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Graphene Photodetector Based on Interfacial Photogating Effect with High Sensitivity

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ABSTRACT

Graphene-based photodetectors have attracted attention for realizing optoelectronic devices including photodetectors. We report a graphene field effect transistor on silicon for broadband light detection from the ultraviolet to near-infrared region, which is compatible with the silicon technology and does not need a complicated fabrication process. The photodetectors show an improved responsivity. Specifically, fabricated graphene photodetectors shows a photo-responsivity of ~980 A/W at room temperature. These results provide a promising for the development of graphene-based optoelectronic applications with the broadband photodetection from the ultraviolet to near-infrared region.

Keywords: Graphene, Silicon, Photodetectors, Photogating effect, Near-infrared Photodetector

1. INTRODUCTION

Semiconductor optoelectronic devices play an essential role in various applications from imaging, optical communication, remote sensing, military to environment monitoring.[1-5] Graphene owns unique optoelectrical properties such as high carrier mobilities and gapless, which appeal for ideal photodetectors. The realization of graphene photodetectors with low-cost, high quantum efficiency, fast photo-response, and high sensitivity in the ultraviolet to infrared region remains one of the challenges in optoelectronics. There are several approaches to improve the performance of photodetectors based on graphene, including hybrid quantum dot – graphene, waveguides microcavities, optical antennas, and plasmonic structures. However, the spectral band-width of these photodetectors is limited because of the large bandgap of quantum dots, the resonant wavelength of waveguide nanostructures, and the narrow resonance frequencies of nano-plasmonic structures. The fabrication of these photodetectors also requires complicated fabrication processes, leading to high-cost. These, therefore, constitute the main obstacle to the wide optoelectronic applications of graphene.

We applied the concept of the interfacial photogating effect from graphene on a *p*-type silicon/silicon dioxide (*p*-Si/SiO_2) structure.[6, 7] For photogating effect, electrons or holes are trapped in an absorber layer, while the oppositely charged carriers transfer to graphene and rapidly recirculate in the graphene channel controlled by a drain-source bias voltage, leading to a photogating effect.[8, 9] Similarly, the light absorption in the *p*-doped silicon substrate generates additional photovoltage at the Si/SiO_2 interface, which modulates the graphene conductance by capacitive coupling through the SiO_2 layer. Furthermore, this device is compatible with the silicon technology, and does not require a complicated fabrication process. In this paper, we investigate the photo-response of the graphene photodetectors based on the interfacial photogating effect with the photo-responsivity of ~ 980 A/W.

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2. METHODS AND EXPERIMENTAL DETAILS

2.1. Device fabrication of graphene field effect transistor

We used a *p*-doped Si wafer (1 – 10 Ω.cm) to fabricate graphene photodetectors. A 300-nm silicon dioxide (SiO_2) was grown thermally on the *p*-Si substrate at 1050 °C. A metal back-gate contacting to the *p*-Si substrate was designed using photolithography, then HF etching solution was employed to remove the SiO_2 layer, after that 10-nm Cr and 100-nm Au metal films were deposited using e-beam thermal evaporation. Metal drain and source contacts (10-nm Cr and 100-nm Au layers) for transport measurements were defined by photolithography and deposited by using the e-beam evaporation method. After the lift-off process, the Si/SiO_2 wafer with metal contacts was cleaned by oxygen plasma for 4 minutes to eliminate photoresist residue.

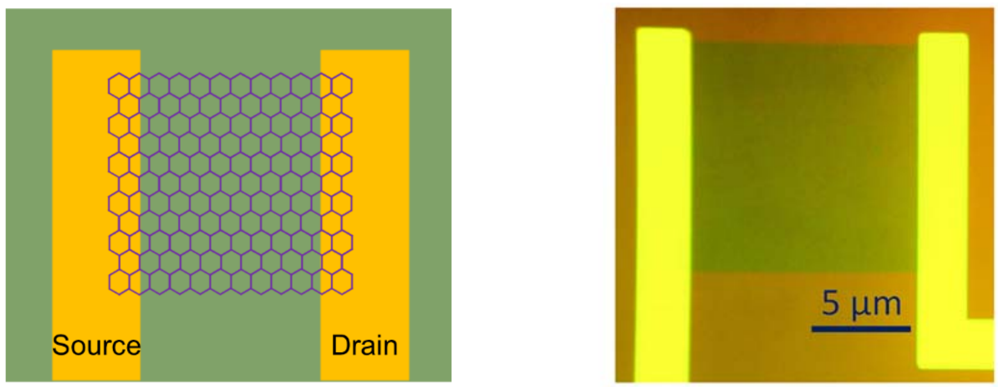

Figure 1: Structure of graphene-based photodetectors. (left) Schematic diagram of the graphene-based device including source, drain contacts and graphene. (right) An image of the graphene photodetector.

