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Room temperature operation of 1.55 μm wavelength-range GaN/AlN quantum well intersubband photodetectors

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Abstract: The room-temperature operation of a GaN/AlN quantum well infrared photodetector (QWIP) using the intersubband transition (ISBT) in a GaN/AlN multiple quantum well (MQW) was demonstrated for the first time. The GaN/AlN QWIP was operated under DC biasing with a vertically conductive geometry to the MQW layer. A clear photoinduced response was observed for P polarized 1.47 μm light irradiation. Dependencies of the photoresponse on the applied DC bias voltage, and the polarization and wavelength of incident light were evaluated for the GaN/AlN QWIP. The maximum responsivity was estimated to be 0.11 mA/W for a DC bias of 15 V at room temperature.

Keywords: GaN/AlN, intersubband, quantum well, photodetector, optical communication wavelength, nitride

Classification: Photonics devices, circuits, and systems

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1 Introduction

Intersubband transition (ISBT)-based optical devices have received increasing attention in recent years. For the optical communication wavelength range of around 1.3∼1.55 μm, several material systems have been used to realize ISBT. ISBT is an attractive candidate for the mechanism of next-generation optical communication devices such as ultrafast all-optical switches, detectors, and quantum cascade lasers.

In the III-nitride material system, ISBT absorption in the optical communication wavelength range has been reported using GaN/Al(Ga)N multiple quantum wells (MQWs) with a conduction band offset of as high as 2 eV [1, 2, 3]. The III-nitride-based ISBT has two important properties suited for next-generation optoelectronic devices: ultrafast carrier relaxation speed compared with other ISBT materials and nontoxicity. For example, an ultrahigh-speed carrier relaxation time of 140 fs was observed in GaN/AlN ISBT [4].

The GaN/Al(Ga)N-based quantum well infrared photodetector (QWIP) was reported by Hofstettera et al. at around the 1.55 μm wavelength region [5]. The operation was limited in the low-temperature region of 10-170 K. Very recently, ISBT absorption by GaN/AlN multiple quantum dots was observed at room temperature with a peak absorption wavelength in the range of 1.41–1.54 μm and a narrow full width at half maximum (FWHM) of 88 meV [6]. Infrared photodetectors using multiple quantum dots have also been reported in the 1.38 μm wavelength region at 77 K [7]. In this study, we report the first demonstration of the room-temperature operation of the GaN/AlN QWIP in the 1.55 μm wavelength range.

2 Fabrication of GaN/AlN QWIP

A GaN/AlN QWIP was grown by rf-plasma-assisted molecular beam epitaxy (RF-MBE) on a (0001) Al_2O_3 substrate. Figure 1 shows a schematic diagram of the GaN/AlN QWIP fabricated in this study. Following a high-temperature AlN buffer layer (d = 160 nm), which was used to control the epitaxial layer polarity so as to follow the Ga-polarity, a Si-doped GaN

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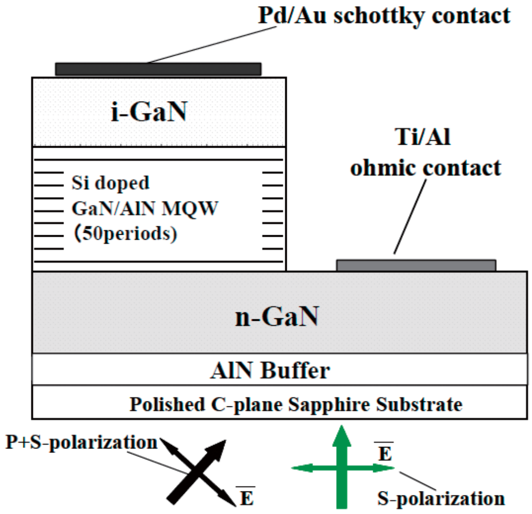

Fig. 1. Schematic diagram of GaN/AlN quantum well infrared photodetector (QWIP). The geometry of the incidence angle of light used to measure the photoresponse for P+S polarized light (black arrow) and S polarized light (green arrow) is also shown.

layer (d = 800 nm, n = $1 \times 10^{18}\,\mathrm{cm}^{-3}$), 50 periods of a Si-doped GaN/AlN MQW layer, and an undoped GaN top layer (d = 300 nm) were grown. For the MQW, Si was selectively doped into the center of each AlN barrier layer. The thicknesses of the GaN well and AlN barrier layers were estimated by X-ray diffraction measurement to be 1.42 nm (5.5 ML) and 3.14 nm (12.6 ML), respectively. The electron density of the MQW was estimated to be $2 \times 10^{19}\,\mathrm{cm}^{-3}$ by Hall effect measurement.

