Effects of interface stoichiometry on the structural and electronic properties of $Ga_{1-x}In_xSb/InAs$ superlattices

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We report an investigation of the effects of interface layer composition on the structural and electronic properties of $Ga_{1-x}In_xSb/InAs$ superlattices, which are of interest for infrared detector applications. Shutter sequencing during growth of a series of $Ga_{0.75}In_{0.25}Sb$ (8 ML)/InAs (13 ML) superlattices by molecular-beam epitaxy has been employed to select structures with GaInAs-like interfaces, InSb-like interfaces, and intermediate choices of interfacial composition. Comparison of x-ray diffraction scans from the superlattices confirms that a superlattice with GaInAs-like interfaces has a 1.6% smaller average interatomic spacing in the growth direction than a sample with InSb-like interfaces, in near agreement with expected interfacial bond length differences. Hall measurements of intrinsic carrier concentrations at high temperatures indicate an increase in superlattice energy gap when interfaces are switched from InSb-like to GaInAs-like, consistent with intuitive expectations. Low temperature Hall measurements suggest that both the type and the level of background doping in $Ga_{1-x}In_xSb/InAs$ superlattices may depend upon interfacial composition.

I. INTRODUCTION

Heterostructures containing combinations of arsenides and antimonides are of interest for a number of electronic and optoelectronic device applications, including field effect transistors,[1] 2–5 μm semiconductor lasers,[2] THz oscillators,[3] and superlattice infrared (IR) detectors.[4,5] In many of these structures, multiple possibilities exist for bond configurations at arsenide/antimonide heterointerfaces. Tuttle *et al.* demonstrated recently that the transport properties of InAs/AlSb quantum wells (QWs) can be profoundly affected by interfacial composition.[6] We anticipate that an understanding of the electronic effects of varying interfacial composition will be of vital importance in realizing many of the potential device applications of mixed arsenide/antimonide heterostructures.

We report here a study of the consequences of varying interfacial composition in $Ga_{1-x}In_xSb/InAs$ superlattices, which are potential candidates for IR detector applications in the 8–14 μm range and beyond.[4,5,7,8] Since the atoms residing on both group III and group V sublattices change across a $Ga_{1-x}In_xSb/InAs$ interface, it is possible to obtain two distinctly different interfacial bond configurations. If a $Ga_{1-x}In_xSb$ layer is terminated with a final monolayer of Sb, the adjoining InAs layer will commence with a monolayer of In (assuming that group III and group V atoms are restricted to their respective sublattices), leading to InSb bonds across the interface (an "InSb-like" interface). Conversely, if a $Ga_{1-x}In_xSb$ layer is terminated with a final monolayer of $Ga_{1-x}In_x$, the adjoining InAs layer will commence with a monolayer of As, resulting in $Ga_{1-x}In_xAs$ bonds across the interface (a "GaInAs-like" interface). It should be noted that intermediate interfacial compositions are also possible; an example is described in Sec. II. It is reasonable to expect that the choice of interfacial composition and growth conditions will play a key role in determining the nature and quantity of interfacial defects, which may have implications for detector performance.

II. MOLECULAR-BEAM EPITAXY GROWTH

The $Ga_{1-x}In_xSb/InAs$ superlattices studied here were grown by molecular-beam epitaxy (MBE) in a Perkin Elmer 430P system equipped with reflection high-energy electron diffraction (RHEED), and cracked arsenic and antimony sources. The superlattices were deposited on thick (0.5–1.0 μm) stress–relaxes GaSb buffer layers on lattice-mismatched, (100)-oriented, InP or GaAs substrates. The procedure we use for deposition of GaSb buffer layers has been described elsewhere.[9,10] All of the superlattices described here consist nominally of 8 ML (25 Å) of $Ga_{0.75}In_{0.25}Sb$ and 13 ML (39 Å) of InAs. Total superlattice thicknesses are 80 periods (0.5 μm). Superlattices with these parameters, in which growth was interrupted (no group III flux) in an Sb_2 flux for 5 s at each interface, have previously been shown to result in samples with energy gaps near 110 meV (11 μm).[5] The method used to reproducibly select substrate temperatures for these structures has been described elsewhere.[9]

