High-Quality InSb Grown on Semi-Insulting GaAs Substrates by Metalorganic Chemical Vapor Deposition for Hall Sensor Application *

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High-quality InSb epilayers are grown on semi-insulting GaAs substrates by metalorganic chemical vapor deposition using an indium pre-deposition technique. The influence of V/Ⅲ ratio and indium pre-deposition time on the surface morphology, crystalline quality and electrical properties of the InSb epilayer is systematically investigated using Nomarski microscopy, atomic force microscopy, high-resolution x-ray diffraction, Hall measurement and contactless sheet resistance measurement. It is found that a 2-μm-thick InSb epilayer grown at 450°C with a V/Ⅲ ratio of 5 and an indium pre-deposition time of 2.5 s exhibits the optimum material quality, with a root-mean-square surface roughness of only 1.2 nm, an XRD rocking curve with full width at half maximum of 358 arcsec and a room-temperature electron mobility of 4.6×10^4 *cm*^{2}*/V·s. These values are comparable with those grown by molecular beam epitaxy. Hall sensors are fabricated utilizing a 600-nm-thick InSb epilayer. The output Hall voltages of these sensors exceed 10 mV with the input voltage of 1 V at 9.3 mT and the electron mobility of* 3.2×10^4 *cm*^{2}*/V·s is determined, which indicates a strong potential for Hall applications.*

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Owing to its highest electron mobility (7.8×10^4 cm^2/V·s, 300 K) and narrow bandgap (0.17 eV, 300 K), InSb is a unique Ⅲ–V semiconductor suitable for applications including high-sensitivity Hall sensors,[1,2] high-speed and high-frequency devices[3,4] and infrared detectors.[5,6] Till now, high-quality InSb and devices have been mostly grown by molecular beam epitaxy (MBE).[7–9] As an alternative growth technique, metalorganic chemical vapor deposition (MOCVD) could enable lower-cost and higher-volume production.[10–12] However, InSb growth by MOCVD is generally more challenging than by MBE, in which the window of optimal V/Ⅲ ratio is very narrow due to the low vapor pressure of antimony. Even a small deviation would result in either indium droplets at lower V/Ⅲ ratio or Sb-related hillocks at higher V/Ⅲ ratio on the surface. In addition, the growth temperature requirement is also stringent because Sb sources such as trimethylantimony (TMSb) at lower temperature may not fully decompose, while at higher temperature InSb could melt. Finally, semi-insulting (SI) substrates are usually required for magnetic and electronic device applications. Due to the lack of SI InSb substrates, InSb is often grown on SI GaAs substrates. However, the large lattice mismatch (14.6%) between InSb and GaAs would lead to a large number of dislocations, especially at the epi-substrate interface. Several approaches have been proposed to improve the material quality, including two-step growth method,[7] buffer engineering,[8] and indium pre-deposition technique.[9,12] By simply introducing indium precursor to the reactor before InSb growth, indium pre-deposition technique is proven to be a simple but effective method for high-quality InSb growth.

In this Letter, we have thoroughly studied the influence of V/Ⅲ ratio and the indium pre-deposition time on the surface morphology, crystalline quality and electrical properties of InSb grown on SI GaAs by MOCVD. Under the optimized growth condition, InSb Hall sensors are successfully fabricated and their performance is very promising for practical applications.

InSb epilayers were grown on epi-ready SI GaAs (001) substrates in an Aixtron 2400 G3 reactor capable of $5 \times 4''$, $8 \times 3''$ and $11 \times 2''$ configurations. Trimethylindium (TMIn), trimethylantimony (TMSb), trimethylgallium (TMGa) and arsine (AsH_3) were used as precursors for indium, antimony, gallium and arsenic, respectively. Prior to the growth, the GaAs substrate was annealed for 10 min under AsH_3 flow at 650℃ for oxide removal and then a 100 nm GaAs buffer was grown at the same temperature. The reactor temperature was then ramped down to 450℃ for InSb growth at a growth rate of about 0.25 nm/s.

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None of the samples studied in this work were intentionally doped.

