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A 2DEG back-gated graphene/AlGaN deep-ultraviolet photodetector with ultrahigh responsivity*

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A graphene/AlGaN deep-ultraviolet (UV) photodetector is presented with ultrahigh responsivity of 3.4×10^5 A/W at 261 nm incident wavelength and 149 pW light power. A gain mechanism based on electron trapping at the potential well is proposed to be responsible for the high responsivity. To optimize the trade-off between responsivity and response speed, a back-gate electrode is designed at the AlGaN/GaN two-dimensional electron gas (2DEG) area which eliminates the persistent photocurrent effect and shortens the recovery time from several hours to milliseconds. The 2DEG gate is proposed as an alternative way to apply the back gate electrode on AlGaN based devices on insulating substrates. This work sheds light on a possible way for weak deep-UV light detection.

Keywords: graphene/AlGaN, deep-ultraviolet, high responsivity, photodetector

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1. Introduction

Deep-UV detection is indispensable in applications like UV warning, corona detection, and biological analysis. In most application scenarios, the UV intensity of the measured targets is usually not high. Due to the strong absorption and scattering of UV light by gas molecules or dust in the environment, the UV signal that can finally be detected by the detector is very weak. This situation puts forward higher requirements on the detector's weak light detection capability. AlGaN is a favorable material for deep-UV detection owing to its wide and tunable bandgap from 3.4 eV to 6.2 eV. Normal p–n and Schottky AlGaN photodetectors do not meet the demand for weak UV light detection because of a lack of gain mechanism.[1–3] AlGaN based avalanche photodiode has a high gain but the performance is very sensitive to material defects introduced by lattice and thermal mismatch on foreign substrates.[4] Recently, graphene/semiconductor structures were reported to demonstrate high gain and high responsivity which lead to excellent weak light detection capability.[5–8] Such photodetector structure does not have strict requirements on the material quality and it has been proved that some surface states are good for the responsivity.[9] This provides an opportunity for high responsivity AlGaN based photodetectors. However, there is always a trade-off between the responsivity and response speed. Especially, the persistent photocurrent phenomenon could last for thousands of seconds or even days which severely limits the use of such photodetectors. Introducing a back-gate is reported to eliminate the persistent photocurrent in graphene/SiO_2/Si system.[5] But for AlGaN grown on insulating substrates or with complicated interlayers on the substrates, it is hard to applying the back-gate directly on the substrate. In addition, the previous work has confirmed that the surface states can prolong the carrier lifetime and induce high gain and corresponding responsivity of 5.83 A/W.[9] But the method of introducing surface states is unstable for the device fabrication process. In this work, a graphene/AlGaN photodetector on GaN supporting layer is proposed. The potential well at the AlGaN/GaN interface traps the photo-excited electrons and prolongs the carrier lifetime, which leads to a high gain and ultrahigh responsivity of 3.4×10^5 A/W at 261 nm incident wavelength and 149 pW light power. Besides, a back-gate is designed at the AlGaN/GaN 2DEG region, which effectively eliminates the persistent photocurrent effect and accelerates the recovery speed from a couple of hours to milliseconds. This work paves a way for AlGaN based deep-UV weak light detection.

2. Materials and methods

The photodetector consists of a layer of graphene atop the AlGaN layer (25 nm) with Al fraction of 25% on a GaN (3 μm)/AlN transition layer/sapphire platform grown by metal organic chemical vapor deposition (MOCVD). The AlGaN barrier is non-doped and the dislocation density of the Al-

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GaN layer is in the order of 10^8 cm^{-2}, the graphene is defect free. As shown in Fig. 1(a), the structure features three Ohmic electrodes with two on the front of graphene denoted as D and S, and one in connection with the 2DEG channel formed at the AlGaN/GaN interface, which is denoted as the back-gate. The back-gate Ohmic contact is realized by rapid thermal annealing at 850 ℃ for 30 s in a N_2 environment after Ti/Au/Ni/Au metal deposition on the AlGaN/GaN surface. The D and S Ohmic contacts are formed by Ag deposition on graphene. The widths of the D and S electrodes are 500 μm, while the distance between them is 300 μm. The graphene is synthesized by chemical vapor deposition on Cu foil and transferred by using polymethylmethacrylate (PMMA) as the supporting film. The electrical measurements were conducted by Keithley 4200. Laser with 261 nm wavelength (UV-F-261, by Changchun New Industries Optoelectronics Technology Co., Ltd.) was used to generate illumination and the light power was attenuated by a series of neutral density filters.

