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Metal–insulator–semiconductor–insulator–metal structured titanium dioxide ultraviolet photodetector

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Abstract

Titanium dioxide (TiO_2) thin films were prepared by an atomic layer deposition technique and a metal–insulator–semiconductor–insulator–metal structured ultraviolet photodetector was fabricated from the TiO_2 thin films. Meanwhile, a metal–semiconductor–metal structured photodetector was also fabricated under the same condition for comparison. By measuring their photoresponse properties, it was found that the existence of an insulation layer is effective in improving the photodetector's responsivity. The mechanism for the improvement has been attributed to the carrier multiplication occurring in the insulation layer under a high electric field.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Photodetectors operating in the ultraviolet (UV) region have many potential commercial and military applications. For example, visible-blind UV photodetectors can be used in space communications, ozone monitoring and flame detection [1–6]. Currently, Si is still the prevailing material for UV detection. However, optical filters are indispensable for UV detection using Si-based photodetectors because they usually show obvious response to visible and near infrared light for the small bandgap of Si (1.12 eV), which will increase the complexity and cost of the photodetectors. With the advent of optoelectronic devices fabricated on wide bandgap semiconductors, it becomes possible to produce high performance UV photodetectors based on these materials, and GaN- and ZnO-based materials have been highlighted in this field [7–10]. However, since both ZnO and GaN are direct bandgap semiconductors, radiative recombination may occur between the photo-generated electrons and holes before they are separated and collected; thus the performance of the photodetectors will be degraded. As a wide bandgap semiconductor, titanium dioxide (TiO_2) has a similar bandgap (3.2 eV) to GaN and ZnO. Its indirect bandgap character makes TiO_2 a strong candidate in the application of UV photo-detection [11, 12]. Up to date most of the reports on TiO_2-based UV photodetectors are metal–semiconductor–metal (MSM) structured, in which two interdigital contacts are deposited on top of TiO_2 layers. However, the responsivity of the MSM photodetectors is usually below expectation because the photo-generated carriers may be trapped by the structural imperfections on the surface of the films. One possible way to solve this problem is to insert an insulating layer between the metal contacts and the TiO_2 layer to form a metal–insulator–semiconductor–insulator–metal (MISIM) structured photodetector. In fact, such an insulation layer had been

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employed to improve the performance of infrared and visible photodetectors in the 1990s [13–16]. It was found that the performance of the photodetectors was really improved effectively in this way. However, no report on MISIM structured TiO_2 UV photodetectors can be found to the best of our knowledge.

In this paper, an MISIM structured TiO_2 UV photodetector was prepared, and it was found that the responsivity of the photodetector is significantly larger than that of the MSM structured photodetector, and the mechanism for the enhancement has been discussed.

2. Experiments

The TiO_2 films studied in this paper were prepared on glass substrates in an atomic layer deposition (ALD) technique. The detailed growth conditions can be found elsewhere [17]. The precursors used were titanium tetraisopropoxide (TTIP : $Ti[OCH(CH_3)_2]_4$) and water (H_2O), and high-purity nitrogen was used as a carrier to lead the precursors into the growth chamber. The substrate temperature was fixed at 200 °C and the flow rate of nitrogen carrier at 20 sccm during the growth process. The growth cycle was composed of a 10 ms pulse of H_2O, a 3 s purging to exhaust the excess precursor, a 15 ms pulse of TTIP and another 3 s purging. The above cycle was repeated 2500 times for the growth. TiO_2 films employed as the active layer of the photodetectors in this paper were obtained in this way. An aluminium oxide (AlO_x) layer was deposited onto the TiO_2 thin films using a magnetron sputtering equipment (JZCK-400DJ) acting as an insulation layer for the MISIM photodetector. The growth conditions of the AlO_x layer were as follows: the background vacuum in the growth chamber was 9.0×10^{-4} Pa. The temperature in the chamber was fixed at 300 °C and the pressure at 1.0 Pa during the sputtering process. Finally, Au contact was deposited onto the AlO_x layer using vacuum evaporation, and interdigital electrodes were formed via a lithograph and wet-etching process. Meanwhile, an MSM structured TiO_2 photodetector was also fabricated under the same procedure for comparison. For the MSM photodetector, the fabrication process was the same as the MISIM one except that the AlO_x layer was absent. The absorption spectrum of the TiO_2 films was recorded in a Shimadzu UV-3101PC scanning spectrophotometer. Current–voltage (I–V) curves of the photodetectors were measured using a Hall measurement system (LakeShore 7707). The spectral responsivity of the photodetectors was measured using a 150 W Xe lamp, monochromator, chopper (EG&G 192) and lock-in amplifier (EG&G 124A).

3. Results and discussion

The UV–visible absorption spectrum of the TiO_2 films is shown in figure 1. There appears an absorption edge at around 350 nm, which corresponds to the near-band-edge absorption of TiO_2. The absorption in the visible spectrum region is significantly smaller than that in the UV region, which suggests that the TiO_2 films are promising in the application of UV photodetectors [1, 18].

