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Solid-phase epitaxial growth of $In_xGa_{1-x}As$ on InP substrate

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1. Introduction

Low-temperature-grown (LTG) GaAs [1] is used as photoconductive antennas (PCAs) excited by lasers with wave lengths of 0.8 µm for terahertz (THz) emission and detection, because its properties include high resistivity, high carrier mobility, and ultra-short carrier lifetime. However, PCAs being usable for the fiber lasers with wavelengths of 1.5 µm are recently required to develop less expensive and more compact THz time-domain spectroscopy systems. Therefore, LTG GaAs-based III-V compound semiconductors with bandgaps corresponding to 1.5-µm band, such as InGaAs [2] and GaAsSb [3], are candidate materials for these PCAs. Previous studies succeeded in generation and detection of THz-waves using PCAs made of LTG InGaAs, and it was reported that LTG-InGaAs layers for the PCAs have been grown at 130-180 ˚C [4,5]. We already revealed that amorphous $In_{0.42}Ga_{0.58}As$ deposited at a substrate temperature of 180 ˚C crystallized after annealing [6]. In this study, we focused on the crystallized $In_xGa_{1-x}As$ layers and carried out detailed structural investigation for them.

2. Experiment procedures

The amorphous $In_xGa_{1-x}As$ samples were directly deposited on semi-insulating (001) InP substrates using molecular beam epitaxy equipment at substrate temperatures of 130 ˚C. We performed Indium composition analysis using Electron Prove Micro Analyzer. Beryllium was doped into the $In_xGa_{1-x}As$ layer to intend to reduce carrier lifetime and increase resistivity. The thickness of $In_xGa_{1-x}As$ layers were 1.6 µm. After the deposition, the samples were annealed at 400 and 600 ˚C for 30 minutes, 1 and 6 hours under H_2 atmosphere with a cover wafer of GaAs to perform crystallization of $In_xGa_{1-x}As$ layers. The characterization of the crystallized $In_xGa_{1-x}As$ layers was performed using X-ray diffraction (XRD) measurement and transmission electron microscopy (TEM) observation.

3. Results and discussion

Figures 1(a)-1(c) show the reciprocal space maps (RSMs) of $In_{0.48}Ga_{0.52}As$ which was deposited at 130 ˚C on the InP substrate before and after annealing. As can be seen in Fig. 1(a), diffraction peak of InP substrate can be confirmed,while other peak can also be confirmed in Fig. 2(b). This suggests that amorphous $In_{0.48}Ga_{0.52}As$ was crystallized by annealing [6]. The small q_x intensity distribution was induced after annealing at 600 ˚C (Fig. 1(c)) and this implies the small crystallographic mosaicity and large domain size of the crystallized InGaAs layer.

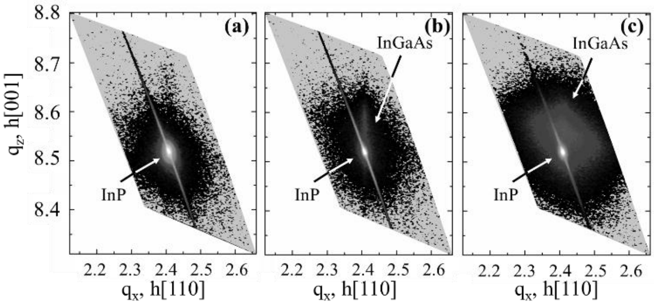

Fig. 1 Annealing temperature dependence of RSMs of the $In_{0.48}Ga_{0.52}As$ layers measured around 115 InP. (a) Before annealing, (b) annealed at 400 ˚C, and (c) annealed at 600 ˚C.

Figure 2 shows the XRD spectra of the same $In_{0.48}Ga_{0.52}As$ samples as shown in Fig. 1. In addition to the diffraction peaks derived from (200) and (400) planes of InP substrate, the peaks derived from (111), (220), and (311) planes of $In_{0.48}Ga_{0.52}As$ are confirmed. Moreover, the relative intensity ratio [7] of each crystal plane of polycrystalline GaAs almost being agree with the intensity ratio of these peaks. Therefore, it can be assumed that polycrystalline layer also exists in these as-deposited and annealed $In_{0.48}Ga_{0.52}As$ samples.

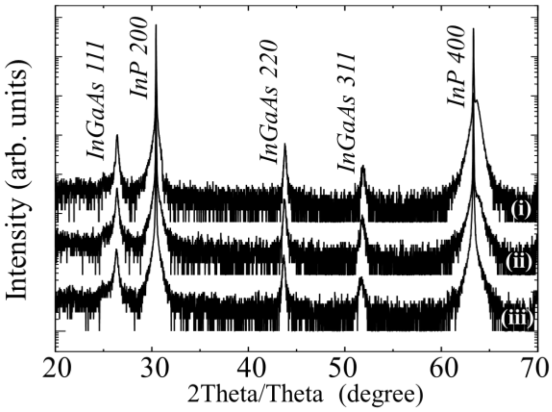

Fig. 2 Annealing temperature dependence of XRD spectra measured with the 2θ-θ method for the $In_{0.48}Ga_{0.52}As$ sample: Annealed at (i) 600 ˚C, and (ii) 400 ˚C, and (iii) before annealing.

