Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp139-140

C-2-03

Wafer Transfer of Hydrothermally Grown ZnO Film and Its Application on Vertical Structure Ultraviolet Photodetectors with Metal Substrate

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Abstract:

Vertical structure hydrothermally grown (HTG) ZnO-based heterojunction (HJ) ultraviolet photodetector (UV-PD) via a simple transfer process is demonstrated. An electroplated 100-μm-thick nickel (Ni) layer was deposited onto the HJ-PD surface and the layer structure was removed from the original substrate through a mechanical peeling process. The optoelectronic properties of vertical and lateral UV-PD under UV light (365 nm, 1 mW/cm^2) are investigated and discussed. Owing to the much improved optoelectronic performances of the vertical structure allowing a relatively shorter current path and more uniform current distribution, a UV sensitivity (J_{UV}/J_{dark}) as high as 183 has been obtained from the prepared vertical HTG-ZnO-based UV-PD.

1. Introduction

Zinc oxide (ZnO) is a well-known semiconductor material with a direct wide band gap of 3.37 eV and a large exaction binding energy of about 60 meV at room temperature, which make it suitable for ultraviolet photodetectors (UV-PDs) application [1-2]. For past decades, hydrothermal growth (HTG) of single crystalline ZnO films on sapphire substrate and its application on ultraviolet photodetectors (UV-PDs) have attract a lot of attention [3]. However, the material properties of HTG-ZnO films grown on SiO_2/Si, metal or glass substrates are usually poor because of the lack of lattice-matched substrates, which limits its device applications. Moreover, the interface between the HTG-ZnO film and substrate is abundant in dislocations and defects, which strongly degrades both the electric and photoelectric properties. To avoid the impact of the HTG-ZnO/substrate interface, a simple substrate transfer technique is demonstrated. Using a mechanical peeling process, the whole HTG-ZnO layer was removed from the original substrate. Characterization of the fabricated vertical-structure HTG-ZnO-based UV-PDs and comparisons with those of convention lateral structures without wafer transfer are presented and discussed.

2. Experimental

The key fabrication processes of the vertical structure UV-PDs based on HTG ZnO film via mechanical peeling transfer are schematically shown in Fig. 1. First, a 100-nm-thick ZnO films was sputtered on sapphire substrate (001) using radio frequency (RF) sputtering to serve as a seed layer. These samples were placed in a solution of 0.06 M zinc nitrate hexahydrate ($Zn(NO_3)_2{\cdot}6H_2O$) and hexamethylenetetramine ($C_6H_{12}N_4$) at 70°C for 15 h for the growth of ZnO films (1 μm). After that, these samples were rinsed in deionized water for 10 min and dried in nitrogen (N) gas. Second, a 500-nm-thick p-type cuprous oxide (p-Cu_2O) film was deposited on the HTG-ZnO films by RF sputtering. Third, a 200-nm-thick nickel (Ni) electrodes was deposited on the p-Cu_2O layer by electron beam (e-beam) evaporation. Subsequently, an electroplated 100-μm-thick nickel (Ni) layer was made, which will serve as a new substrate and the p-electrode for UV-PD. Finally, the Cu_2O/HTG-ZnO device was lifted off from sapphire substrate by a mechanical peeling process, and then a 200-nm-thick titanium (Ti) layer for serving as the n-electrode was deposited on HTG-ZnO films by e-beam evaporation. It is noted that the adhesion of the HTG-ZnO film to the seed layer/sapphire substrate is much weaker as compared with other interfaces of the layer structure, which thus guarantees the transfer of the device structure with a good yield. Also note that the sapphire substrate after wafer removal process and be reused for other HTG process. A comparison of the vertical structure ZnO-based HJ HTG UV-PD and the one with conventional lateral structure is shown in Fig. 2.