3. Results and discussion

The band diagram of the graphene/AlGaN/GaN layers is shown in Fig. 1(b). As the intermediate AlGaN layer is thin and insulating, the band diagram is mainly determined by the work function difference between graphene and GaN and the polarization effect. The work functions of the graphene and the unintentionally doped GaN are 4.6 eV and 4.1 eV, respectively.[10] Because of the polarization induced 2DEG, the work function of GaN at the AlGaN/GaN interface is smaller. Due to the Fermi-level alignment at the thermal equilibrium state, the Fermi-level in graphene will be elevated, resulting in n-type conduction. The band bendings of AlGaN and GaN are primarily determined by the polarization field.

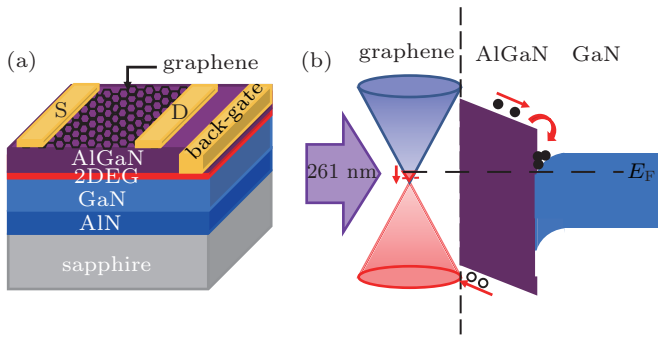


Fig. 1. (a) The epitaxial structure of the hybrid graphene/AlGaN photodetector. (b) The band diagram of the graphene/AlGaN/GaN layers.

Under 261 nm light illumination, the photo-excited electron–hole pairs by the photons absorbed in the AlGaN layer are effectively separated by the high polarization induced electric field. The holes are injected to graphene while the electrons are drifted to and trapped in the triangular potential well at the AlGaN/GaN interface. The injected holes in graphene lowers the quasi Fermi-level. Beyond that, the trapped electrons in the potential well form the negative space charges and will induce the reduction of electrons in graphene through capacitive effect. This effect will also lower the quasi Fermi-level in graphene. The experimental results would confirm that the capacitive effect is the main mechanism in the device. According to the analysis, the Fermi-level in graphene will decrease anyway and then the current in graphene between the D and S electrodes is decreased under light illumination. The photocurrent, calculated from the current in light minus the dark current, is illustrated in Fig. 2(a) under different illumination power from 149 pW to 1 mW and bias voltage from −1 V to 1 V. The photocurrent is negative at positive bias, indicating the decrease of the graphene current in light. Part of the photons will also be absorbed by GaN, the photo-excited electrons in the 2DEG potential well will also induce Fermi-level reduction in graphene. The detector responsivity is obtained from the absolute value of the photocurrent (I_{ph}) divided by the incident light power (P_{in}). The responsivity versus the DS bias voltage is illustrated in Fig. 2(b), the responsivity increases with the bias voltage because of the faster carrier transport in graphene due to the larger electric field. The responsivity evolution with the incident light power at the bias of 1 V is shown in Fig. 2(c). The maximum responsivity reaches 3.4×10^5 A/W under the lowest light power of 149 pW. Such high responsivity comes from a gain mechanism. The gain in the hybrid graphene/semiconductor photodetectors is denoted as gain $= \tau_{\text{lifetime}}/\tau_{\text{transit}}$,[11–13] where τ_{lifetime} is the lifetime of the photo-excited carriers, and τ_{transit} is the carrier transport time in graphene between the D and S electrodes. Due to the high mobility of electron in graphene, τ_{transit} is in the order of μs. Although shortening the D–S distance or increasing the bias voltage can decrease τ_{transit} and correspondingly increase the gain, it will not change by orders of magnitude. The gain will be more effectively improved by tuning τ_{lifetime}. In the proposed structure, the photo-excited electrons are drifted to and trapped in the potential well at the AlGaN/GaN interface. The energy barrier at the interface prevents electrons from recombination with the holes and then prolongs the τ_{lifetime}. The measured gain is extracted with the equation gain $= (I_{ph}/e)/(P_{in}/h\upsilon)$, where e is the electron charge, and $h\upsilon$ is the photon energy. The gain evolution is illustrated in the right ordinate of Fig. 2(c), a maximum gain of 1.6×10^6 is obtained under 149 pW light illumination power. It is also seen that the responsivity decreases with the increase of the illuminance power. As the gain comes from the electron trapping in the 2DEG triangle potential well, the more trapped electrons at high power, the weaker the electronic confinement ability due to the repulsive Coulomb potential and the gain is diminished. In addition, the more trapped electrons, the electric field in AlGaN is also decreased and the photo carrier sep-

