Epitaxial Wafer for Near Infrared Sensor with High Sensitivity

Kei FUJII*, Takashi ISHIZUKA, Youichi NAGAI, Yasuhiro IGUCHI and Katsushi AKITA

Photodiodes (PDs) in the near infrared region (1.0-2.5 µm) are expected to be used for non-destructive analysis in many fields such as pharmaceutical and food industries. The authors have succeeded in the development of InGaAs/GaAsSb type-II quantum well (QW) structures that satisfy low dark current and cut-off wavelength up to 2.5 µm. Low dark current, more than one order of magnitude lower than molecular beam epitaxy (MBE), was realized by fabricating PDs with InP capping layers grown by organometallic vapor phase epitaxy (OMVPE). A large number of QWs with high crystal quality were successfully grown by optimizing the growth condition. The maximum external quantum efficiency (EQE) in the near infrared region was about 48%, which is higher than that of MBE. These results indicate the possibility of high-performance analysis equipment that enables more detailed analysis.

Keywords: near infrared, photodiode, high sensitivity, type-II quantum well, OMVPE

1. Introduction

The near infrared spectroscopy has been attractive for non-destructive analysis because many molecules have overtones and combination tones of fundamental vibrations in the near infrared region between 1.0 µm and 2.5 µm. Recently, there is great interest in real-time near infrared spectroscopy from the view point of safety and quality control in many production fields, such as pharmaceutical and food industries. Photodiodes (PDs) with cut-off wavelength*1 up to 2.5 µm, low dark current*2, high sensitivity, and high speed operations are essentially required for the spectroscopy.

InGaAs pin-PDs lattice-matched*3 to InP substrates have very low dark current and high sensitivity. The mass production technology of the PDs has progressed because they are used for optical fiber communication. However, the PDs can only analyze limited material because of their cut-off wavelength up to 1.7 µm. PDs with the cut-off wavelength up to 2.6 µm have been fabricated using In-rich lattice-mismatched InGaAs layers on InP substrates(1). However, the dark current of the lattice-mismatched InGaAs PDs becomes higher, with the cut-off wavelength being longer, where cooling system is required for the reduction of the dark current. HgCdTe (MCT) detectors are predominantly used for imaging applications in the near infrared region. However, they require cooling systems because of their high dark current, and have poor uniformity and productivity.

So far, it has been reported that InGaAs / GaAsSb quantum wells (QWs) with type-II staggered band alignments is a candidate to realize both an optical response up to 2.5 µm and low dark current(2). As shown in **Fig. 1**, optical transitions which occur by overlapping of wavefunction between the valence band (VB) in the GaAsSb and the conduction band (CB) in the InGaAs corresponds to the wavelength of 2.5 µm region. InGaAs / GaAsSb type-II QW structures are attractive for realizing low dark current pin-PDs in the near infrared region because InGaAs and GaAsSb are lattice-matching to InP substrates. The dark current, due to thermal excitation, is expected to be suppressed because the effective small bandgap is realized by combining large bandgap materials. Moreover, the cut-off wavelength can be adjusted by changing the layer thickness of QWs. A large number of QWs with high crystal quality is necessary for the enough sensitivity because transition probability is low due to spatially separated electrons and holes.

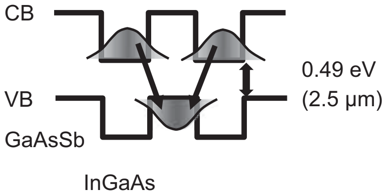

Fig. 1. Band structure of InGaAs / GaAsSb QWs

Molecular beam epitaxy (MBE) is generally used for the growth of GaAsSb to suppress phase separation(3). However, it is difficult to grow InP capping layer which is of great advantage to suppress surface leak current. On the other hand, it is easy to grow InP capping layer by using organometallic vapor phase epitaxy (OMVPE), and OMVPE is a suitable method for mass production. Though it was difficult to grow GaAsSb by OMVPE, it was reported that the growth of GaAsSb without phase separation was realized by growing at low temperature(4). We have developed a large number of InGaAs / GaAsSb type-II QW structures with high crystal quality that exhibit low dark current and cut-off wavelength up to 2.5 µm. In this work, we report the growth of epitaxial wafers with InGaAs / GaAsSb type-II QW structures and the property of PDs with the QW structures.

