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GaSb/GaInSb quantum wells grown by metalorganic vapor phase epitaxy

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Single and multiple quantum wells of GaSb/GaInSb were grown by metalorganic vapor phase epitaxy. X-ray diffraction on an 80 Å single well confirmed the $Ga_{1-x}In_xSb$ composition to be $x = 0.15$, for which the lattice mismatch is $\approx 1.0\%$. Photoluminescence and photoconductivity from this sample both showed a signal due to carriers in the well, the position of which was in good agreement with the calculated band diagram. Shubnikov–de Haas oscillations in the transverse magnetoresistance (ρ_{xx}) of a four-period multiquantum well, and the associated quantum Hall effect, indicated that a two-dimensional hole gas was present in one of the wells. Unusually, the strongest oscillations were seen for occupancy of an odd number of (spin split) Landau levels ($\nu = 1,3,5,...,$etc.) This sample also showed luminescence peaks at 738 and 755 meV which were attributed to recombination in the wells.

Epitaxial deposition of antimonide-based III-V compounds can be used to fabricate a number of potentially useful narrow band-gap devices. Lasers and photoconductive detectors[1] have already been grown by molecular beam epitaxy (MBE) using the GaAsSb system. These operate in the 1.2–1.7 μm region important for fiber optic applications. Incorporating In into GaSb reduces the band-gap energy and allows infrared (IR) sensors to be made which can operate over the range 1.6–5 μm. Despite these applications, relatively little effort has gone into exploring the epitaxial growth and properties of the antimonides. Bulk layers of both constituents have been successfully deposited by MBE (GaSb,[2,3] GaInSb[4]) and by metalorganic vapor phase epitaxy (MOVPE) (GaSb,[5–8] GaInSb[9]). So far no two-dimensional (2D) structures have been reported. In this letter we discuss the characteristics of GaSb/GaInSb quantum wells (QWs) grown by MOVPE. Before depositing these structures, the optimum conditions were established for the growth of bulk GaInSb layers ($< 10\ \mu$m) with 0–50% In.

The reactor used to deposit these materials has been described elsewhere.[7,8] Growth was at atmospheric pressure and 600 °C from TMGa, TMIn, and TMSb starting materials with palladium diffused hydrogen as the carrier gas. The substrates used were GaAs (100) cut 2° off towards ⟨110⟩. Characterization techniques included transmission electron microscopy (TEM), triple-crystal x-ray diffraction, Hall effect and magnetoresistance measurements, photoconductivity (PC), photoluminescence (PL), and IR absorption.

IR spectra from bulk layers showed a strong absorption, corresponding to the GaInSb band gap, from which the indium concentration was estimated. From Hall effect measurements, values of the carrier concentration (p_H) and mobility (μ_H) were obtained for $Ga_{1-x}In_xSb$ samples with $0.5 > x > 0$. GaSb layers were electronically comparable to those achieved by MBE,[2] with $\mu_H = 4850$ cm^2/V s and $p_H = 8 \times 10^{15}$ cm^{-3} at 77 K. However, incorporation of even a small amount of indium resulted in an increase in p_H and an even more rapid decrease in μ_H. For example, $Ga_{0.8}In_{0.2}Sb$ had $p_H = 1 \times 10^{16}$ cm^{-3} and $\mu_H = 986$ cm^2/V s at 77 K. Thick layers (10 μm) produced higher mobilities than thinner ones (3 μm) while mobilities in excess of 2000 cm^2/V s at 1.5 K were obtained for carriers in $Ga_{0.85}In_{0.15}Sb$/GaSb QWs. The implication is that dislocations resulting from the large lattice mismatch of the ternary compound to GaAs (7–15%) are responsible for the drastic reduction in the mobility of bulk layers. Similar Hall results have been reported for MBE GaInSb,[4] with a substantial improvement in mobility accompanying the use of an AlInSb buffer layer to reduce the lattice mismatch.

All of the QW samples grown showed evidence of carrier confinement from the position of the peaks in their PL spectra. However, the results presented here will concentrate on data from two samples. These are: (a) sample 290, a single quantum well (SQW) of 80 Å GaInSb, and (b) sample 294, a multiquantum well (MQW) with four wells of approximately, 20, 40, 50, and 70 Å and barriers of 200 Å. Both samples had a 300 Å capping layer and a 2 μm buffer layer of GaSb; the GaInSb wells contained 15% In. The lattice mismatch in this system is about 1% for this composition and the corresponding predicted critical thickness h_c is about 70 Å for a single layer.[10,11] Wells have been grown up to 80 Å thick (sample 290) with no sign from TEM measurements that dislocations are relaxing the strain. More sensitive techniques, such as scanning PL, are required to accurately determine h_c.[12]

