FC3 HIGH QUALITY InGaAs/InP AND InAlAs/InP HETEROSTRUCTURES BEYOND THE MATTHEWS-BLAKESLEE CRITICAL LAYER THICKNESS

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ABSTRACT

Mismatched epitaxial layers of InGaAs and InAlAs were grown on InP by molecular beam epitaxy. Double-crystal x-ray diffraction measurements show that the crystalline quality of the layers consistently remains unperturbed to thicknesses up to 3-8 times the Matthews-Blakeslee critical layer thickness. The findings are applied to the growth of high-performance mismatched InAlAs/InGaAs/InP heterostructure field-effect transistors.

INTRODUCTION

Ternary alloys of $In_xGa_{1-x}As$ and $In_yAl_{1-y}As$ are of increasing interest for both electronic and optical devices. Much work has focussed on the $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ alloys because they can be grown lattice-matched to InP substrates. The use of mismatched epitaxial layers, however, allows much greater freedom to design heterostructure devices with desired optical and electronic properties.

If the lattice mismatch between the epilayer and substrate is small and the layer is thin, the mismatch will be accomodated entirely by strain in the layer. In this case, the symmetry of the epilayer lattice distorts from cubic to tetragonal, and the layer is said to be coherent or pseudomorphic. If the layer is sufficiently thick and mismatched, the formation of misfit dislocations at the substrate/epilayer interface becomes energetically favorable. These dislocations relieve strain, allowing the epilayer lattice to relax back toward its natural cubic symmetry. The point at which misfit dislocations begin to form is known as the *critical layer thickness*. Although several theories attempt to predict the critical layer thickness, experimental techniques which are extremely sensitive to dislocations generally support the model of Matthews and Blakeslee.[1-3] Despite this, several groups have reported high-performance optical and electronic devices from heterostructures violating the Matthews-Blakeslee limit.[4] A solution to this controversy requires a simple, non-destructive technique to access the suitability of heterostructures for device applications before device processing. In this study, we experimentally investigate the impact of lattice mismatch on the crystalline quality of epitaxial layers, using double-crystal x-ray diffraction (DCXRD) as a characterization tool.

EXPERIMENTAL PROCEDURES

This study utilized 150 samples grown by molecular beam epitaxy (MBE) on semi-insulating (001) InP substrates. The epitaxial layers were grown in a Riber model 2300 solid-source MBE system. The substrate temperature, measured by a thermocouple and optical pyrometer, was about 500°C. The V:III ratio was between 15:1 and 25:1. Growth rates ranged from 0.6 to 0.9 μm/hr. Most samples consisted of single epitaxial layers of either InGaAs or InAlAs, but some multi-layer structures were also studied.

The samples were characterized by DCXRD to determine layer composition, strain, and crystalline quality. The rocking curves were measured by a Bede model 300 system with Cu-Kα radiation and an InP first crystal oriented for the (004) reflection. Symmetric (004) reflection rocking curves were measured for all samples. In addition, asymmetric (115) or (224) reflection data was collected for selected samples.

RESULTS AND DISCUSSION

1. Crystalline Quality

The full-width at half-maximum (FWHM) of a DCXRD peak is often cited as a figure merit for an epitaxial layer. The FWHM is sensitive to crystalline imperfection. For example, the presence of misfit dislocations will result in a local tilting of lattice planes and a broadening of the peak.[5] Even for perfect crystals, however, the FWHM is a function of layer thickness, with thinner layers producing broader peaks.[5] Hence, as a figure of merit for crystalline quality, we take the ratio of the experimental to the theoretical FWHM. For sets of samples with constant thickness, as mismatch increases we typically observe an abrupt transition at which the FWHM ratio suddenly increases, presumably due to the formation of misfit dislocations or three-dimensional growth. We show an example for InGaAs in fig. 1. The five heterostructures are nominally identical except for the composition of a 3000 Å InGaAs layer. In addition to the epilayer and substrate peaks, we observe a series of Pendellosung fringes on four of the samples. These fringes result from interference effects from the epilayers and indicate a coherent, high-quality layer.[5] For the samples with

