High sensitivity Hall devices with AlSb/InAs quantum well structures*

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AlSb/InAs quantum well (QW) structures and InAs films on GaAs (001) substrates were grown by molecular beam epitaxy (MBE). We investigated the dependence of electron mobility and two-dimensional electron gas (2DEG) concentration on the thickness of an InAs channel. It is found that electron mobility as high as 19050 $cm^2 \cdot V^{-1} \cdot s^{-1}$ has been achieved for an InAs channel of 22.5 nm. The Hall devices with high sensitivity and good temperature stability were fabricated based on the AlSb/InAs QW structures. Their sensitivity is markedly superior to Hall devices of InAs films.

Keywords: antimonide semiconductors, quantum well, molecular beam epitaxy

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1. Introduction

The principle of operation of Hall devices is based on the classical Hall effects. They are used in many fields, especially as magnetic sensors. Since the first generation of Hall magnetic sensors were commercially available in the mid-1950s, the sensors have been developing quickly along with the progress of material growth technology, such as molecular beam epitaxy (MBE) and metal–organic chemical vapor deposition (MOCVD). AlSb/InAs QW material system is a very attractive system due to the high electron mobility (30000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at a temperature of 300 K) , the electron saturation velocity (4×10^7 $cm \cdot s^{-1}$) of InAs, and the large conduction band offset between InAs and AlSb (1.35 eV).[1–7] However, a large number of difficulties of material growth must be overcome. The first step is to find a semi-insulating (SI) substrate lattice matched to 6.1-Å materials. The epitaxial growths of antimonide semiconductors on GaAs and Si substrates have attracted considerable attention due to their high semi-insulating performance, large area, favorable thermal properties, and low cost. However, due to the lattice mismatches of at least 7% between the antimonide material and these substrates, the high density of misfit dislocations (concentration of 10^8 cm^{-2}–10^{10} cm^{-2}) weakens the electrical properties of Hall devices. Thus, the growth of high quality antimonide material on GaAs and Si substrates is necessary for device applications. Due to both the anion and the cation change across the AlSb/InAs interface, it is possible to grow such wells with different types of interfaces, with either InSb-like or AlAs-like bond configuration. Tuttle *et al.*[8] showed that the formation of an AlAs interface in QWs induces a high concentration of As on Al antisite defects. These antisite defects as interface donors introduce massive charged-impurity scattering into the QW, which is the main reason for most of the drastic mobility reduction. In this work, we grow AlSb/InAs QW structures and InAs films on GaAs (001) substrates by MBE technology. Moreover, we investigate the influence of the thickness of InAs QWs on electron mobility and two-dimensional electron gas (2DEG) concentration. Finally, we fabricate Hall devices with excellent characteristics.

2. Experiment

As a comparison, two types of Hall devices based on an AlSb/InAs QW structure and an InAs film, respectively, were fabricated. The samples were grown on semi-insulating GaAs (001) substrates in an EPI GENII MBE system. Arsenic and antimony were supplied by valved cracker cells to produce As_2 and Sb_2, respectively. An optical pyrometer was used to monitor the substrate temperature. Growth temperatures were calibrated from the oxide desorption temperature. After the deoxidization of the GaAs substrates at 580 °C, a 200-nm GaAs buffer layer was grown to obtain a smooth GaAs surface exhibiting a sharp (2×4) reflection high-energy electron diffraction (RHEED) pattern followed by a 1-μm AlSb buffer layer grown at 510 °C. The InAs channel layers were then grown at different channel thicknesses. Following the InAs layer, AlSb upper barriers and InAs cap layers were added. The AlSb/InAs

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interfaces were forced to be InSb-like by migration-enhanced epitaxy (MEE). It should be noted that this QW structure is unintentionally doped. The material structure is shown in Fig. 1. The Hall devices with Ti/Pt/Au ohmic electrodes, defined using a conventional UV-line lithography technique, were fabricated by wet-etching and lift-off processes. The devices were covered with Si_3N_4 as a passivation layer. The crystalline quality of the samples was evaluated by double-crystal X-ray diffraction measurements (DCXRD) utilizing a Bede D1 high-resolution X-ray diffractometer (Cu Kα1 radiation). Atomic force microscope (AFM) images were taken using a Veeco NanoScope three-dimensional AFM to characterize the surface morphology of the epilayers. The electrical properties of epitaxial layers were characterized by Hall/van der Pauw measurements.

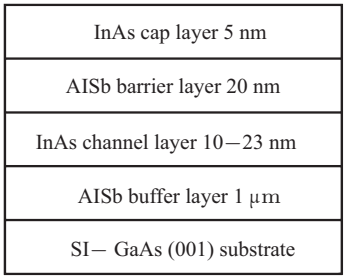


Fig. 1. Schematic cross section of an AlSb/InAs QW structure.

3. Results and discussion

The (004) double crystal X-ray diffraction spectra for one sample with an InAs channel of 15 nm are shown in Fig. 2. The largest peaks are the GaAs substrate and AlSb buffer layer that is 99% relaxed and has a full width at half maximum (FWHM) of 195 arcsec. The InAs channel is clearly seen and has a FWHM of 1030 arcsec. The small FWHM and the position of the peak suggest that the InAs channel is coherently strained to the AlSb barrier layer. AFM images acquired from an InAs channel of 15 nm are shown in Fig. 3. The RMS roughness over a 10 μm×10 μm area was measured to be 2.67 nm. The cracks in the crystallographic orientation,[1–10] observed on the surface, are attributed to threading dislocations propagating throughout the InAs channel.[9]

