Dual-band MgZnO ultraviolet photodetector integrated with Si


Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

We have constructed a dual-band ultraviolet photodetector by growing high quality Mg_xZn_{1-x}O layers on Si substrate with molecular beam epitaxy. The device performance was studied by current-voltage, capacitance-voltage, spectra photoresponse, and time-resolved photoresponse characterizations. It demonstrates a high UV/visible light rejection ratio of more than 2 orders of magnitude and a fast response speed of less than 100 ms. The cutoff wavelength can be at solar-blind (280 nm)/visible-blind (301 nm) region by applying 1 V forward/2 V reverse bias. The working principle of the dual-band photodetector was finally investigated by interpretation of the specific carrier transport behavior with the energy band diagram. © 2013 AIP Publishing LLC [http://dx.doi.org/10.1063/1.4802486]
muti-emission behavior as shown in Fig. 1(b). Comparing Fig. 1(c) with Fig. 1(b), the PLE peak of the H-MgZnO layer is at 283 nm with a 90 meV blue shift from the PL emission. This blue shift is known as Stokes shift which is induced by the inhomogeneous distribution of electrostatic potentials in MgZnO ternary alloys. The PD was finally fabricated by photolithography and liftoff technique with Ti/Au electrode as the front contact on the MgZnO epilayer and indium as the back contact on Si substrate. The top view of the PDs in optical microscope can be seen in Fig. 1(d).

Current-voltage (I-V) measurement result of the PD (Fig. 2(a)) shows a distinct rectifying behavior with a rectification ratio of about 80 under $V = 3$ V. A low leakage current of $I = 2 \times 10^{-9}$ A was found at $V = 3$ V in the dark, i.e., $1.58 \times 10^{-6}$ A cm$^{-2}$, which indicates a good quality of MgZnO/BeO/Si interfaces. In the forward bias, the curve can be divided into two regions as shown in Fig. 2(a). In region I where the applied bias is lower than 2.2 V, the line shape follows the relationship of a p-n junction

$$I = I_0 \exp\left(\frac{qV}{nKT}\right) - 1,$$

where $I_0$, $V$, $n$, $K$, and $T$ are reverse saturation current, bias voltage, ideality factor, Boltzman constant, and absolute temperature, respectively. By fitting the curve, the value of ideality factor is determined as 8.9. Such a large ideality factor may result from the large series resistance $R_s$, which is estimated as $4 \times 10^7$ $\Omega$ by

$$R_s = \frac{dV}{dI} - nKT/I_0.$$

In region II when the bias rises above 2.2 V, it is not a simple exponential relationship between the current and voltage, which may be caused by the combination of Schottky contact nature of Ti/Au electrode and space charge limited current.

Capacitance-voltage (C-V) measurement was conducted at 10 MHz from $-5$ V to 4 V. It is found that the capacitance of the PD stays at around 1.49 pF (Fig. 2(b)). We ascribe this to the huge series resistance from MgZnO. Because of the completely depleted thin MgZnO layers (comparing with the thick Si substrate), the depletion depth profile of the device is not seriously changed as almost all the applied bias falls on the MgZnO layers. As a result, the capacitance changes little against applied voltage. Therefore, almost constant capacitance was observed from the C-V measurement. By fitting the curve, the average carrier concentration and the electron mobility of MgZnO film are estimated as $1 \times 10^{14}$ cm$^{-3}$ and 0.01 cm$^{-1}$ V$^{-1}$ s$^{-1}$, respectively. The strong Mg-O bonding energy in MgZnO alloys results in a large decrease of oxygen vacancy density, which contributes to a significant reduction of n-type carriers. The low carrier mobility is caused by the strong lattice scattering in the deformed MgZnO crystal field. Low mobility always means that the carriers possess low energy; hence, they are prone to being blocked by energy barriers (or band offsets), relating to the device working principle discussed later.

The interesting cutoff wavelength-selectable photoresponse features were shown in Fig. 3(a). When the PD is working under a forward bias of 1 V, we can see that a responsivity of $13$ mA W$^{-1}$ with a sharp cutoff at 280 nm corresponds to the optical bandgap of H-MgZnO layer, right in the solar-blind spectrum region. The rejection ratio of solar-blind UV to visible light is about 2 orders of magnitude. While under a reverse 2 V bias, the peak responsivity is $6$ mA W$^{-1}$ with a 301 nm cutoff in visible-blind region, corresponding to the optical bandgap of L-MgZnO layer. The shoulder response at 347 nm arises from the thin B-MgZnO layer. Regardless of forward or reverse biases, no visible light response was observed from the silicon substrate.