aration capability is degraded. These are responsible for the decrease of responsivity at high power.

Figure 2(d) compares the responsivity performance of the photodetector in this work with other (Al)GaN based UV photodetectors. It is seen that the responsivity of conventional (Al)GaN based metal–semiconductor–metal (MSM), PIN, and Schottky structure photodetectors is very low (< 1 A/W).[1–3,14] The plasmonic enhanced (Al)GaN structure can improve the responsivity to several A/W, but still does not meet the demand for weak light detection.[15] The responsivity of the (Al)GaN nanowire-based structures can reach thousands of A/W and the highest responsivity even reaches 10^7 A/W,[16–18] while the wavelengths are beyond 300 nm and the fabrication process is complicated. Recently reported graphene/GaN hybrid structures also obtain thousands of A/W responsivity.[19] The responsivity performance in this work is further improved by the potential well electron trapping mechanism at the AlGaN/GaN heterostructure interface. AlGaN/GaN based photoconductive detector without graphene has also been reported to present the highest responsivity of 4×10^3 A/W at 250 nm.[20] This value is obtained at 3 V bias voltage and the distance between the current collecting electrodes is 8 mm, thus the electric field along the current channel is approximately 3750 V/cm. In our work, the highest responsivity of 3.4×10^5 A/W is achieved with the electrodes distance of 300 μm and 1 V bias (which means the electric field along the current channel is approximately 33 V/cm). According to the linear evolution of photocurrent with the bias voltage in Fig. 2(a), the responsivity should also increase linearly with the channel electric field. The responsivity performance of the devices should be compared at the same electric field. If considering the same electric filed, the responsivity of our device should be 10^4 times larger than that of the AlGaN/GaN based photodetector without graphene. The superiority of the graphene/AlGaN/GaN in our research is the use of the potential well at the 2DEG region as the electron trapping site and the graphene as the carrier transport layer, which prolongs the carrier lifetime and induces the high gain and great responsivity.