The chemical vapor deposition single layer of graphene on a copper foil from Graphenea Inc. was transferred onto the Si/SiO_2 substrate with metal contacts.[10] The chemical vapor deposition graphene on the copper foil was spin-coated by poly-(methyl-methacrylate) (PMMA), after that the copper foil was etched by 0.3 M ammonium persulfate solution for 1 hour at 25 °C. Graphene with the PMMA film was rinsed with deionized water for 10 minutes and transferred onto the Si/SiO_2 substrate with source and drain electrodes. The structure was kept in a vacuum for 12 hours to create adhesion. The sample was baked at 85 °C for 10 minutes, then at 135 °C for 20 minutes. After that, PMMA is removed by acetone for 1 hour, followed by IPA for 30 minutes. Photolithography and oxygen plasma etching were employed to fabricate a (20 × 20) μm^2 graphene pattern.[5, 11]

The structure of graphene-based photodetectors is shown in the Figure 1. A schematic diagram is a presentation of the graphene photodetectors including source, drain contacts and graphene (Figure 1-left). In order to check the structure of graphene photodetector devices, we have taken images of the photodetector using a field-emission scanning electron microscope, LEO (Zeiss) 1550. Figure 1-right shows a image of our photodetector. The image shows the chemical vapor deposition graphene layer on the device with metal contacts.

2.2. Electrical and optoelectronic measurements

The electrical and photoresponse measurements were tested by two Keithley source-meters units. The Keithley 2450 is to set a constant voltage between source and drain contact, V_{SD}, while Keithley 2400 is employed to vary the back-gate voltage, V_{BG}. The drain current, I_D, is collected by using the Keithley 2450 under dark and light illumination.

The devices were characterized in a black anodized aluminum box to eliminate ambient light. A polarizing beam-splitter and a half-wave plate are employed to vary the power of a diode-pumped solid state laser operating at 532 nm (Coherent Verdi-V2). We employed a diaphragm with a diameter of 10 mm on the cap of the black anodized aluminum box to form the light source with uniform intensity distribution.

3. RESULTS AND DISCUSSION

The photoresponse characteristics of the graphene-based photodetector at V_{SD} = 0.5 V are shown in Figure 2. We have observed the drain current, I_D, as a function of the back-gate voltage, V_{BG}, under dark and illumination conditions of the diode-pumped solid-state laser operating at 532 nm. The power of this light source was 0.7 nW. As can be seen from Figure 2-left, the I-V characteristic curve shifts toward positive of the back-gate voltage, V_{BG}, under illumination power.