The surface of InSb samples was inspected under a Nomarski microscope and their morphology was analyzed by a tapping-mode atomic force microscopy (AFM, Bruker Dimension ICON). To evaluate the crystalline quality, X-ray diffraction (004) rocking curves were recorded in a Bruker D8 Discovery diffractometer in double-axis configuration. The carrier mobility and sheet carrier concentration of epitaxial layers were probed by Hall measurement using the standard Van der Pauw method at room temperature (Accent HL5500), and the sheet resistance was also measured using the contactless method (Lehighton LEI-1510).

To fabricate the Hall sensor, device isolation was achieved by conventional photolithography and inductively coupled plasma dry etching. Ohmic contact was then made by e-beam evaporation of Cr/Au. Finally, the device was passivated by SiN_x grown by plasma enhance chemical vapor deposition.

To explore the optimal V/Ⅲ ratio, direct InSb growth was carried out at 450℃ under V/Ⅲ ratios of 4.6 (S1), 5 (S2) and 5.52 (S3). The thickness of these samples was fixed at 400 nm.

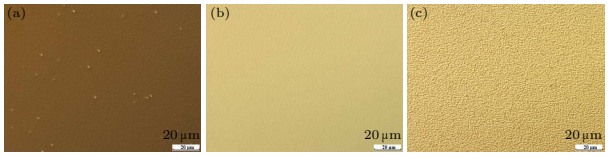

Fig. 1. Nomarski microscope photographs of InSb samples grown with different V/Ⅲ ratios of (a) 4.6, (b) 5 and (c) 5.52.

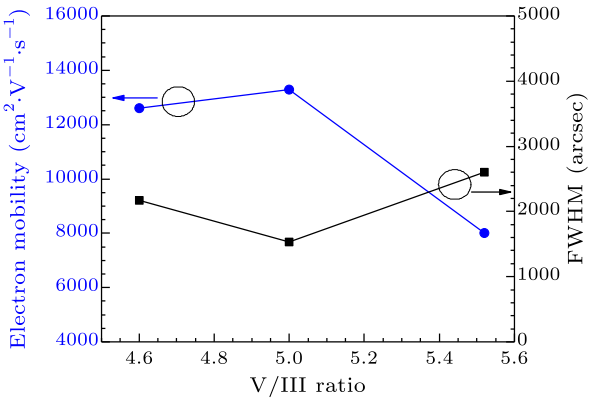

Fig. 2. The dependence of electron mobility at room temperature and FWHM of XRD (004) rocking curve on the V/Ⅲ ratio of directly-grown InSb.

Figure 1 shows the surface morphologies of the three samples by the Nomarski microscopy. S2 with a V/Ⅲ ratio of 5 has a smoother surface. At a lower V/Ⅲ ratio of 4.6, bright dots appear on the surface, which could be indium droplets. At a higher V/Ⅲ ratio of 5.52, the surface becomes rough due to the condensation of excess antimony. Compared to other volatile group V elements, such as arsenic or phosphorus, excessive antimony would neither incorporate into the growing layer nor evaporate but does accumulate on the surface and form a second phase. A similar phenomenon has also been reported by Biefeld and coworkers.[11] The results of the room-temperature Hall mobilities and full width at half maximum (FWHM) values of the XRD (004) rocking curves are displayed in Fig. 2. S2 was found to have the lowest FWHM of 1536 arcsec and the highest electron mobility of 1.3×10^4 cm^2/V·s, which is consistent with the surface quality. All of the samples were determined to be n-type, which is probably due to native defects.

Even with the optimized V/Ⅲ ratio, the surface morphology of directly grown InSb is still undulated. To further improve the morphology and material quality, an indium pre-deposition technique was implemented by introducing TMIn before InSb growth. The growth temperature and V/Ⅲ ratio were fixed at 450℃ and 5, respectively. The pre-deposition time is set to be 0 s (S2), 2.5 s (S4) and 5 s (S5). The thickness of all of the samples was fixed at 400 nm.

