Journal of Crystal Growth 95 (1989) 193–196
North-Holland, Amsterdam

GROWTH PHENOMENA AND CHARACTERISTICS OF STRAINED $In_xGa_{1-x}As$ ON GaAs

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We have investigated the molecular beam epitaxial growth, structural and optical properties of InGaAs on GaAs. We have focused first on the initial stages of growth where the growth is expected to be under coherent strain and second on the nature of single and multiple quantum well heterointerfaces.

In the present study, we have critically examined two aspects of strained layer epitaxy: (a) the initial growth modes as a function of the growth parameters, and (b) the nature of heterostructures and quantum wells with thicknesses extending well beyond the equilibrium critical thickness. For case (a) theoretical and experimental studies have been made and from thermodynamic considerations, it is clear that as the strain increases, the free energy minimum surface of the epitaxial layer is not atomically flat, but three-dimensional (3D) in form. Photoluminescence (PL) and absorption measurements on thick multiple quantum well (MQW) structures grown with and without intermediate composition buffer layers indicate that these structures are comparable in quality to lattice matched GaAs/AlGaAs MQWs. Further transmission electron microscopy (TEM) results confirm that dislocation free MQW regions with thicknesses extending well over the equilibrium critical thickness can be achieved by molecular beam epitaxy (MBE).

In fig. 1, we show the measured change in surface lattice constants as obtained from the reflection high energy electron diffraction (RHEED) integral order spacings, from video recording. Data were obtained by digitizing individual frames of the videotape into a 480 × 480 array with 256 grey scale and loaded into the computer. Slices through the array were taken across the integral order RHEED lines and the intensity distribution plotted. By analysis of the dynamic changes of these peaks, we see dramatic movement at higher temperatures. At low temperatures, where impinging atoms are unable to move in a correlated manner to reach the free energy minimum surface, the lattice constant remains close to the substrate's. However, at higher temperatures, a monotonic change of the lattice constant is observed. It should be mentioned that similar data has recently been

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(North-Holland Physics Publishing Division)

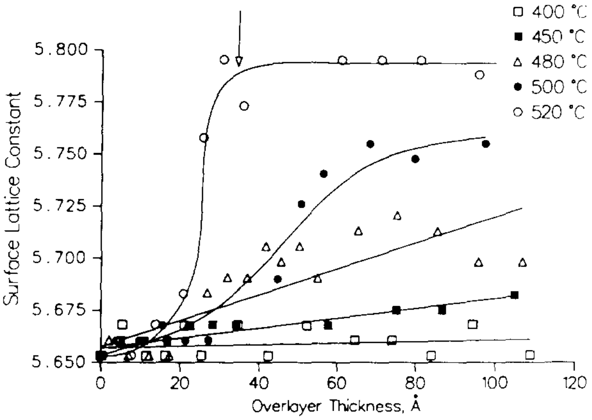

Fig. 1. Surface lattice constant measured by RHEED integral order spacing with increasing overlayer thickness of MBE grown $In_{0.35}Ga_{0.65}As$ on GaAs at various substrate temperatures. The arrow represents the calculated critical thickness according to equilibrium theory.

presented by Whaley and Cohen [1]. These results can be explained in terms of a physical model [2] which shows that the presence of strain forces the system to go towards a 3D island mode for conditions near equilibrium. The surface lattice constant for a smooth growth front should be the same as that of the substrate lattice constant until the critical thickness and then abruptly change to the epilayer bulk lattice constant. On the other hand, for 3D island growth, the surface constant should show a monotonic change from the substrate to the bulk epilayer value, and this is observed experimentally for In contents larger than 15%.

A series of single and multiple quantum well structures upto a total strained MQW thickness of 2 μm were grown for the present study. Some of the structures had an intermediate composition buffer layer between the substrate and the strained single quantum well (SQW) or MQW. Low temperature (20 K) PL measurements were made to ascertain the optical quality of the quantum wells. The PL spectra measured for SQWs are characterized by sharp excitonic transitions. The linewidths for 100 Å $In_{0.1}Ga_{0.9}As/GaAs$ wells are ~ 1.0–1.5 meV, which are comparable to those measured in high-quality GaAs/AlGaAs quantum wells. We believe that the dramatic improvement in the optical quality results from (a) source and system preparation and purity, and (b) the growth condition. With respect to the latter, the important factors are the incorporation of adequate buffers to trap impurities and smoothen the growth front, and an ideal growth rate resulting in a near ideal two-dimensional layer-by-layer growth.

The linewidths for p–i(strained MQW)–n samples grown with and without intermediate composition buffers (1.5–2.5 meV) are almost identical as are the peak intensities. These linewidths confirm the high quality of the heterointerfaces. Low temperature absorption spectra for the samples are well resolved, showing both the light- and heavy-hole transitions. The assignments for these peaks were made from a theoretical model which takes into account size quantization and strain effects [3]. Stokes shifts as small as 1.7 meV confirm the superior quality of the heterinterfaces. These results, coupled with those for the strained SQWs and MQWs, indicate that as far as optical properties are concerned, the incorporation of an intermediate composition buffer layer has little impact. The growth kinetics and growth modes play a more important role.