Response speed is another critical parameter which decides whether a PD can be used in practical applications. In our experiments, transient response was performed by periodic UV illumination. It is found that the PD has a very fast response speed to UV light. The 10%-90% “on” and “off” response time both at forward and reverse biases is less than 100 ms (Fig. 3(b)), which is the limit of our testing system. No persistent photocurrent was observed, indicating a high
crystalline quality of the film with very few deep level defects or interface states.\textsuperscript{21,22}

To understand the working principle of the solar-blind/visible-blind selective UV PD, we used the energy band diagram which was schematically drawn according to Anderson-Shockley model. As shown in Fig. 4(a) under equilibrium condition, type-II heterojunction forms at the B-MgZnO/Si interface whilst type-I heterojunctions form between the three MgZnO epitaxial layers. When the UV PD is under illumination at a forward bias as shown in Fig. 4(b), photons with energy higher than 4.4 eV (wavelength <280 nm) will be strongly absorbed near the surface of the H-MgZnO layer and hence generate electron-hole (e-h) pairs. Under the driving force of the electrical field, the photon-generated holes and electrons can easily drift to the Ti/Au electrodes and Si substrate, respectively, raising a strong solar-blind response at 280 nm (black line in Fig. 3(a)). In the case of lower energy (wavelength >280 nm) illumination, photons can penetrate the H-MgZnO layer and be absorbed by low-Mg content L-MgZnO, B-MgZnO, and Si. However, the photon-generated holes will be effectively blocked by the barriers of valence band offsets and recombine with the electrons, making no contribution to electrical conduction. Therefore, only solar-blind photoresponse from the H-MgZnO layer was observed at forward bias.

However, when the PD is under illumination at a reverse bias, as shown in Fig. 4(c), the situation is much different. Because of the limit penetration depth of UV rays in wide bandgap semiconductors (around 50 nm for MgZnO),\textsuperscript{23} photon-generated e-h pairs by UV light will congregate near the surface of H-MgZnO layer in the case of illumination with a wavelength less than 280 nm. Holes cannot immediately transport through the whole H-MgZnO layer to reach Si substrate due to its low mobility as mentioned above but...
rapidly recombine with those electrons which are blocked by the Schottky barrier before forming a distinct photocurrent. The L-MgZnO layer is much thinner and closer to the Si substrate. Therefore holes generated by lower energy photons can transport to the Si substrate easily, resulting a UV-B response at a wavelength of 301 nm (red line in Fig. 3(a)). The shoulder response at 347 nm from the B-MgZnO layer was observed in a similar fashion. Interestingly there is no visible light response from Si substrate at reverse bias either, which can be illustrated by the electron-electron scattering process in an asymmetric quantum well.24 Notice the conduction band minimum of B-MgZnO layer falls between those of the Si substrate and L-MgZnO layer, forming an asymmetric electron well as shown in Fig. 4(d).Photon-generated electrons in Si were scattered by electrons from this quantum well and the barrier at B-MgZnO/L-MgZnO interface. As a consequence, the electrons generated in Si wafer by visible light illumination cannot reach the H-MgZnO side to form photocurrent. Additionally, due to a series of band offsets for electrons, the responsivity at reverse bias is much lower than that at forward bias as shown in Fig. 3(a). Although the value of photoresponsivity at both forward and reverse biases is still not high enough, we believe it can be promoted by further optimization of the device structures.

In summary, a type of cutoff wavelength-selectable UV PD was invented by growing high-quality wurzite Mg$_{x}$Zn$_{1-x}$O layers with different Mg contents on Si substrate using rf-MBE technique. By simply controlling the polarity of the applied bias, the PD can respond to either solar-blind waveband or visible-blind waveband with sharp cutoff wavelengths. The UV/visible rejection ratio is about 2 orders of magnitude with a fast response speed less than 100 ms. This kind of PD combines the important 3rd-generation oxide semiconductor with the well-developed 1st-generation Si semiconductor, which we believe will have a strong influence on the realization of integrated multi-band UV detectors.

This work was supported by the Ministry of Science and Technology (Grant Nos. 2011CB302002, 2011CB302006, and 2009CB929404) of China, the National Science Foundation (Grant Nos. 61076007, 11174348, 51272280, 11274366, and 61204067), Chinese Academy of Sciences, and Beijing Synchrotron Radiation Facility.

---