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Growth and properties of $InAs_xSb_{1-x}$, $Al_yGa_{1-y}Sb$, and $InAs_xSb_{1-x}/Al_yGa_{1-y}Sb$ heterostructures

J.H. Kim, D. Yang, Y.-C. Chen and P. Bhattacharya

Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122, USA

A series of undoped InSb and $InAs_xSb_{1-x}$ layers were grown using tetramer Sb_4 and As_4 sources on (100)-oriented semi-insulating GaAs and InP substrates with different growth parameters. Very high electron mobilities (70,000 and 110,000 $cm^2/V \cdot s$ in InSb at 300 and 77 K, respectively) and n-type conductivity are obtained for all alloy compositions. The flux ratio P_{Sb}/P_{In} played a crucial role in determining the surface morphology and the mobility of InSb films. Barrier heights of Al/p-$Al_yGa_{1-y}Sb$ Schottky diodes are measured and are 0.4 eV. A 300 Å Si-doped $InAs_{0.8}Sb_{0.2}$ channel region sandwiched between undoped $Al_{0.4}Ga_{0.6}Sb$ buffer and gate barrier regions has $\mu = 1000$ $cm^2/V \cdot s$ and $n_s = 5.4 \times 10^{12}$ cm^{-2} at 300 K. 1 μm gate FETs made with this heterostructure have shown a maximum extrinsic $g_m = 160$ mS/mm and $f_T = 5$ GHz at 300 K.

1. Introduction

The Sb-containing alloys, and their heterostructures are becoming increasingly important for long-wavelength optoelectronic and cryogenic electronic device applications. In particular, the $InAs_xSb_{1-x}$ alloys produce the lowest bandgap in the family of III–V compounds. They are therefore suitable for detectors and sources operating at wavelengths in the 3–5 μm and 8–12 μm windows where the atmospheric absorption goes to a minimum [1–3]. However, in the development of materials and heterostructures for application to high speed and high frequency microelectronics, the antimony-bearing compounds have lagged behind. There are several reasons for this. Lack of suitable substrates and their large lattice mismatch to GaAs and InP is one. The existence of large miscibility gaps precludes the growth of high quality materials at lower temperatures by equilibrium and non-equilibrium techniques. On the other hand, because of their low bandgaps, the transport properties are expected to improve considerably at low temperatures and therefore these materials and devices would be important for cryogenic applications. However, recent epitaxial materials grown by molecular beam epitaxy (MBE) exhibit type conversion and degradation of the transport properties as the measurement temperature is lowered from 300 K [4–6].

InAs, InSb, and their binary alloys have favorable transport properties compared to GaAs or InP. As mentioned above, they have higher low-field mobility. In addition, the Γ–L and Γ–X intervalley separations are about 1 eV or larger, leading to negligible intervalley scattering and higher peak velocities. This will potentially improve the performance of submicron devices also. Therefore, if some of the problems mentioned earlier can be alleviated, one stands to gain from the superior materials characteristics.

In this paper, we report the growth and transport properties of $InAs_xSb_{1-x}$ heteroepitaxial layers, and the characteristics of $Al_yGa_{1-y}Sb/Al$ Schottky diodes. We have also investigated $InAs_xSb_{1-x}/Al_yGa_{1-y}Sb$ heterostructures grown by MBE on GaAs and InP substrates for the realization of field effect transistors (FETs). Finally, we report the structure of $InAs_xSb_{1-x}/Al_yGa_{1-y}Sb$ heterostructure field effect transistor (HFET) and its performances. The DC and high frequency performance of 1 μm gate FETs made with InAsSb/AlGaSb heterostructures are described.

