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Monoclinic-Ga_2O_3 nanowire-based solar-blind photodetectors

Wen-Yin Weng[1], S. J. Chang[1], G. J. Huang[1] and S. P. Chang[1]

[1] Institute of Microelectronics and Department of Electrical Engineering
Center for Micro/Nano Science and Technology
Advanced Optoelectronic Technology Center
National Cheng Kung University, Tainan 701, TAIWAN
Phone: (+886) 6-2757575-62400-1208 E-mail: weng.wenyin@gmail.com

1. Introduction

Monoclinic-Ga_2O_3 (β-Ga_2O_3) is an interesting semiconductor material that has attracted much attention in recent years. It has been shown that thin-film-type β-Ga_2O_3 can be used for gas sensors, phosphors, transparent conductors, and transparent electronic devices. With bandgap energy of 4.9 eV, thin-film-type β-Ga_2O_3 solar-blind photodetectors have also been demonstrated [1]. Other than thin-film-type photodetectors, it is also possible to fabricate one-dimensional (1D) nanowire photodetectors. Compared with thin-film-type photodetectors, 1D nanowire photodetectors could provide a high photoconductivity gain due to the surface-enhanced electron-hole separation efficiency [2-3]. Recently, Feng et al. reported the growth of β-Ga_2O_3 nanowires by evaporating metallic Ga directly onto Au-coated Si substrate [4]. For the fabrication of solar-blind photodetector, they carefully placed one single nanowire to connect two pre-fabricated Au electrodes. Although they achieved a high photocurrent to dark current contrast ratio, no spectral response of their β-Ga_2O_3 nanowire photodetectors was reported. In this study, we report the vapor-liquid-solid (VLS) growth of β-Ga_2O_3 nanowires by heating the GaN/sapphire template and the fabrication of solar-blind β-Ga_2O_3 nanowire photodetector. Physical properties of the nanowires and the electro-optical properties of the fabricated photodetector will also be discussed.

2. Experimental

The GaN/sapphire template used in this study was prepared by depositing a 30-nm-thick GaN low-temperature nucleation layer and a 2-μm-thick GaN epitaxial layer on sapphire substrate by metalorganic chemical vapor deposition. Prior to the growth of nanowires, we dipped the GaN/sapphire template in a diluted hydrochloric acid water solution ($HCl:H_2O$=1:1) for 5 minutes to remove native oxide. We then deposited a 3-nm-thick Au film onto the GaN surface by e-beam evaporator. Subsequently, we placed the template on an alumina boat, and inserted it into a quartz tube furnace purged with Argon gas. We then raised the temperature to 500^{o}C and kept at 500^{o}C for 20 min to form Au nano-particles. After the formation of Au nano-particles, we raised the temperature again to 1100^{o}C to grow the nanowires by injecting 0.8 sccm O_2 gas into the furnace for 120 min. After the growth, the furnace was naturally cooled down to room temperature.

3. Results and Discussion

Figure 1(a) shows top-view field emission scanning electron microscope (FESEM) image of the nanowires prepared in this study. As shown in this figure, it was found that randomly oriented 1D nanowires were grown across the entire 2-inch GaN/sapphire template. Figure 1(b) shows an enlarged top-view FESEM image of the same sample. It was found that average length and diameter of the nanowires were around 10 μm and 100 nm, respectively. It was also found that an Au nano-particle exists on the top of each nanowire. This indicates that these nanowires were grown by VLS process. Figure 2 shows x-ray diffraction (XRD) spectrum measured from the as-grown sample. The sharp XRD peaks observed in the spectrum can be indexed to (102), (-104), (-202), (-111), (111), (104), (-113), (-213), (-313), (311) and (-217) of β-Ga_2O_3 (JCPDS file No.11-0370). The observation of these peaks indicates that the nanowires prepared in this study were β-Ga_2O_3 with the lattice constants a = 5.80Å, b = 3.04Å, and c = 12.23Å. At atmospheric pressure, it is known that GaN decomposes at 800^{o}C [5]. During the growth of nanowires, the GaN epitaxial layer will decompose into metallic Ga and N_2 gas since the growth temperature was 1100^{o}C. The metallic Ga and Au nano-particles should then form Au-Ga alloy. With the injected O_2 gas, β-Ga_2O_3 nanowires can thus be grown through VLS process.

For the fabrication of nanowire photodetector, a thick Ti/Al/Ti/Au (30/100/30/100nm) film was deposited through an interdigitated shadow mask onto the nanowires to serve as contact electrodes. We designed the pattern on the metal mask so that fingers of the interdigitated electrodes were 2 mm wide and 2.2 mm long with a finger spacing of 0.2 mm. It should be noted that the high density, randomly oriented nanowires shown in figure 1 could provide electrical paths for the two interdigitated electrodes. Figure 3 shows current-voltage (I-V) characteristics of the fabricated β-Ga_2O_3 nanowire photodetector measured in dark (dark current) and under illumination (photocurrent). During photocurrent measurement, we illuminated the sample with 255 nm UV light by dispersing a 300 W xenon lamp with a monochromator. It was found that measured dark current and photocurrent both increased linearly with the applied bias. Such an observation suggests that contacts between the deposited Ti/Al/Ti/Au electrodes and β-Ga_2O_3 nanowires were pure Ohmic. With 10 V applied bias, it was found that measured dark current was only 2.44×10^{-10} A.

