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Deep ultraviolet photodiodes based on the β-Ga_2O_3/GaN heterojunction

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ABSTRACT

A deep ultraviolet (UV) photodiode was fabricated using a heterojunction between β-Ga_2O_3 and GaN, and its UV sensitivity was investigated. A thin β-Ga_2O_3 layer was prepared on p-type GaN template substrate by gallium evaporation in oxygen plasma. The β-Ga_2O_3 layer had a (−2 0 1)-oriented crystal structure on (0 0 1) GaN. A device based on the β-Ga_2O_3/GaN heterojunction exhibited good rectifying properties. Under reverse bias, the current increased linearly with an increase in the deep-UV light intensity. The responsivity of the photodiode was highest under deep-UV light below a wavelength of 240 nm. The response time of the photodiode to deep-UV light was in the order of sub-milliseconds.

1. Introduction

Deep ultraviolet (UV) photodetectors have a wide range of applications, including flame sensors, UV radiation monitoring below the ozone hole, and as photodetectors for optical communication in space. β-Ga_2O_3, which has a band gap (E_g) of 4.9 eV, is a promising candidate as a UV photodetector material that is blind to wavelengths above 280 nm, known as a solar-blind photodetector. Kokubun et al. demonstrated photodetection using β-Ga_2O_3 films prepared on (0 0 0 1) sapphire substrates using the sol–gel method [1]. Oshima et al. demonstrated UV photodetection using single β-Ga_2O_3 crystals [2], and fabricated practical β-Ga_2O_3-based flame detectors [3]. Suzuki et al. have also reported the high responsivity for UV photodetection using single β-Ga_2O_3 crystals and a high resistance cap layer [4].

It is common to use pn junctions for photodetectors. pn junctions are expected to be applied for phototransistor devices and photodiode arrays. However, it is currently difficult to prepare Ga_2O_3 pn junctions due to the difficulty in producing p-type Ga_2O_3. One possible solution is to use a heterojunction with another semiconductor in which it is possible to produce p-type conduction.

In our previous study, we fabricated a deep-UV photodiode using the heterojunction between n-type β-Ga_2O_3 and p-type 6H-SiC (E_g = 3.02 eV) [5]. The deep-UV photodiode was demonstrated with the highest sensitivity to deep-UV light below a wavelength of 260 nm, and the response time to deep-UV light was in the order of milliseconds.

In the present study, a deep-UV photodiode was fabricated using a heterojunction between β-Ga_2O_3 and GaN with a band gap of 3.4 eV, and its UV sensitivity was investigated. It is considered that the combination between β-Ga_2O_3 and GaN is more promising than that between β-Ga_2O_3 and SiC. There have been some studies on GaN prepared on β-Ga_2O_3 single crystals [6,7]. Two crystals of GaN and β-Ga_2O_3 can be grown with an epitaxial relation to each other, even though GaN has the wurtzite structure and β-Ga_2O_3 is a monoclinic structure. A UV sensor device with a Ga_2O_3/GaN structure has been developed by oxidation of a GaN thin film on a sapphire substrate [8,9]. However, the β-Ga_2O_3 layer was not oriented with respect to GaN, so that the heterojunction between Ga_2O_3 and GaN could not be used as an active part of the device.

We demonstrate here that an oriented β-Ga_2O_3 thin film can be prepared on a GaN layer. For application as a deep-UV photodiode, the combination of β-Ga_2O_3 with GaN is expected to reduce the sensitivity for longer wavelengths because GaN has a wider bandgap than SiC (4H- 3.26 eV, 6H- 2.93 eV).

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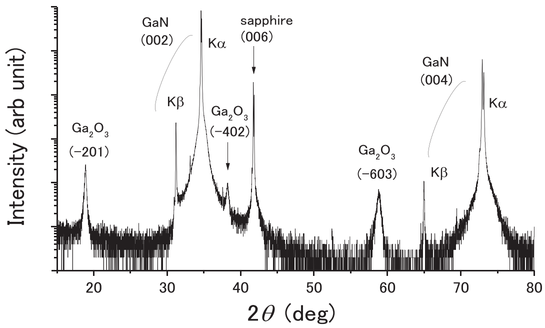

Fig. 1. XRD pattern for β-Ga_2O_3 thin film formed on a GaN template substrate on sapphire. XRD intensity is shown on a logarithmic scale.

2. Experimental

2.1. Preparation of β-Ga_2O_3 thin films

p-Type GaN template substrates with a Mg doping density of 1×10^{19} cm^{-3}, which was purchased from NTT Advanced Technology Corp., were used. (0 0 1) oriented GaN layers were formed on a buffer layer on the (0 0 1) *c*-plane of sapphire substrates. The carrier density of the p-type GaN after annealing treatment was estimated to be approximately 1×10^{17} cm^{-3}. The substrate wafers were cut to a size of approximately 10 × 10 mm^2.

Two thin β-Ga_2O_3 layers with thicknesses of 116 nm and 175 nm were prepared on p-type GaN template substrates by gallium evaporation in oxygen plasma. The substrate temperature was kept at 800 °C and the radio frequency power for the oxygen plasma was 100 W. The method for the formation of β-Ga_2O_3 layer has been described in reference [10].

