Narrow band gap InGaSb, InAlAsSb alloys for electronic devices

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Solid source molecular beam epitaxy has been used to grow random alloy quaternary InAlAsSb and ternary InGaSb alloys with a 6.2 Å lattice constant for use in electronic devices such as *p-n* junctions and heterojunction bipolar transistors (HBTs). Several *p-n* hetrojunctions composed of *p*-type InGaSb and one of several different *n*-type InAlAsSb alloys have been fabricated and show good rectification with ideality factors near one. In addition, several of these alloys have been used to make an *n-p-n* HBT that has demonstrated a dc current gain of 25. [DOI: 10.1116/1.2201448]

I. INTRODUCTION

The desire for high-speed electronic and electro-optical devices has driven the interest in developing devices using narrow band gap high mobility InAs with wide band gap AlSb and GaSb. Much of this effort has focused on these materials along with their ternary and quaternary alloys latticed matched to InP and GaSb substrates. Devices using InSb, which has a large lattice mismatch to the available substrates, have also been explored because InSb has an electron mobility near 50 000 $\mathrm{cm}^2/\mathrm{V\,s}$ at room temperature. Part of the attraction of these materials is the wide range of conduction and valence band offsets that is available enabling the use of band gap engineering to optimize device performance. The heterojunction bipolar transistor (HBT) is an example of an important electronic device whose performance can be enhanced by tailoring the valence and conduction band offsets. Long wavelength lasers and detectors, high electron mobility transistors, along with terahertz sources and detectors are among the other devices that are under development or proposed because their performance would be enhanced by exploiting the high mobilities and band gap engineering available with these materials. To take full advantage of these materials it is necessary to be able to grow material over a range of lattice constants from approximately 6.1 Å, the lattice constant of InAs, AlSb, and GaSb, to near 6.47 Å, the lattice constant of InSb.

Glisson *et al.* (Ref. 1) and Vurgaftman *et al.* (Ref. 2) have developed interpolation methods for estimating the band gaps, band offsets, and lattice constants of a variety of III-V ternary and quaternary alloys starting with known properties of binary and ternary alloys. Their results have lead to an interest in working with heterojunctions composed of narrow band gap $\mathrm{In}_z\mathrm{Ga}_{1-z}\mathrm{Sb}$ and quaternary alloys of $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}_y\mathrm{Sb}_{1-y}$. By varying the In/Al and As/Sb fractions it is possible to obtain a wide range of band gaps while maintaining a fixed lattice constant. Glisson indicates that at room temperature with a 6.2 Å lattice constant the band gaps would range from near 0.16 eV for $\mathrm{InAs}_{0.66}\mathrm{Sb}_{0.34}$ to 1.7 eV for $\mathrm{In}_{0.19}\mathrm{Al}_{0.81}\mathrm{Sb}$. Vurgaftman's analysis indicates that the 6.2 Å $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}_y\mathrm{Sb}_{1-y}$ alloys have a relatively large valence band offset, near 360 meV, relative to lattice matched $\mathrm{In}_{0.27}\mathrm{Ga}_{0.73}\mathrm{Sb}$, and that the offset is almost independent of x and y. A result of the valence band behavior is that the large variations in band gap of the $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}_y\mathrm{Sb}_{1-y}$ produce large changes in the conduction band offset relative to $\mathrm{In}_{0.27}\mathrm{Ga}_{0.73}\mathrm{Sb}$. This makes these combinations of alloys attractive in applications where it is desirable to have flexibility in choosing conduction band offsets. These band properties are very useful for the development of a *n-p-n* HBT where a large valence band offset helps to block parasitic hole currents from flowing from the base to the emitter, and conduction band offsets impact performance. The work of Glisson and Vurgaftman paints an interesting picture but several different alloys need to be grown and measured to develop a more precise understanding of the dependence of the band structure on alloy composition and the electronic transport properties.

