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Structural and electrical properties of GaSb, AlGaSb and their heterostructures grown on GaAs by metalorganic chemical vapor deposition

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Abstract

A systematic study of structural and electrical properties of GaSb and AlGaSb grown on GaAs by metalorganic chemical vapor deposition is reported. In general, the results obtained from surface morphologies, X-ray linewidths and Hall properties are consistent with each other and indicate that the optimal growth conditions for GaSb are at 525°C around V/III = 1. A highest hole mobility of 652 $cm^2/V \cdot s$ at RT (3208 $cm^2/V \cdot s$ at 77 K) and a lowest concentration of 2.8×10^{16} cm^{-3} (1.2×10^{15} cm^{-3} at 77 K) were obtained for GaSb grown under this optimal condition. Compared to the GaSb growth, a smaller V/III ratio is needed for the AlGaSb growth to protect the surface morphology. When Al was incorporated into GaSb growth, mobility decreased and carrier concentration increased sharply. The AlGaSb grown at 600°C had a background concentration about one order of magnitude lower than the AlGaSb grown at 680°C. Room-temperature current–voltage characteristics of GaSb/$Al_xGa_{1-x}Sb$/GaSb show a rectifying feature when Al composition x is higher than 0.3, suggesting a valence-band discontinuity at the AlGaSb/GaSb interface. A leakage current much higher than the value predicted by the thermionic emission theory is observed at 77 K, presumably due to a large number of dislocations generated by the huge lattice mismatch between GaSb and GaAs.

1. Introduction

Semiconductor III–V compounds containing Sb are promising materials for infrared, optical and high-speed devices in the spectral region from 1.3 to 6.5 μm [1–3]. Moreover, GaSb has high hole mobility [4] and therefore, is a good candidate for conductive layers of p-channel field-effect transistors. These devices have usually been grown by liquid phase epitaxy or molecular beam epitaxy (MBE) with relatively little data available for growth of AlGaSb by metalorganic chemical vapor deposition (MOCVD) [5–10].

Growth of smooth and high purity Sb compounds by MOCVD is more difficult presumably due to complex growth kinetics and impurities [9], which are normally present in gases in an MOCVD system. For example, Chidley et al. [9] found that both the crystallinity and electrical quality of MOCVD grown AlGaSb were limited by carbon contamination from TMAl material. Properties of AlGaSb will undoubtedly affect the GaSb/AlGaSb interface quality and the properties of overgrown GaSb. To be able to

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grow high-quality bulk GaSb and AlGaSb layers is imperative for the success of MOCVD GaSb/AlGaSb technology. Despite some reports on the electrical properties of GaSb and AlGaSb [5–10], very little data is available on the details of variation with growth conditions. Therefore, we undertake MOCVD growth of GaSb and AlGaSb and characterize their structural and electrical properties by a Normarski optical microscope, double-crystal X-ray diffraction and Hall measurement to find their optimal growth conditions. To study the effect of the undoped AlGaSb layer on the leakage current in devices, several GaSb/$Al_xGa_{1-x}Sb$/GaSb heterostructures were grown on p^+-GaAs substrates with different Al compositions. Current–voltage (I–V) characteristics were used to see the current blocking capability of the AlGaSb layer and also to study the interface quality.

2. Experimental procedure

The GaSb and AlGaSb layers were directly grown on Cr-doped semi-insulating GaAs(100) substrates

