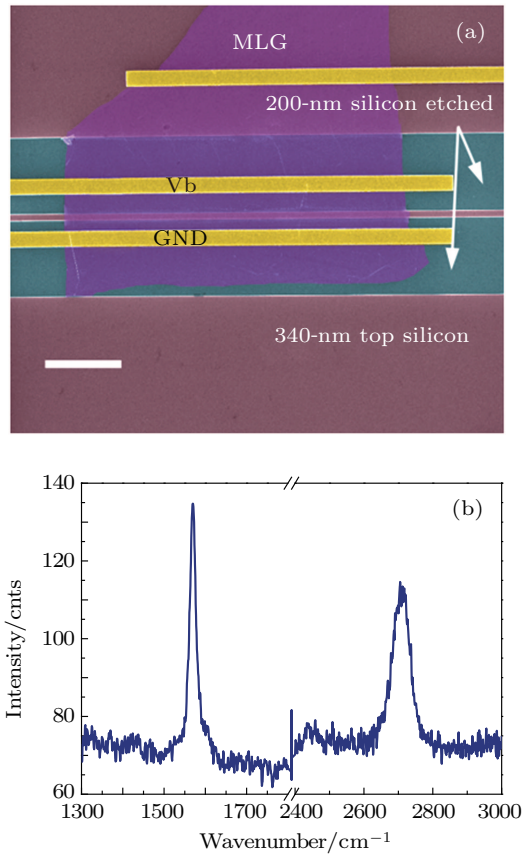


Fig. 1. (color online) (a) A top-view false-color SEM image of the device, showing MLG (purple), etched region (green), and metal electrodes (yellow), with a scale bar of 5 μm. (b) Raman spectrum of MLG at 488 nm.

Figure 2(a) shows the photoresponses to 808-nm normal incident with increasing incident power density. The photoresponsivity R is fitted to be 0.11 A·W^{-1} (Fig. 2(b)), two orders of magnitude higher than the values of state-of-the-art graphene photodetectors reported previously.[8–13] We consider that such a remarkable enhancement in R is due to photoconductive effect as discussed below rather than the increased light absorption, since MLG can only increase absorption by a factor of 6–10 (number of layers).

The external quantum efficiency (EQE, η) for absorbed photon conversion into conducting electrons can be determined by

$$\eta = \frac{I_{\rm pc}/q}{P_{\rm in} \times n\alpha/h\nu}, \tag{1}$$

where $I_{\rm pc}$ is the measured photocurrent, $P_{\rm in}$ is the incident power, $h\nu$ is the photon energy, q is electron charge, n is the number of MLG layers, and α is the absorption coefficient of single layer graphene. For two-dimensional (2D) materials such as MLG, most of the incident power is not absorbed. Therefore we consider that it is reasonable to introduce into the formula a term $n\alpha$, which represents the absorption coefficient of MLG. The EQE at 808 nm is calculated to be 168%, indicating that the mechanism of photoresponse is photoconductive effect.[16–18]

In addition to 808 nm, photoresponses at 1550 nm, 620 nm, and 500 nm are also measured. Photoresponsivities and EQEs at all wavelengths are summarized in Table 1. At 1550 nm, the photoresponse is moderate, while at 808 nm and even shorter wavelengths (620 nm and 500 nm), photoresponses are increased.