Figure 1 depicts the shutter sequences we have used to produce superlattices with $Ga_{0.75}In_{0.25}As$-like and InSb-like interfaces. In the case of $Ga_{0.75}In_{0.25}As$-like interfaces, deposition of each 13 ML thick InAs layer is followed by a 5 s "soak" in As in an attempt to terminate the layer with As atoms. A 1×2 RHEED pattern is observed during both the InAs layer and As soak. Next, the As shutter is closed, and the Ga and In shutters are opened (without an accompanying group V flux) for the time required for deposition of 1 ML of $Ga_{0.75}In_{0.25}$. This step results in a transforma-

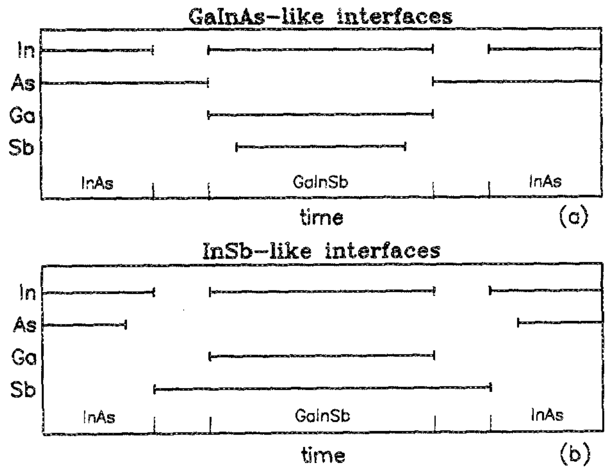

FIG. 1. Illustration of MBE shutter sequences (not to scale in time) used to produce $Ga_{1-x}In_xSb$/InAs superlattices with (a) GaInAs-like interfaces, and (b) InSb-like interfaces. Solid bars indicate time periods in which shutters are open.

tion of the RHEED pattern to 4×4 (presumably a metal rich surface reconstruction). The Sb shutter is then opened for the time needed to deposit 6 ML of $Ga_{0.75}In_{0.25}Sb$ (nominally resulting in 6 ML of $Ga_{0.75}In_{0.25}$ separating 7 ML of Sb), and closed again for the time required for a single monolayer of $Ga_{0.75}In_{0.25}$. The characteristic 1×3 RHEED pattern observed during growth of the $Ga_{0.75}In_{0.25}Sb$ layer is transformed to a 4×1 pattern (again due to a metal rich reconstruction) when the Sb shutter is closed. The sample is then soaked for 5 s in an As flux, resulting in a 1×3 RHEED pattern, prior to the next 13 ML InAs deposition.

In the case of InSb-like interfaces, deposition of each 8 ML thick $Ga_{0.75}In_{0.25}Sb$ layer is followed by a 5 s soak in Sb. A transformation from 1×3 to 1×5 in surface reconstruction is observed during the Sb soak. Next, the Sb shutter is closed, and the In shutter is opened for the time needed to deposit a monolayer of In, resulting in a return to a 1×3 RHEED pattern. The As shutter is then opened for the time needed to deposit 11 ML of InAs (nominally resulting in 11 ML of In separating 12 ML of As) and closed again for the time required for a single monolayer of In. The 1×2 RHEED pattern observed during growth of the InAs layer is transformed to a 2×4 pattern when the As shutter is closed. The sample is then soaked for 5 s in an Sb flux, resulting in a 1×3 RHEED pattern, prior to the next 8 ML $Ga_{0.75}In_{0.25}Sb$ deposition.

In addition to $Ga_{1-x}In_xSb$/InAs superlattices with all InSb-like interfaces and all GaInAs-like interfaces, we have grown one sample in which $Ga_{1-x}In_xSb$ on InAs interfaces are grown InSb-like and InAs on $Ga_{1-x}In_xSb$ interfaces are grown GaInAs-like, and one sample with the opposite interfacial configurations. We have also grown a superlattice with an intermediate interfacial composition by depositing interfacial monolayers consisting of In (0.5 ML)/$Ga_{0.75}In_{0.25}$ (0.5 ML) sandwiched between Sb-terminated $Ga_{0.75}In_{0.25}Sb$ and As-terminated InAs layers. We note that the total group III deposition times are the same for all cases, ensuring that the number of monolayers in each superlattice period are unaffected by the choice of interfacial composition.