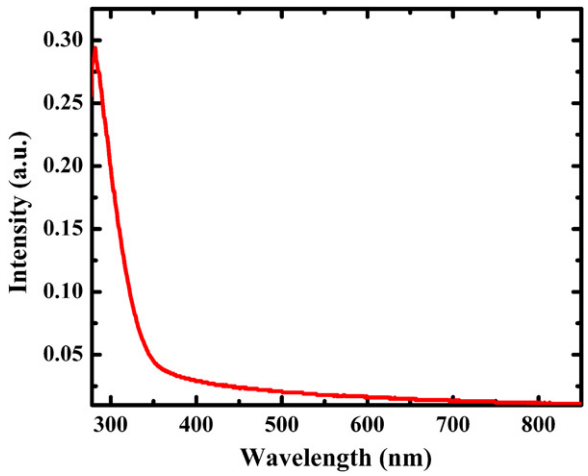

Figure 1. The UV–visible absorption spectrum of the TiO_2 films.

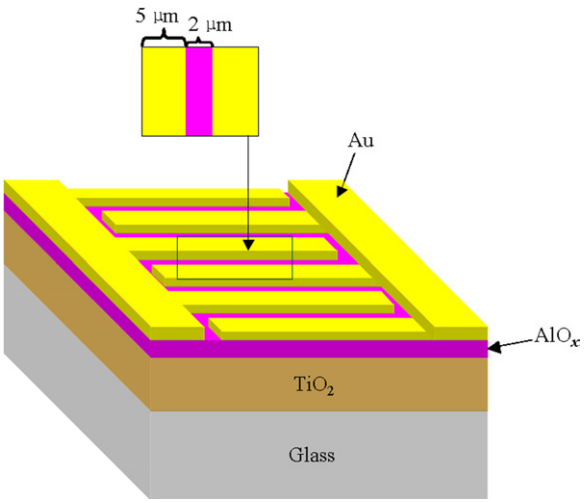

Figure 2. Schematic diagram of the MISIM structured TiO_2 UV photodetector.

Figure 2 shows the schematic diagram of the MISIM photodetector fabricated from the TiO_2 films. The thickness of the TiO_2 film is about 55 nm, and that of the AlO_x layer is about 20 nm. The Au fingers of the interdigital electrode are 500 μm in length and 5 μm in width, and the inter-electrode spacing is 2 μm. The I–V curves of the MISIM and MSM structured TiO_2 photodetector measured under dark conditions are shown in figure 3. An obvious rectifying effect can be observed from both curves, which indicates that Schottky behaviours have been obtained. It is noteworthy that the dark current of the MISIM photodetector is smaller than that of the MSM one at small bias (<4 V), while the situation is reverse at a large bias (>4 V). The above phenomenon may result from the carrier multiplication due to the impact ionization process occurred in the AlO_x layer under a high electric field, which will be detailed in the following text. Note that the slight asymmetric lineshape of the I–V curves may be caused by the different contact states at the metal–insulator interfaces.

The response spectra of the MISIM and MSM structured photodetectors under 30 V bias are shown in figure 4. The two photodetectors have a very similar response curve, and both

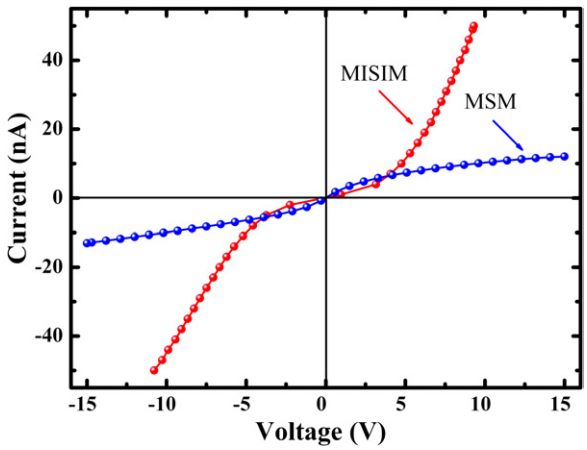

Figure 3. I–V curves of the MISIM and MSM structured TiO_2 UV photodetectors measured in dark.

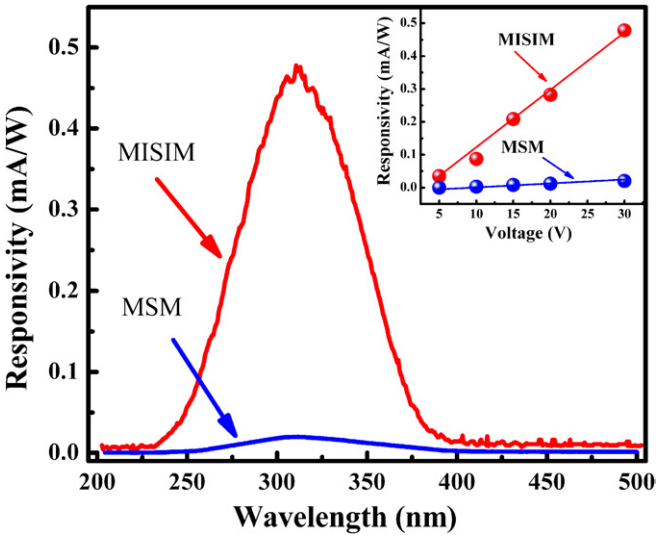

Figure 4. Photoresponse of the MISIM and MSM structured TiO_2 UV photodetectors measured at 30 V bias; the inset shows the dependence of the peak responsivity of the two photodetectors on applied bias.