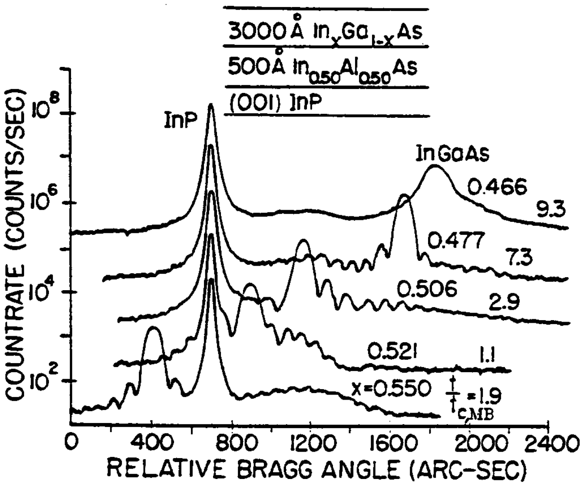

Figure 1: DCXRD (004) rocking curves for five heterostructures shown in inset. The broad peaks at about 1200 arc-sec are the 500 Å InAlAs buffer layers. The scans for samples with x ≤ 0.521 are shifted up one decade for clarity.

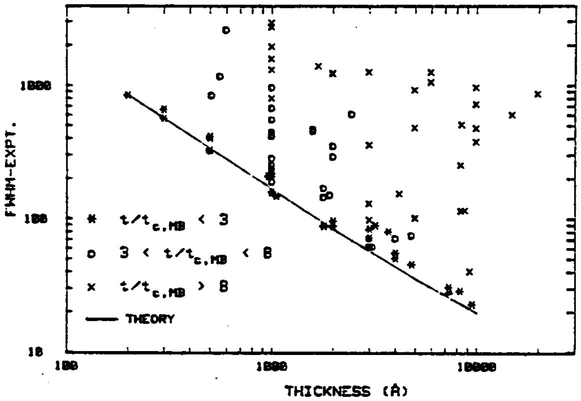

Figure 2: (004) DCXRD peak width versus InGaAs or InAlAs thickness. Samples are coded based upon the ratio of layer thickness to Matthews-Blakeslee critical thickness. Solid line is from simulations using dynamical diffraction theory.[7]

$0.477 \leq x \leq 0.550$, the FWHM ratio is between 1.1 and 1.5 and sharp fringes are present. For the 5th sample (x = 0.466), however, the FWHM ratio jumps to 2.4 and the fringes disappear. The transition occurs when the layer thickness exceeds the Matthews-Blakeslee critical layer thickness[6] ($t_{c,MB}$) by about a factor of eight.

In fig. 2, we show (004) DCXRD epitaxial peak width as a function of thickness for all our InGaAs and InAlAs samples, in both compression and tension. The samples are coded based upon the ratio of the layer thickness to $t_{c,MB}$. The solid line is the theoretical FWHM which was determined by simulations using dynamical diffraction theory.[7] We observe samples with FWHM's approximately equal to the theoretical values for layers ranging from 200 Å to 1.0 μm. It is not necessary for the layer to be thinner than $t_{c,MB}$ in order to achieve a FWHM ratio close to one. In fact, as fig. 3 illustrates, for $t/t_{c,MB} < 3$ the FWHM ratio is always between 1.0 and 1.8, independent of $t/t_{c,MB}$. We observe a transition region for $3 < t/t_{c,MB} < 8$, with the FWHM ratio varying from 1.0 to 10. For $t/t_{c,MB} > 8$, the ratio ranges from 2 to 80. In fig. 3 we code the samples based upon lattice relaxation, R. We define relaxation as the ratio of the parallel mismatch (averaged in the orthogonal [110] and [1$\bar{1}$0] directions) and the relaxed mismatch, and measure it by a combination of symmetric and asymmetric DCXRD scans.[8] Several samples in fig. 3 show a large (> 2) FWHM ratio without significant relaxation (R < 10%), suggesting that the FWHM ratio is more sensitive to the onset of crystalline imperfection than relaxation. In fact, one can define empirical critical thicknesses based upon lattice relaxation (as was done previously[9,10]) and our FWHM ratio. In a plot of epilayer thickness versus relaxed lattice mismatch (fig. 4), we see that the FWHM ratio (curve b) detects crystalline imperfection at thicknesses about a factor of 3 lower than lattice relaxation (curve a). The modified Matthews-Blakeslee critical thickness (curve c) is also included for comparison.[6]