The surface morphology of the SQW structures was featureless. In the other samples we observed that, in general, samples with intermediate composition buffers showed a very slight cross-hatch pattern, while those without the buffer layers showed none, even in the 2 μm thick p–i–n diodes. The cross-sectional TEM (XTEM) data shown in fig. 2, indicate clearly that there are no propagating dislocations in the MQW region, with and without an intermediate composition buffer layer. This result is puzzling in terms of the existing models of critical thickness. However, Van der Merwe and Jesser [4,5] have recently made calculations which show that the critical thickness of free standing superlattices with small misfits is more than 4 times that of a single epilayer on a thick substrate. However, even this four-fold enhancement does not explain results in our samples without intermediate composition buffers, which have strained MQWs with total thicknesses greatly exceeding that predicted by Van der Merwe and Jesser [4,5]. To further study these phenomena, the MQW samples, which previously showed no dislocations, were annealed in a hydrogen ambient at

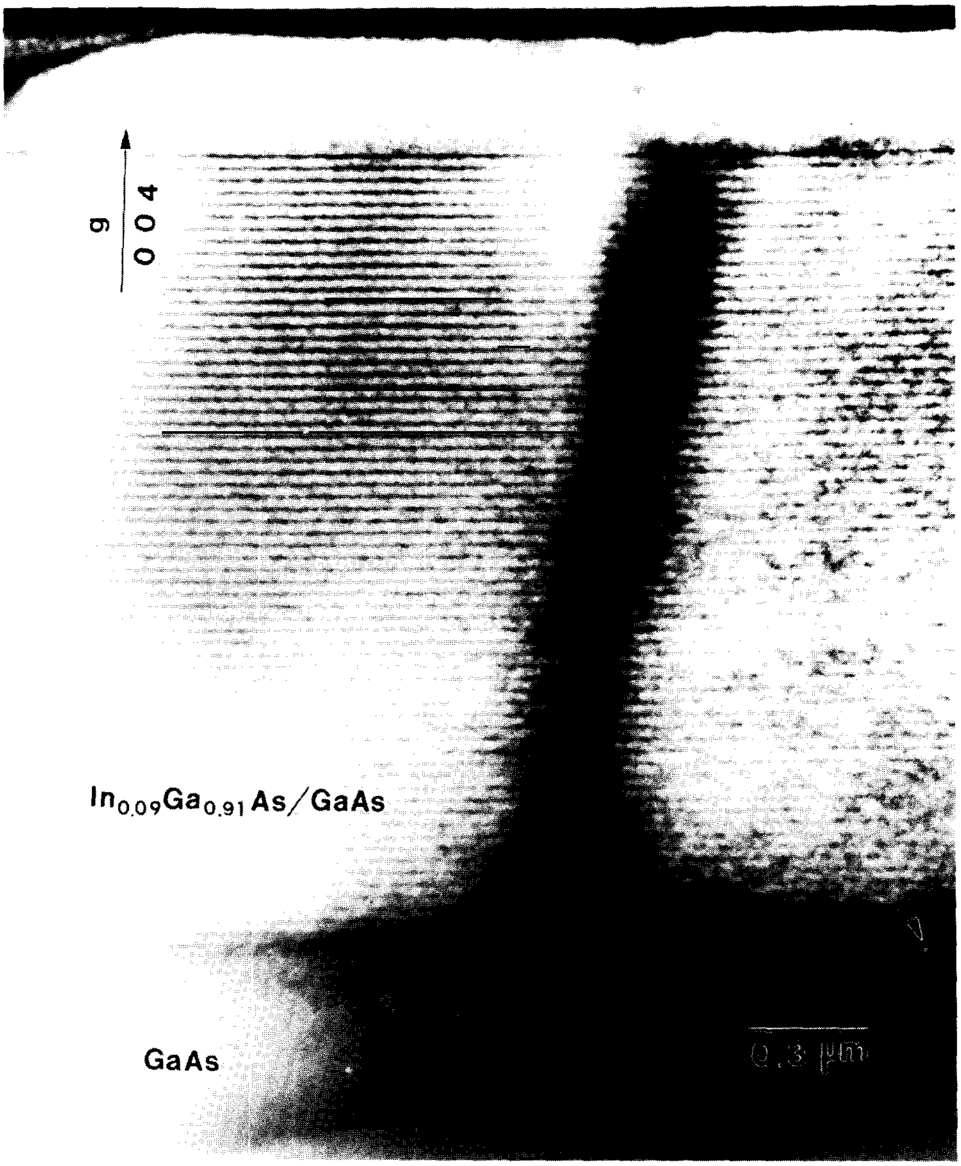

Fig. 2. Cross-sectional TEM results of a p–i(strained MQW)–n modulator. The absence of dislocations in the MQW region should be noted.

830 °C for 30 min and characterized in the same manner as the other strained MQW samples. Upon annealing the samples showed an increase in the PL linewidth, by a factor of 5.5. The samples also showed the presence of dislocations with XTEM, though the surface morphology remained unchanged. Therefore, at this point, it can be stated that: (a) with our growth conditions, there exists a metastable state where dislocation free growth is possible with MBE, a non-equilibrium growth technique, and (b) the cross-hatch pattern is a growth related phenomena due to the generation of misfit dislocations and the consequent step growth which takes place.

The work is being supported by the National Science Foundation (MRG Program) under grant DMR-8602675, the Department of Energy under grant DE-FG02-86ER45250 and the Army Research Office (URI Program) under contract DAAL03-87-K-0007.

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