

Visible-blind ultraviolet photodetector based on double heterojunction of n -ZnO/insulator-MgO/ p -Si

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Exploiting a double heterojunction of n -ZnO/insulator-MgO/ p -Si grown by molecular beam epitaxy, a visible-blind ultraviolet (UV) photodetector has been fabricated. The photodetector shows a rectification ratio of $\sim 10^4$ at ± 2 V and a dark current of 0.5 nA at a reverse bias of -2 V. The photoresponse spectrum indicates a visible-blind UV detectivity of our devices with a sharp cut off at the wavelength of 378 nm and a high UV/visible rejection ratio. The key role of the middle insulating MgO layer, as a barrier layer for minority carrier transport, has been demonstrated. © 2009 American Institute of Physics. [DOI: 10.1063/1.3103272]

Recently, ultraviolet (UV) photodetectors based on a wide band-gap semiconductor material, such as ZnO ($E_g = 3.37$ eV), have attracted more attention because of their extensive applications in civil and military areas. The merit of wide band-gap semiconductor UV photodetectors is the large UV/visible rejection ratio in comparison with the narrow band-gap semiconductor UV photodetectors, such as Si ($E_g = 1.12$ eV), which exhibits a wide photoresponse spectrum covering UV and visible region. Both Schottky contact and p - n junction type of ZnO-based UV photodetectors have been realized and reported.¹⁻⁴ However, owing to the lack of stable and controllable p -type ZnO films, in most cases, heterojunctions were used to fabricate ZnO-based UV photodetectors with a different p -type semiconductor, such as NiO,⁵ 6H-SiC,⁶ Si (Refs. 7-9) and so on. Undoubtedly, among all of these p -type semiconductors, the commercial silicon is the best candidate for ZnO-based p - n junction UV photodetectors because of its low cost and widely used integrated circuit technology. However, reported n -ZnO/ p -Si photodetectors⁷⁻⁹ remain an obvious photoresponse to visible light, although the UV photoresponse is increased due to ZnO, which would limit its direct application in UV detection under a visible light background.

In this letter, we report the fabrication of a visible-blind UV photodetector based on a double heterojunction of n -ZnO/insulator-MgO/ p -Si grown by molecular beam epitaxy (MBE). The photoresponse spectrum indicates a visible-blind UV detectivity of our devices with a sharp cutoff of responsivity at the wavelength of 378 nm, which corresponds to the near band edge absorption of ZnO. Moreover, an obvious suppression of photoresponse to visible light is observed in our device.

The MBE growth of a high-quality single crystalline ZnO (0001) film on Si (111) substrates by using a low-temperature interface engineering technique has been reported in our previous study.¹⁰ There, a thin MgO (111) layer was sandwiched between substrate Si (111) and top ZnO (0001) film to prevent the Si surface from oxidation and served as nuclei for single-domain epitaxy of ZnO. Now, the middle MgO layer was increased to 50 nm to form a

double heterojunction of n -ZnO/insulator-MgO/ p -Si (p -insulator- n), which retained the in-plane epitaxial relationship $[10\bar{1}0]_{\text{ZnO}} \parallel [11\bar{2}]_{\text{MgO}} \parallel [11\bar{2}]_{\text{Si}}$. Our UV photodetector fabricated based on this p -insulator- n double heterojunction contains a top ZnO (0001) layer, which is an unintentionally doped n -type film with an electron concentration of $\sim 10^{16}$ cm⁻³ and a thickness of 500 nm while the Si substrate is a 2 in. commercial boron doped p -type Si (111) wafer with a hole concentration of $\sim 10^{18}$ cm⁻³. A reference ZnO film grown on c -sapphire substrate with the same growth conditions was used to determine carrier concentration by van der Pauw method and to examine Ohmic contact of metal electrodes on ZnO. The Ohmic contact on ZnO film is a circular Ti (~ 20 nm)/Au (~ 40 nm) electrode with a diameter of 300 μm , which was defined by the standard lithography technique and was deposited by magnetron sputtering, followed by annealing at 300 °C in vacuum for 5 min. Indium was pasted on the back side of the p -Si wafer with a large area of ~ 1 mm² to serve as the Ohmic electrode on p -Si. Current-voltage (I - V) characteristics of the photodetector were measured by using a Keithley source meter 2400. A 5 W (Hg) lamp was employed to provide the 365 nm UV for the photocurrent measurement, and the spectral photoresponse was performed by using a Nicolet Evolution 300 equipment.

