Cubic GaN/AlN multiple quantum well photodetector

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Photodetectors based on intersubband transitions in molecular beam epitaxially grown cubic GaN/AlN multiple quantum wells were fabricated and tested. The presence of the intersubband transition was confirmed by using the optical absorption technique for structures with different well widths. Samples were polished into waveguide configuration on which the devices were fabricated. The photoresponse spectra were collected in the temperature range of 77–215 K under the influence of small bias voltages. All devices exhibit photovoltaic effect where the photoresponse is observed at zero bias voltage. Theoretical calculations of the intersubband transition were performed and found to be in agreement with the observed results. © *2008 American Institute of Physics*.
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There is an increasing interest in extending the applications of III-nitride materials from the ultraviolet and visible spectral region into the near- and midinfrared regions due to the increasing interest in the 1.30–1.550 μm spectral region for optical communications.[1–5] This can be accomplished by investigating the intersubband transitions in quantum wells[6] and superlattices,[7] which unlike GaAs/AlGaAs system, can be observed in the near- and mid-infrared spectral region due to the large conduction band offset between GaN and AlN. These transitions were reported for the GaN hexagonal structures[8–14] and most recently, in a nonpolar cubic GaN structure.[15] The hexagonal GaN/AlN quantum wells exhibit a large piezoelectric effect causing a significant band pending due to the large built-in electric field. On the other hand, spontaneous polarization that causes the piezoelectric effect almost does not exist in cubic GaN and cubic AlN. Thus, it is of interest to investigate the intersubband transitions in this particular cubic GaN/AlN quantum structure. The absence of the polarization is beneficial in case of photodetectors since the band bending associated with the polarization usually complicates the design of the device.[16] Photodetectors based on the intersubband transitions in the hexagonal GaN/AlN multiple quantum wells were reported with the emphasis on the wavelength of 1.5 μm.[9–11,17–23] However, mid- and near-infrared photodetectors based on cubic GaN/AlN quantum wells were not reported.

In this letter, we report on the photoresponse of photodetectors based on intersubband transitions in nonpolar GaN/AlN multiple quantum wells grown on cubic SiC substrate. The tested devices exhibit a photoresponse in the spectral region of 1.0–4.00 μm. The photoresponse spectra were measured in the temperature range of 77–215 K under bias voltages ranging between 0.0 and 75 mV. All of the devices show a photovoltaic effect. Furthermore, the dark current was measured at both 77 and 300 K. The presence of the intersubband transitions was confirmed by using the optical absorption technique. The intersubband transitions were calculated and a good agreement between the calculated and measured results was obtained.

The multiple quantum well samples were grown at 720 °C on freestanding 3C–SiC (001) substrates by plasma assisted molecular beam epitaxy. 100 nm thick cubic GaN buffer was deposited on a 3C–SiC substrate by using the reflection high-energy electron diffraction (RHEED) control of the growth process as described previously.[24] Subsequently, 20 period GaN/AlN quantum wells were grown. The barrier thickness was fixed at 1.35 nm for all of the samples while the well thickness is changed for different samples but kept in the range of 1.6–2.1 nm. The barrier and well thicknesses were determined by using x-ray diffraction and RHEED oscillations. The quantum wells were capped with a 100 nm thick *c*-GaN layer. Both the cap and buffer layers were doped with $[\mathrm{Si}]=1.33\times10^{18}\ \mathrm{cm}^{-3}$ as determined by the electrochemical capacitance-voltage technique.[15] After each layer, the growth was interrupted for 30 s to allow excess metal to evaporate from the surface. Four samples with different quantum well widths were used in this study and waveguides were cut from each sample. The device mesas were fabricated by using dry etching method. The square mesas were $1.2\times1.2\ \mathrm{mm}^2$ with a height of 200 nm. A metallization scheme of Ti/Al/Ni/Au with thicknesses of 10/25/10/50 nm was deposited at the bottom and top GaN contact layers. The optical absorption measurements were recorded by using a Bruker Fourier-transform 125HR spectrometer. The photoresponse spectra were obtained by using a Perkin–Elmer Fourier-transform spectrometer in conjunction with a continuous flow cryostat and Keithley preamplifier. The dark current measurements were made by using Keithley 4200-SCS.