Triple-crystal x-ray diffraction measurements[13] were performed on sample 290, the SQW. This yielded the lattice parameters parallel and perpendicular to the sample surface normal as well as the layer thickness.[14] Knowing the parallel and perpendicular lattice parameters, the In content of the GaInSb well could be estimated. This was found to be 15%, in good agreement with IR absorption measurements on bulk layers deposited under the same conditions. At this In level therefore, there was no evidence of strain affecting the composition of the ternary compound as has been observed in other systems.[15,16]

Using the above results and deformation potential theory to account for the effect of strain on the band gap,[17–19] the band diagram was calculated for sample 290. This is shown

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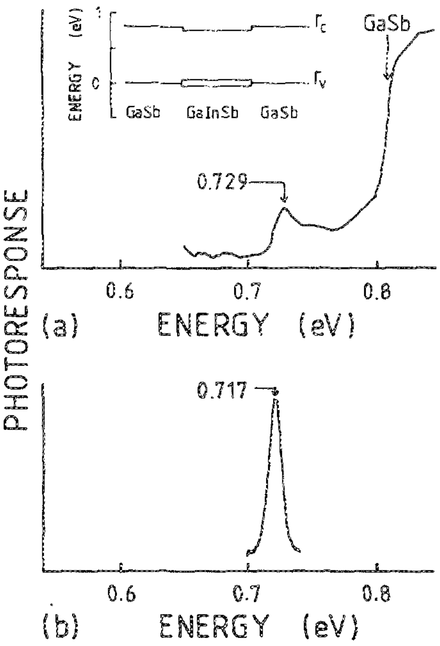

FIG. 1. (a) Photoconductivity at 4 K of sample 290 (80 Å, SQW of $Ga_{1-x}In_xSb$/GaSb with $x = 0.15$). Inset: band structure diagram for sample 290. (b) Photoluminescence at 4 K from sample 290.

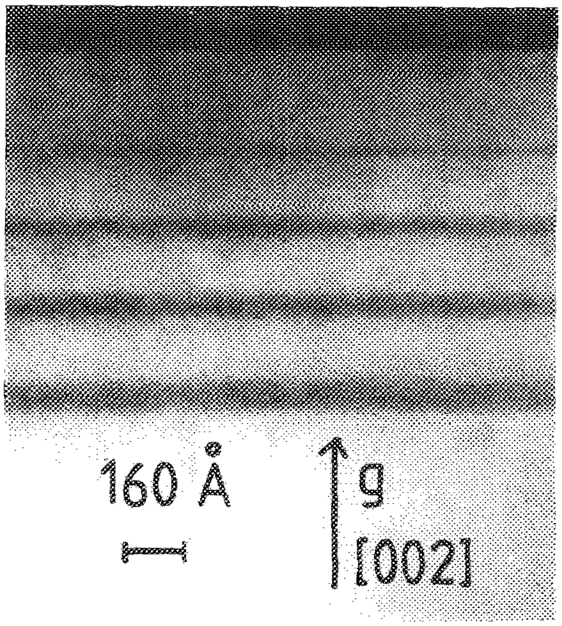

FIG. 2. (002) dark field TEM micrograph of sample 294 (a MQW of GaSb/$Ga_{0.85}In_{0.15}Sb$ with wells of 20, 40, 50, and 70 Å and 200 Å barriers). (Magnification: ×630 000.)

in Fig. 1. The band offsets were estimated using the model-solid approach of Van de Walle and Martin[19] which also takes the effect of strain into account. A band gap of 0.71 eV was found for $Ga_{0.85}In_{0.15}Sb$ confined by GaSb barriers, resulting in a type 1 quantum well. PL and PC from 290 are also shown in Fig. 1. The strong photoconductive onset at 0.81 eV is due to the GaSb barriers. The narrow 1*s* exciton at 729 meV in the PC [Fig. 1(a)] is indicative of the high quality of the strained layer. The corresponding PL peak at 717 meV shows a small Stoke's shift [Fig. 1(b)]. The shift is comparable to that found in GaInAs-InP quantum wells,[20] where it was attributed to the thermalization down to lower density, localized states in PL, compared to the participation of free excitons in either absorption or photoconductivity. Alloy composition or well width fluctuations uniformly distributed throughout the structure would provide localized, lower energy states. The PC results and the band diagram are in good agreement suggesting a total confinement energy of the order of 20 meV shared between the $m_J = 3/2$ hole well and the electron well. This value is consistent with the low barriers (50 meV) in both the conduction and valence bands, although it is also possible that the confinement energy is slightly underestimated. If there is any relaxation of the strain by dislocations, the In content calculated from the x-ray measurements will be underestimated and hence the band gap overestimated. An error of 1% In would reduce the calculated band gap by 6 meV and hence, increase the binding energy by a similar amount.