There are very few papers in the literature on the molecular beam epitaxy (MBE) growth of random alloys of $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}_y\mathrm{Sb}_{1-y}$ with $0.2 < x < 0.8$ and $0.2 < y < 0.8$ (Refs. 3 and 4) that describe their electronic properties[4] or show the operation of *p-n* junctions made with them. The early focus of this work has been to develop methods for growing several of these alloys and to determine their electronic transport properties. The second step has been to use the *n*-type $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}_y\mathrm{Sb}_{1-y}$ alloys with *p*-type $\mathrm{In}_{0.27}\mathrm{Ga}_{0.73}\mathrm{Sb}$ to form rectifying *p-n* junctions. The use of the narrow band gap $\mathrm{In}_{0.27}\mathrm{Ga}_{0.73}\mathrm{Sb}$ should lead to large saturation currents needed for high-frequency, low-power applications, and the valence band offset should minimize diffusion capacitance effects that limit the frequency response of *p-n* homojunctions. The focus has been on alloys with a 6.2 Å lattice constant that could ultimately be used in a HBT similar to that sketched in Fig. 1, while the individual *p-n* junctions may have other applications.

This article presents some of the steps taken to optimize the growth of the alloys of interest, and it lists some of their electronic properties. It also demonstrates that it is possible to use them in *p-n* heterojunctions. GaSb substrates with lattice constant of 6.095 Å have been chosen for the initial growth studies to minimize effort needed to develop buffers to accommodate the lattice mismatch between the 6.2 Å lay-

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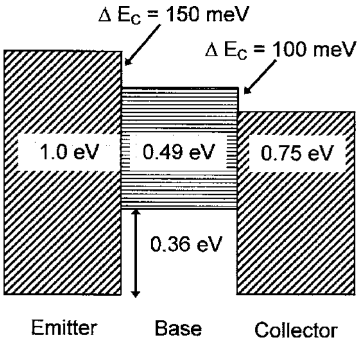

FIG. 1. Band gaps and band offsets for the emitter $In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$, base $In_{0.27}Ga_{0.73}Sb$, and collector $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ alloys for a 6.2 Å HBT based on the works by Glisson *et al.* (Ref. 1) and Vurgaftman *et al.* (Ref. 2).

ers and substrate. These layers enable the development of growth procedures based on the results of atomic force microscopy (AFM) topography, x-ray, and photoluminescence measurements and finally on I-V from *p*-*n* junctions. GaSb substrates have a limited usefulness, as unintentionally doped GaSb substrates are *p* type. However, they are useful for determining growth goals to be obtained when using semi-insulating GaAs or InP substrates with a larger lattice mismatch that requires more demanding buffer layers.

The limits on growing these alloys by MBE in thin epilayers are not well understood. Miscibility problems make it impossible to grow bulk $In_xAl_{1-x}As_ySb_{1-y}$ alloys with the range of x and y of interest here.[3,5] The impact of any phase separation on the electronic properties of these alloys and the impact on the *p*-*n* junctions using them are also uncertain.

II. EXPERIMENT

The quaternary and ternary layers with a 6.2 Å lattice constant reported here were grown by solid source MBE using procedures to produce $In_xAl_{1-x}As_ySb_{1-y}$ random alloys rather than digital alloys. The growth of a quality buffer to accommodate the lattice mismatch to the substrate is an important ingredient in obtaining good material. A 1–2 μm thick AlSb buffer layer with a lattice constant of 6.1355 Å was grown first on the GaSb at a substrate temperature of 510 °C to help accommodate for the 6.2–6.095 Å lattice mismatch. Growing quality 6.2 Å layers on SI-GaAs with a lattice constant 5.653 Å has been somewhat harder. A variety of alloys with and without step graded compositions have been tried, but the easiest and somewhat successful buffer remains a 1–2 μm thick AlSb layer, though the results indicate the quality of the AlSb grown on GaAs is not as good as that on GaSb. A detailed comparison of the AlSb layers themselves has not been made. The 6.2 Å quaternary and ternary layers reported here are at least 1 μm thick and grown directly on the AlSb buffer.