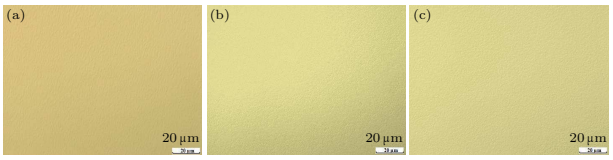

Fig. 3. Nomarski microscope photographs of InSb samples grown with different indium pre-deposition times of (a) 0 s, (b) 2.5 s and (c) 5 s.

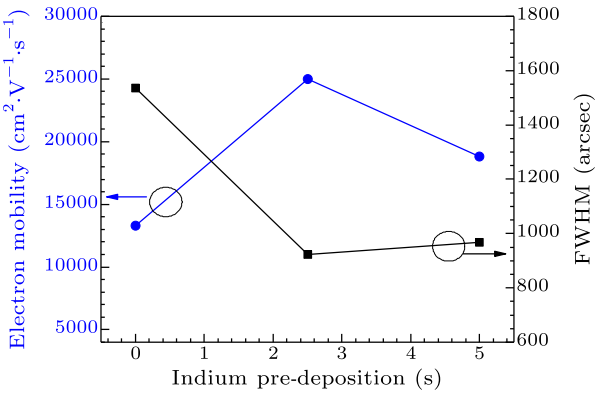

Fig. 4. The dependence of electron mobility at room temperature and FWHM of XRD (004) rocking curve on the indium pre-deposition time.

From Nomarski microscopy, the surfaces of S4 and S5 appear to be smoother as compared to S2 where no indium pre-deposition was applied as shown in Fig. 3. Figure 4 shows the room-temperature Hall electron mobilities and the FWHM values of the XRD (004) rocking curves. S4 with a pre-deposition time of 2.5 s has achieved the best quality with the lowest FWHM of 924 arcsec and the highest electron mobility of 2.5×10^4 cm^2/V·s. It is speculated that the presence of indium may have altered the energetics of GaAs

surface whereby formation of InSb nucleation centers is enhanced and layer-by-layer growth of InSb is promoted. At a longer indium pre-deposition time of 5 s (S5), increased FWHM and decreased electron mobility indicate the degradation of crystalline quality, yet S5 still has better material quality than S2 without indium pre-deposition. Accumulation and clustering of indium on GaAs is considered to account for crystalline degradation of S5.[12]

A 2-μm-thick InSb was then grown with the growth temperature of 450℃, a V/Ⅲ ratio of 5, and an indium pre-deposition time of 2.5 s. Increasing the thickness of InSb tends to improve its material quality. Figure 5 displays surface morphology probed by AFM for a $10 \times 10\,\mu m^2$ scan area and the root-mean-square (RMS) roughness is only 1.2 nm. From XRD, the FWHM of (004) rocking curve is only 358 arcsec. From room-temperature Hall measurement, the electron mobility is as high as $4.6 \times 10^4\,cm^2/V{\cdot}s$ and the background carrier concentration is $2.7 \times 10^{16}\,cm^{-3}$. These values are comparable with those grown by MBE[7–9] and are considered to be promising for Hall sensor applications.

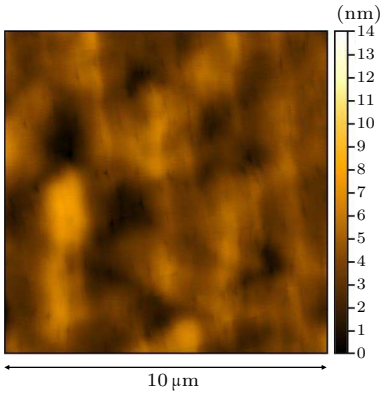

Fig. 5. The $10 \times 10\,\mu m^2$ AFM image of a 2-μm-thick InSb layer. The RMS roughness is only 1.2 nm.