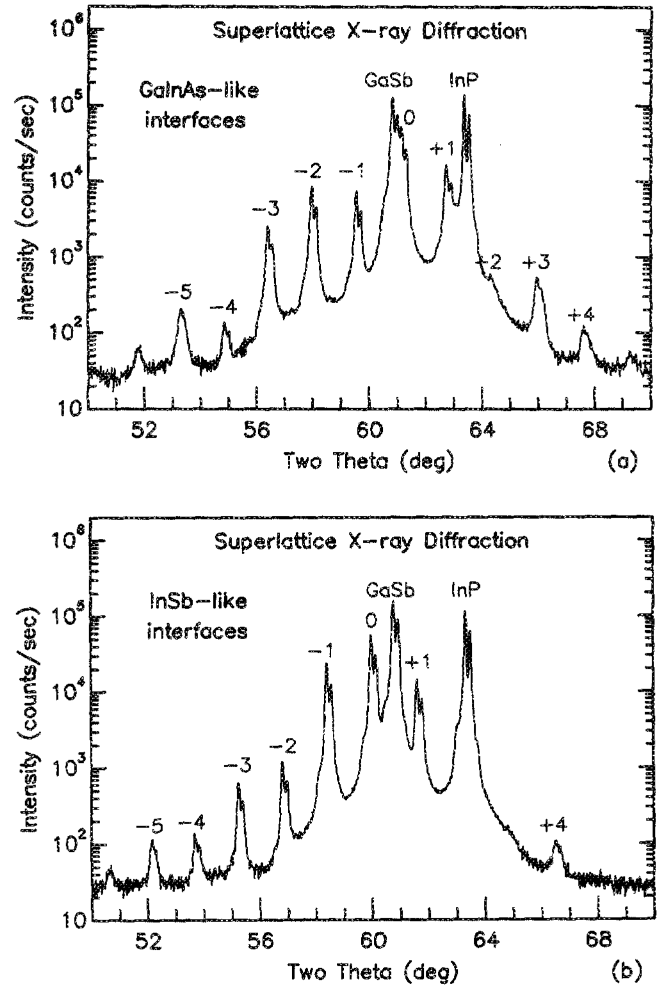

FIG. 2. $\Theta/2\Theta$ x-ray diffraction scans from $Ga_{0.75}In_{0.25}Sb$ (8 ML)/InAs(13 ML) superlattices with (a) GaInAs-like interfaces and (b) InSb-like interfaces. The samples were irradiated with Cu $K\alpha$ x-rays. Each peak appears to be bimodal due to the $K\alpha$ doublet. The InP substrate peak, GaSb buffer peak, and superlattice satellite indices are labeled in each scan. A significant difference in average interatomic spacing (zeroth order x-ray satellite) is observed.

III. X-RAY DIFFRACTION

Structural analysis of the $Ga_{1-x}In_xSb$/InAs superlattices discussed here has been performed via (400)-like $\Theta/2\Theta$ x-ray diffraction. The period and average interatomic spacing of each superlattice has been determined from the x-ray data by measuring the satellite spacings and zeroth order satellite position, respectively. Figures 2(a) and 2(b) show $\Theta/2\Theta$ x-ray diffraction data taken from $Ga_{1-x}In_xSb$/InAs superlattices with all GaInAs-like and all InSb-like interfaces, respectively. A striking shift in zeroth order peak position is observed between the two diffraction scans (note that the zeroth order peaks in the two scans are on opposite sides of the GaSb buffer layer peak), indicating a significant difference in average interatomic spacing between the two superlattices. We believe that this

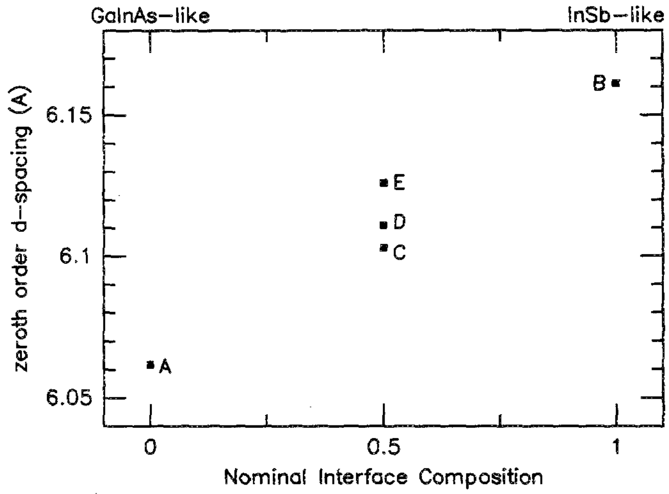

FIG. 3. Plot of zeroth order d-spacing vs nominal interfacial composition for five $Ga_{1-x}In_xSb/InAs$ superlattices. Sample A = all GaInAs-like interfaces; Sample B = all InSb-like interfaces; Sample C = GaInAs-like interfaces when growing InAs on GaInSb and InSb-like interfaces when growing GaInSb on InAs; Sample D = opposite of Sample C; Sample E = intermediate interfacial composition. The data show a clear correlation between average interatomic spacing and nominal interfacial composition.

shift results from the tremendous difference between the interfacial bond lengths of InSb and GaInAs.