Fritz showed the importance of experimental resolution in measurements of critical layer thickness.[3] In particular, direct measurement of relaxation by DCXRD can give anomalously large values of critical thickness[9,10] because a substantial number of dislocations are required before DCXRD can detect the resulting change in strain. By using the FWHM ratio, we have improved the sensitivity of DCXRD to crystalline imperfection. Our results do not necessarily imply the total absence of misfit dislocations in samples with FWHM ratios near unity. Although we cannot rule out the possibility of dislocations in layers with, for example, $t/t_{c,MB} = 3$, such layers do exhibit high crystalline quality and may be useful for many device applications. We note, however, a recent report[11] of MBE-grown $In_{0.54}Ga_{0.46}As$ layers on InP in which almost complete relaxation was observed for $t/t_{c,MB} = 3.4$. One possible explanation for this discrepancy is a kinetic-limited relaxation process, with their growth temperature higher than ours.[12]

Our findings have important implications regarding the use of DCXRD as a characterization tool. First, we note that substantial orthorhombic distortion is present in partially relaxed epilayers of crystals with the zinc-blende structure (including III-V's).[8,13] Hence, a total of four asymmetric scans as well as a symmetric scan is required to measure the composition. Fortunately, from fig. 3 we see that substantial relaxation does not usually begin until the thickness is about 10 times $t_{c,MB}$. As long as

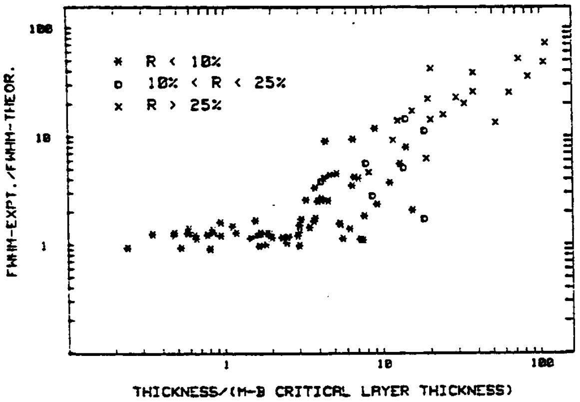

Figure 3: Ratio of experimental to theoretical DCXRD (004) peak width versus ratio of thickness to Matthews-Blakeslee critical thickness. InGaAs and InAlAs layers in both compression and tension are included, coded by lattice relaxation, R.

$t < 10(t_{c,MB})$, a single (004) measurement should yield the correct composition. In practice, the critical thickness cannot be calculated until the composition is known. Since the (004) peak width begins to broaden before significant relaxation occurs, one is safe in assuming neglibile relaxation (and avoid asymmetric measurements) if the FWHM ratio is less than about two.

2. Application: Pseudomorphic HFET's

We applied our findings to the growth of pseudomorphic heterostructure field-effect transistors (HFET's).[14] The structure is shown in fig. 5a and consists of (bottom to top): 1000 Å InAlAs buffer, 75 Å InGaAs sub-channel, 100 Å Si-doped InGaAs channel, 300 Å InAlAs pseudo-insulator, and 50 Å InGaAs cap. All the layers were nominally lattice-matched except for the InAlAs insulator which was intentionally grown AlAs-rich to increase the electron confinement and the breakdown voltage of the device.[14,15] The (004) DCXRD scan of the epitaxial structure is shown in fig. 5b. We simulated the structure using the nominal layer thicknesses and adjusting the compositions to obtain a good match with the experimental data. The best-fit compositions are those given in fig. 5a, and the corresponding simulated rocking curve is shown in fig. 5c. The buffer is the thickest layer and hence gives the peak with the largest intensity and narrowest width (except for the InP substrate). We see that the composition of the buffer (0.506 ± 0.002) is close to the lattice-matched value (0.521). The 300 Å insulator layer also gives a distinct peak, with an estimated InAs mole fraction of 0.415 ± 0.005. The 175 Å channel/subchannel is too thin to produce a distinct peak; our estimate of $x = 0.54 \pm 0.01$ is based upon the structure in the $\Delta\theta = 500$ to 1500 arc-sec range. We note that the insulating layer is a factor of two thicker than $t_{c,MB}$. The experimental FWHM of the insulator is 500 arc-sec, compared to 490 arc-sec for the simulation. This good agreement, along with the presence of Pandellosung fringes in the experimental curve, indicates a coherent heterostructure. The device results were excellent.[14] If dislocations are present in the FET, their density is insufficient to degrade device performance in any appreciable way.

