Transport of modulation-doped $Al_{0.2}Ga_{0.8}Sb/GaSb$ heterojunctions

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Abstract. Mobilities and carrier densities of modulation doped $Al_{0.2}Ga_{0.8}Sb/GaSb$ heterostructures are presented for the first time. The structures studied were grown by molecular beam epitaxy and consisted of a single heterojunction with Te compensation doping to reduce the intrinsic p-type background. Hall measurements were performed from 30–300 K, giving p-type mobilities peaking at 3240 cm^2/Vs, a considerable improvement over previous reported bulk mobilities for samples with compensation doping. Growth trials on bulk material have also been carried out to investigate the optimum growth conditions for future structures, with the aim of minimising the occurrence of natural growth defects in GaSb, which act as acceptors. Together these measurements lay the ground work for (magneto)transport studies of two-dimensional charge-carriers in $Al_xGa_{1-x}Sb/GaSb$ heterostructures, which has not been previously reported.

1. Introduction

GaSb has been known and well-studied as an optoelectronic material for many years, but knowledge of its electronic properties is limited [1]. It has an electron effective mass of 0.039 m_e (where m_e is the mass of the electron), 0.58 times that of GaAs, and a narrow band gap of 0.812 eV at 0 K. In many ways, GaSb is a close relation of GaAs, with minimal lattice mismatch to its natural tertiary barrier material (AlGaSb) [2]. However, development in GaAs transport structures have far surpassed GaSb, which has been limited to basic bulk measurements, with this stagnating in the 1990's. A prime reason for the vast knowledge on GaAs is the availability and cheap cost of high-quality substrates for subsequent growth, from which various confined systems have been created, giving us a wealth of understanding of the material. Other III-V semiconductors, such as GaSb, have to compromise their material quality when grown on a GaAs substrate due to the lattice mismatch. Here, to decrease the strain we incorporate an interfacial misfit array (IMF) layer which significantly reduces threading dislocation in the growth direction (measurement plane), leading to higher quality material more suited to electrical applications [3]. Further improvements can be gained from modulation doping and confinement which have not yet been realised in GaSb for transport measurements.

Hole transport investigations in GaSb are much more extensive than electron transport, with various groups having investigated the low-temperature range and multiple carrier concentrations. These are generally on unintentionally p-doped or insufficiently compensation n-doped bulk GaSb structures. GaSb is a nominally p-type material with a high acceptor defect producing a carrier concentration of $\sim 1\times10^{17}$ cm^{-3} [4]. From various investigations, the cause of this high concentration has been found to be a native defect in the form of a doubly accepting gallium antisite (Ga_{Sb}) [5]. Previous growth studies have shown that by lowering the growth temperature and the V/III flux ratio, these intrinsic defects can be decreased to 1×10^{16} cm^{-3}, and by changing the growth further, n-type GaSb is achievable through a different defect, though the transport details of this are not known [6].

Clearly, there is room for expansion in the field of electron and hole transport in GaSb. Our work investigates transport in $Al_{0.2}Ga_{0.8}Sb$/ GaSb heterojunctions, with Te modulation doping to compensate the p-type background, avoiding the creation of more scattering centers in the conducting channel. This lays the groundwork for creation and (magneto)transport measurement of two-dimensional charge carriers in $Al_xGa_{1-x}Sb$/GaSb heterostructures.

2. Growth, fabrication and experimental details

All structures were grown using molecular beam epitaxy (MBE) on semi-insulting GaAs substrates with an IMF layer at the GaSb/GaAs interface to prevent threading dislocations. Two different sets of samples were grown: $Al_{0.2}Ga_{0.8}Sb$/GaSb heterostructures and bulk GaSb.