Reflection high-energy electron diffraction (RHEED) oscillations have been used to determine the temperatures of In, Al, or Ga sources needed to obtain the proper flux. Obtaining useful Sb and As fluxes is somewhat harder as the relative incorporation rate depends on growth rate and temperature. Valved Sb_2 and As_2 sources were used, and the valve setting to obtain the desired flux was checked for each source before each growth. Several test structures were grown and tested to determine the As and Sb fluxes that resulted in the best alloys. While useful As and Sb fluxes have been found, a more detailed study needs to be made to determine if other values would produce higher quality $In_xAl_{1-x}As_ySb_{1-y}$. Growing the $In_{0.27}Ga_{0.73}Sb$ is an easier task as it is not a mixed Sb and As alloy.

The substrate temperature when using GaSb substrates was determined by using RHEED to monitor the 5× to 3× reconstruction transition after first growing a few nanometers of GaSb. This transition has been reported in the literature and for the Sb_2 flux used here it occurred at a substrate temperature of 440 °C.[6] When growing on GaAs substrates, the temperature was determined by using optical spectroscopy to monitor the spectra of the light passing through the GaAs from the substrate heater.

Double crystal x-ray measurements were made to determine the lattice constant and as a judge of the quality of the material. Atomic force microscopy was used to measure the surface morphology, as a smooth surface is a measure of the material quality. Smooth surfaces are also necessary if complex circuits with many devices are to be developed. Low temperature photoluminescence (PL) experiments have provided useful information in judging the quality of the material and in estimating the band gap. As a first approximation for these 1 μm thick layers, the peak in the PL was assumed to be due to band-to-band recombination and therefore approximately equal to the band gap.[7] Additional PL work is under way to better understand the recombination processes that are involved and to measure the band offsets. Secondary-ion-mass spectroscopy (SIMS) measurements have been made to obtain alloy compositions. Hall effect measurements were made on layers grown on SI-GaAs substrates as the GaSb substrates are *p* type and it is difficult to electrically isolate the MBE layer from the substrate. GaTe has been used for the *n*-type dopant in both the $In_xAl_{1-x}As_ySb_{1-y}$ and $In_{0.27}Ga_{0.73}Sb$ alloys. Beryllium has been used as the *p*-type dopant in $In_{0.27}Ga_{0.73}Sb$.

III. RESULTS

The focus has been on the growth of two quaternaries, $In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$ and $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ as these are candidates for use in *p*-*n* heterojunctions and as the emitter and collector, respectively, of an HBT. Early growth studies focused on x-ray measurements of the lattice constant, atomic force microscopy of the surface morphology,[8] and low temperature photoluminescence to estimate the band gap.[7] These helped to determine the optimum substrate temperature to be 350–400 °C, and to choose suitable As_2 and Sb_2 fluxes. The 6.2 Å layers were grown at a 1 ML/s (ML denotes monolayer) rate to a thickness of 1 μm. Several attempts to grow each alloy were required to determine the Φ_{Sb}/Φ_{As} flux ratios of 3 and 8 for the $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ and $In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$ alloys, respectively. The total group V to total group III flux ratio was 16 for both alloys.

TABLE I. Hall data for the alloys.

Alloy	Carrier concentration (cm^{-3})	Mobility ($cm^2/V\,s$)
$In_{0.27}Ga_{0.73}Sb$	3×10^{19} (*p* type)	160 (*p* type)
	9×10^{16} (*n* type)	11×10^3 (*n* type)
$In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$	5.5×10^{16} (*n* type)	2.7×10^3
$In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$	1.6×10^{17} (*n* type)	7×10^2

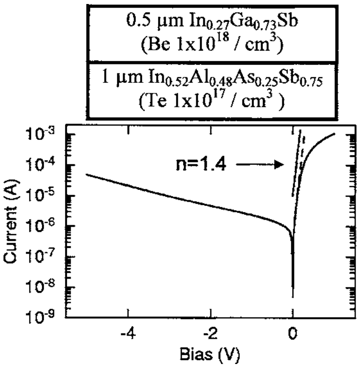

FIG. 2. Current-voltage data for an $In_{0.27}Ga_{0.73}Sb/In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$ *p-n* heterojunction. The solid line is the raw data, the dashed line is the data corrected for series resistance effects, and the short line indicates a line with an ideality of 1.4.