A vertically conductive geometry QWIP was fabricated by the following process. Mesa stripes 200 μm wide were formed by reactive ion etching from the surface down to the n-GaN layer. Then, a Pd(80 nm)/Au(100 nm) Schottky top contact (1375x150 μm^2) and a Ti(35 nm)/Al(110 nm) ohmic bottom contact (250x50 μm^2) were formed by electron beam evaporation and a conventional lift-off process. The ohmic contact was annealed at 540°C for 20 s in N_2 ambient.

3 Experimental details

The GaN/AlN QWIP was electrically connected in series to a DC voltage source and a 100 Ω resistance. The photoresponse characteristics of the QWIP were measured at room temperature using a 1.47 μm laser (120 mW) as a light source. A linearly polarized laser beam, whose polarization direction was controlled to lie parallel to the plane of incidence, was incident from the substrate side. The laser beam was collimated by a ball lens with a diameter of about 500 μm and electrically modulated in 480 Hz pulse. The voltage across the resistance, which arose due to a photocurrent, was detected by a lock-in amplifier synchronized with the incident light pulses.

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The experiment was performed for two incidence angles, slanting and normal incidence directions, as shown in Fig. 1. The polarization of the light beam inside the ISBT region can be controlled by the incidence direction; that is the slanting incidence gives P+S polarized light and the normal incidence only S polarized light. ISBT absorption occurs when the light has a P polarized component, namely, an electrical field normal to the quantum wells. In contrast, the S polarized light passes through the GaN/AlN MQW with no ISBT absorption.

4 Photoresponse of GaN/AlN QWIP at room temperature

The room-temperature photoresponse of the GaN/AlN QWIP for the 1.47 μm light was measured under negative biasing; that is, a negative voltage was applied to the Schottky top contact. Figure 2 shows the photocurrents for the slanting and normal incidence directions as a function of negative bias voltage, where the typical dark current-voltage characteristic is show in the inset. A clear photoresponse was observed for the slanting incidence (P+S polarized light). By estimating the incident power of the P-polarized light component from the incidence angle, the detection responsivity was evaluated. The maximum responsivity of the GaN/AlN QWIP was 0.11 mA/W at 15 V.

Meanwhile, we notice that the small photoresponse occurred even for the normal incidence (S polarized light). This may be due to the light scattering

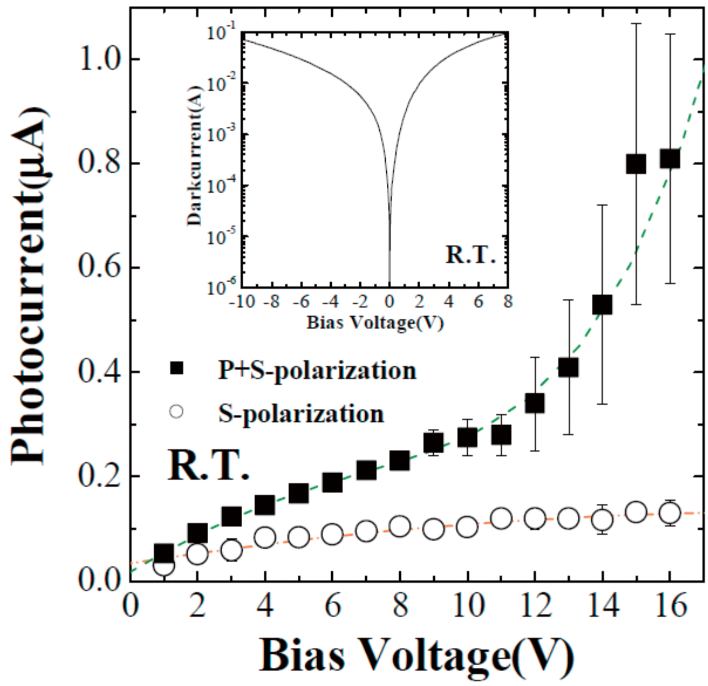

Fig. 2. Photocurrent versus negative bias voltage at room temperature for P+S-polarized light (black square) and S-polarized light (white circle). The inset shows the current-voltage characteristic at room temperature.

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at the slightly rough surface of the polished substrate generating the P polarized component. It is also known that the threading dislocation of GaN has a polarization-dependent-absorption-like ISBT in the optical communication wavelength range [8]. The dislocation-related photoresponse, therefore, should be accounted for. We fabricated a 1.6-μm-thick GaN photodetector to confirm that the photoresponse at 1.47 μm was negligibly smaller than that of the GaN/AlN QWIP. This time the photocurrent for P+S polarized light rapidly increased for bias voltages above 11 V (see Fig. 2). The increase is qualitatively explained to be due to the probability of electrons tunneling through AlN barriers being enhanced at high bias voltages. The noise component in the photocurrent also for bias voltages increased above 11 V; this may be brought about by the heating of the device due to increased dark current in the high-bias-voltage region.