Figure 3 is a plot of the measured zeroth order d-spacing versus nominal interfacial composition for each of the five superlattices studied here. In the plot, the superlattice with InSb-like interfaces is assigned a nominal interfacial composition of 1, while the superlattice with GaInAs-like interfaces is assigned a value of 0. The superlattices with half of each type of interface and the superlattice with intermediate interfacial configuration (described in Sec. II) are assigned nominal compositions of 0.5. The plot shows a clear correlation between nominal interfacial composition and the resulting interatomic spacing. Ideally, a change from InSb-like interfaces to GaInAs-like interfaces would result in two $Ga_{0.75}In_{0.25}Sb$ bonds per superlattice period becoming $Ga_{0.75}In_{0.25}As$ bonds, and two InSb bonds per superlattice period becoming InAs bonds. Assuming that the interfacial layers are coherently strained, and that there are a total of 42 bonds per superlattice period, we would expect a difference in average interatomic spacing of 1.4% between the two cases. From Fig. 3, the measured average interatomic spacing of the sample with GaInAs-like interfaces is 1.6% smaller than that of the sample with InSb-like interfaces. Hence, the measured difference in average interatomic spacing is in good agreement with that expected from a complete change from InSb-like interfaces to GaInAs-like interfaces.

IV. HALL MEASUREMENTS

Due to the narrow energy gaps of $Ga_{1-x}In_xSb/InAs$ superlattices, samples which are not intentionally doped show intrinsic behavior at high temperature ($>$ 250 K). Hall measurements at these temperatures are dominated by electron transport, as electron mobilities are greater than hole mobilities (due to the difference in effective mass). Neglecting the dependences of energy gap and effective density of states on temperature, the number of intrinsic carriers n_i is proportional to $\exp(-E_g/2kT)$, where E_g is the energy gap of the superlattice. Hence, high temperature Hall data can be used to estimate E_g. Figure 4 is a plot of the measured intrinsic carrier concentrations (plotted on a logarithmic scale) versus $1000/T$ for the $Ga_{1-x}In_xSb/InAs$ superlattices with InSb-like and GaInAs-like interfaces. The data reveal that the superlattice with InSb-like interfaces has a higher intrinsic carrier

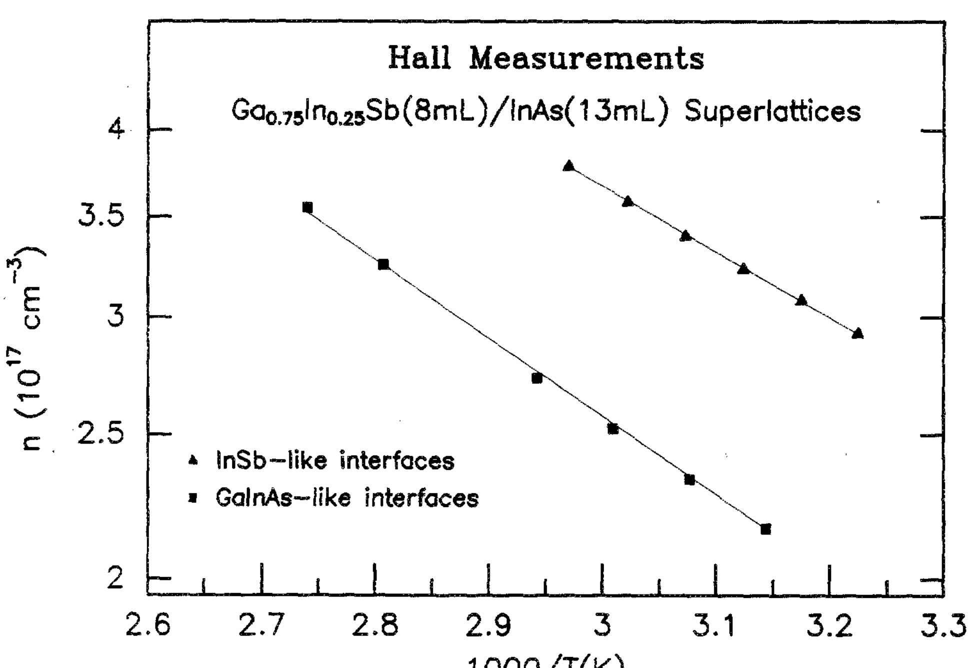

FIG. 4. Plot of intrinsic carrier concentrations (on a logarithmic scale) vs 1000/T(K) for superlattices with GaInAs-like interfaces (squares) and InSb-like interfaces (triangles). The data were obtained by Hall effect measurements.

