Epitaxial Wafer of Multiple Periodic Layer for Midwavelength Infrared Detectors with High Sensitivity

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Midwavelength infrared (MWIR: 3-5 μm) detectors with high sensitivity and fast response are strongly demanded for hazardous gas detection and satellite observation. In recent years, InAs/GaSb superlattices (SLs) have been a subject of intense study as the absorption region of the MWIR detector. Although organometallic vapor phase epitaxy (OMVPE) is advantageous for mass production compared with molecular beam epitaxy (MBE), the number of reports on the OMVPE growth of InAs/GaSb SLs is limited. In this work, we fabricated high-quality 100-period InAs/GaSb SLs on GaSb substrates by OMVPE. MWIR detectors with 100-period SLs showed a dark current density of 2×10^{-4} A/cm^2 at -50 mV and 77 K, and an external quantum efficiency of 15% at 3.5 μm and 20 K. These results indicate that the InAs/GaSb SLs could offer excellent structural and electrical properties for high-performance MWIR detectors.

Keywords: mid-wavelength infrared, photodetector, detector, superlattice, OMVPE

1. Introduction

The normal vibration of molecules and radiation waves from objects have energy absorbed in the mid-wavelength infrared (MWIR) band of 3 to 5 μm. Therefore, high-sensitivity, fast-response MWIR detectors for this wavelength band are desired for use in toxic-gas detectors, night-vision cameras, thermographic systems, and Earth observation satellites. Conventionally, mercury cadmium telluride [HgCdTe (MCT)] has been used as a sensor material for the MWIR band. However, as an alternative material to MCT, indium arsenide-gallium antimonide (InAs/GaSb) superlattices,*1 which theoretically make superior detectors, are attracting interest.(1) InAs/GaSb superlattices have a theoretically low dark current*2 and can be easily tailored to a desired wavelength for detection. Moreover, they are environmentally advantageous because they contain no mercury.

To optimize the characteristics of an InAs/GaSb superlattice for a sensor, its crystal qualities, such as the smooth surface and abrupt interface, are important. Regarding the production of InAs/GaSb superlattices, development examples using molecular beam epitaxy (MBE) do exist. However, few reports are available on organometallic vapor phase epitaxy (OMVPE).(2) This is because Sb-containing material systems are generally subject to phase dissociation of Sb, thereby making MBE, which enables epitaxial growth at low temperatures, more desirable for facilitating epitaxial growth. Table 1 compares OMVPE with MBE. OMVPE offers higher epitaxial growth rates, maintainability, and productivity than MBE. As an Sb-containing material produced by OMVPE, an InGaAs/GaAsSb superlattice on an InP substrate was successfully fabricated for near-infrared (wavelength: 1–2.5 μm) detectors. Using this superlattice, we have realized and commercialized high-performance near-infrared detectors.(3) In the present study, we applied our unique low-temperature OMVPE growth technique to the growth of Sb-containing materials and fabricated an InAs/GaSb superlattice on a GaSb substrate. This report presents the epi-wafer characteristics of the InAs/GaSb superlattice fabricated by OMVPE and the characteristics of a detector fabricated from the InAs/GaSb superlattice.

Table 1. Comparison of OMVPE and MBE

	Organometallic vapor phase epitaxy (OMVPE)	Molecular beam epitaxy (MBE)
Crystalline quality of Sb-containing crystal	High quality due to use of our original growth technique instead of chemical reaction (moderate quality)	High quality by physical vapor deposition
Growth rate	Fast	Slow due to need to ensure high crystalline quality
System maintenance	Simple	Difficult

2. Epitaxial Growth

Table 2 shows the lattice constants of GaSb, InAs, and InSb. With the epitaxial growth of an InAs/GaSb superlattice on a GaSb substrate, dislocations resulting from the difference in the lattice constant (−0.62%) between GaSb and InAs degrade the detection characteristics. To reduce the dislocations, MBE generally involves quasi-reduction of the difference in the lattice constant by inserting InSb layers between the InAs and GaSb layers.(4)-(6) In contrast, the epitaxial growth of InSb by OMVPE has been considered to be difficult because of its low melting point of InSb (527°C) compared with typical substrate temperatures during growth.(7) To overcome this challenge, we used our low-temperature OMVPE growth technique and succeeded in the growth of an InAs/GaSb superlattice that contains

InSb layers. The substrate temperature during growth was reduced to 500°C, which is a relatively low level in the case of OMVPE.