For the slanting incidence, the polarization direction of the incident laser beam was rotated continuously on the plane vertical to the incidence direction and the photoresponse of the GaN/AlN QWIP was evaluated. Depending on the rotation angle, the P polarized beam component in the ISBT region varied sinusoidally. We observed that the photoresponse changed by following the same sine function as that of the P polarization. This tendency indicates that light detection occurred for the P polarized light absorption in the ISBT region.

From these experiments, it was proved that the room-temperature operation of GaN/AlN QWIP in the optical communication wavelength was demonstrated.

5 Wavelength dependence of GaN/AlN QWIP

The wavelength dependence of the photocurrent of the GaN/AlN QWIP was evaluated. In this measurement, a wavelength-tunable laser ($\lambda = 1.54\sim 1.62\,\mu$m) with an output power of 8 mW was employed as the light source. The collimated laser beam was irradiated on the edge facet of the QWIP and a 7 V bias voltage was applied to the GaN/AlN QWIP. Figure 3 shows wavelength dependences of the photocurrent of QWIP and the ISBT absorption of GaN/AlN MQW.

The GaN/AlN MQW sample was cut out from the same wafer used to fabricate the QWIP. The ISBT absorption spectrum was obtained by multipass transmission measurement. A halogen lamp was used as a light source, the light was irradiated through a mechanical chopper, a monochromator and a Glan-Thompson prism to a sample edge, and then detected by an electrically cooled PbS detector with a lock-in amplifier. Absorption occurred only for P polarized light. The ISBT absorption peak was fitted by two Lorentz functions with peak wavelengths of 1.71 μm and 1.99 μm. The FWHM of the peak at 1.71 μm was 132 meV.

In order to compare the ISBT absorption spectrum of GaN/AlN MQW with the photocurrent of the GaN/AlN QWIP, the vertical scale of Fig. 3 was normalized at 1.542 μm. With increasing wavelength from 1.54 to 1.62 μm,

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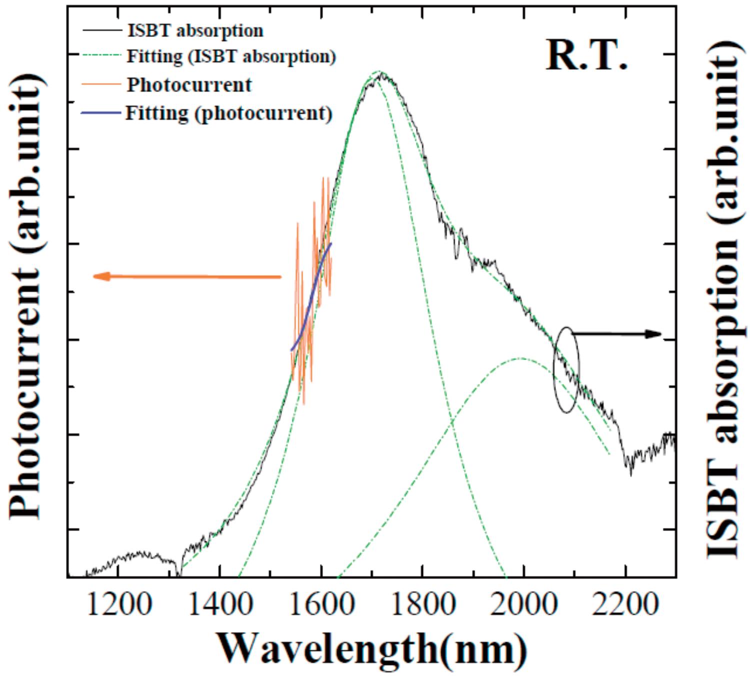

Fig. 3. Comparison between wavelength dependence of photocurrent (orange line) and ISBT absorption spectrum (black line) under 7 V bias voltage. The blue line is a fitting of photocurrent and the green line is a fitting of the ISBT absorption spectrum by the Lorentz function.

the photocurrent sharply increased, although the light intensity of the tunable laser was constant. The wavelength dependences of both the photocurrent and the ISBT absorption were approximately coincident with each other.

6 Conclusion

The room-temperature operation of a GaN/AlN MQW QWIP was achieved for the first time. The photoresponse of the GaN/AlN QWIP was clearly dependent on the polarization of the incident light emitted into the GaN/AlN MQW region. Only the P polarized light was detected. It was therefore proved that ISBT was the mechanism of the photoresponse in the GaN/AlN QWIP. The wavelength dependences of the QWIP photocurrent and the ISBT absorption in the GaN/AlN MQW showed good agreement with each other. The maximum responsivity of QWIP for the 1.47 μm light used was estimated to be 0.11 mA/W.

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