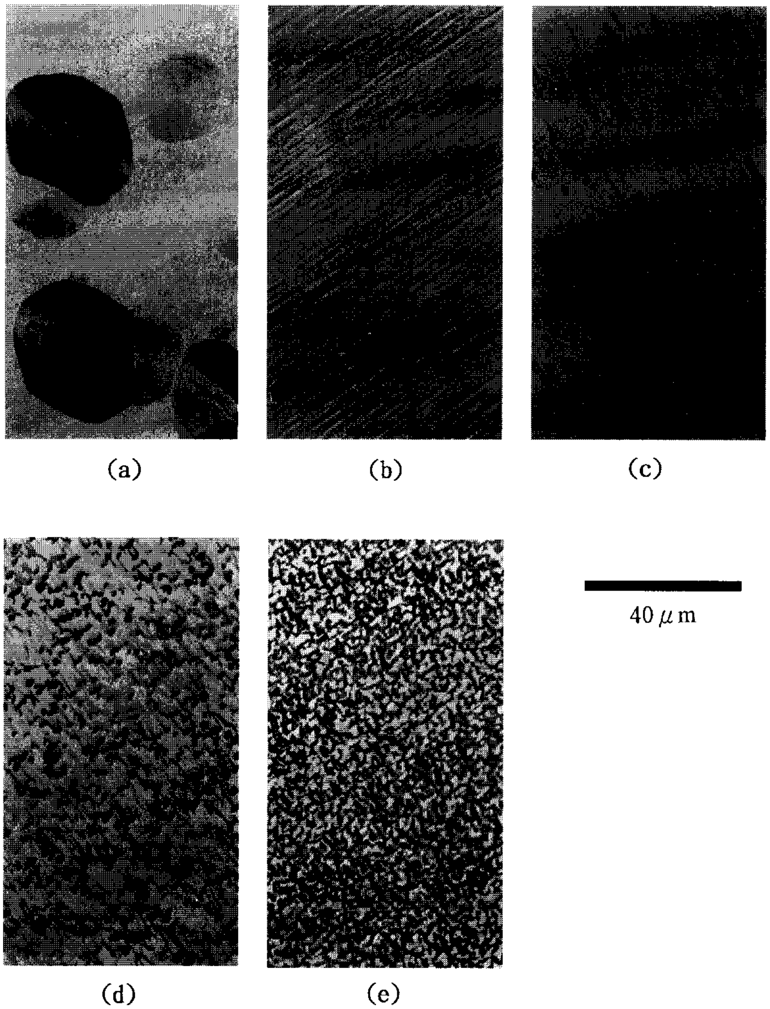


Fig. 1. The surface morphologies of the GaSb layers grown at (a) 500, (b) 525, (c) 550, (d) 575 and (e) 600°C with V/III = 1. It can be seen that the surface morphology is very sensitive to GaSb growth temperature. GaSb grown at 525 and 550°C had smooth morphology.

by the MOCVD system run at one atmosphere and has been discussed elsewhere [11]. We used TEGa, TMAl and TMSb sources. For studying the optimal growth conditions for GaSb, 1 μm thick undoped GaSb was grown at a substrate temperature (T_s) varying from 500 to 600°C with a V/III ratio kept at unity. Due to the low pressure of Sb, the V/III ratio was normally kept at a value not far away from unity. Next, T_s was fixed while varying the V/III ratio from 0.6 to 1.4. The growth rate of GaSb was kept at about 1 μm/h. For growth of AlGaSb, T_s was varying from 600 to 680°C with V/III = 2. Several AlGaSb layers with different Al compositions were grown to study the effect of the Al composition on the layer quality. The Al composition was determined by electron beam microprobe analysis after GaSb and AlSb calibrations.

After bulk growths of GaSb and AlGaSb, GaSb/AlGaSb/GaSb (1.5 μm undoped GaSb/0.2 μm undoped AlGaSb/1 μm undoped GaSb) heterostructures with different Al compositions were grown on p$^+$-GaAs substrates. After growth, mesa