Figure 3 shows cross-sectional TEM images and electron diffraction patterns for the $In_{0.48}Ga_{0.52}As$ samples. In case of the as-deposited sample, the cross-sectional TEM image indicates that the $In_{0.48}Ga_{0.52}As$ layer is divided into two layers (Fig 3(a)). Figures 3(a)-3(c) show that an amorphous layer is deposited directly on the single crystalline InP substrate and a columnar crystal layer is grown on the amorphous layer. On the other hand, for the annealed sample, electron diffraction pattern changed to be spotty (Fig. 3(f)) being similar to that of InP substrate (Fig. 3(e)), while the pattern for the same layer of the as-deposited sample shows a halo pattern including a ring-shaped pattern (Fig. 3(c)). This result indicated that the amorphous $In_{0.48}Ga_{0.52}As$ layer was crystallized after annealing, and the $In_{0.48}Ga_{0.52}As$ layer and InP substrate have the same inplane lattice parameters because the XRD peaks in RSM were aligned parallel to the q_z axis (Fig. 1(b)).

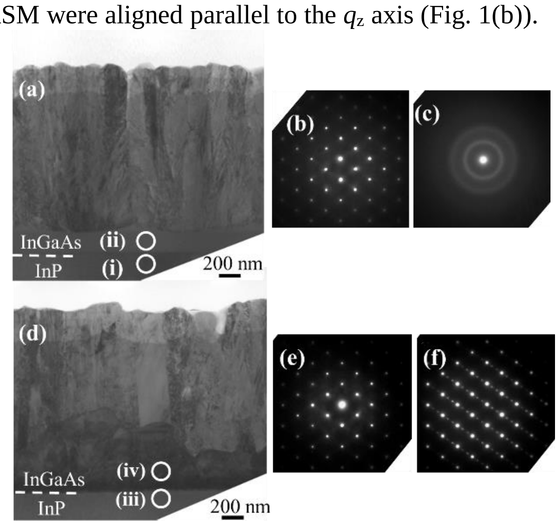

Fig. 3 TEM images and electron diffraction patterns.
(a) Cross-sectional TEM image of as-deposited sample, and diffraction patterns (b) and (c) corresponding to layers (i) and (ii), respectively.
(d) Cross-sectional TEM image of annealed sample, and diffraction patterns (e) and (f) corresponding to layers (iii) and (iv), respectively.

Two weak satellite spots are also observed between main electron diffraction derived from each crystal plane with magnified diffraction pattern (Fig. 4(a)). As a factor of this, it is conceivable that twins were formed in the thermally crystalized layer. According to the previous study, when twins were present in AlGaAs on AlGaAs substrate, a diffraction pattern being similar to the one shown in Fig. 4(a) was obtained [8,9]. Moreover, with enlarged TEM image near the vicinity of the center of the crystallized $In_{0.48}Ga_{0.52}As$ layer, a twin shown in Fig. 4(b) was confirmed. It can be considered the factor which induces formation of twins is surface roughness of substrate. For example, previous studies showed that a lot of twins exist in the AlGaAs layers when the layer was epitaxially grown on AlGaAs substrate without cleaning of the surface of the substrate [7,8].

Figure 5 shows dark-filed TEM images of the annealed $In_{0.48}Ga_{0.52}As$ samples. Thickness of the crystallized $In_{0.48}Ga_{0.52}As$ layer after annealing at 600 ˚C for 30 minutes is about 500 nm (Fig. 5(a)), whereas that of the crystallized

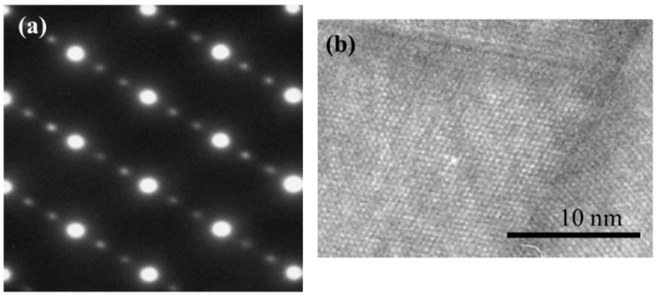

Fig. 4 Enlarged (a) diffraction pattern and (b) TEM image

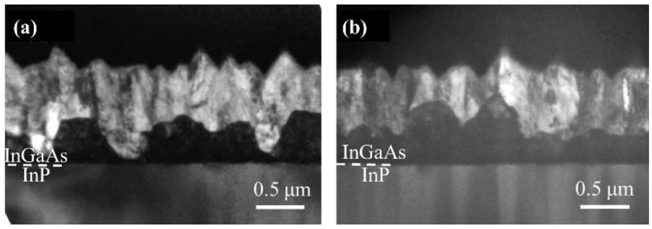

Fig. 5 Annealing time dependence of dark-filed TEM images of the $In_{0.48}Ga_{0.52}As$ samples annealed at 600 ˚C. (a) Annealed for 30 minutes, and (b) for 6 hours.

$In_{0.48}Ga_{0.52}As$ layer after annealing at 600 ˚C for 6 hours is about 700 nm (Fig. 5(b)). Therefore, the crystallized $In_{0.48}Ga_{0.52}As$ layer was grown from the substrate side into the direction of the surface of the sample with increasing annealing time. This demonstrated that $In_{0.48}Ga_{0.52}As$ can be grown by solid phase epitaxy on (001)InP substrate.

4. Conclusion

In this study, solid phase epitaxial growth (SPEG) of $In_{0.48}Ga_{0.52}As$ on (001)InP substrate was confirmed. The formation of twins in the SPEG layer was also confirmed, which was formed probably due to the interface roughness between SPEG layer and the layer just beneath it.

Acknowledgements

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