Figure 2 shows a TEM micrograph of sample 294, the MQW. The contrast between the two layers is rather low but the wells appear to be flat with interfaces abrupt to within three atomic layers and no dislocations emanating from the heterojunctions. At 4 K, luminescence from 294 (Fig. 3) showed four peaks at 738, 755, 772, and 792 meV. The weaker peaks at 772 and 792 meV are close to the energies of the acceptor peak and bound exciton in bulk GaSb and may arise from the barrier layers. The other two peaks have never been observed in any of our bulk GaSb layers, however, and are due to quantum well transitions. The strongest peak at 738 meV is thought to result from the widest 70 Å well and the peak at 755 meV from the adjacent 50 Å well. These values are again consistent with the expected energies for wells of this size.

Like all the GaSb/GaInSb QWs grown, sample 294 was *p* type with a 77 K mobility and carrier concentration dominated by the bulk GaSb. Below 77 K however, the QWs did not show the strong impurity freezeout characteristic of the bulk material and at 1.2 K, Hall measurements showed a hole concentration of $p = 1.2 \times 10^{11}$ cm^{-2} with a mobility of 2100 cm^2/V s. The high mobility at this temperature is due to the formation of a 2D hole gas in the QWs. Proof of this can be seen in Fig. 4, which shows Shubnikov–de Haas oscil-

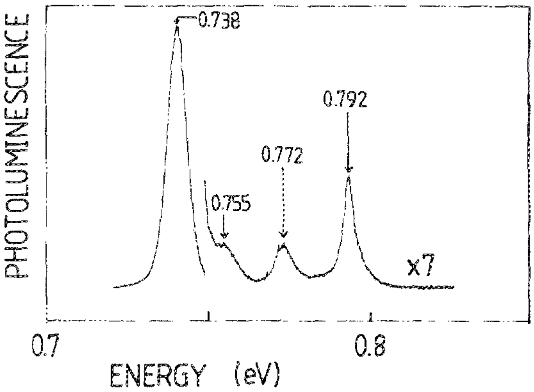

FIG. 3. Photoluminescence at 4 K from sample 294 (shown in Fig. 2).

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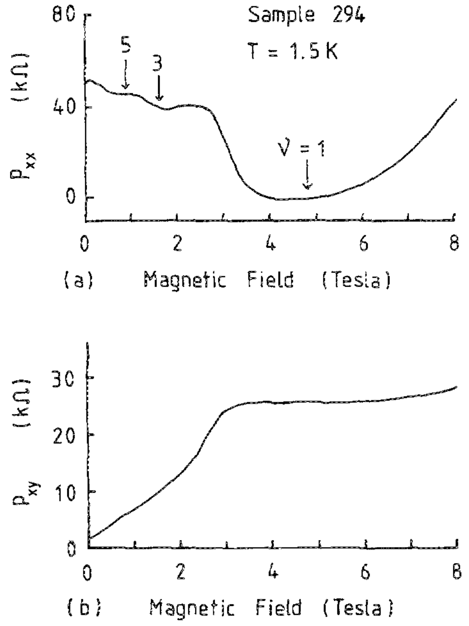

FIG. 4. (a) Shubnikov–de Haas oscillations in the transverse magnetoresistance (ρ_{xx}) shown by sample 294 at 1.5 K. The odd ν levels, giving rise to the strongest oscillations, are indicated. (b) Hall resistance (ρ_{xy}) for sample 294 at 1.5 K.

lations in the transverse magnetoresistance (ρ_{xx}) and the associated quantum Hall effect (ρ_{xy}). Rotation of the sample through an angle θ relative to the magnetic field, B, showed that the features were determined only by the perpendicular component of the field, $B\cos\theta$, thus confirming the 2D nature of the carriers.

The periodicity of the oscillations $\{B_F = [\Delta(1/B)]^{-1}\}$ gives a carrier concentration of $p = B_F e/h = 1.15\times10^{11}$ cm^{-2}, in good agreement with the Hall measurement, and indicating that all of the carriers are confined in a single well (most probably the largest, 70 Å, well). An unusual feature of the oscillations is that the strong resistivity minima and Hall plateau correspond to the occupancy ($\nu = ph/eB$) of an odd number of levels ($\nu = 1,3,5$). The most striking example is for $\nu = 1$, which gives the very large ρ_{xx} minimum and Hall plateau at around 4–6 T. This suggests that the spin splitting has been enhanced (maybe due to the lifting of the inversion symmetry by the strain and by the asymmetric electric field present in the wells) and also that the hole masses may be heavy, as has been seen in p-type GaAs/GaAlAs heterojunctions.[21] This result is particularly surprising since the upper strain split level in the wells is the $m_J = 3/2$ level which should exhibit a low in-plane mass.

In summary, GaSb/$\text{Ga}_{1-x}\text{In}_x\text{Sb}$ QWs have been grown up to 80 Å thick with $x = 0.15$. The position of PL and PC peaks from an 80 Å SQW agreed well with the calculated band diagram. A MQW showed SdH oscillations in ρ_{xx} at 1.5 K and an associated quantum Hall effect indicating the formation of a 2D hole gas in one of the GaInSb wells. Luminescence was also detected from the two thickest wells (70 and 50 Å).

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