For the heterostructures 1 µm of GaSb was grown on GaAs, followed by a 20 nm spacer layer of undoped $Al_{0.2}Ga_{0.8}Sb$ and then 100 nm of n-type $Al_{0.2}Ga_{0.8}Sb$ (Te doped). These modulation-doped samples were grown with a substrate temperature of 505 °C, a Sb/Ga growth rate ratio of 2.2, these are the standard growth conditions used in this study (STSR) and a Ga_2Te_3 source provided the doping. Both slab and δ-plane doping were achieved. The structure is shown in the inset of figure 1, where the δ-plane equivalent structure has the same layer dimensions and spacer as the slab, and a sheet concentration of 1×10^{12} cm^{-2}. From bulk trials the intrinsic hole concentration for these growth conditions is estimated to be ~5×10^{17} cm^{-3}. The $Al_{0.2}Ga_{0.8}Sb$ is doped enough to partially compensate, but not form a triangular well at the junction, therefore transport in the thick GaSb layer (1 µm) is considered bulk. Hall bars with an aspect ratio of ~30:1 were created using standard top-down photolithography fabrication techniques. Ohmic contacts were achieved with a multilayer metal composition of Pd/In/Pd/Au (5/40/4/100 nm), however, they were high resistance. Low-frequency DC Hall measurements were performed over a range of temperatures from 30–300K in magnetic fields up to ±0.5 T.

Growth trials were carried out on bulk structures of 2 µm of GaSb on GaAs, grown at various temperatures and V/III ratios, giving unintentional hole concentrations that varied between 4 and 20 $\times10^{16}$ cm^{-3} at room temperature. Further details of the growth of these structures can be found in section 4. Tellurium doping was varied and gave rise to electron concentrations up to 6×10^{17} cm^{-3}. Unlike the modulation doped structures, contact was made using indium solder in a ~ 1 cm^2 van der Pauw geometry.

3. Mobility and carrier concentration in $Al_{0.2}Ga_{0.8}Sb$/ GaSb heterojunctions

The transport properties of the modulation-doped samples are shown in figures 1 and 2. As there is minimal difference between the slab and delta samples for both the carrier concentration and the mobility, only the slab doped sample is shown in figure 2. It can be seen in figure 2 that carrier density decreases exponentially with decreasing temperature, with the onset of freeze out at ~150 K. The mobility steadily increases with decreasing temperature until 70 K, where it reaches a maximum before sharply decreasing at low temperature as the carriers freeze out.

A two carrier fit was implemented on the conductivity data of all measurements, following the method of Reed *et al*.[7]. From this analysis it was concluded that the samples can be considered single carrier as a significant majority of the carriers across all temperatures are holes. Hole concentration peaked at 2.2×10^{16} cm^{-3}, with the electron density consistently being calculated as <6% of the total carrier concentration.

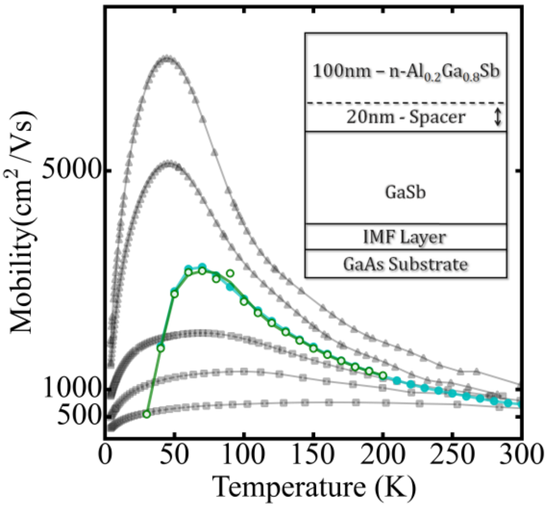

Figure 1. Mobility against temperature for modulation doped samples, slab doped (○) and delta doped (●) compared to bulk structures grown and measured by Dutta *et al.* [8] Te compensated (□) and pure GaSb (▲).

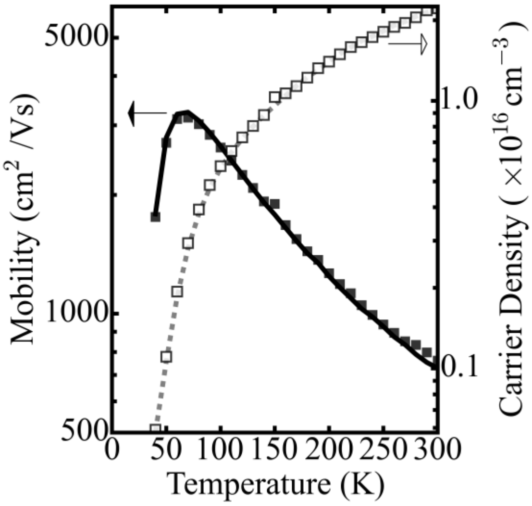

Figure 2. Mobility as a function of temperature for a GaSb slab doped heterojunction (-), calculated hole mobility (■) with their associated carrier densities (--,□).