2. Growth of InGaAs/GaAsSb QWs

Figure 2 shows the schematic structure of the epitaxial wafer. The epitaxial wafers were grown on S-doped InP (001) substrates by OMVPE. In the OMVPE growth, organometallic sources combined with career gas are supplied on heated wafers. The growth temperature is less than 600˚C. First, a 0.15 µm-thick Si-doped n-InGaAs buffer layer was grown on a S-doped InP substrate, followed by a lattice-matched In$_{0.53}$Ga$_{0.47}$As (5 nm) / GaAs$_{0.51}$Sb$_{0.49}$ (5 nm) type-II QW layer. The number of QWs was varied from 50 to 450 pairs. To evaluate the QW structure of 250 pairs, cross-sectional transition electron microscopy (TEM) images and X-ray diffraction (XRD) patterns for the (004) reflection were measured.

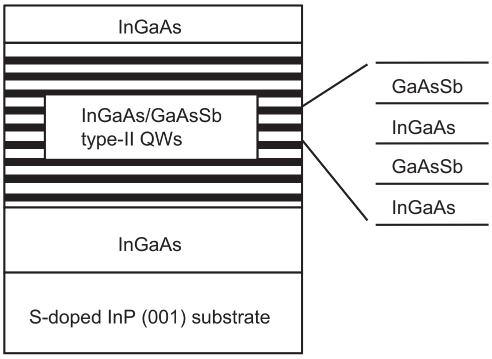

Fig. 2. Schematic structure of QW structure

3. Evaluation of InGaAs/GaAsSb QWs

The InGaAs / GaAsSb QWs with steep interface is required for the PDs with low dark current. We successfully obtained the PDs with low dark current by optimizing the growth condition and gas switching sequence.

The cross-sectional TEM image of the QW structure of 250 pairs is shown in **Fig. 3**. Periodical structure without dislocations due to lattice mismatch is clearly observed. The XRD patterns of the QW structures of 250 pairs are shown in **Fig. 4**. Distinct satellite peaks resulting from the periodical structure of QWs were clearly observed. They are in good agreement with simulations. It suggests that QWs with steep interfaces, which is required for low dark current, are successfully grown by abrupt gas switching and precise control of composition.

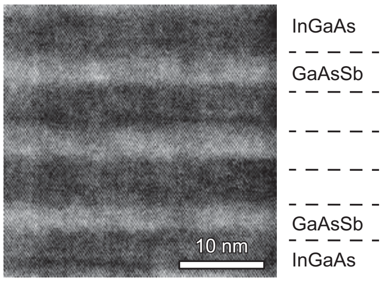

Fig.3. Cross sectional TEM image

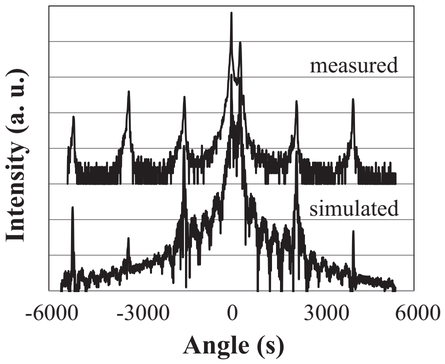

Fig. 4. XRD patterns of the QW structures

It is necessary for PDs with high sensitivity to increase the thickness of the absorption layer by the increasing number of QWs. However, the dark current increases with the increasing number of QWs, due to crystal deterioration caused by the accumulation of strain and defects at the interface of QWs. The XRD patterns of the QW structures with different numbers of QWs are shown in **Fig. 5**. Distinct satellite peaks were observed in all samples. This result indicates that crystal deterioration was not observed, even though the number of QWs increased to 450 pairs.

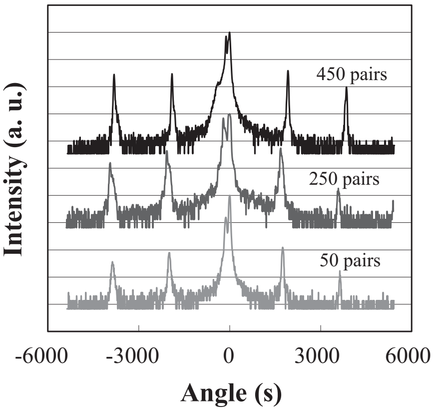

Fig. 5. XRD patterns of the QW structures with different numbers of QWs

The QW structure was further studied by photoluminescence (PL) at room temperature. The photoexcitation source was a YAG:Nd laser, operating at 1064 nm. InSb cooled at 77 K was used for a detector. **Figure 6** shows the PL spectrum of the QW structure. The peak wavelength is 2520nm, which is considered to originate from type-II transition. It is expected to realize cut-off wavelength up to 2.5 µm by fabricating PDs with the QWs. **Figure 7** shows the PL intensity of the QW structure as a function of the number of QWs. The PL intensity gradually increased with the increasing number of QWs, indicating that light absorption occurs in the whole region of type-II QWs. This result sug-