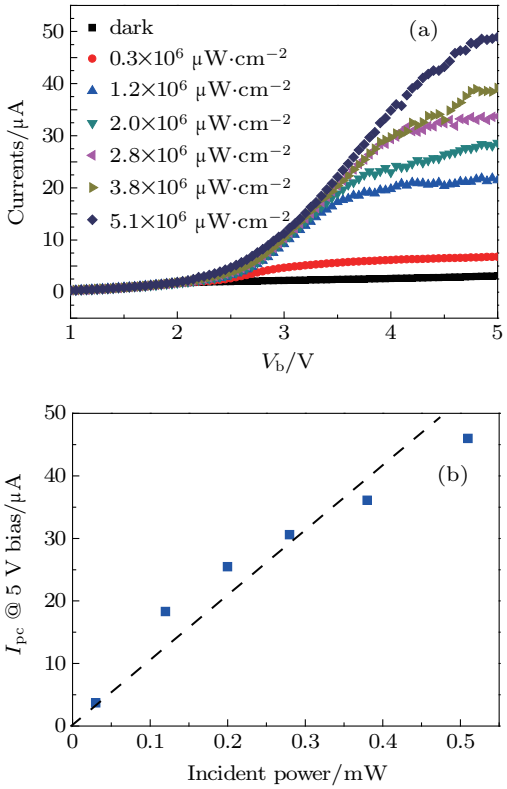


Fig. 2. (color online) (a) Photoresponses at 808 nm with increasing incident power density. (b) Photocurrent $I_{\rm pc}$ at 5-V bias voltage as a function of incident power. Dashed line refers to linear fitting.

Table 1. Summary of photoresponsivity R and external quantum efficiency η at different wavelengths.

λ/nm	R/A·W^{-1}	EQE η/%
1550	1.1×10^{-5}	8.8×10^{-6}
808	0.1	168.9
620	296.1	592920.5
500	278.5	690750.0

As shown in Fig. 3, the spatially resolved current mapping is obtained. The light source is the 808-nm laser output through a tapered fiber. The spot size is estimated to be smaller than 3 μm. The position of the laser spot is controlled by a micro manipulator with 0.5-μm spacing. The precision of the micro manipulator is 0.1 μm. A 3-V direct current (DC) bias is applied to the device while scanning the focused laser spot over the device along the dashed line marked in the inset. Multiple current values at each of the positions are measured and the measured values are averaged as presented in Fig. 3. In recent experiment, photovoltaic graphene photodetector at zero

applied source–drain bias shows two photocurrent maxima with opposite polarization in the vicinity of metal contacts.[9] The separation of photo-generated carriers is attributed to the band bending due to the presence of work function steps between graphene and metal contacts. Here, however, we have only one current peak located in the center of MLG channel. Although the external electric field facilitates the separation of electron–hole pairs, the spatially resolved current mapping should be asymmetric with respect to the MLG channel center, since the direction of the external electric field is the same as that of the intrinsic electric field resulting from the band bending on one side of MLG channel while opposite on the other side. Therefore, with considering the single symmetric current peak taken from our device, we conclude that the photocurrent stems from MLG channel rather than previously reported MLG/metal contact.

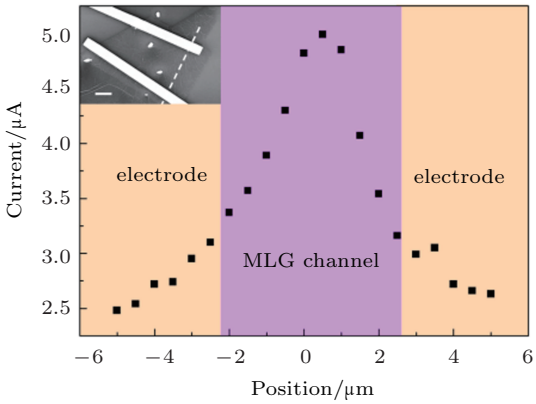


Fig. 3. (color online) The spatially resolved current mapping of the device. Inset shows the SEM image of the device. Scale bar is 2 μm.

The temporal response of the device is also measured. A DC 5-V bias is applied to the device. The light source is a 500-nm laser which is chopped at 100 Hz by a mechanical chopper and the photoresponses are recorded via a waveform monitor. The rising and falling time of the photoresponse are 0.5 ms and 0.74 ms respectively, far longer than the intrinsic carrier lifetime in graphene. Such a long response time is generally considered as a hallmark of photoconductive effect.[16–18] Inset shows the waveform recorded in one chopping cycle.