Figure 1 shows the I - V characteristic of the p -insulator- n photodetector in dark. The Ohmic contact of Au/Ti/ZnO is

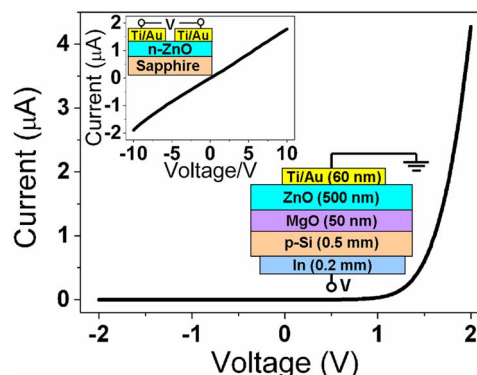


FIG. 1. (Color online) The current-voltage (I - V) characteristic of the photodetector based on n -ZnO/insulator-MgO/ p -Si double heterojunction.

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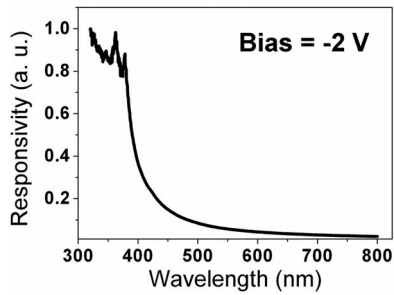


FIG. 2. Spectral responsivity of the n -ZnO/ i -MgO/ p -Si heterojunction photodetector at a reverse bias of -2 V.

confirmed by the linear I - V curve in the inset of Fig. 1. The p -insulator- n photodetector in dark presents a typical rectifying characteristic of a p - n junction diode with a rectification ratio of $\sim 10^4$ at ± 2 V. Moreover, the reverse dark current is lower than 1 nA at -2 V. To characterize our device, the electrical mode for stripe-geometry double heterojunction diode is used,¹¹ assuming an equivalent circuit of a resistance R in series with an ideal heterojunction diode. The ideal diode is described by the ideal heterojunction diode equation as

$$I = I_s \left[\exp\left(\frac{qV_j}{nkT}\right) - 1 \right], \quad (1)$$

where I_s is the reverse saturation current, V is the applied voltage on the heterojunction, n is an exponential parameter, q is the electronic charge, k is the Boltzmann constant, and T is the Kelvin temperature. Considering the series resistance R in the circuit, the derivative of current-voltage relation takes the form

$$I \frac{dV}{dI} = IR + \frac{nkT}{q}, \quad (2)$$

where V is the external voltage and dV/dI is the differential resistance.¹¹ The reverse saturation current I_s is calculated to be 0.1 nA for our photodetector. And the series resistance R is about 50 k Ω , which mainly comes from the middle MgO layer.

The typical spectral responsivity of the p -insulator- n photodetector at a reverse bias of -2 V is shown in Fig. 2. A sharp cutoff of responsivity is observed at the wavelength of 378 nm, which corresponds to the near band edge absorption of ZnO, whereas almost no photoresponse was observed over the whole visible region. The UV/visible rejection ratio is about 45, which demonstrates that the device can work well in UV region without the influence of visible light as a background.

To illuminate the principle of the visible-blind UV p -insulator- n photodetector, the energy band diagram of the n -ZnO/insulator-MgO/ p -Si double heterojunction derived from Anderson model is drawn in Fig. 3. The values of band offsets are estimated using the electron affinity 4.05,^{12,13} 0.85,¹⁴ 4.35 eV^{12,13} and band gap 1.12, 7.7,¹⁵ 3.37 eV for Si, MgO, and ZnO, respectively. Figure 3(a) shows the energy band diagram of the p -insulator- n heterojunction under the condition of thermal equilibrium. The Fermi level keeps constant across the entire region of the heterojunction resulted from carriers' diffusion with forming the depletion regions in both p - and n -sides and built-in electric field. The width of depletion region in n -ZnO is much larger than that in p -Si,

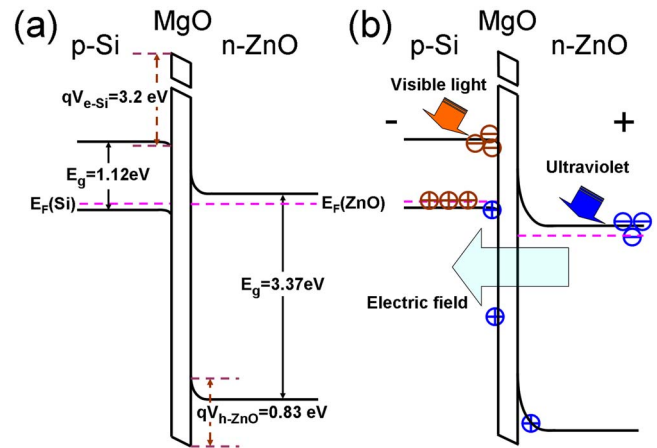


FIG. 3. (Color online) The energy-band diagrams of n -ZnO/insulator-MgO/ p -Si heterojunctions (a) under zero bias and in dark and (b) under reverse bias and in light illumination. The circles with a line and a cross inside stand for the photogenerated electrons and holes, while the brown and blue relate to the visible and UV excitation in depletion regions of p -Si and n -ZnO, respectively.