The small dark current should be attributed to the highly resistive nature of the undoped β-Ga_2O_3 nanowires.

Figure 4 shows spectral responses of the fabricated β-Ga_2O_3 nanowire photodetector measured with different bias voltages. It should be noted that photoresponses of the fabricated photodetector were flat in the short-wavelength region while sharp cutoff occurred at 255 nm. This indicates that the fabricated β-Ga_2O_3 nanowire photodetector was indeed solar-blind. With an incident light wavelength of 255 nm and an applied bias of 1 V, it was found that measured responsivity of the photodetector was 6.8×10^{-5} A/W. As we increased the bias voltage to 10 V, it was found that measured responsivity increased to 8×10^{-4} A/W. It can be seen clearly that measured responsivity increased with applied bias. This suggests that photoconductive gain exist in the sample. Similar to ZnO nanowire photodetectors, oxygen molecules on the nanowire surface carry negative charges by capturing free electrons from the n-type β-Ga_2O_3. Therefore, it creates a depletion layer with low conductivity near the surface. Under 255 nm UV irradiation, electron-hole pairs will be generated in the depletion region. The photo-generated holes oxidize the adsorbed negatively charged oxygen ions on the surface while the remaining electrons in the conduction band increase the conductivity. These oxygen-related hole-trap states at the nanowire surface prevent charge-carrier recombination and prolong the photo-carrier lifetime. Thus, we can achieve the large photoconductivity gain in our β-Ga_2O_3 nanowire photodetector [2-3]. The large photoconductive gain suggests that the β-Ga_2O_3 nanowire photodetector proposed is potentially useful as a solar-blind photodetector.

4. Conclusions

In summary, we report the growth of β-Ga_2O_3 nanowires by heating the GaN/sapphire template and the fabrication of β-Ga_2O_3 nanowire photodetector by depositing interdigitated contact electrodes. It was found that average length and diameter of the β-Ga_2O_3 nanowires were around 10 μm and 100 nm, respectively. It was also found that the fabricated photodetector was solar-blind with sharp cutoff at 255 nm. With an incident light wavelength of 255 nm and an applied bias of 10 V, it was found that measured responsivity of the photodetector was 0.8 mA/W.

References

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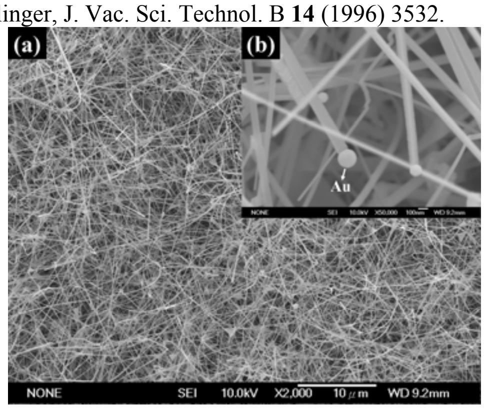

Figure 1 (a) Top-view SEM micrograph of the β-Ga_2O_3 nanowires prepared in this study. (b) shows an enlarged top-view SEM micrograph of the same sample.

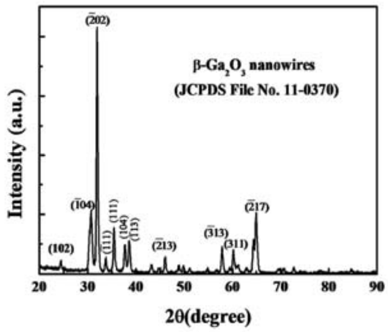

Figure 2 XRD spectrum measured from the as-grown sample.

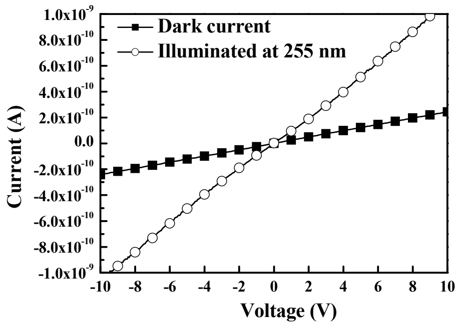

Figure 3 I-V characteristics of the β-Ga_2O_3 nanowire photodetector measured in dark and under 255 nm UV illumination.

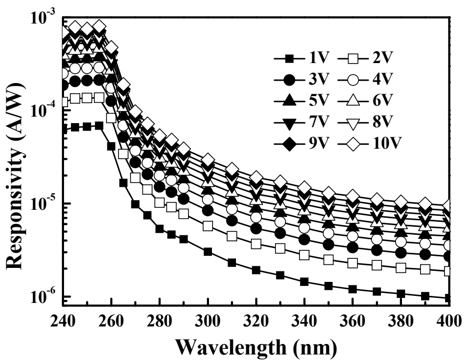

Figure 4 Spectral responses of the β-Ga_2O_3 nanowires photodetector measured with different applied biases.