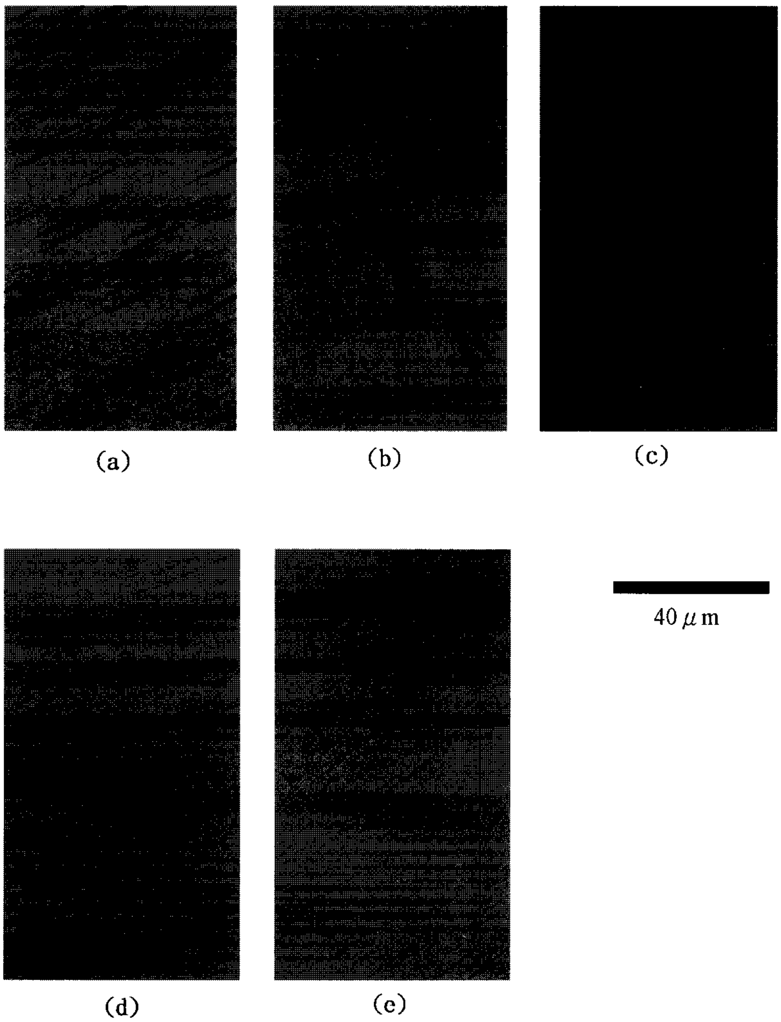


Fig. 2. The surface morphologies of the GaSb layers grown at 525°C with a V/III ratio of (a) 0.6, (b) 0.8, (c) 1.0, (d) 1.2, (e) 1.4. No marked effect of the V/III ratio on GaSb mophology is noticed. This result shows that the GaSb layers grown at T_s = 525°C had smooth surfaces irrespective of the values of the V/III ratio (0.6 to 1.4).

diodes with an area of 7.06×10^{-4} cm^{-2} were made by evaporating Au–Ge dots on top of the structures. The resulting devices were characterized for a leakage current at various temperatures between 77 and 300 K.

3. Results

3.1. GaSb growth

To illustrate the effect of T_s on the surface morphology, we show in Fig. 1 GaSb grown at 500, 525, 550, 575 and 600°C with V/III = 1 (flow rate = 8.9 $\times 10^{-6}$ mol/min). It can be seen that the surface morphology is very sensitive to T_s. GaSb grown at 525 and 550°C had smooth morphology. $T_s > 550$°C, morphologies of all the GaSb layers became rough. For 500°C growth, the surface showed three-dimensional cone-shaped structures, which were likely to be the result of a large sticking coefficient and a very low surface mobility of Sb on the growth surface.

Keeping T_s at the optimal value of 525°C, GaSb was grown with a V/III ratio from 0.6 to 1.4. Fig. 2 shows the resulting morphologies of the GaSb layers. We did not notice any marked effect of the V/III ratio on the GaSb morphology. V/III = 0.6 was sufficient to protect the GaSb surface grown at 525°C. This result showed that GaSb layers grown at T_s = 525°C had smooth surfaces irrespective of the values of the V/III ratio (0.6 to 1.4). However, V/III = 0.6 was not enough for GaSb if grown at 550°C. The grown surface became rough and puckers could be seen on it. The density of the surface puckers decreased with increasing V/III ratio, and disappeared when the V/III ratio reached unity. This is expected since a higher V/III ratio is needed to protect the surface if grown at a higher temperature. Besides T_s and the V/III ratio, the absolute TMSb flow rate also affects the GaSb morphology. We found that at higher TMSb flow rate, GaSb with good morphology could be grown at higher T_s.