Figure 4 shows the electron mobility and the sheet electron concentration as a function of the thickness of the InAs channel at room temperature. The thickness of the InAs channel layer ranges from 10 nm to 25 nm. It can be seen that, with the thickness of the InAs channel layer increasing from 10 nm to 12.5 nm, the electron mobility increases quickly from 9099 $cm^2 \cdot V^{-1} \cdot s^{-1}$ to 15810 $cm^2 \cdot V^{-1} \cdot s^{-1}$. Based on our previous calculations,[10] the strong scattering resulting from the interface roughness in the interface between AlSb and InAs is dominant for the electron mobility in an InAs channel thinner than 10 nm. When the thickness of an InAs channel layer increases from 12.5 nm to 22.5 nm, the electron mobility can be as high as 19050 $cm^2 \cdot V^{-1} \cdot s^{-1}$. This phenomenon suggests that the influence of interface roughness on electron mobility is weakened. When the thickness of the InAs channel layer is larger than 25 nm, the electron mobility decreases slowly. However, according to our calculations,[10] the electron mobility is almost constant at room temperature when the InAs channel layer is thicker than 20 nm. Our experiments imply that the occurrence of misfit dislocations, which are due to the 1.3% lattice mismatch between AlSb and InAs, when the thickness of the InAs channel layer exceeds 25 nm. For 2DEG concentration, large numbers of electrons as high as 5×10^{11} cm^{-2}–8×10^{11} cm^{-2} that accumulate in the QW are attributed to the deep donor in the undoped AlSb buffer layer, electrons at the surface pinning level, and the AlSb/InAs interface donor.[11] With the thickness of the InAs channel layer increasing, there is a significant increase of 2DEG concentration, which indicates a gradual drain of electrons in the deep donor of the AlSb buffer layer.

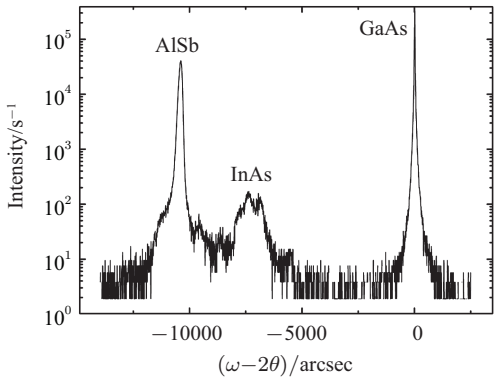


Fig. 2. Symmetric ω–2θ scan in the vicinity of the (004) Bragg peaks for AlSb/InAs QW structures.

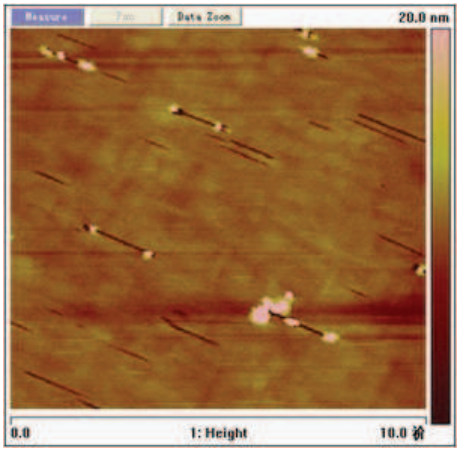


Fig. 3. (color online) AFM image over a 10 μm×10 μm area of InAs channel QW structures.

Table 1 shows the characteristics of two types of Hall devices, such as the mobility, input resistance, output resistance,

sensitivity, and temperature stability. As the table shows, the room-temperature sensitivity of 110 $mV{\cdot}mA^{-1}{\cdot}kG^{-1}{\cdot}k\Omega^{-1}$ was achieved for the Hall devices based on AlSb/InAs QW, which is almost twice as sensitive as the devices based on InAs films. The high mobility of the 2DEG structure is advantageous to the high sensitivity for Hall devices. The temperature stability of Hall devices based on AlSb/InAs QWs is 0.2%/°C, which is a little worse than that of those based on InAs films. The higher sheet carrier concentration can improve the operation temperature. Thus, by optimizing the δ-doping and 2DEG structure design, we can obtain good sensitivity and temperature stability simultaneously.

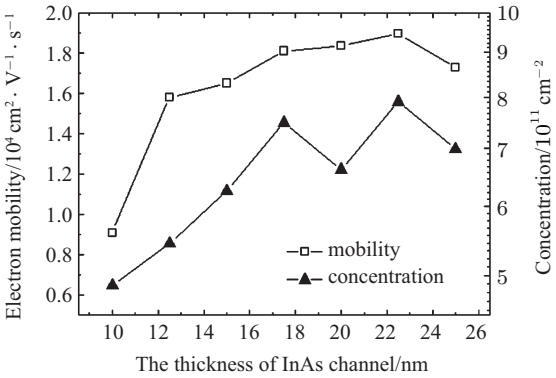


Fig. 4. Electron mobility and concentration as a function of the thickness of the InAs channel layer.

Table 1. Characteristics of two types of Hall devices based on AlSb/InAs QW and InAs films, respectively, at room temperature.

Sample	Type	Mobility 300 K/$cm^2 \cdot V^{-1} \cdot s^{-1}$	Input resistance/Ω	Output resistance/Ω	Sensitivity /$mV \cdot mA^{-1} \cdot KG^{-1} \cdot K\Omega^{-1}$	Temperature stability/$\% \cdot {}^{\circ}C^{-1}$
A	AlSb/InAs QW	19050	605	609	110	0.2
B	InAs film	9000	300	300	56	0.18

4. Conclusion

In summary, we grew AlSb/InAs QW structures and InAs films on GaAs (001) substrates by MBE technology, and according to these, Hall devices were fabricated. The characteristics of Hall devices based on AlSb/InAs QW structures have been significantly improved, compared with that of the InAs film devices.

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