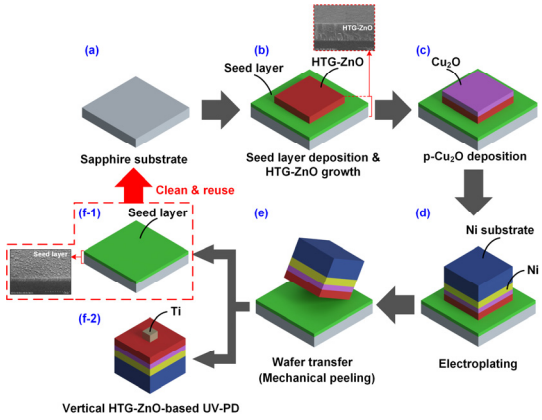
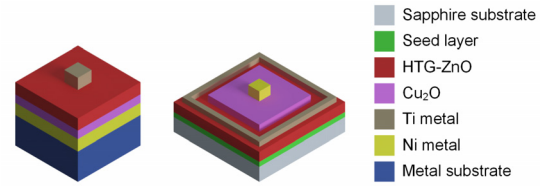


Fig. 1 The key process flow of vertical structure HTG-ZnO-based UV-PD via a mechanical peeling wafer transfer technique.



(a) (b)

Fig. 2 Schematic diagrams of (a) vertical and (b) lateral structure HTG-ZnO UV-PD structures.

3. Results and Discussion

The material properties of the prepared ZnO films were analyzed by X-ray diffraction (XRD) and results were shown in Fig. 3. On the basis of the diffraction peak that corresponded to the (002) plane shown in Fig. 3, the growth of ZnO films via HTG are indexed to have a hexagonal wurtzite signal according to the standard JCPDS card [4]. This indicates that the HTG ZnO films are mainly composed of self-organized growth and closely packed crystalline columnar ZnO with the *c*-axis vertical to the substrate surface.

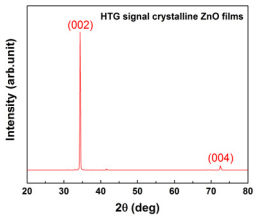


Fig 3 XRD pattern of signal crystalline HTG-ZnO films with signal crystalline structure.

Figure 4 (a) shows the energy band diagram of the p-Cu_2O/HTG-ZnO UV-PD under thermal equilibrium. Note that the electron concentrations in the HTG-ZnO film and the hole concentration in the annealed Cu_2O are 2×10^{17} and 2×10^{14} cm^{-3}, respectively, based on Hall measurements. A much larger depletion region (about 500 nm) can be expected on the Cu_2O layer, which would play the main role in photo detection. The band offsets between ZnO and Cu_2O are ΔE_c=0.9 eV and ΔE_v = 2.17 eV, respectively [5]. The J-V characteristics of the vertical and lateral HTG-ZnO-based UV-PDs in darkness show in Fig. 4 (b). It can be seen that the vertical structure HTG-ZnO-based UV-PDs exhibits a higher forward current and a lower reverse current within 0 ~ -1.5 V, which could be mainly attributed to that the vertical structure allows a shorter current path and get rid of seed layer after wafer transfer, as a result, a much smaller series resistance and a more uniform forward current distribution as compared with that of the lateral device can be obtained.

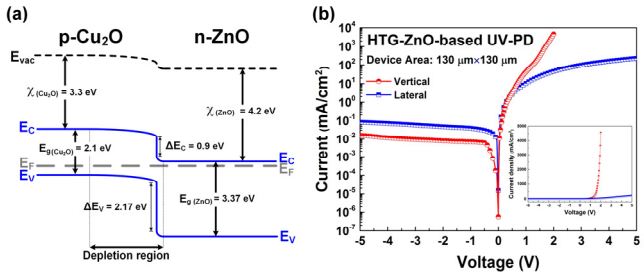


Fig. 4. (a) The energy band diagram of p-Cu_2O/HTG-ZnO UV-PD under thermal equilibrium. (b) Experimental J-V characteristics of the fabricated HTG-ZnO-based UV-PDs in the dark. The inset shows the same J-V curves in linear scale.