The structural quality of GaSb on GaAs was examined by taking the (400) reflection from a double-crystal X-ray diffraction. Two peaks diffracted from two source signals can be resolved for the substrate and the epitaxial layer, which is indicative of high quality material. Fig. 3 shows the full width at half maximum (FWHM) for 1 μm thick GaSb layers grown at different T_s under V/III = 1. A minimum FWHM of 360 arcsec was observed for GaSb grown at 525°C and a sharp increase was seen for GaSb grown at $T_s \geq 550$°C. The result that GaSb grown at 525°C has a minimum FWHM correlates well with the result of morphology. To illustrate the effect of the V/III ratio on the structural quality, we show in Fig. 4 the variation of FWHM for GaSb grown under different V/III ratios. For 525°C

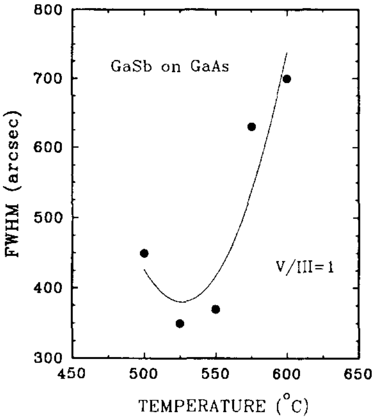


Fig. 3. The full width at half maximum (FWHM) of X-ray diffraction for a 1 μm thick GaSb layer grown at different temperatures under V/III = 1. A minimum FWHM of 360 arcsec was observed for GaSb grown at 525°C and a sharp increase was seen for GaSb grown at $T_s \geq 550$°C.

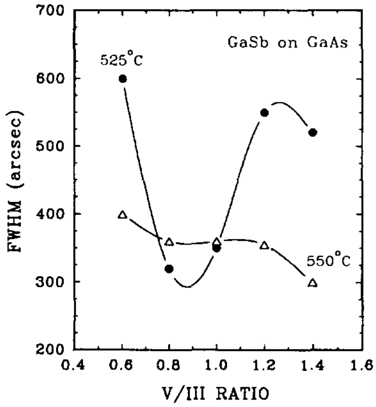


Fig. 4. The variations of the full width at half maximum (FWHM) of X-ray diffraction for the GaSb layer grown under different V/III ratios at a growth temperature of 525 or 550°C. For 525°C growth, FWHM shows a minimum around V/III = 0.8 and 1. For 550°C growth, the FWHM decreased with increasing V/III ratio.

growth, FWHM shows a minimum around V/III = 0.8 and 1. For 550°C growth, FWHM decreased with increasing V/III ratio. These FWHM results are consistent with those of surface morphologies.

Electrical properties of GaSb on GaAs were characterized by Hall measurement at room temperature (RT) and 77 K. Unintentionally doped GaSb was all p-type. Fig. 5a and 5b show the growth temperature dependent properties of GaSb layers. A highest hole mobility of 652 cm^2/V · s at RT (3208 cm^2/V · s at 77 K) and a lowest concentration of 2.8×10^{16} cm^{-3} (1.2×10^{15} cm^{-3} at 77 K) were obtained for GaSb grown at 525°C under V/III = 1. This mobility is comparable to the highest ever reported [9] by MOCVD and indicates a low level of impurity compensation. Mobility at 77 K decreased sharply with either increasing or decreasing T_s away from 525°C. For GaSb grown at 575 or 600°C, $N_A - N_D$ at RT was even as high as 10^{17} cm^{-3}. The lack of temperature dependence of mobility between RT and 77 K for GaSb grown at 575 and 600°C suggests a high level of impurity compensation, thus background impurity or stoichiometric defect density may even be higher than shown. We also recorded the Hall data on GaSb grown at 525 and 550°C, respectively, as a function of V/III ratio. The results are shown in Fig. 6a for mobilities and Fig. 6b for hole concentrations. GaSb grown at 525°C has a higher mobility and lower hole concentration than GaSb grown at 550°C. The measured mobilities at 77 K show weak dependence on the V/III ratio. For the case of