2. The growth and transport properties of $InAs_xSb_{1-x}$

Heteroepitaxial $InAs_xSb_{1-x}$ layers ($0 \leq x \leq 1$) were grown on Fe-doped (100 InP substrates and semi-insulating GaAs (100) substrates in a Riber 2300P MBE system. Elemental arsenic and antimony were used as the group V sources, producing predominantly As_4 and Sb_4 species. After oxygen desorption under As_4 overpressure (1.5×10^5 Torr), the growth of InAsSb was initiated as substrate temperature ranging from 350–500°C, as measured by an infrared pyrometer. The growth rate varied in the range 0.8–1.0 μm/h and the flux ratio J_{Sb_4}/J_{In} was varied in the range of 0.3 to 4.0. The thickness of these directly grown layers varied in the range of 1.0–14.0 μm. In-situ examination of the crystalline nature of growth was done by reflection high energy electron diffraction (RHEED) measurements with 10 keV electron beams along the (110) azimuth. The observed spotty nature of the RHEED pattern at the initiation of growth indicates a three dimensional growth mode resulting from the large lattice mismatch. After growth of a few hundred ångströms, the spots change to streaks with a (1 × 3) reconstruction, indicating continuous coverage and smoothening of the growth front. Our observations were essentially same as those in previous reports [7].

We have grown InSb films (1 μm thick) on (100) InP substrates with different partial pressure ratios P_{Sb_4}/P_{In}. The measured room-temperature Hall mobilities of 1 μm InSb films grown on InP with different partial pressure ratios are shown in fig. 1 as a function of the partial pressure ratio. All the samples are n-type and the highest electron mobility can be observed in the sample with P_{Sb_4}/P_{In} ratio of 6 and a corresponding beam flux ratio J_{Sb_4}/J_{In} of 2. The above observations suggest that the flux ratio, J_{Sb_4}/J_{In}, plays a crucial role in determining the surface morphology and the electron mobility in the heteroepitaxial InSb films due to the high sticking coefficient of Sb_4 molecules at

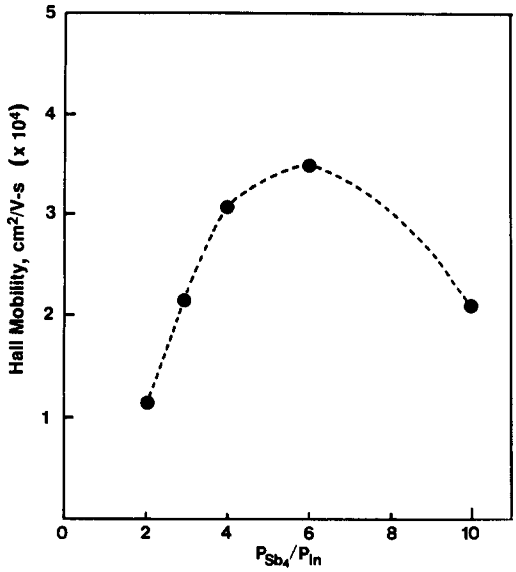

Fig. 1. Variation of measured Hall mobilities with p_{Sb_4}/P_{In} in 1 μm InSb films grown on InP at 380°C and 1 μm/h. The dashed line joins the data points.

the growth temperature used. Similar results were obtained in the InSb films grown on (100) GaAs substrates. The measured mobilities of $InAs_xSb_{1-x}$ with different composition ratios are shown in fig. 2. All samples are n-type. The mobility of InSb is 70,000 $cm^2/V \cdot s$ at room temperature and 110,000

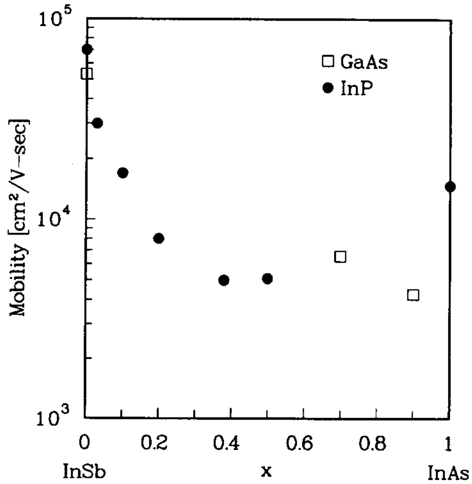

Fig. 2. Variation of measured room-temperature electron mobility with alloy compositions in $InAs_xSb_{1-x}$ films grown on GaAs and InP.