Previous work investigating scattering mechanisms and defects in GaSb was undertaken by Dutta *et al* on bulk GaSb structures, both undoped and compensation-doped with Te. These structures were entirely GaSb single crystals, and so had no strain defects [8]. Their work concluded that in the undoped samples the mobility was limited by phonons above 45 K and by ionized impurities below 45 K, whereas the doped samples were ionized impurity limited at all temperatures. By comparing to their work on Te compensated samples (squares in figure. 1), it is shown that our samples have higher mobility between 40 and 200 K, despite having more potential strain, and form a curvature more similar to the pure samples than the doped. The carriers in our sample close to the junction will be scattered by the Te remote ionized impurities, but will this have only a small effect on the majority in the thick GaSb conducting channel. Therefore, the extrinsic impurity scattering in our samples is minimal compared to the scattering created by Te ionized impurities in the bulk doped samples studied by Dutta *et al*. Above 200 K the mobilities are comparable, and below 70 K carrier freeze-out causes a decrease in our mobility.

Overall, our results show good promise for future high-mobility (magneto)transport measurements on $Al_xGa_{1-x}Sb$/GaSb heterostructures. Further to these samples, a growth trial has been carried out to explore the defect density's dependence on growth conditions, with the aim of obtaining even higher mobility material.

4. Growth study of bulk GaSb

It has been known for many years that GaSb's high acceptor concentration primarily originates from defects in the growth in the form of a gallium antisite (Ga_{Sb}); a gallium atom in the lattice site of an antimony atom [5]. These defects occur regardless of the growth method but are heavily dependent on growth conditions. Due to the less than unity sticking coefficient of Sb, a V/III growth ratio of more than 1 is required at all times. However in the case of GaSb, counter intuitively, a greater Sb excess leads to an increase in GaSb defects, creating a very narrow optimum growth window for GaSb with low unintentional doping. To investigate this relationship between growth conditions and defect density, we have performed growth trials on MBE-grown GaSb samples. Figure 3(a) shows the variation in measured carrier density with intended doping carrier concentration. The intended doping concentration is determined from a series of InSb calibration samples, with appropriate correction for the growth rate of GaSb.