Table 2. Lattice constants of GaSb, InAs, and InSb

	Lattice constant (Å)	Difference in lattice constant from GaSb
GaSb	6.096	-
InAs	6.058	-0.62%
InSb	6.479	+6.28%

First, OMVPE was used to fabricate an epi-wafer that had an InAs/GaSb superlattice as an absorption layer. Figure 1 shows the structure after growth of the epi-wafer. Onto a tellurium-doped GaSb (001) substrate, a p-GaSb layer was grown, followed by the growth of an InAs/GaSb superlattice comprising 100 repeated and alternately stacked InAs and GaSb layers. InSb layers were inserted in the superlattice to reduce dislocation. Last, an n-InAs layer was grown as a surface contact layer. Incidentally, a cutoff wavelength*[3] was designed for the 5 µm band.

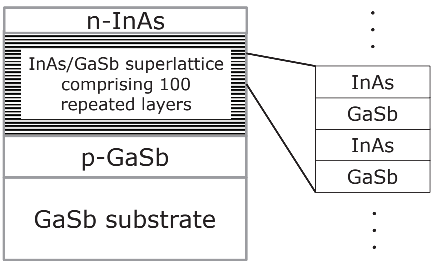

Fig. 1. Epi-wafer structure

The crystal quality of the fabricated epi-wafer was evaluated by atomic force microscopy (AFM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and photoluminescence (PL).

3. Characteristics of the Epi-Wafer

Figure 2 shows an AFM image of the surface of the fabricated epi-wafer. The surface was smooth with no substantial irregularities, defects, or dislocations that could adversely affect the detection characteristics. Moreover, the surface roughness (Rms) value was significantly small at 0.3 nm.

Next, Fig. 3 shows a cross-sectional TEM image of the epi-wafer. No dislocation or defects were observed across the entire 100 repeated layers, proving that the formed superlattice interface was abrupt and smooth. Figure 4 shows the XRD measurement results for the epi-wafer (004). The peak of the GaSb substrate roughly coincided with the 0th peak resulting from the lattice constant of the InAs/GaSb superlattice, revealing that the insertion of the InSb layer was sufficiently effective for mitigating the difference in lattice constant between the GaSb and InAs layers. Additionally, distinct satellite peaks were observed across the −3rd to +3rd orders, indicating that the epi-wafer had an abrupt superlattice interface, being consistent with the cross-sectional TEM results shown in Fig. 3. These results prove that our low-temperature OMVPE growth technique is effective for growing high-quality InSb layers and for forming an InAs/GaSb superlattice with an abrupt and smooth interface by mitigating the difference in lattice constant.

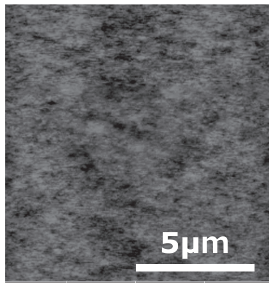

Fig. 2. AFM image of epi-wafer surface

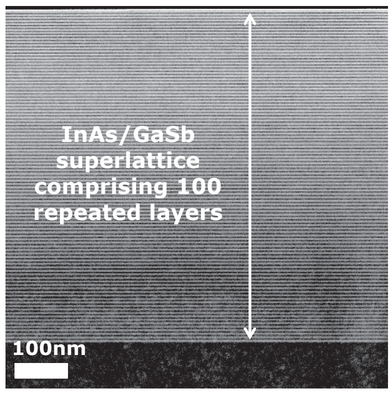

Fig. 3. Cross-sectional TEM image of the InAs/GaSb superlattice

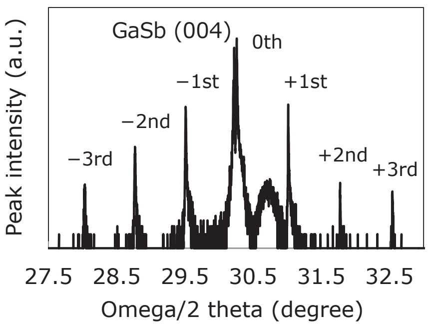

Fig. 4. (004) XRD measurement results

Figure 5 shows the PL measurement results obtained to evaluate the optical characteristics of the epi-wafer at a temperature of 4 K and with an Nd:YAG laser (wavelength: 1064 nm) as the excitation light source. The observed emission spectrum of the InAs/GaSb superlattice contains a PL peak wavelength of 5.6 µm as intended in the design. This suggests that the epi-wafer fabricated in this study is suitable for sensing MWIR wavelengths in the 5-µm band, as designed.