The normalized photoresponse spectra of the three devices with well thicknesses of 1.6, 1.65, and 2.1 nm for devices 1518, 1544, and 1547, respectively, are plotted in Fig. 1. The spectra were measured at 77 K under zero bias voltage. These spectra are due to transitions from the occupied states in the ground state miniband to unoccupied states in the excited minibands. Since the active region of each device is composed of 20 GaN/AlN periods, minibands are formed instead of discrete energy levels. Each miniband is made of 20 close energy levels and the width of the excited state miniband is usually larger than that of the ground state mini-

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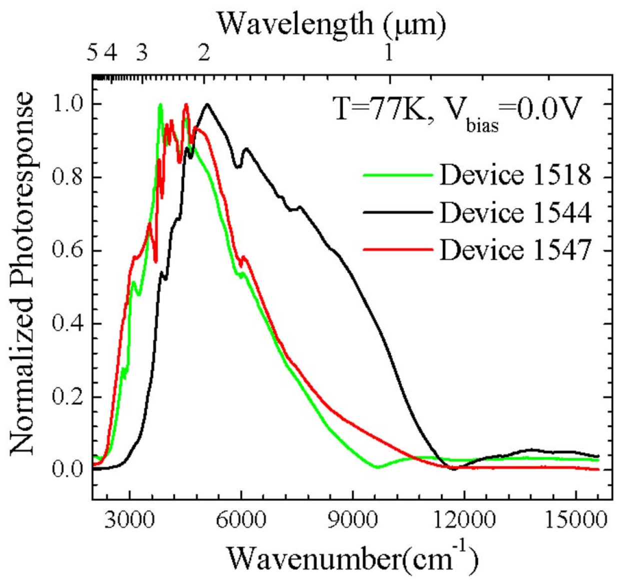

FIG. 1. (Color online) The photoresponse spectra measured for four different devices at 77 K and under zero bias voltage.

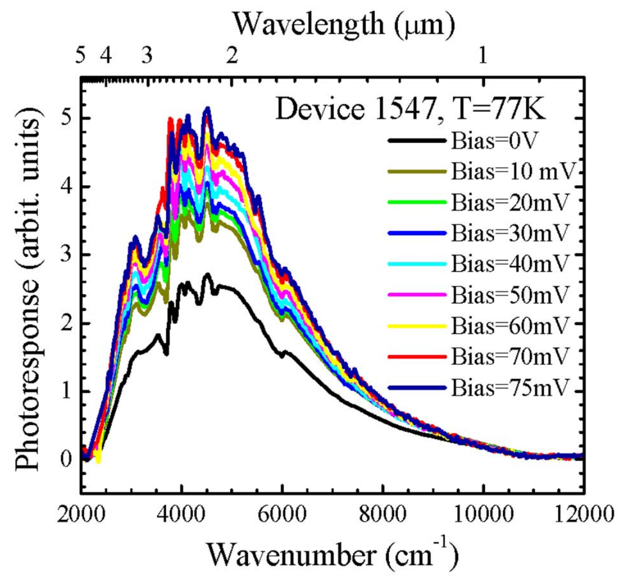

FIG. 3. (Color online) The photoresponse spectra of device 1547 measured at 77 K under different bias voltages.

band. Due to the dispersion of the energy levels within the minibands, one expects to observe broad photoresponse spectra, which confirmed in the spectra displayed in Fig. 1. The spectral shape of the photoresponse displays an asymmetrical behavior, which can be explained in terms of both bound-to-bound and bound-to-continuum transitions. Detailed discussion regarding the spectra line shapes of bound-to-bound and bound-to-continuum transitions is presented in Ref. 25. The threshold wavelength of the spectra is about 4.0 μm with some variations due to the different GaN quantum well thicknesses.

The presence of the intersubband transition was confirmed by using the optical absorption technique, as shown in Fig. 2, in which the absorption and photoresponse spectra are plotted. The photoresponse spectrum is broader than that of the optical absorption. Furthermore, the optical absorption spectrum is more symmetrical as compared to the photoresponse spectrum. A possible explanation can be stated as follows. The optical absorption spectrum is due to transitions from the occupied states in the ground state miniband to the unoccupied states in excited state miniband. On the other hand, the photoresponse spectra due to photoexcited carriers are collected at the electrode. The sources of these carriers are from various transitions with the bound-to-bound and bound-to-continuum minibands, which lead to the broader spectral behavior. The transitions from bound to continuum are usually difficult to probe by using the optical absorption technique due to their smaller oscillator strengths, as compared to those of bound-to-bound transitions.