Figure 5 shows the energy diagram of the device. As a demonstration, we regard the trapping energy as an electron trap. The absorption of photon $h\nu$ creates electron–hole pairs. The energy of the photo-generated electrons is $h\nu/2$ higher than the Fermi level of MLG.[22] At 1550 nm (∼ 0.8-eV photon energy), since the energy of the photo-generated electrons is lower than the trapping energy, the transfer of photo-induced electrons from MLG to the trapping energy is forbidden (Fig. 5(a)). Therefore there is negligible photoconductive effect. However, at 808 nm (∼ 1.53-eV photon energy), 620 nm and 500 nm, the energies of photo-generated electrons are higher than the trapping energy (Fig. 5(b)). Therefore the photo-generated electrons transfer into the trapping energy level, and thus leave behind the photo-generated holes cycling in MLG, thereby producing the photoconductive effect. Accordingly, we estimate that the position of the trapping energy is somewhere between 0.4 eV and 0.76 eV (half the incident photon energy) higher than the Fermi level of MLG.

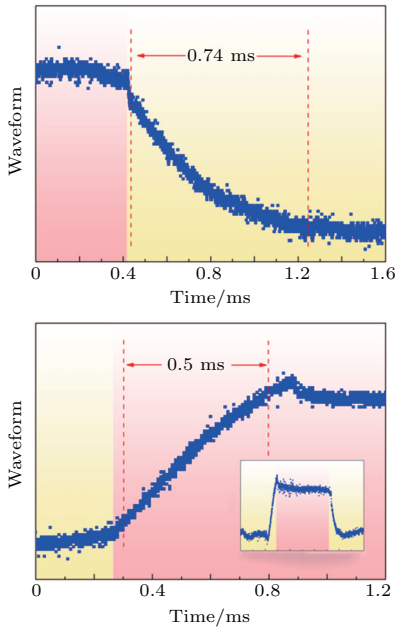


Fig. 4. (color online) Temporal response of the device. Top: the falling edge of the photoresponse. The falling time is measured to be 0.74 ms. Bottom: the rising edge of the photoresponse. The rising time is measured to be 0.5 ms. Inset shows the waveform recorded in one chopping cycle.

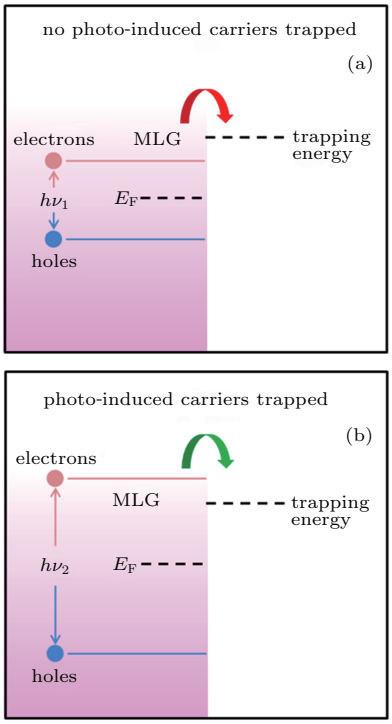


Fig. 5. (color online) (a) Energy diagram at 1550 nm where the transfer of the photo-induced electrons from MLG to the trapping energy is forbidden. (b) Energy diagram at 808 nm, 620 nm, and 500 nm where photo-generated electrons transfer into the trapping energy level, and thus leave behind the photo-generated holes cycling in MLG, thereby producing the photoconductive effect.

Although we attribute such high photoresponses to the photoconductive effect, the origin of the trapping energy is still unknown. We speculate that it may result from the ICP-etching-induced surface states such as dangling bonds, roughness and residual chemicals. This requires our further study of surface science but it is beyond the scope of this paper.

4. Conclusions

In summary, we fabricate multi-layer graphene photodetectors on ICP etched SOI substrates. A photoresponsivity exceeding 200 $A \cdot W^{-1}$ is obtained at each of 620 nm and 500 nm. The rising and falling times of the device are measured to be 0.5 ms and 0.74 ms, respectively. The working mechanism is attributed to the photoconductive effect. The single current peak in the spatially resolved current mapping proves that the photoresponse stems from MLG. In addition, the process of photons converting into conducting electrons is described in detail. According to the distinct difference in the photoresponses at 1550 nm and 808 nm, we estimate that the position of the trapping energy is somewhere between 0.4 eV and 0.76 eV higher than the Fermi energy of MLG.

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