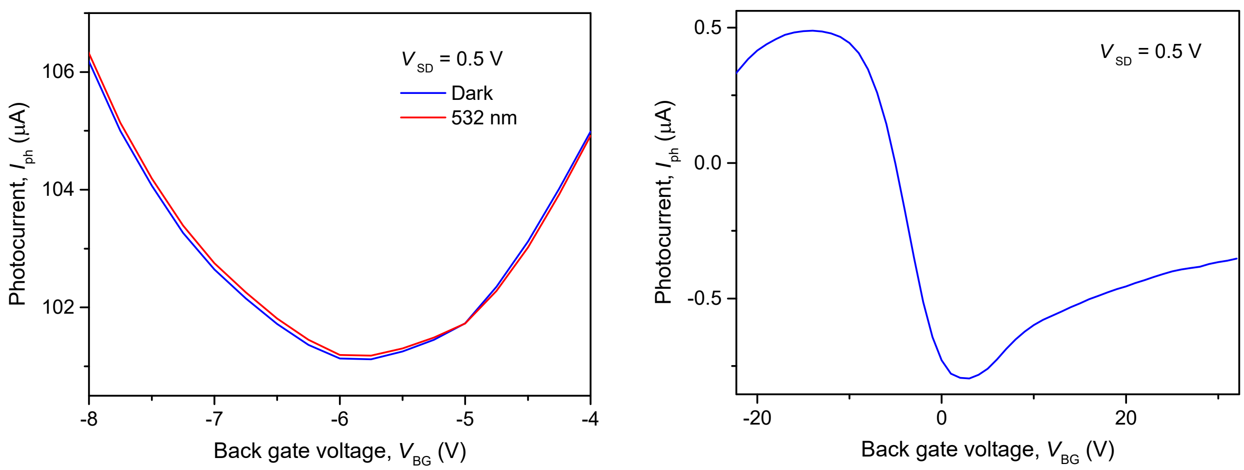

Figure 2: (left) I_D–V_{BG} characteristics of the graphene FET photodetector under dark and illumination conditions. The source-drain bias voltage, V_{SD}, is 0.5 V. (right) Photocurrent as a function of back-gate voltage under laser illumination of 0.7 nW.

The net photocurrent of the photodetector was obtained by subtracting the dark-current from the illumination current ($I_{ph} = I_{illumination} - I_{dark}$). The photocurrent curve under the illumination power of 0.7 nW is plotted in Figure 2-right. A net photocurrent of ~0.76 μA has been observed at V_{bg} = 2 V. It shows that the magnitude of photocurrent increases with illumination power.

The horizontal shift of the I-V transfer curve is originated from the interfacial photogating effect at the *p*-Si/SiO_2 interface where charge carriers are accumulated.[6, 7] Due to the mismatch of the work functions between *p*-Si and SiO_2, the energy band is bending at the Si/SiO_2 interface. The bending of the energy band creates a depletion region near the interface, and a built-in electrical field is emerged. The photo-induced electron-hole pairs in the *p*-doped Si substrate are separated due to the built-in electrical field. While the electrons are moved to the *p*-Si/SiO_2 interface, the holes are diffused to the Si substrate. The process leads to an additional negative gate voltage at the *p*-Si/SiO_2 interface that modulates the conductivity in the graphene channel through the SiO_2 insulator layer by capacitive coupling, and thus, lowers the Fermi level of graphene. The effect increases the hole density in the graphene channel, resulting in the positive photocurrent in the device. This also explains the horizontal shift of the transfer characteristic (I-V) curve toward the positive back-gate voltage under light illumination.

To gain insight into the characteristics of the graphene photodetector, we performed the power dependence of the photocurrent current (Figure 3) under the 532-nm illumination, at V_{BG} = 2 V and V_{SD} = 0.5 V. Under low illumination power varying from 0.25 nW to 4.9 nW, the photocurrent increases linearly, and the photo-responsivity of our detector is ~ 980 A/W. The number of carriers genearted from light absorption is proportional to the laser power. Besides, the photocurrent is proportional to the potential created by the band bending at the interface. The height of the potential decreases gradually to the flat band, where there is no electrical field to separate electrons and holes. It means that photo-induced electrons at the *p*-Si/SiO_2 interface will contribute to the photocurrent. The photocurrent will linearly increase under low illumination power. As we increase the illumination power, a higher concentration of carriers (electrons and holes) is generated in the *p*-Si near the Si/SiO_2 interface. Electrons and holes recombined in a short time due to the high mobility of carriers in silicon.[12] These electrons will not contribute to the additional negative gate voltage that modulates the conductivity of the graphene channel, and thus, the photo-responsivity gradually saturates at high illumination intensity. The high photo-responsivity is originated from the large number of photogating induced holes and the high carrier mobility in graphene. This value is significantly higher than other values for commercial silicon photodetectors.