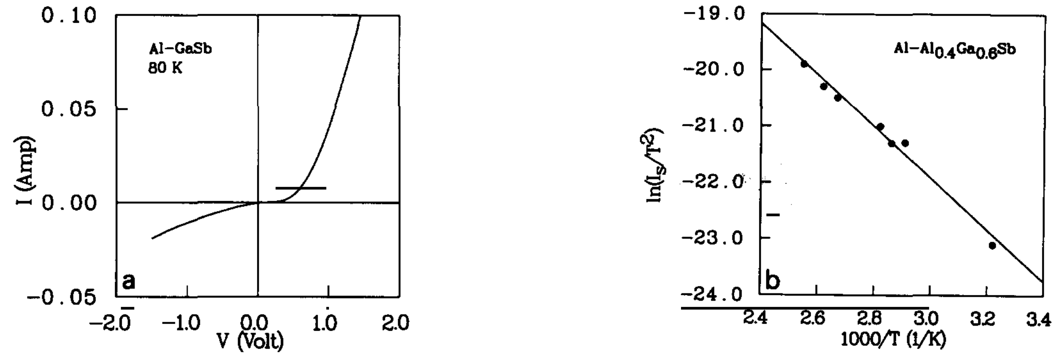

Fig. 3. (a) $I-V$ characteristics at 80 K of Al/GaSb diodes and (b) $\ln(J_s/T^2)$ versus $10^3/T$ plot of $Al/Al_{0.4}Ga_{0.6}Sb$ diode.

$cm^2/V \cdot s$ at 77 K, and the mobility of InAs on InP is 15,000 $cm^2/V \cdot s$ at room temperature. The mobility rapidly drops with alloying, probably due to a combination of increased lattice mismatch and clustering effects. However, the mobility values compare very favorably with $InAs_xSb_{1-x}$ films grown by liquid phase epitaxy on InSb substrates. This also indicates that clustering effects rather than dislocation effects are responsible for the degradation in mobility.

3. The growth and schottky diode characteristics of $Al_yGa_{1-y}Sb$ epitaxial layers

An important parameter in the design and fabrication of FETs are the barrier height and leakage current of the Schottky gate contact. Since in our heterostructures, the Schottky diode is fabricated on an AlGaSb layer, we have examined the properties of Al/AlGaSb Schottky diodes. A 1 μm layer of AlGaSb Be-doped p-type 5×10^{16} cm^{-3} was grown on P^+-GaSb substrates. 500 μm diameter Al Schottky diodes were made on the layers by electron beam evaporation through a shadow mask. Forward and reverse-bias current–voltage measurements were made on the diodes as a function of temperature in the range 80–400 K. The $I-V$ characteristics of a GaSb diode at 80 K are shown in fig. 3a. The reverse saturation current is 8.83 μA and the breakdown voltage is 3 V. Fig. 3b shows the $\ln(J_s/T^2)$ versus $10^3/T$ plot for an $Al_{0.4}Ga_{0.6}Sb$ diode in accordance with the Richardson equation. The barrier heights obtained from the analysis of these data are 0.37 and 0.4 eV for GaSb and $Al_{0.4}Ga_{0.6}Sb$, respectively. Mead and Spitzer [8,9] and Sadiq and Joullie [10] have reported barrier heights of 0.55 and 0.7 eV for Au/p-type AlSb Schottky diodes. Mead and Spitzer cleaved the samples in vacuum before depositing the Au layer. Assuming an increase of barrier height with bandgap, our results are in fair agreement with the data of Mead and Spitzer. These are first reported data on barrier height of MBE grown AlGaSb.

4. The structures and the performance of $InAs_{0.8}Sb_{0.2}/Al_{0.4}Ga_{0.6}Sb$ HFET

For an FET it is important to realize a thin channel with good transport properties. We used InAsSb as a channel and AlGaSb as a barrier material. The schematics of the doped-channel heterostructure FET grown on semi-insulating GaAs is shown in fig. 4. The sheet electron concentration and mobility in the 300 Å Si-doped $InAs_{0.8}Sb_{0.2}$ channel at 300 K are 5.4×10^{12} cm^{-2}

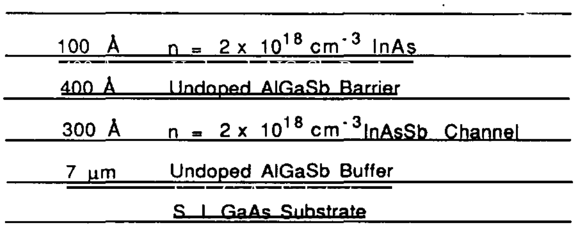

Fig. 4. Schematic of InAsSb/AlGaSb heterostructure FET grown by MBE on GaAs.