due to the high ratio of the hole concentration of p -Si to the electron concentration of n -ZnO. There is a potential barrier for electrons in p -Si with a barrier height $V_{e-Si} = 3.2$ V on the interface p -Si/ i -MgO, while on the interface n -ZnO/ i -MgO exists another one for holes in n -ZnO with a barrier height $V_{h-ZnO} = 0.83$ V. Under visible and UV illumination, the transport process of photogenerated carriers in depletion regions of both n -ZnO and p -Si at a reverse bias is schematically shown in Fig. 3(b). Visible light can transmit through the n -ZnO film and be absorbed in the depletion region of p -Si, resulting in the photogeneration process of electron-hole pairs. The internal electric field drives the photogenerated electrons toward the n -ZnO side, but they cannot cross over the interface between p -Si and i -MgO due to the high potential barrier (3.2 V) for electrons and immediately recombine with holes, which results in the block of the consecutive photogenerated process. That is the reason why no visible response was observed. On the other hand, UV light with a wavelength shorter than 378 nm is absorbed in the depletion region of n -ZnO, which results in photogenerated electron-hole pairs. Given the 500 nm thickness and the strong absorption of UV light of ZnO film, it is considered that the UV light is fully absorbed by ZnO film without any arrival on Si side. The photogenerated electrons drift toward Ti/Au electrode while holes do toward the p -Si side under the electric field. The holes can transmit through the i -MgO layer in large quantities due to the relatively low barrier height (0.83 V) on the interface n -ZnO/ i -MgO, which leads to a large photocurrent. Therefore, the p -insulator- n double heterojunction shows an obvious photoresponse to visible-blind UV light with an efficient suppression of photoresponse to visible light.

To further demonstrate the key role of the middle i -MgO layer in visible-blind UV detecting, a n -ZnO/MgO(~ 6 nm)/ p -Si double heterojunction was prepared and its photoresponse characteristic is compared with that of the n -ZnO/insulator-MgO(~ 50 nm)/ p -Si heterojunction, as shown in Figs. 4(a) and 4(b), respectively. It is revealed that the n -ZnO/MgO(~ 6 nm)/ p -Si heterojunction exhibits an obvious photoresponse to visible light and much lower ratios of UV photocurrent (I_{UV}) to visible photocurrent (I_{visible}) and

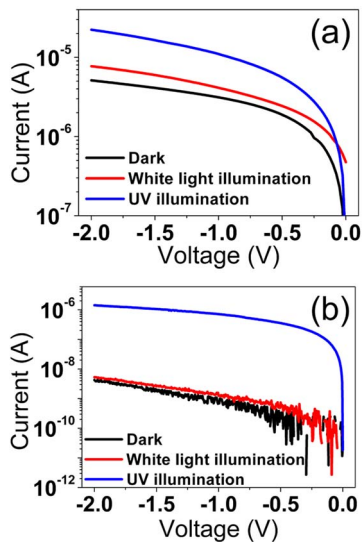


FIG. 4. (Color online) I - V characteristics of the n -ZnO/ i -MgO/ p -Si heterojunctions with (a) ~ 6 nm thick MgO and (b) ~ 50 nm thick MgO at a reverse bias in dark (black line), white light illumination (red line), and 365 nm UV illumination (blue line).

dark current (I_{dark}). Both dark current and photocurrent increase a lot as the thickness of the i -MgO layer decreases in the p -insulator- n heterojunction compared with that in Fig. 4(b). These changes depending on thickness of the middle MgO layer can be understood by considering that the 6 nm thin MgO layer serves as only a buffer layer for ZnO epilayer growth but not a good insulating layer due to the formation of nonstoichiometric MgO_x ($x < 1$) caused by the diffusion of Mg on the interface Si/MgO.¹⁰ In other words, because of the poor insulation of the thin MgO layer, the photoresponse behavior of n -ZnO/MgO(~ 6 nm)/ p -Si heterojunction is similar to that of the reported n -ZnO/ p -Si photodetectors,⁷⁻⁹ which remain an obvious photoresponse to visible light. Thus, it is necessary to form a MgO layer with a good insulation, which can effectively prevent the electron injection from p -Si side to n -ZnO side at a reverse bias in both cases of dark and visible light illumination due to the high potential barrier of MgO layer for electrons.

In summary, a visible-blind UV photodetector based on double heterojunction of n -ZnO/insulator-MgO/ p -Si has been fabricated and characterized by photoresponse spectrum. A cutoff of UV detectivity at the wavelength of 378 nm was observed, which indicates the photodetector has a photoresponse to UV but a rejection to visible light. And the high UV/visible rejection ratio at -2 V indicates a high signal-to-noise ratio of our photodetector. We suggest that the middle i -MgO layer takes the dual role, i.e., a buffer layer for the epitaxial growth of the p -insulator- n double heterojunction and a barrier layer for the realization of visible-blind UV detectivity of the p -insulator- n photodetector with a high UV/visible rejection ratio.

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