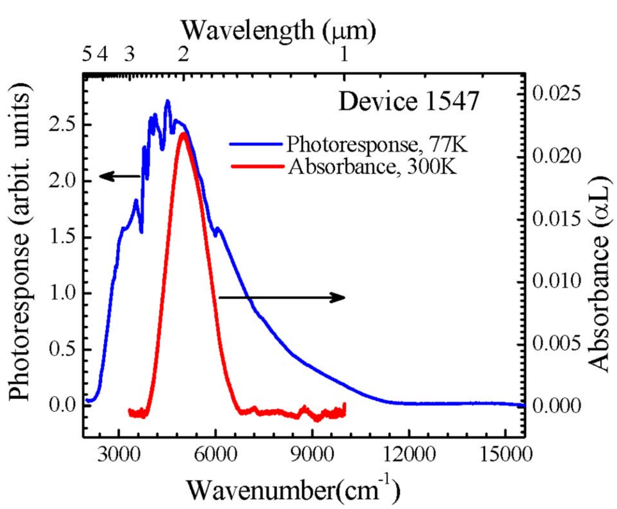

FIG. 2. (Color online) The photoresponse and optical absorbance spectra of device 1547 measured at 77 and 300 K, respectively.

The present cubic GaN/AlN multiple quantum well photodetectors exhibit a photovoltaic effect where the photoresponse can be observed at zero bias voltage, as shown in Figs. 1 and 3. The photoresponse, however, increases as the bias voltage increases from 0.0 V to 75 mV. Beyond this voltage, the photoresponse is degraded due to the large dark current when the voltage is increased from zero to 0.12 V. This small photovoltaic effect may be due to a small band bending caused by the variation of the carrier concentration in the cap and buffer in one hand and the carrier concentration in the active region (20 periods). Growth asymmetry may also be the source of the photovoltaic effect.

The photoresponse of device 1544 was investigated as a function of temperature at zero bias voltage, as shown in Fig. 4. The intensity of the photoresponse was observed to increase as the temperature is increased from 77 to 150 K. The observed increase in the photoresponse with temperature is due to the increased probability of thermal excitation of photoexcited carriers into the continuum. As the temperature increases above 150 K, the photoresponse starts to decrease and becomes noise, as shown in the spectra collected at 200 and 215 K. The photoresponse disappears for temperatures above 215 K, where the dark current is significantly high.

The intersubband transitions were calculated by using transfer matrix model.[26] The theoretical calculations were also supported by the calculated values obtained by using the Schrödinger–Poisson self-consistent (SPSC) model[27] and finite element analysis model.[28] A good agreement between the measured and calculated results was obtained. For the calculated results, the conduction band offset was taken[29] as 1.11 eV and the GaN well widths are 1.6, 1.65, and 2.1 nm

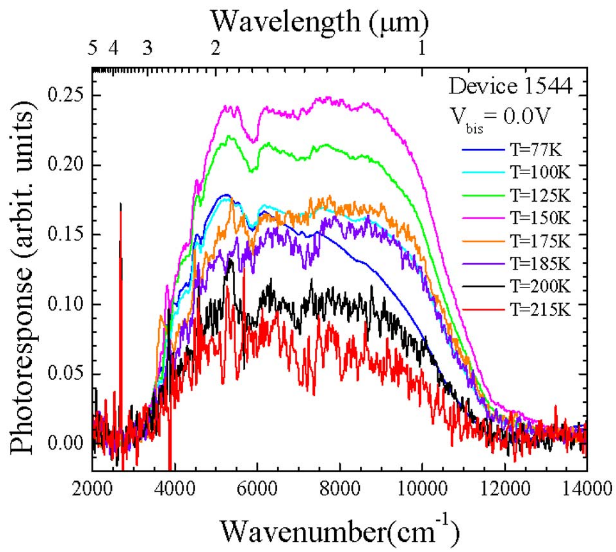

FIG. 4. (Color online) The photoresponse spectra of device 1544 measured at different temperatures under zero bias voltage.

for devices 1518, 1544, and 1547, respectively. The effective mass of the electron was taken as $0.19m_0$ and $0.28m_0$ for the GaN, and AlN, respectively.[30]

In conclusion, photodetectors based on intersubband transitions in cubic GaN/AlN grown on 3C–SiC substrates were fabricated and tested. The photoresponse spectra were observed to cover the spectral region of 1–4 μm and peak at around 2.5 μm. All of the tested devices exhibit a small photovoltaic effect. The photoresponse was measured at 77 K and was found to exist at temperatures as high as 215 K. Furthermore, the photoresponse spectra were complemented by the optical absorption spectra of the intersubband transitions in the quantum well structures. The intersubband transitions were also calculated by using three different models. A good agreement was obtained between the calculated and measured results.

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