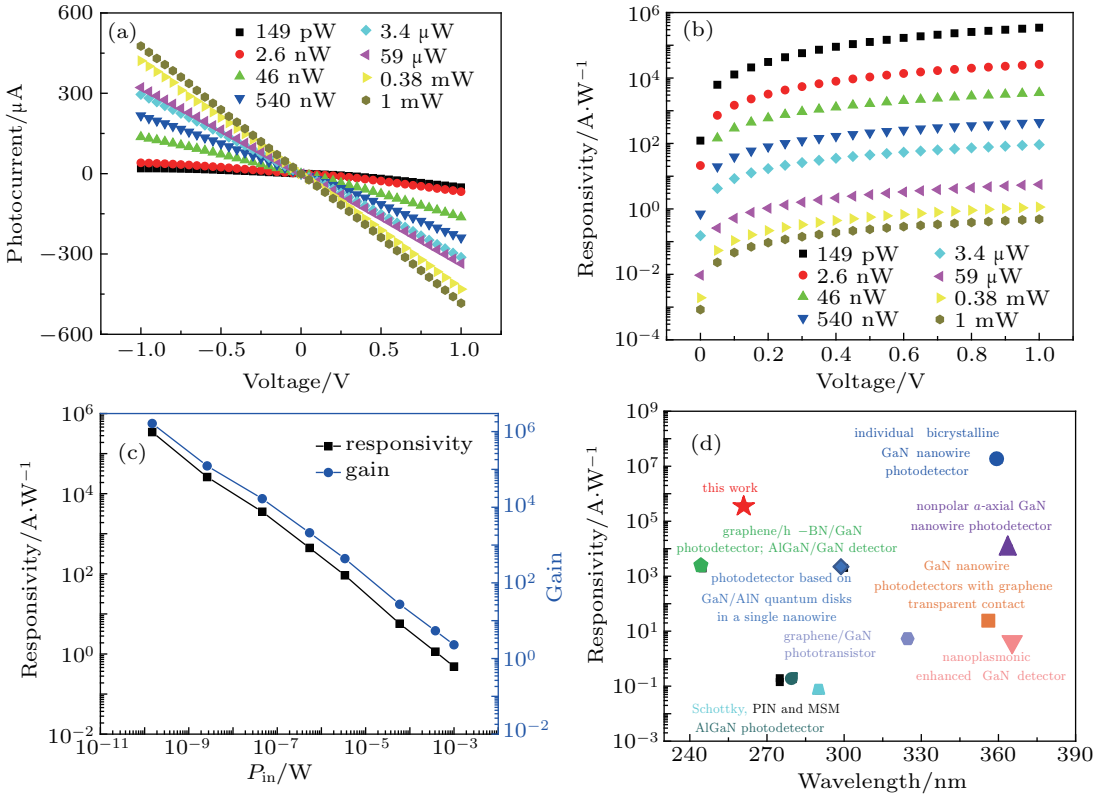


Fig. 2. (a) Photocurrent evolution with the bias voltage under different incident power. (b) Responsivity evolution with the bias voltage. (c) The responsivity (left ordinate) and gain (right ordinate) evolution with the incident light power at the bias voltage of 1 V. (d) Responsivity comparison with other (Al)GaN based photodetectors.

Figure 3 illustrates the transient property of the photodetector at the moment of switching on or off the light. It is defined that the time for the current from the dark value to the steady value in light when switching on the light is the rise time (t_r), while the time for the current to recovery to the dark value when turning off the light is the fall time (t_f). As shown in Fig. 3(a) without applying a back-gate voltage, the graphene current at a DS bias of 0.5 V decreases when the light is switched on, indicating a negative signal. The t_r is 547 s extracted from 10% to 90% of the signal. The long rise time is possible to be induced by the interface trap states that form a trapping barrier for the electrons. For the situation of switch-