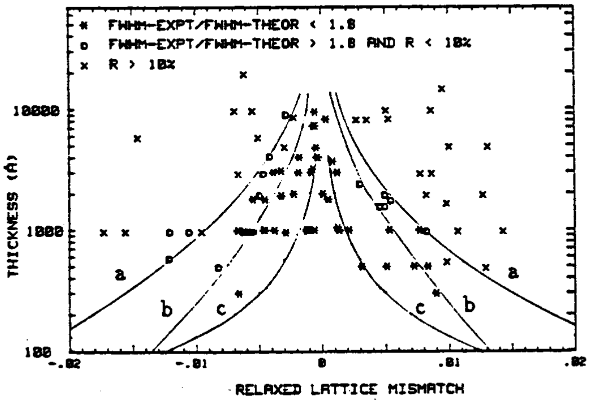

Figure 4: Thickness versus relaxed lattice mismatch for InGaAs and InAlAs in both compression and tension on InP. Samples are coded by the DCXRD peak-width ratio and lattice relaxation. Curves **b** and **a** are empirical, showing the onset of DCXRD peak broadening and significant lattice relaxation, respectively. The modified Matthews-Blakeslee critical thickness[6] is included for comparison (curve **c**).

CONCLUSIONS

We have investigated the impact of lattice mismatch on epitaxial layers of InGaAs and InAlAs grown by MBE on InP. Using asymmetric DCXRD measurements, we found that significant lattice relaxation does not occur until layer thicknesses exceed the Matthews-Blakeslee limit by about a factor of ten. The (004) DCXRD peak width and interference fringes are shown to be more sensitive to structural imperfection than direct measurements of relaxation. The crystalline quality of epitaxial layers of InGaAs and InAlAs consistently remains unperturbed to thicknesses up to 3-8 times the Matthews-Blakeslee critical layer thickness. The findings are applied to the growth of high-performance pseudomorphic InAlAs/InGaAs/InP HFET's.

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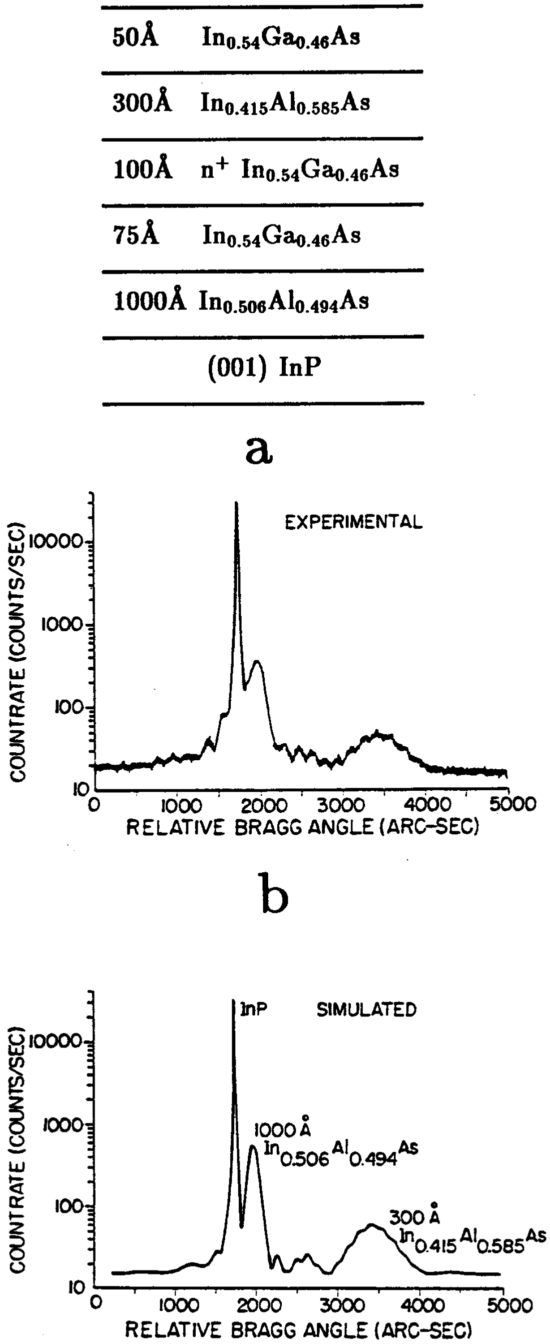

Figure 5: (a) Cross section of HFET epitaxial heterostructure, (b) experimental DCXRD data, and (c) simulated DCXRD data. Peaks from the InAlAs buffer and insulator layers are identified.

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