The β-Ga_2O_3 layers had a (−2 0 1)-oriented crystal domain structure. Fig. 1 shows an X-ray diffraction (XRD) pattern ($\theta - 2\theta$ scan) for the β-Ga_2O_3 thin film formed on a (0 0 1) GaN template substrate. Only the (−2 0 1) related peaks of β-Ga_2O_3, (0 0 2) peak from GaN, and (0 0 6) peak from sapphire were observed. This indicates that the (−2 0 1) plane of the β-Ga_2O_3 layer is parallel to both the surfaces of the (0 0 1) GaN layer and the (0 0 1) *c*-plane of the sapphire substrate. This orientation of β-Ga_2O_3 crystal is the same as that for β-Ga_2O_3 layers that were formed directly on (0 0 1) sapphire substrates [10,11].

2.2. Device structure

Deep-UV sensor devices were fabricated with a planar structure using the β-Ga_2O_3 layer formed on the GaN template substrate. A cross-sectional schematic diagram of the photodiode structure is shown in Fig. 2. Silicon dioxide was initially formed on the GaN layer by spin-coating of a sol–gel solution as a lift-off layer. The SiO_2 layer was etched selectively using the first photolithographic process. The β-Ga_2O_3 layer was then formed by the evaporation of gallium in oxygen plasma. The SiO_2 layer was then etched with HF. Only the β-Ga_2O_3 layer on GaN was left selectively.

The two photolithographic processes were used to obtain layers of Pt/Ti/Pt/Au on the p-type GaN as an ohmic electrode and a thin 10 nm Au layer onto the remaining β-Ga_2O_3 layer as a semi-transparent Schottky electrode. The area of the thin Au electrode was approximately 0.2 mm^2. Fig. 2 shows a photograph of the resultant device. Au wire was connected to the thin Au electrode and ohmic electrode with conductive cement. With the p-type GaN side positive, the forward bias direction was defined for the p–n type device.

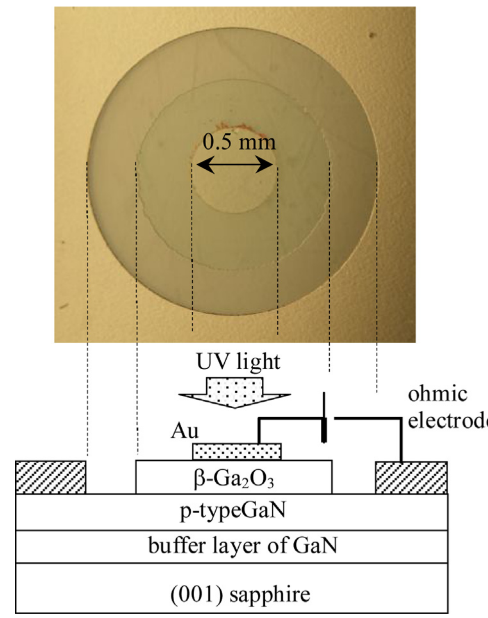

Fig. 2. Photograph and cross-sectional schematic of the deep UV sensor device based on β-Ga_2O_3/GaN heterojunction.

2.3. Measurements

Current–voltage (*I*–*V*) characteristics of the Deep-UV sensor devices were measured in dark condition and under various UV-light illumination intensities. The relative intensity of the UV-light was increased from 0.1% to 100% using a deuterium lamp and several types of neutral density filters. The light power density of the deuterium lamp was 22 mW/cm^2 as a rough estimate using a standard photo diode.

The spectral response of the devices was measured in the wide wavelength region from 200 to 500 nm using a monochromator with a xenon arc lamp as the optical excitation source.

The transient responses of the photodiodes were measured. The pulses were produced by passing the light from a deuterium lamp through a light chopper. The waveform of the light pulses was monitored using a silicon avalanche photodiode detector (APD) module.

3. Results and discussion

3.1. UV sensing properties

Fig. 3 shows the current–voltage (*I*–*V*) characteristics of the photodiode in the dark, where Fig. 3(a) and (b) show a semi-logarithm plot and linear plot of the *I*–*V* characteristics, respectively. We called the bias forward direction when the p-type GaN was under positive bias. Because the current is increased when the diode is biased in forward direction, we distinguished the diode characteristics are based on p–n heterojunction. The diodes exhibited good rectifying properties. The rectifying ratio was round 1.5×10^5 at 4.5 V. The current increased exponentially following a turn-on voltage of approximately 2.8 V. Fig. 3(a) shows that the forward current increased with a good exponential relationship at bias voltages higher than 3 V and the estimated ideality factor was approximately 3.7. The characteristics in the higher current region indicated a large series resistance of ca. 40 kΩ. It is supposed that the series resistance originates from the p-type GaN and β-Ga_2O_3 layers. The reverse current was lower than 10^{-9} A for a reverse-bias voltage up to 8 V under dark conditions.

Fig. 3(a) and (b) also show the current–voltage characteristics for the photodiode under various UV-light illumination intensities.