have a peak responsivity at around 310 nm. Nevertheless, the maximum responsivity of the MISIM photodetector is about 0.48 mA W^{-1}, which is almost 23 times larger than that of the MSM one (0.02 mA W^{-1}). The dependence of the peak responsivity of the MISIM and the MSM structured TiO_2 photodetectors on the applied bias is shown in the inset of figure 4. It can be found that by increasing the applied bias, the peak responsivity of both photodetectors increases almost linearly in the range from 5 to 30 V. Note that the discrepancy between the responsivity of the two photodetectors becomes even larger at large bias, which is also a result of the carrier multiplication process, as depicted below.

The mechanism for the improved responsivity is due to the insertion of the AlO_x insulation layer. A schematic illustration of the band alignments of the MISIM structure is shown in figure 5. Owing to its dielectric nature, most of the voltage will be applied onto the insulation layer. At 4 V bias, the electric field in the AlO_x layer is about 1×10^6 V cm^{-1} considering the thickness of the AlO_x is only about 20 nm. Under the

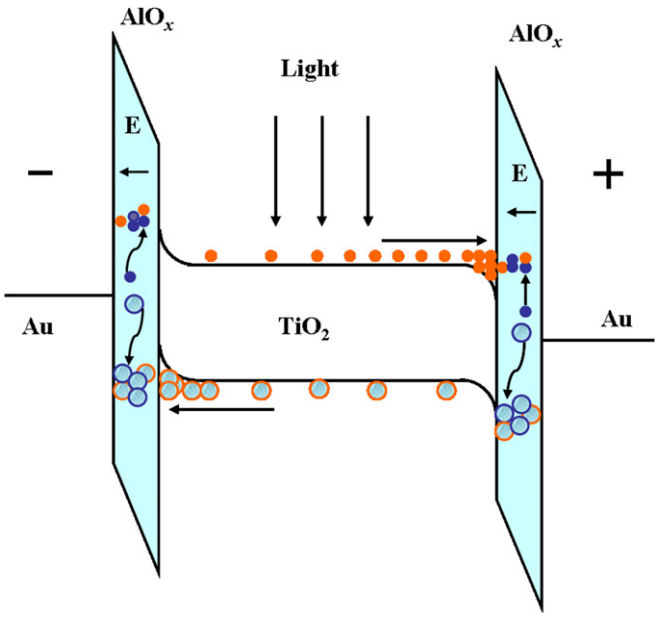

Figure 5. The schematic illustration of the band alignment of the MISIM structured TiO_2 UV photodetector revealing the carrier multiplication process.

effect of the bias voltage, the electrons and holes in the TiO_2 film will shift to the electrodes. At the TiO_2/AlO_x interface, the carriers will be accelerated considerably under such a high electric field. With much kinetic energy, they will impact with the lattice of the AlO_x layer, and some electrons in the valence band will be excited. In this way, some additional electrons and holes are generated in the AlO_x layer by the impact ionization process [19, 20]. These generated carriers will also drift to the corresponding electrodes under the bias. Thus the number of carriers that can be collected by the interdigital electrodes is increased. As a result, the dark current of the MISIM photodetector is larger than that of the MSM one at large bias (>4 V). While at small bias (<4 V), the electric field in the AlO_x layer is below its threshold ionization energy, thus no impact ionization process occurs, and the AlO_x layer acts as a blocker that hinders the drift of carriers. Therefore, the dark current of the MISIM photodetector is smaller than that of the MSM one at small bias, but larger at large bias, as shown in figure 3.

As for the responsivity of the photodetectors, the electric field in the insulation layer will be 7.5×10^6 V cm^{-1} at 30 V bias, which is larger than the threshold ionization energy of the AlO_x layer. Thus, under the impact of the photo-generated carriers in the TiO_2 film, carriers multiplication process will occur in the AlO_x layer. While in the MSM structured photodetector, such a carrier multiplication process is absent because of the absence of the insulation layer. As a result, the responsivity of the MISIM photodetector is significantly enhanced. At larger bias, the carriers will gain more kinetic energy, thus more carriers will be generated in the impact ionization process. Therefore, the responsivity discrepancy between the two photodetectors increases at larger bias, as shown in the inset of figure 4.

4. Conclusions

In summary, MISIM structured TiO_2 UV photodetectors have been fabricated. It is found that the existence of an AlO_x insulation layer underneath the interdigital electrodes enhances the responsivity of the photodetector significantly compared with a MSM structured photodetector. The mechanism for the enhancement has been attributed to the carrier multiplication process occurring in the insulation layer caused by impact ionization under the relatively high electric field.

Acknowledgments

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