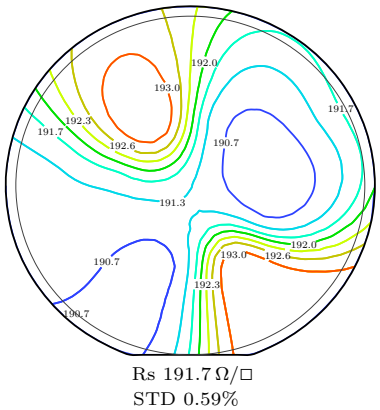

Fig. 6. The values of R_{sh} mapping of 600-nm-thick InSb epilayer on a 2-inch SI GaAs.

InSb Hall sensors were fabricated utilizing a 600-nm-thick InSb epilayer grown on a 2-inch SI GaAs substrate under optimized conditions. Figure 6 shows a mapping of sheet resistance (R_{sh}) measured by LEI-1510. Average R_{sh} of 191.7 Ω/□ with a standard deviation of only 0.59% was achieved. Electron mobility and bulk carrier concentration at room temperature were measured to be $3.4 \times 10^4\,cm^2/V{\cdot}s$ and $1.6 \times 10^{16}\,cm^{-3}$, respectively. Figure 7 presents the Hall voltage (U_H) as a function of the input voltage (U) of three representative sensors at room temperature at 9.3 mT. From 0.2 V to 2.0 V these sensors show linear output and U_H exceeds 10 mV at U of 1 V. The relationship between U_H and U can be described as $U_H = GB\mu U$, where U_H and U represent the Hall voltage and the input voltage, respectively, G is the geometric factor that is determined to be 0.084 from GaAs Hall sensors with the same device geometry, B is the magnetic flux density, and μ is the carrier mobility. Because B is fixed at 9.3 mT, μ of $3.2 \times 10^4\,cm^2/V{\cdot}s$, $3.5 \times 10^4\,cm^2/V{\cdot}s$ and $2.9 \times 10^4\,cm^2/V{\cdot}s$ can be deduced from the $U - U_H$ relationship for the three sensors. It is worth noting that the average electron mobility of $3.2 \times 10^4\,cm^2/V{\cdot}s$ is close to the results from direct Hall measurement of the epilayer. The performance of the Hall sensors is very promising for practical applications, which indicates a strong potential of MOCVD-grown InSb using the indium pre-deposition technique.

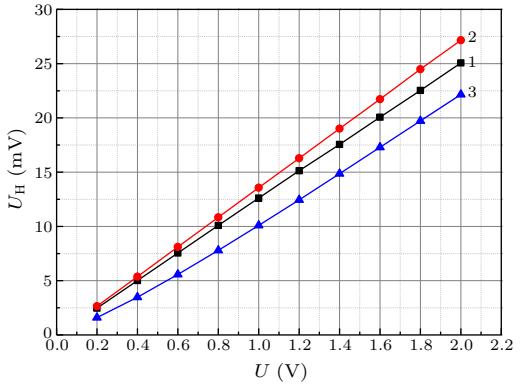

Fig. 7. The dependence of Hall voltage (U_H) on the input voltage (U) for three Hall sensors.

In summary, we have investigated the influence of V/Ⅲ ratio and indium pre-deposition time on the quality of InSb grown on GaAs by MOCVD. At 450℃, the optimal V/Ⅲ ratio is determined to be 5 where no indium or antimony-related defects appear, and optimal indium pre-deposition time of 2.5 s is determined where the presence of indium promotes layer-by-layer growth of InSb. The AFM, XRD and room-temperature Hall measurement results show that the 2-μm-thick InSb epilayer grown under optimal condition yields the best quality with an RMS roughness of 1.2 nm, XRD FWHM of 358 arcsec and an electron mobility of $4.6 \times 10^4\,cm^2/V{\cdot}s$, which are comparable with those grown by MBE. InSb Hall sensors were then fabricated utilizing a 600-nm-thick InSb epilayer grown under optimized conditions. It is found

that with the input voltage of 1 V at 9.3 mT, the output Hall voltages exceed 10 mV. Electron mobility of $3.2 \times 10^4\,\mathrm{cm}^2/\mathrm{V{\cdot}s}$ deduced from $U - U_\mathrm{H}$ relationship indicates the high quality of InSb grown on SI GaAs by MOCVD.

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