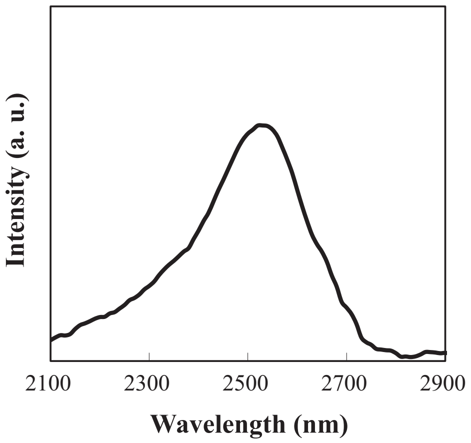

Fig. 6. PL spectrum of the QW structure

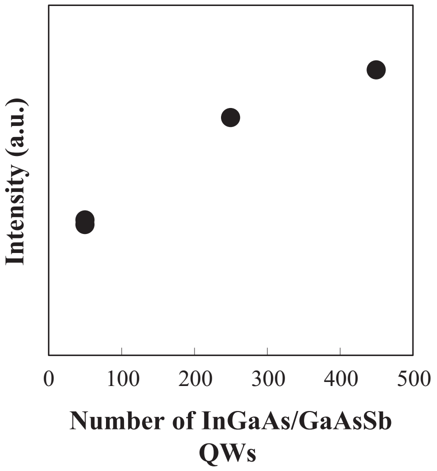

Fig. 7. PL intensity of the QW structure as a function of the number of QWs

gests the feasibility of fabricating high sensitivity PDs with an extremely high number of QWs.

4. Fabrication of InGaAs/GaAsSb type-II PDs

PDs with InGaAs/GaAsSb type-II QWs as an absorption layer were fabricated. **Figure 8** shows the schematic structure of the fabricated planar type pin-PDs. A 1.0 μm-thick InGaAs intermediate layer was grown on the QW structure, followed by a 0.8 μm-thick InP capping layer. The p-n junction was formed in the InGaAs intermediate layer by the selected thermal diffusion of zinc. SiN and SiON were used for passivation films and anti-reflection coatings, respectively. Au-Zn and Au-Ge-Ni were evaporated as p-electrodes and n-electrodes, respectively. These are similar to conventional pin-PDs for optical communication systems. The diameter of the light-receiving region was varied from 15 to 250 μm.

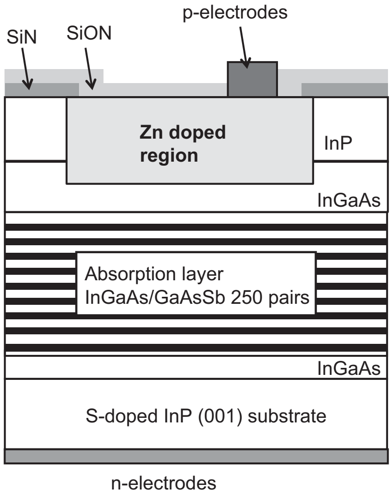

Fig. 8. Schematic structure of PDs

5. Evaluation of type-II PDs

We fabricated InGaAs/GaAsSb pin-PDs with different numbers of QWs in order to investigate the property of the pin-PDs.

The diameter of each device was varied from 15 to 250 μm. The number of InGaAs/GaAsSb QWs was 250 pairs. **Figure 9** shows the dark current of the pin-PDs as a function of diameter. Dark current increased with the increasing diameter of the light-receiving region. Dark current density was calculated 7.0 μA/cm^2 from **Fig. 9**. This value is more than one order of magnitude lower than that in Ref. 3, owing to the suppression of surface leak current by using the InP capping layers.