ing off the light, the current only recovers almost 50% to its initial value until 1000 s. According to the exponential trend of the recovery curve, the t_f is estimated to lasts for hours, which is called the persistent photocurrent phenomenon. The persistent photocurrent is because the electrons in the potential well must overcome a potential barrier through thermal emission to diffuse to graphene and recombine (as shown in Fig. 3(b)). Although the ultrahigh responsivity enables weak light detection capability of the detector, one must wait hours during two detection activities due to the persistent photocurrent. To solve this problem, a back-gate detrapping method is used to eliminate the persistent photocurrent. The back-gate is designed at the 2DEG region at the AlGaN/GaN interface. At the moment of switching off the light, a negative back-gate voltage of −1.5 V is applied, the voltage rejects the electrons in the potential well or at the interface states to graphene and recombine with the holes there. The current immediately recovers to its initial value in 100 ms with the help of the back-gate voltage as shown in Fig. 3(c). The peak is due to the leakage current between D and back-gate electrodes. Under the negative back-gate voltage, the AlGaN barrier is lowered and the electrons in the well are injected to graphene through the electric field assistant emission or even tunneling mechanism (as shown in Fig. 3(d)). The experimental results confirm the function of the back-gate in eliminating the persistent photocurrent phenomenon, which makes the graphene/AlGaN photodetector more feasible in weak deep-UV light detection.

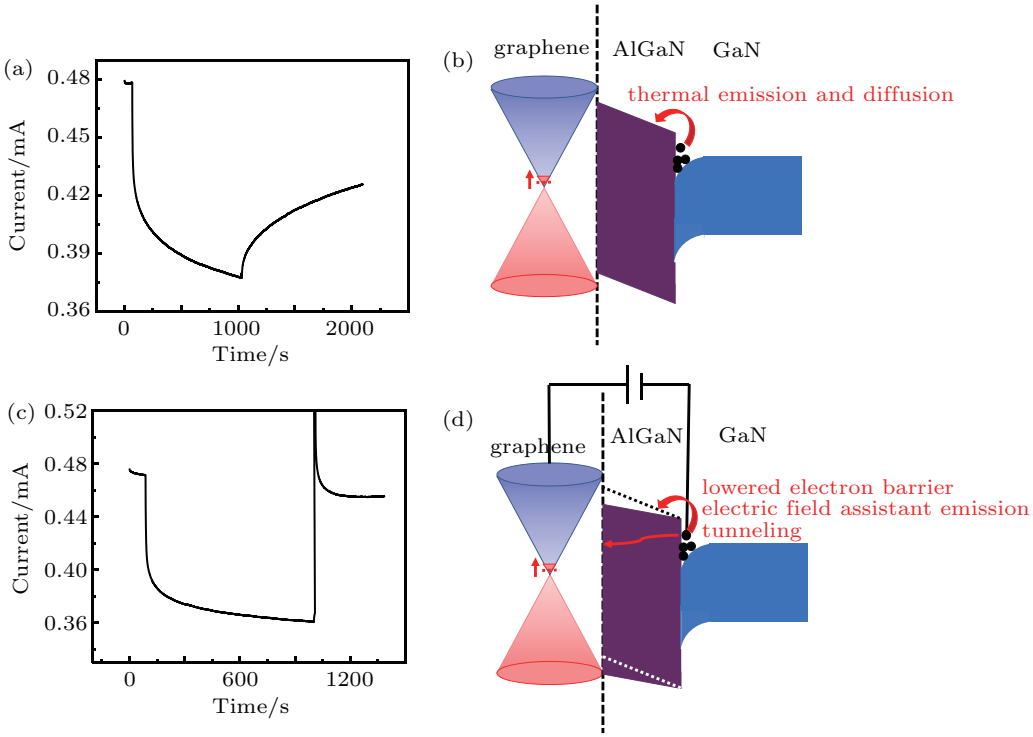


Fig. 3. (a) Temporal response of the device to 15 μW light switching transient without back-gate voltage. (b) The mechanism for the persistent photocurrent. (c) Temporal response of the device with back-gate voltage at the moment of switching off the light. (d) The mechanism for the elimination of the persistent photocurrent.

4. Conclusion

In summary, a highly sensitive deep-UV photodetector based on a graphene/AlGaN structure is demonstrated. An ultrahigh responsivity of 3.4×10^5 A/W is achieved based on the gain mechanism enhanced by the electron trapping at the potential well. In addition, a back-gate at the 2DEG region is designed to eliminate the persistent photocurrent phenomenon. The current recovery time is accelerated from a couple of hours to 100 ms by the back-gate.

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