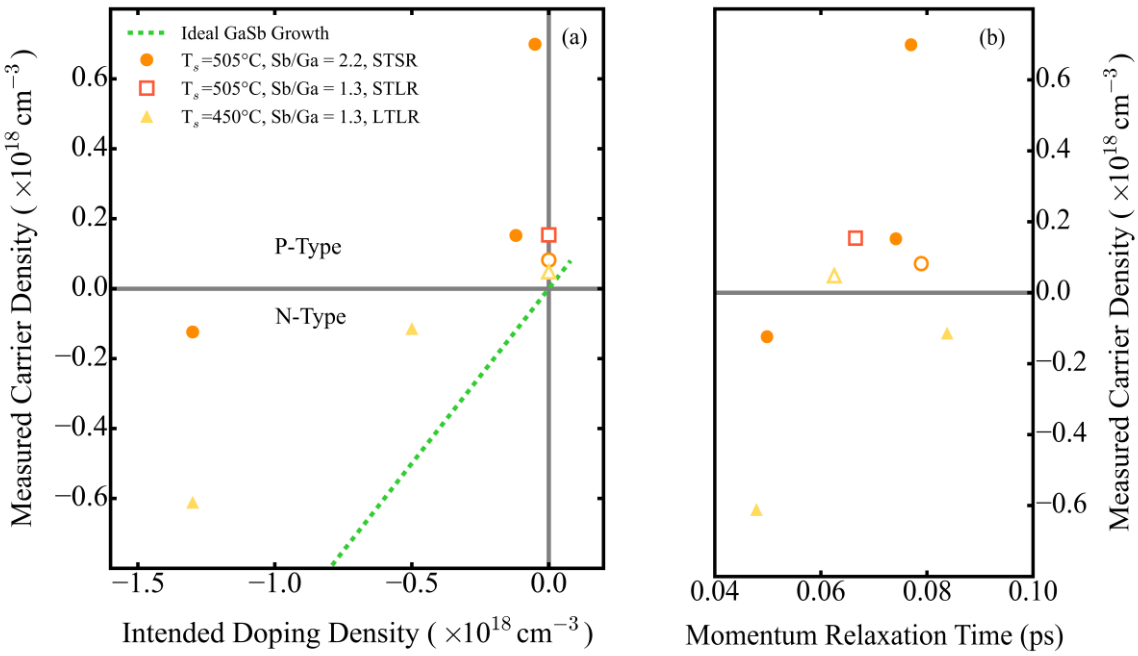

Figure 3. (a) Measured carrier density against intended doping density at room temperature for 3 growth conditions (key shown in the figure). Undoped samples are shown as open symbols and the ideal GaSb growth, shown as a dashed line, is a 1:1 relationship between intended doping density and measured carrier density. **(b)** Momentum relaxation time against measured carrier density. The positive measured carrier density represents hole concentration and the negative carrier density represents electron concentration. Symbols have the same meaning as in (a).

It can be seen from figure 3(a) that for undoped samples (zero on horizontal axis), a lower growth temperature and V/III growth ratio (triangle) yields the most reduced defect density and is named the LTLR growth condition. For increased intended n-type doping, measured carrier density does not follow the ideal 1:1 ratio, veering away from the ideal case. Despite this, a reasonable n-type carrier concentration of 6×10^{17} cm^{-3} is obtained with the LTLR growth condition, so these conditions give a measured carrier density that is closest to the ideal at all intended doping densities.

Figure 3(b) shows the corresponding room temperature momentum relaxation time for each of the samples in figure 3(a). For the undoped samples (open symbols) the longest momentum relaxation time is for the growth conditions of STSR growth condition (circle). However, the difference is modest. In the p-type regime the momentum relaxation time for this growth condition appears approximately invariant with measured carrier density. This may suggest that for p-type samples mobility is phonon limited at room temperature.

In the n-type regime, it can be seen that the LTLR samples show a decrease in momentum relaxation time with increasing n-type carrier density, suggesting, much like Dutta *et al.*, a greater influence from ionized impurity scattering. The equivalent STSR n-type sample (circle) has a reduced momentum relaxation time compared with the LTLR sample of the same carrier density, suggesting that in the n-type regime a LTLR growth produces less scatter and therefore has a better material quality. To add certainty to these results a more varied growth trial would need to be carried out.

Overall, this points to a lower temperature and V/III flux ratio giving improved growth, resulting in improved carrier densities and mobilities. Thus, the results of this growth trial allow for higher mobility material for future (magneto)transport measurements on $Al_xGa_{1-x}Sb$/GaSb heterostructures.

5. Conclusions

We have reported, for the first time, an investigation of the transport properties of modulation-doped $Al_xGa_{1-x}Sb/GaSb$ heterojunctions, and growth trials on bulk GaSb. The mobility of modulation compensation-doped samples was greater than for bulk compensation-doped samples due to the reduced scattering from remote ionized impurities compared to bulk dopants. The mobility of the slab modulation-doped sample peaked at 3240 cm^2/Vs at 70 K for a carrier concentration of 2.8×10^{17} cm^{-3}, with similar values for the δ doped sample. A bulk growth study concluded that low growth temperature and low V/III reduces the number of defects, which create the high p-type background in GaSb. This improves the momentum relaxation time for n-type GaSb, and should have a similarly beneficial effect in modulation-doped samples. Thus, this work sets the scene for (magneto)transport studies of high-mobility two-dimensional charge carriers in $Al_xGa_{1-x}Sb/GaSb$ heterostructures.

Acknowledgments

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