$In_xAl_{1-x}As_ySb_{1-y}$ and $In_{0.27}Ga_{0.73}Sb$ layers with an rms surface roughness of 1.3 nm over a 5×5 μm^2 were eventually produced. With GaAs substrates, a roughness of 1.1 nm has been measured for an $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ layer with a 0.5 μm AlSb/0.1 μm GaSb/1 μm AlSb buffer. To date, 5.7 nm is the best roughness for $In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$ on GaAs with a 2 μm AlSb buffer as little effort has been devoted to growing it on GaAs. Maintaining the growth temperature is important in obtaining quality growths. This is harder to do with the wider band gap GaAs substrate than the GaSb as the substrate heater light passing through the GaAs heats the narrower band gap $In_xAl_{1-x}As_ySb_{1-y}$ as it grows. A lack of temperature stability is expected to result in fluctuations in the alloy composition as qualitative comparisons of the data indicate that the relative incorporation of As and Sb depends on the growth temperature. The $In_{0.27}Ga_{0.73}Sb$ alloys are also grown with a substrate temperature between 350 and 400 °C.

Measurements of the carrier concentration, mobility, and the current-voltage characteristics of *p-n* heterojunctions provide important information needed to improve the growth processes and to understand the limits of the alloys under development in this work. Table I lists the transport properties of $In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$, $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$, and $In_{0.27}Ga_{0.73}Sb$, layers. Transport data were measured for both *n*- and *p*-type $In_{0.27}Ga_{0.73}Sb$. The *n*-type layers have high mobilities at high carrier concentrations that make them a good candidate for the buffer between GaAs and a 6.2 Å layer. The high electron and hole mobilities also make $In_{0.27}Ga_{0.73}Sb$ useful as the base of a HBT. The *p*-type mobility indicated here is larger than the mobility at similar hole concentrations of GaAsSb, 30–40 $cm^2/V\,s$,[9] or InGaAs, 60–80 $cm^2/V\,s$,[10] the semiconductors used for the base layers in InP HBTs are now under development. This is important, as it is necessary to minimize the base resistance between the base Ohmic contact and the area under the emitter. High electron mobility and high electron velocity are also important qualities of the base layer as they are indicators of an electron's ability to move quickly from the emitter to collector. The 11 000 $cm^2/V\,s$ electron mobility at a concentration of 9×10^{16} cm^{-3} shown here is higher than the electron mobility of 8000 $cm^2/V\,s$ measured at a similar carrier concentration in InGaAs used in HBTs lattice matched to InP.[10] The specific contact resistance of unalloyed Ohmic contacts to *p*-type InGaSb with a hole density of 2.9×10^{19} cm^{-3} has been measured to be 7.6×10^{-8} $\Omega\,cm^2$ which is lower than the contact resistance to the InGaAs base in an InP HBT.[11] The photoluminescence[7] indicates the band gap of $In_{0.27}Ga_{0.73}Sb$ is near 0.5 eV, which will lead to low voltage operation and low-power dissipation in both *p-n* junctions and HBTs.

A mobility as high as 2700 $cm^2/V\,s$ has been measured for an $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ layer. This is about half the value of 5400 $cm^2/V\,s$ for InP used in some high performance InP-based HBTs. Alloy scattering may play a role in the low mobility, but the large mobility variations found among several samples and the large variations in the rms roughness indicate that defects may be limiting the mobility at this time, and suggests that improvements in the mobility are still possible. The same expectation holds for the $In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$ alloy particularly since the quality of these layers grown on GaAs is not as high as those grown on GaSb as judged by the AFM roughness.