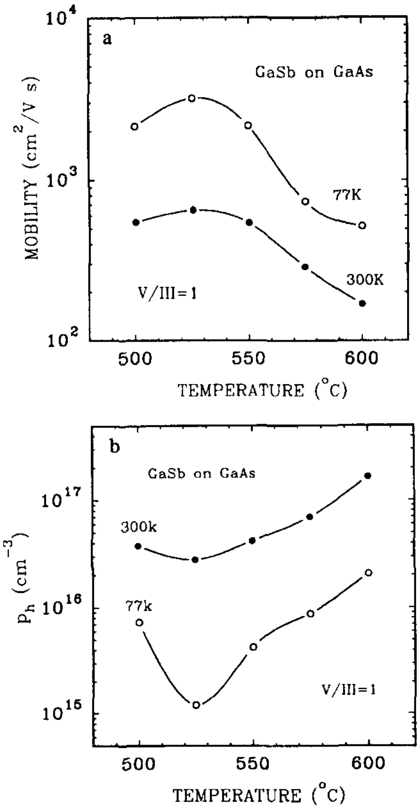


Fig. 5. (a) Measured hole mobilities and (b) concentrations at 77 and 300 K as a function of GaSb growth temperature. The V/III ratio was kept at unity during the growth. A highest hole mobility of 652 cm^2/V·s at RT (3208 cm^2/V·s at 77 K) and a lowest concentration of 2.8×10^{16} cm^{-3} (1.2×10^{15} cm^{-3} at 77 K) were obtained for GaSb grown at 525°C under V/III = 1.

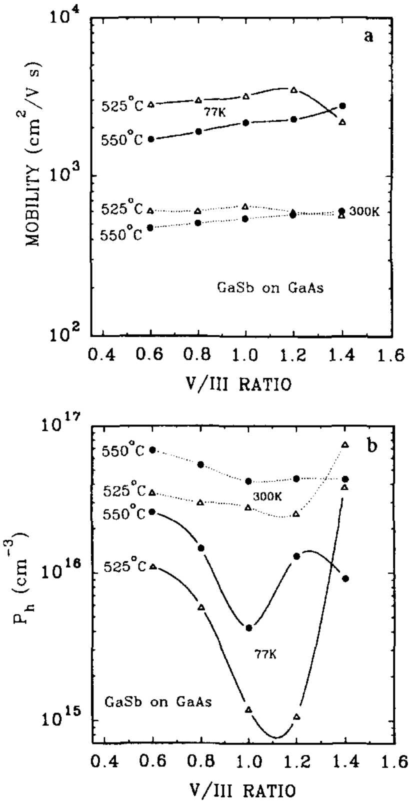
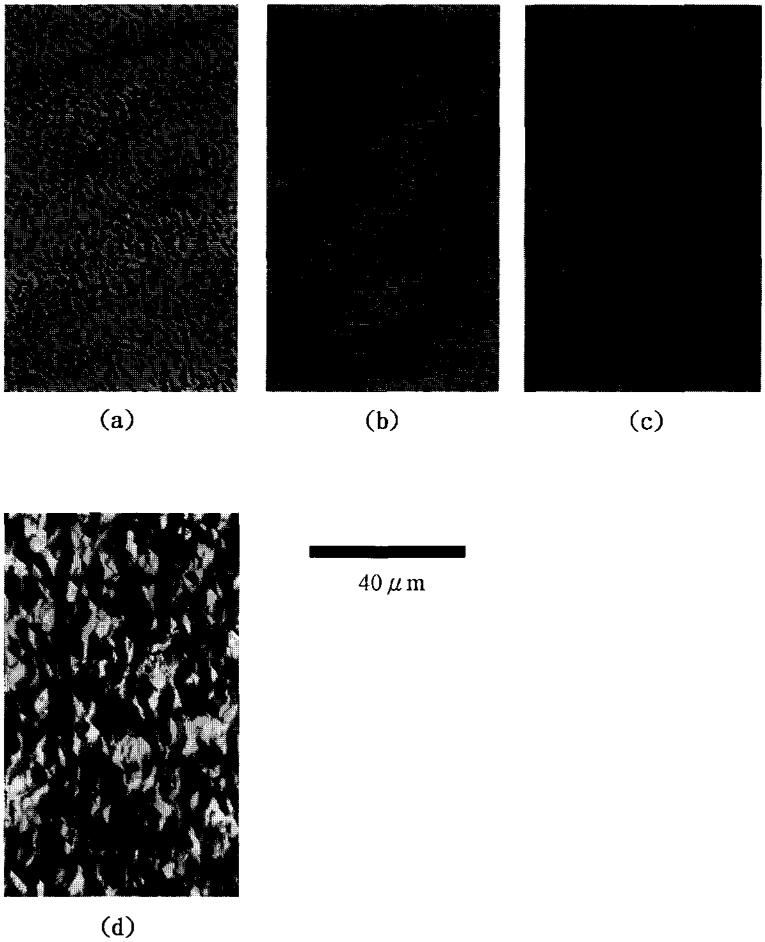


Fig. 6. (a) Measured hole mobilities and (b) concentrations at 77 and 300 K as a function of V/III ratio. The GaSb layers were grown at 525 and 550°C, respectively. A weak dependence of mobility on the V/III ratio was observed. For the case of T_s = 525°C, the highest mobilities and lowest concentrations were observed for V/III around 1.0 and 1.2.