Figure 5 shows the measured reverse-biased J-V characteristics of the vertical and lateral HTG-ZnO-based UV-PDs in the dark and under visible and UV light (365 nm, 3 mW/cm^2) illumination conditions. The experimental results indicate that both the vertical and lateral structures devices are visible light blind and with good sensitivity to UV light. Note the vertical device is with a relatively more stable photocurrent as compared with the lateral device.

Figure 6 shows the dynamic photo response of the vertical and lateral UV-PDs. The response times of the devices with vertical and lateral structure are about 4.5 and 54 s and the recovery times are about 1.4 and 23 s, respectively. The vertical device shows a 183-fold increase in the current at -1 V with irradiation under 365 nm UV light and a power density of 3 mW/cm^2 compared with the lateral structure. The enhanced photo response of the vertical device could be mainly attributed to the lower series resistance and better current distribution. In addition, light reflection on the rough and texture surface of the single crystalline HTG-ZnO film after the removal of sapphire substrate is significantly suppressed, which could further enhance the photo response of the vertical device.

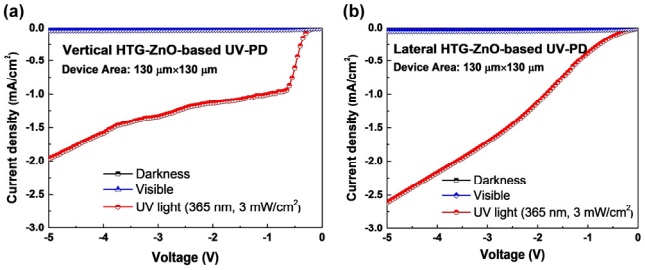


Fig. 5. Comparisons of experimental J-V characteristics of vertical and lateral HTG-ZnO-based UV-PDs irradiated by visible and UV lights.

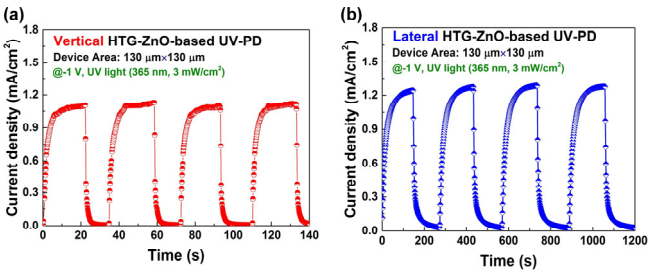


Fig. 6. Transient response of photocurrent density of (a) vertical and (b) lateral HTG-ZnO UV PDs. Wavelength and intensity of UV light are 365 nm and 3 mW/cm^2, respectively.

Table I Comparison of optoelectronic properties of vertical and lateral HTG-ZnO-based UV-PDs.

Structure	Response (J_{UV}/J_{dark})	J_{UV} (mA/cm^2)	J_{dark} (mA/cm^2)	Rise time (s)	Fall time (s)
Vertical (this work)	**183**	**1.10**	**0.006**	**4.5**	**1.4**
Lateral (this work)	40	1.24	0.03	54	23
[6]	16.23	-	-	~4	~3
[7]	2.5	-	-	10	10

4. Conclusions

The fabrication of a vertical structure Cu_2O/HTG-ZnO HJ UV-PDs via a simple wafer transfer process with considerably improved UV sensitivity has been demonstrated. Experimental results reveal that the vertical HTG-ZnO-based UV-PDs films have a superior response characteristic to UV light (3 mW/cm^2 at 365 nm) with an increase in the photocurrent of about 183-fold compared with the device with a lateral structure. The improved UV light response of the vertical device could be attributed to the vertical structure provides a shorter current path and lower interface trap density than those of the conventional lateral one. It is expected that the wafer transfer technology demonstrated in this study could be very beneficial for device application based on HTG ZnO films.

Acknowledgements

This work was supported by the Ministry of Science and Technology (MOST), Taiwan, under contract No. MOST 104-2221-E-006-066, and MOST 104-2221-E-006-130-MY3.

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