concentration than the sample with GaInAs-like interfaces, consistent with a smaller energy gap. Furthermore, the slopes of the two sets of data differ by about 20%, consistent with a difference of 25 meV in energy gap. This observation is in accord with the intuitive expectation that the presence of 1 ML of relatively wide gap material in a superlattice with GaInAs-like interfaces will increase its energy gap relative to a superlattice with 1 ML of InSb, which is a narrow gap material.

Low temperature Hall measurements of our $Ga_{1-x}In_xSb/InAs$ superlattices generally reveal unintentional *p*-type background concentrations in the 10^{16} cm^{-3} range. However, the superlattice with GaInAs-like interfaces displays *n*-type carrier concentrations at low temperatures. Possible explanations for this observation include the formation of a surface inversion layer, or the creation of As antisite defects. The remaining four superlattices included this study all showed *p*-type behavior at low temperatures. There is evidence that antimonides tend to contain group III antisite defects, which result in high background acceptor levels.[11] Determination of the source and reduction of the level of unintentional background doping in $Ga_{1-x}In_xSb/InAs$ superlattices is the subject of ongoing investigations.

V. SUMMARY

Mixed antimonide/arsenide heterostructures are of interest for a number of potential device applications. In most, if not all, of these structures, atoms residing on both the group III and the group V sublattices change across the heterojunction interfaces. The result is a nonuniqueness in the configuration of interfacial bonds. It is possible that the control of electrically active interfacial defects may hinge upon control of these interfacial compositions; many potential device applications would likely benefit from such a capability. We have studied the specific case of $Ga_{1-x}In_xAs$-like and InSb-like interfaces in $Ga_{1-x}In_xSb/InAs$ superlattices, which are of interest for infrared detector applications. X-ray diffraction scans revealed a significant difference in average interatomic spacing between superlattices with nominally GaInAs-like and InSb-like interfaces, verifying that these interfacial compositions can be controlled via MBE shutter sequencing. Hall measurements of intrinsic carrier concentrations indicated that superlattices with GaInAs-like interfaces have slightly larger energy gaps than those with InSb-like interfaces, in agreement with intuitive expectations. Low temperature Hall measurements suggested that background doping levels may vary significantly with interfacial composition.

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[1] L. F. Luo, R. Beresford, W. I. Wang, and H. Munekata, Appl. Phys. Lett. **55**, 789 (1989).
[2] H. K. Choi and S. J. Eglash, Appl. Phys. Lett. **59**, 1165 (1991).
[3] E. R. Brown, J. R. Söderström, C. D. Parker, L. J. Mahoney, K. M. Molvar, and T. C. McGill, Appl. Phys. Lett. **58**, 2291 (1991).
[4] D. L. Smith and C. Maihiot, J. Appl. Phys. **62**, 2545 (1987).
[5] R. H. Miles, D. H. Chow, J. N. Schulman, and T. C. McGill, Appl. Phys. Lett. **57**, 801 (1990).
[6] G. Tuttle, H. Kroemer, and J. H. English, J. Appl. Phys. **67**, 3032 (1990).
[7] D. H. Chow, R. H. Miles, J. R. Söderström, and T. C. McGill, Appl. Phys. Lett. **56**, 1418, 1990.
[8] I. H. Campbell, I. Sela, B. K. Laurich, D. L. Smith, C. R. Bolognesi, L. A. Samoska, A. C. Gossard, and H. Kroemer, Appl. Phys. Lett. **59**, 846 (1991).
[9] D. H. Chow, R. H. Miles, C. W. Nieh, and T. C. McGill, J. Cryst. Growth. **111**, 683 (1991).
[10] D. H. Chow, R. H. Miles, J. R. Söderström, and T. C. McGill, J. Vac. Sci. Technol. B. **8**, 710 (1990).
[11] K. F. Longenbach and W. I. Wang, Appl. Phys. Lett. **59**, 1117 (1991).