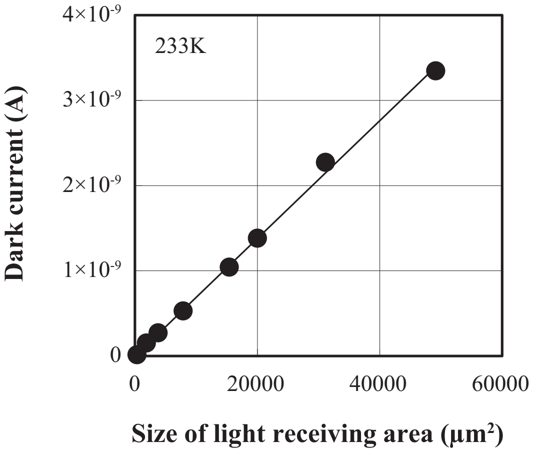

Fig. 9. Dark current as a function of diameter

Figure 10 shows the temperature dependence of dark current density. The relationship between dark current density and temperature is expressed by the **following equation**;

$$I_d \propto \exp(-\frac{E_g}{nkT})$$

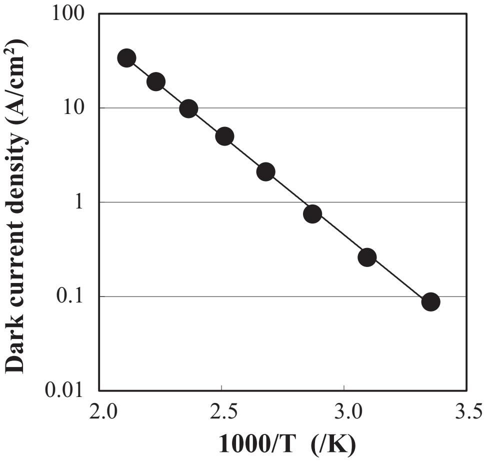

Fig. 10. Temperature dependence of dark current density

where E_g is the bandgap, k is the Boltzmann constant and T is the temperature. The n-value is unity when the diffusion current is dominant, and becomes two when the generation-recombination current is dominant. The ideality factor n calculated from the temperature dependence of dark current density was 1.2, indicating that the generation-recombination process is sufficiently suppressed. These results indicate that it is possible to fabricate low dark current InGaAs/GaAsSb type-II PDs grown by OMVPE.

Finally, the external quantum efficiency (EQE) of InGaAs/GaAsSb pin-PD is shown in **Fig. 11**. The measurement was carried out at room temperature being irradiated by a laser with a wavelength of 2.0 μm and power density of 16 mW/cm^2 from the p-electrodes side of the PDs. Bias voltage was 1 V at reverse. The EQE increased almost linearly when increasing the number of InGaAs-GaAsSb QWs. InGaAs/GaAsSb QWs worked as an absorption layer, and were considered to be fully depleted when they were biased in reverse. The maximum EQE was about 48% with 450 pairs of InGaAs/GaAsSb QWs. This value is 10% higher than that in Ref. 3. These results indicate the possibility of high-performance analysis equipment that enables more detailed analysis by using the PDs.

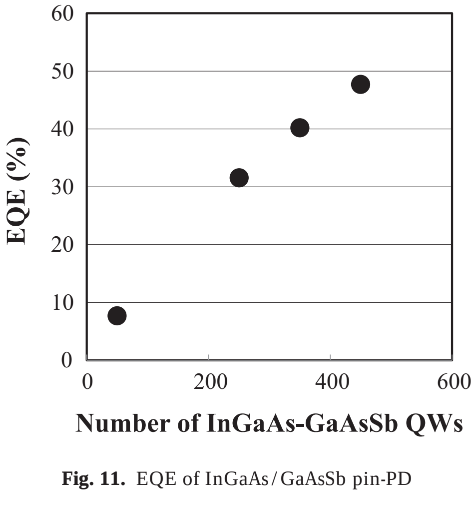

Fig. 11. EQE of InGaAs/GaAsSb pin-PD

6. Conclusion

With the aim to realize non-destructive analysis in the near infrared region, we have developed epitaxial wafers for PDs with type-II QWs as an absorption layer by OMVPE. Low dark current, more than one order of magnitude lower than MBE, was realized by fabricating PDs with InP capping layers grown by OMVPE. The maximum EQE in the near infrared region of 48%, which is higher than that of MBE, was obtained with 450 pairs of QWs. These results indicate the possibility of high-performance analysis equipment that enables more detailed analysis of composition and concentration.

Technical Terms

*1 cut-off wavelength: The longest wavelength that PDs can detect.

*2 dark current: Leak current which occurs without light irradiation.

*3 lattice-match: Matching of lattice constant between different semiconductors.

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