$T_s = 525°C$, highest mobilities and lowest concentrations were observed for V/III around 1.0 and 1.2. While the surface morphology does not clearly show the effect of the V/III ratio, X-ray FWHM and Hall data clearly indicates that the optimal GaSb growth condition is at $T_s = 525°C$ around V/III = 1. Besides this, the results from surface morphology, X-ray linewidth and Hall data are, in general, consistent with each other.

3.2. AlGaSb growth

Typical morphology of undoped AlGaSb on GaAs is mirror-like seen by the naked eye and is similar to or even slightly better than that of GaSb. Several $Al_xGa_{1-x}Sb$ layers with different x were grown to study the effect of Al composition on surface morphology. Compared to the GaSb growth, we found that a small V/III ratio is needed for the AlGaSb growth to protect the surface morphology. Fig. 7 shows the morphologies of $Al_xGa_{1-x}Sb$ with different Al compositions directly grown on GaAs at 600°C. To illustrate that a reduced V/III ratio is needed for AlGaSb growth, we show in Fig. 7a a rough morphology of GaSb grown at 600°C under V/III = 2, due to the insufficiency of Sb to protect the grown surface. When Al was incorporated into the growth, keeping the same Sb flow rate, the morphologies became smooth as Fig. 7b for $x = 0.17$ and Fig. 7c for $x = 0.41$ show. This clearly shows



(a) (b) (c)

(d)

Fig. 7. The surface morphologies of $Al_xGa_{1-x}Sb$ with (a) $x = 0$, (b) $x = 0.17$, (c) $x = 0.41$, and (d) $x = 0.58$ Al composition. The $Al_xGa_{1-x}Sb$ was directly grown on the GaAs substrate at 600°C.

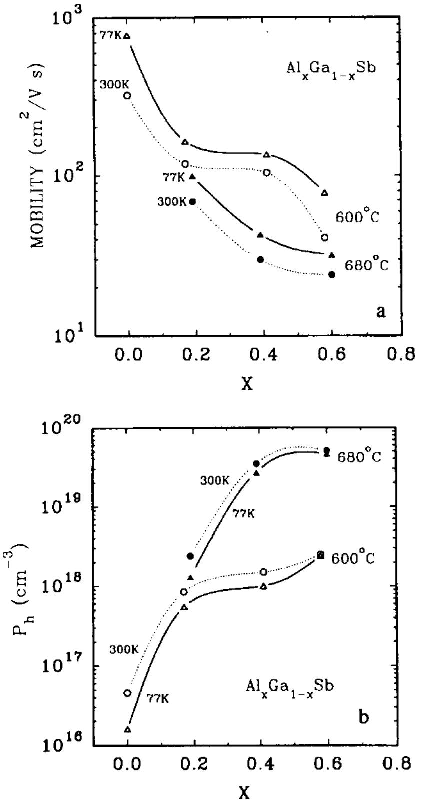


Fig. 8. (a) Measured hole mobilities and (b) concentrations at 77 and 300 K for $Al_xGa_{1-x}Sb$ layers grown at 600 and 680°C, respectively, as a function of Al compositions x. AlGaSb grown at 600°C had a background concentration of about one order of magnitude lower than that of AlGaSb grown at 680°C.

that the incorporation of a small amount of Al to GaSb can improve morphology. However, when Al was increased to 0.58, the morphology became rough due to the insufficiency of Sb as shown in Fig. 7d. We also studied the effect of growth temperature on the surface morphology of AlGaSb. The morphology of AlGaSb grown at 600°C was found to be slightly better than that grown at 680°C under the same V/III.