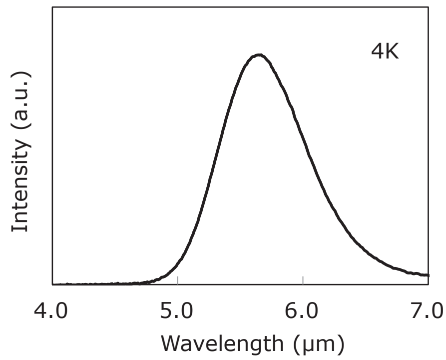

Fig. 5. PL spectrum

4. Detector Fabrication

The device structure shown in Fig. 6 was developed to evaluate the detection characteristics of the epi-wafer that contained an InAs/GaSb superlattice fabricated by OMVPE as the absorption layer. First, the epi-wafer shown in Fig. 1 was subjected to dry etching to physically separate the InAs/GaSb superlattice from the absorption layer. Next, the crystal was covered with a SiO_2 passivation layer, and to collect the photocurrent, an n-contact and a p-contact were formed on the n-InAs layer and the p-GaSb layer, respectively. The n-contact and p-contact were made of Au/Pt/Ti.

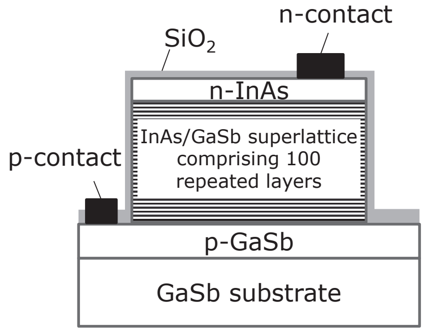

Fig. 6. Cross-sectional view of the detector

5. Detector Characteristics

Figure 7 shows the I-V characteristics of the fabricated detector. The measurement was performed at 77 K. The detector exhibited a rectification property, as shown in Fig. 7. In addition, its dark-current density was suitably low at 2×10^{-4} A/cm^2 (applied voltage: −50 mV), enabling the device to function as a sensor.

Next, the external quantum efficiency of the fabricated detector was measured to evaluate the sensitivity. The measurement results are shown in Fig. 8. The measurement was conducted at a temperature of 20 K, with external light cast from the substrate side. The detector was sensitive in the wavelength range of 3 to 5 µm. The external quantum efficiency was 15% at 3.5 µm.

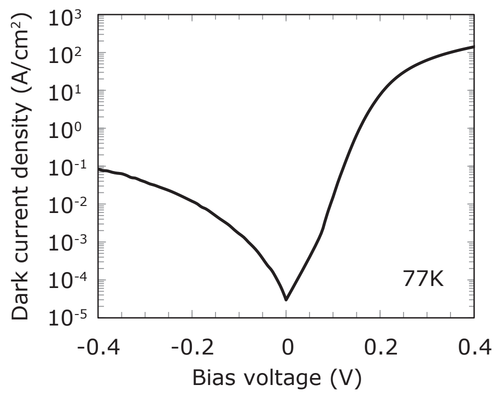

Fig. 7. I-V characteristics

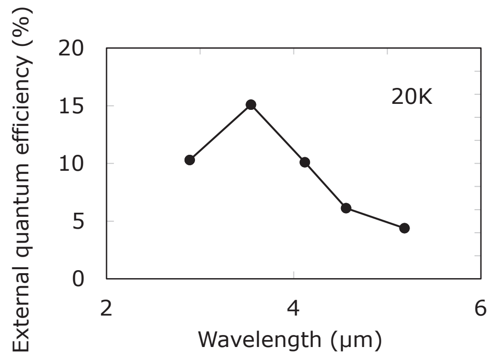

Fig. 8. Sensitivity measurement results

The sensitivity of the detector is expected to improve by increasing the number of repeated layers in the InAs/GaSb superlattice.

6. Conclusion

Using a productive epitaxial growth method, OMVPE, we fabricated InAs/GaSb superlattices on a GaSb substrate to be used for MWIR detectors. Our original Sb-compatible low-temperature OMVPE technique enabled the growth of a high-quality, 100-layer InAs/GaSb superlattice. We also fabricated a detector using the resultant InAs/GaSb superlattice and tested it. Test results revealed that the detector had a good rectification property and achieved a dark-current density of 2×10^{-4} A/cm^2 at an applied voltage of −50 mV and a device temperature of 77 K. The detector was sensitive enough in the wavelength range of 3 to 5 µm and observed a quantum efficiency of 15% at a wavelength of 3.5 µm. These results indicates that the InAs/GaSb superlattice grown in this study will contribute to the creation of a high-performance MWIR band detector.

7. Acknowledgments

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Technical Terms

∗1 InAs/GaSb superlattice: A crystal of alternately stacked InAs and GaSb layers, each several nm thick.

∗2 Dark current: The electric current that flows in a photodetector when it is not exposed to light.

∗3 Cut-off wavelength: The maximum wavelength that a detector can detect.

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