Heterojunctions using *p*-type $In_{0.27}Ga_{0.73}Sb$ and each of the InAlAsSb alloys have been grown on GaSb substrates and processed with conventional optical lithography. Current-voltage data at room temperature are shown in Figs. 2 and 3 for diodes measuring 55×55 μm^2. These results show the feasibility of forming *p-n* heterojunctions that may

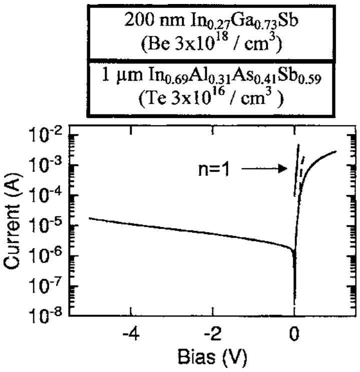

FIG. 3. Current-voltage data for an $In_{0.27}Ga_{0.73}Sb/In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ *p-n* heterojunction. The solid line is the raw data, the dashed line is the data corrected for series resistance effects, and the short line indicates a line with an ideality of 1.

have a value on their own, and the feasibility of forming a HBT as the alloy compositions similar to those that may be used for the base collector and emitter base. In each of these figures the raw data are shown by the solid lines. The dashed line is the data corrected for series resistance effects, and the short solid line parallel to the forward bias data is a line with the indicated ideality factor. Both sets of data have reasonably small ideality factors indicating reasonable quality material. They both show rectification with reverse currents near 5×10^{-6} A at 2 V reverse bias. The small band gap of the $In_{0.27}Ga_{0.73}Sb$ is expected to produce a large saturation current contributing to the measured reverse current. Both interface defects and bulk defects are also expected to contribute to the reverse current, and the larger ideality factor for the diode in Fig. 2 suggests that differences in the defects may be contributing to the somewhat larger higher reverse bias current for that diode. More data and a more in depth analysis are required for these heterojunctions. Having diodes opens the possibility of performing temperature dependent *I-V*, capacitance-voltage, and deep level transient spectroscopy measurements that will provide band gap information and detailed information about growth and process induced defects.

The success with making *p-n* junctions led to the growth and fabrication of a HBT that demonstrated a dc current gain of 25 with a maximum collector current density of 2×10^4 A/cm^2. Details of the layer structure, common emitter, and a Gummel plot have been published.[12] The Gummel data indicate that a collector current density can be reached at lower emitter-base voltage than those reported for an InP HBT.[13] This indicates that it is possible for HBTs with this material system to operate at lower power dissipation than InP HBTs. The device shown in the previous publication was grown on a GaSb substrate, and work is now under way to fabricate *p-n* test structures and HBTs on GaAs substrates.

IV. SUMMARY

Progress has been made in the MBE growth of a group of InAlAsSb and InGaSb alloys with a 6.2 Å lattice constant for use in the development of a low-power, high-frequency heterojunction devices. Heterojunctions have been fabricated and found to exhibit good rectification and small ideality factors. These test junctions are similar to those needed to form a HBT and will be useful in improving growth processes needed to form a high quality HBT. A HBT has also been grown and fabricated and found to have a dc current gain of 25. High collector current densities have been measured at low emitter-base voltages. This is a good indicator that low-power dissipation is possible. These results show that many important steps have been taken in the development of *p-n* heterojunctions and a HBT in this material system. These devices have been grown on GaSb substrates to minimize lattice mismatch effects that become more severe with SI GaAs or InP substrates. Single layers have been grown on SI GaAs enabling the measurement of Hall effect data that indicate that the InGaSb alloy has superior transport properties for use as a base in a HBT. The emitter and collector mobilities are lower than desired, but the quality of the layers judged by the AFM morphology is poorer than that found with GaSb substrates. This may reflect the presence of defects that limit the mobility, leaving significant room for improvement.

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