The electrical properties of undoped AlGaSb are shown in Fig. 8a for mobility and Fig. 8b for concentration as a function of Al composition. Unintentionally doped $Al_xGa_{1-x}Sb$ is p-type. When Al was incorporated into GaSb growth, mobility decreased and carrier concentration increased sharply. The lack of temperature dependence between RT and 77 K illustrates that the impurity or defect scattering are primarily the dominating mechanism. Although their surface morphologies are similar, the electrical properties of AlGaSb are much inferior to GaSb. We tried to grow AlGaSb at several different temperatures to see whether the background concentration could be reduced. However, the effect of varying the growth temperature to lower the background concentration is limited. The best result we obtained was for AlGaSb grown at 600°C. A typical result is shown in Fig. 8, where Hall data are compared for AlGaSb grown at 600 and 680°C (under V/III = 2). The AlGaSb grown at 600°C had a background concentration of about one order of magnitude lower than that of the AlGaSb grown at 680°C. However, their background concentrations were still higher than 10^{17} cm^{-3} and increased apparently with increasing Al composition. A similar sharp increase of background concentration by the incorporation of even a small amount of aluminium had been previously reported [9], and is attributed to carbon contamination in the MOCVD growth. The AlGaSb growth using the new Al source is under investigation. Properties of AlGaSb will affect the AlGaSb/GaSb interface quality and the properties of overgrown GaSb. To be able to grow a low background concentration for AlGaSb is imperative for MOCVD's applications in quantum-confined AlGaSb/GaSb heterostructures.

3.3. I–V characteristics of GaSb / AlGaSb / GaSb structures

The RT I–V characteristics of 1 μm GaSb/0.2 μm $Al_xGa_{1-x}Sb$/GaSb structures in which undoped AlGaSb layers were grown at 600°C are shown in Fig. 9 for several Al compositions. Voltages are measured with respect to the substrate. The whole structure was directly grown on the p$^+$-GaAs substrate following the growth of a 1.5 μm thick undoped GaSb buffer layer. To see whether the interface between the p$^+$-GaAs substrate and the p-GaSb buffer layer will have any effect on devices, an undoped GaSb layer was grown on the p$^+$-GaAs substrate and measured the I–V characteristics. A small ohmic resistance of 2 Ω, mainly due to measurement equipment, was observed, indicating that there is no noticeable potential barrier between them. Thus, the I–V characteristics shown in Fig. 9 are solely due to the GaSb/AlGaSb/GaSb structures.

The AlGaSb layer is expected to behave as a barrier and the current should flow by thermionic emission over the AlGaSb layer. However, from the previous Hall data, we expect a high p-type background doping for the AlGaSb layer. Thus, it is interesting to see whether the AlGaSb layer has any current blocking capability. Fig. 9 shows no appreciable barrier for $x = 0.1$. For $x = 0.3$, the I–V curve clearly shows a rectifying characteristic on both sides of the voltages. Since the high background concentration for 0.2 μm thick AlGaSb, space-charge-limited current conduction can be ruled out for producing this rectifying feature. Therefore, Fig. 9 suggests that there is an appreciable valence-band discontinuity in the GaSb/AlGaSb interface. The GaSb/AlGaSb/GaSb structures have both normal and inverted AlGaSb/GaSb heterointerfaces, which govern the current conduction for positive and negative voltages. The almost symmetrical feature of the I–V characteristics in Fig. 9 indicates that both the normal and inverted AlGaSb/GaSb interfaces have comparable quality.

A valence-band offset of 0.4 ± 0.15 eV between AlSb and GaSb was previously reported [12] by X-ray photoemission measurement. Expecting a linear dependence of band discontinuity on the Al composition, we estimated valence-band discontinuities of 0.12 ± 0.05 eV for $x = 0.3$ and 0.16 ± 0.06 eV for $x = 0.4$. These values should enable us to observe a rectifying feature in the I–V characteristics at RT. The results in Fig. 9 are consistent with this argument. Ideally, the current conduction is governed by thermionic theory. However, since the background concentration of AlGaSb could be higher than 10^{17} cm^{-3}, thermionic field emission [13] is expected to play a part, especially in high-voltage current conduction. The increase of current with voltage in the high voltage range in Fig. 9 is possibly the consequence of this conduction.