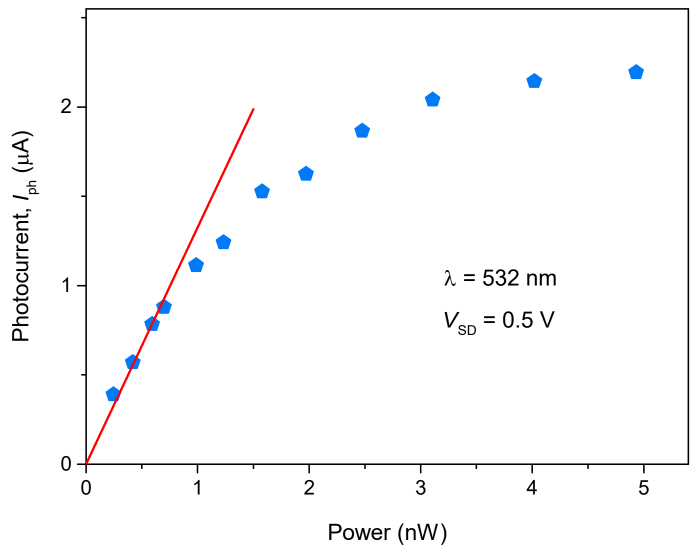

Figure 3: Power dependence of photocurrent at 2 V back-gate voltage and 0.5 V source-drain voltage.

4. CONCLUSIONS

In conclusion, we have demonstrated the fabrication of a high-performance graphene photodetector based on interfacial gating effect from the *p*-doped Si/SiO_2 interface. The photodetectors were highly sensitive to the ultraviolet to near infrared light, corresponding to the band gap energy of silicon. The photo-responsivity of the graphene devices was estimated to be ~ 980 A/W. The simple fabrication with high-performance of the graphene photodetectors has potential applications for broadband sensing from visible to near IR region.

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REFERENCES

1 Koppens, F.H.L., Mueller, T., Avouris, P., Ferrari, A.C., Vitiello, M.S., and Polini, M.: "Photodetectors based on graphene, other two-dimensional materials and hybrid systems," Nat. Nanotechnol., 9, 780, (2014).

2 Ho, V.X., Al Tahtamouni, T.M., Jiang, H.X., Lin, J.Y., Zavada, J.M., and Vinh, N.Q., "Room-Temperature Lasing Action in GaN Quantum Wells in the Infrared 1.5 mu m Region," ACS Photonics, 5, 1303, (2018).

3 Ho, V.X., Dao, T.V., Jiang, H.X., Lin, J.Y., Zavada, J.M., McGill, S.A., and Vinh, N.Q., "Photoluminescence quantum efficiency of Er optical centers in GaN epilayers," Sci. Rep., 7, 39997, (2017).

4 Ho, V.X., Wang, Y., Ryan, B., Patrick, L., Jiang, H.X., Lin, J.Y., and Vinh, N.Q., "Observation of Optical Gain in Er-Doped GaN Epilayers," J. Lumin., 221, 117090, (2020).

5 Ho, V.X., Wang, Y., Cooney, M.P., and Vinh, N.Q., "Graphene-based photodetector at room temperature," Proceedings of SPIE, 10729, 1072907, (2018).

6 Guo, X.T., Wang, W.H., Nan, H.Y., Yu, Y.F., Jiang, J., Zhao, W.W., Li, J.H., Zafar, Z., Xiang, N., Ni, Z.H., Hu, W.D., You, Y.M., and Ni, Z.H., "High-performance graphene photodetector using interfacial gating," Optica, 3, 1066, (2016).

7 Liu, Y.P., Xia, Q.L., He, J., and Liu, Z.W., "Direct Observation of High Photoresponsivity in Pure Graphene Photodetectors," Nanoscale Res. Lett., 12, 93, (2017).

8 Kagan, C.R., Lifshitz, E., Sargent, E.H., and Talapin, D.V., "Building devices from colloidal quantum dots," Science, 353, aac5523, (2016).

9 Konstantatos, G., Badioli, M., Gaudreau, L., Osmond, J., Bernechea, M., de Arquer, F.P.G., Gatti, F., and Koppens, F.H.L., "Hybrid graphene-quantum dot phototransistors with ultrahigh gain," Nat. Nanotechnol., 7, 363, (2012).

10 Novoselov, K.S., Jiang, D., Schedin, F., Booth, T.J., Khotkevich, V.V., Morozov, S.V., and Geim, A.K., "Two-dimensional atomic crystals," P. Natl. Acad. Sci. USA, 102, 10451, (2005).

11 Wang, Y., Ho, V.X., Pradhan, P., Cooney, M.P., and Vinh, N.Q., "Graphene-Germanium Quantum Dot Photodetector with High Sensitivity," Proceedings of SPIE, 11088, 1108809, (2019).

12 Cuevas, A., Macdonald, D., "Measuring and interpreting the lifetime of silicon wafers," J. Sol. Energy, 76, 255, (2004).