Strain relaxation in InAs/GaSb heterostructures

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Heterostructures containing InAs and GaSb are of interest for a variety of optical and electronic devices as well as fundamental studies of band structure. For example, superlattices consisting of thin alternating layers of InAs and GaSb may be suitable for long-wavelength infrared detectors. In addition, resonant tunneling diodes based upon GaSb may be suitable for long-wavelength infrared lattices consisting of thin alternating layers of InAs and GaSb/GaAs heterostructures. In this letter, we examine a variety of InAs layers grown on GaSb. We show that the quality of the GaSb layer influences the strain relaxation in the InAs.

Sample II is superior to I. We investigated the strain relaxation of type-II structures by varying the InAs thickness from 500 Å to 1.0 μm. The (004) DCXRD measurements for six samples are shown in Fig. 3. The classic behavior for mismatched epilayers is for the thinnest layers to be fully strained (coherent) up to a critical thickness, with increasing lattice relaxation (decreasing Δθ) for increasing thickness beyond the critical value. To first order, that is what we observe in Fig. 3. Substantial lattice relaxation does not occur until the layer thickness reaches 3000 Å, more than an order of magnitude larger than the Matthews–Blakeslee limit. As a result of limited resolution, DCXRD measurements are not sensitive to the onset of

0.05 - 1.0 μm InAs
0.3 - 4.0 μm GaSb
~ 0.5 μm GaAs
GaAs (001)

0.05 - 1.0 μm InAs
~ 0.5 μm GaSb
GaSb (001)

FIG. 1. Schematic of the type-I and type-II heterostructures used in this study.

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<tr>
<th>thickness</th>
<th>material</th>
<th>type</th>
<th>substrate</th>
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dislocation formation.\textsuperscript{13} Hence, our results do not necessarily imply the absence of misfit dislocations for thinner layers. These results are relevant to the design of heterostructures in which the electronic or optical properties are sensitive to strain in the InAs.

Information about the epilayer quality can also be extracted from the data. The full width at half maximum (FWHM) is often cited as a measure of structural quality. Even for perfect layers, however, the FWHM is a function of thickness, with thinner layers having larger FWHMs because of the smaller correlation lengths. Hence, we use the ratio of the experimental to the theoretical FWHM as a figure of merit.\textsuperscript{14,15} For samples I and II of Fig. 2, the FWHM ratios are 3.9 and 2.0, respectively. The ratios for the samples in Fig. 3 are: 1.1 (500 Å), 2.0 (1000 Å), 2.2 (2000 Å), 16 (3000 Å), 25 (5000 Å), and 41 (10000 Å). In addition, we observe Pendellosung fringes for the 500 Å sample, indicating good structural quality. The FWHM of the GaSb peak increases with increasing InAs thickness. Similar effects have been observed in other material systems and attributed to strain-induced lattice curvature.\textsuperscript{16}

As indicated in Fig. 2, the relaxation behavior of InAs is a function of the underlying GaSb. To summarize the data from Figs. 2 and 3 as well as several additional type-I samples, we plot the epilayer strain as a function of InAs thickness in Fig. 4. In general, layers on GaSb substrates are less strained than those on GaSb substrates. For example, at a thickness of 2000 Å, InAs on a GaSb substrate is fully strained, but the strain drops to 0.2%–0.4% for GaSb buffer layers on GaAs substrates. For type-I structures, more strain is retained in the InAs layer when the GaSb buffer layer is thicker. These results are consistent with threading dislocations serving as nucleation sites for misfit dislocations. In the case of GaSb buffer layers on GaAs, high densities of threading dislocations form during the coalescence of islands.\textsuperscript{17–19} The dislocation density decreases as layer thickness increases. Hence, fewer nucleation sites will be available for thicker buffer layers, resulting in less relaxation of the InAs. The lowest density of threading dislocations is expected for the GaSb substrates, with etch pit densities less than $10^4$ cm$^{-2}$. We note that in the InGaAs/GaAs system, the density of misfit dislocations in strained InGaAs was found to be a function of the density of threading dislocations in the GaAs substrate.\textsuperscript{20–22} An additional effect might account for part of the observed variation in InAs strain with buffer layer thickness. The GaSb buffer layer could act as a compliant substrate,\textsuperscript{23} with the InAs inducing partial strain relaxation in the GaSb. Our x-ray measurements (not shown) suggest that this effect may be present but is not large enough to account for most of the observed variation in InAs strain.

Finally, we have observed that little or no improvement in InAs coherence can be achieved in type-I samples by varying such factors as doping or growth temperature, or the addition of other intermediate layers. For instance, two samples with 1.0 μm GaSb buffer layers were grown; the InAs thickness was 1000 Å for both, but the InAs growth temperature was 370 °C for one and 500 °C for the other. Within experimental error the measured strains in these two samples and the equivalent sample grown without the superlattice. 10$\times$ (24 Å GaSb/24 Å AlSb), in the center of the GaSb buffer produced a sample which had comparable strain to an equivalent sample (2000 Å InAs) grown without the superlattice. Finally, high doping levels (Si, $n \sim 10^{19}$/cm$^3$) in a 2000 Å InAs sample did not appear to
affect the strain in the InAs. These results do not rule out the possibility that lattice relaxation in type-II structures could be a function of growth temperature or doping.

In summary, we applied x-ray diffraction to investigate lattice strain relaxation in MBE-grown InAs/GaSb heterostructures. We found that the strain in an InAs epilayer can be a strong function of the quality of the underlying GaSb layer. For GaSb substrates, InAs layers as thick as 2000 Å remain coherently strained, despite the 0.6% lattice mismatch.

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