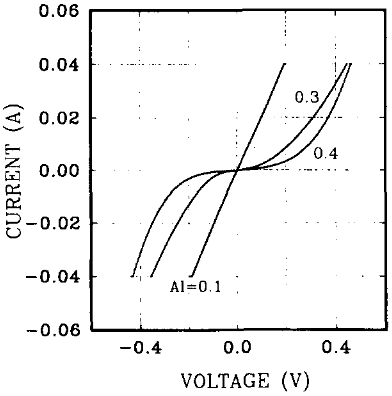


Fig. 9. Room-temperature current–voltage characteristics of GaSb/Al$_x$Ga$_{1-x}$Sb/GaSb structures with different Al compositions for the 0.2 μm thick Al$_x$Ga$_{1-x}$Sb layer. The area of the mesa diodes is 7.06×10^{-4} cm^{-2}. The whole structure was directly grown on the p$^+$-GaAs substrate following the growth of a 1.5 μm undoped GaSb buffer layer.

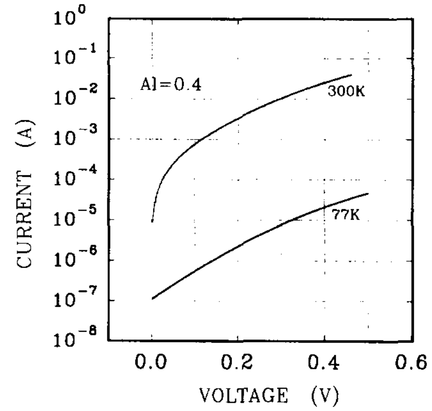


Fig. 10. The current–voltage characteristics of GaSb/Al$_{0.4}$Ga$_{0.6}$Sb/GaSb both at RT and 77 K. The area of the mesa diodes is 7.06×10^{-4} cm^{-2}. The lack of temperature dependence on current is characteristic of defect or impurity-assisted tunneling.

Fig. 10 shows the I–V characteristics both at RT and 77 K for the case of $x = 0.4$. The result shows that the current at 77 K was about two orders of magnitude higher than the value predicted by the thermionic theory. Based on the theory [13], our calculation found that in an interesting voltage range < 0.5 V, thermionic emission is still the dominating conduction even for doping as high as 10^{18} cm^{-3}. The lack of temperature dependence on current is characteristic of defect or impurity-assisted tunneling. This indicates that the AlGaSb contains a large density of defects or impurities. Dislocations generated due to the large lattice mismatch between GaSb and GaAs substrates may be the main defects. These dislocations will extend to the GaSb/AlGaSb interface leading to the degradation of electrical properties.

4. Summary

A systematic study of structural and electrical properties of GaSb grown by metalorganic chemical vapor deposition are reported. Surface morphologies of GaSb are more strongly affected by the growth temperature while not by the V/III ratio (0.6 to 1.4). In general, the results obtained from surface morphologies, X-ray linewidths and Hall properties are consistent with each other and indicate that the optimal growth conditions for GaSb are at 525°C around V/III = 1. A highest hole mobility of 652 $\mathrm{cm}^2/\mathrm{V} \cdot \mathrm{s}$ at RT (3208 $\mathrm{cm}^2/\mathrm{V} \cdot \mathrm{s}$ at 77 K) and a lowest concentration of $2.8 \times 10^{16}\ \mathrm{cm}^{-3}$ ($1.2 \times 10^{15}\ \mathrm{cm}^{-3}$ at 77 K) were obtained for GaSb grown under this optimal condition.

Compared to the GaSb growth, a small V/III ratio is needed for the AlGaSb growth to protect the surface morphology. Unintentionally doped AlGaSb is all p-type. When Al was incorporated into GaSb growth, mobility decreased and concentration increased sharply. The AlGaSb grown at 600°C had a background concentration of about one order of magnitude lower than that of the AlGaSb grown at 680°C. However, their background concentrations were still higher than $10^{17}\ \mathrm{cm}^{-3}$.

Room-temperature current–voltage characteristics of GaSb/$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{Sb}$/GaSb show a rectifying feature when Al composition x is higher than 0.3, suggesting a valence-band discontinuity at the AlGaSb/GaSb interface. A leakage current much higher than the value predicted by the thermionic emission theory is observed at 77 K, presumably due to a large amount of dislocations generated by the huge lattice mismatch between GaSb and GaAs.

Acknowledgements

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