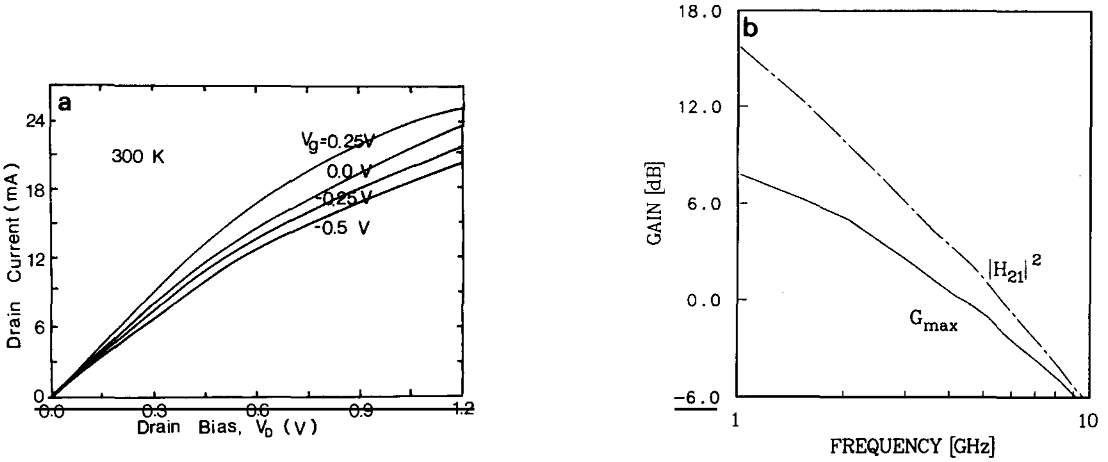

Fig. 5. Measured (a) DC and (b) microwave performance at room temperature for InAsSb/AlGaSb heterostructure FET.

and 1000 $cm^2/V \cdot s$, respectively. Recently, FETs with an undoped channel using the InAs/AlGaSb (or AlSb) heterostructure were reported by Tuttle and Kroemer [11] and Luo et al. [12].

1 $\mu \times 50$ μm gate FETs with a source–drain spacing of 3.5 μm were made by standard photolithography techniques. The source and drain contacts were made with electron beam evaporated Au/Ge/Ni and subsequent alloying. Al gate contacts were formed by electron beam evaporation. Measured room-temperature current–voltage characteristics of the devices are shown in fig. 5a. The devices cannot be pinched off due to a large parallel conduction. The maximum measured transconductance at 300 K is 160 mS/mm. The S-parameter measurements were made on the devices with a CASCADE probe station and a 8510 automatic network analyzer. The measured current gain is shown in fig. 5b. The unity gain cut-off frequency f_T is found to be 5 GHz.

5. Conclusion

We have grown high quality $InAs_xSb_{1-x}$ ($0 \leq x \leq 1$) directly on InP and GaAs substrates by molecular beam epitaxy. The undoped crystals are all n-type at 300 K and at low temperature. The surface morphology and electrical transport properties are strongly dependent on the J_{Sb_4}/J_{In} flux ratio and substrate temperature. The highest mobilities in InSb (10 μm thick) are 70,000 $cm^2/V \cdot s$ and 300 K and 110,000 $cm^2/V \cdot s$ at 77 K, and lower values are measured in the alloys.

We have also investigated the suitability of $Al_yGa_{1-y}Sb$ as a buffer and gate barrier layer in heterostructure FETs. Al Schottky contacts were evaporated on these p-type films and temperature-dependent current–voltage measurements were made. Barrier heights of 0.37 and 0.39 eV are measured in GaSb and $Al_{0.4}Ga_{0.6}Sb$, respectively.

We have made a 300 Å Si-doped $InAs_{0.8}Sb_{0.2}$ channel structure, sandwiched between undoped $Al_{0.4}Ga_{0.6}Sb$ buffer and gate barrier region. It shows $\mu = 1000$ $cm^2/V \cdot s$ and $n_s = 5.4 \times 10^{12}$ cm^{-2} at 300 K. 1 μm gate FETs made with this heterostructure, showed a maximum extrinsic g_m = 160 mS/mm and $f_T = 5$ GHz at 300 K.

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