Transmission electron microscopy of strained $In_yGa_{1-y}As/GaAs$ multiquantum wells: The generation of misfit dislocations

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We have investigated the generation and propagation of misfit dislocations in strained $In_yGa_{1-y}As/GaAs$ multiquantum wells grown by molecular-beam epitaxy, with cross-sectional transmission electron microscopy. The samples are of excellent optical quality, with multiquantum wells having well widths of 100 Å, being characterized by excitonic linewidths and Stokes shifts of 1.5–2.5 and 1–2 meV, respectively. We have examined the growth of 2-μm-thick multiquantum-well samples grown either directly on GaAs, or with an intermediate composition buffer layer, and for the cases of small ($y = 0.07$) and large ($y = 0.16$) misfits. It is seen that for the case of quantum wells with small misfit, grown directly on GaAs, metastable growth can be achieved. This is confirmed by low-temperature absorption measurements and from transmission electron microscopy experiments performed both before and after post-growth thermal annealing. In the case of quantum wells with large misfits directly grown on GaAs, dislocations are generated within the first few periods, and high optical quality is retained in the subsequent free-standing quantum wells. In the case of quantum wells grown with an intermediate composition $In_xGa_{1-x}As$ buffer layer, dislocations are generated at the buffer-GaAs interface, and the freestanding multiquantum well is again of very high quality.

I. INTRODUCTION

Multiquantum wells (MQW) and superlattices (SL) are used extensively at the present time to tailor electronic and optical properties of materials, which helps in the realization of unique and novel device concepts.[1,2] Strained multiquantum wells, particularly in the pseudomorphic regime, add another dimension to the tailoring of material properties and have therefore emerged as important materials for present day electronic and optoelectronic device applications. It is generally accepted that the maximum thickness of a pseudomorphic film, in single layer form, is determined by the balance between the generation of misfit dislocations and the elastic strain built up in the film.[3,4] At this critical layer thickness, the elastic strain is totally or partially relaxed by the generation of misfit dislocations. Recently, processes involved in strain relaxation during heteroepitaxy have been widely studied.[5–7] It is believed that not only the layer thickness and the lattice mismatch, but also the epitaxial growth temperature and the dislocation line tension are important in defining the concept of critical thickness. Moreover, strain relaxation is a kinetically rather than an energetically controlled process.

For a free-standing SL or MQW, the elastic misfit strain ϵ at each individual interface is shared between the well and the barrier regions.[4] This means $\epsilon = f$ for a single strained layer, but $\epsilon = f/2$ in a SL or MQW, where f is the lattice misfit percentage. The experimental results[8–10] agree reasonably well with the theoretical predictions of Matthews and Blakeslee.[4] However, it is not clear whether, for a SL or MQW, the critical thickness of the total structure remains the same as that of a single heterostructure. In this study, we have compared the critical thickness and dislocation generation in InGaAs/GaAs MQW grown either directly on GaAs substrates or with an intermediate composition buffer. We have investigated the interface region of GaAs and InGaAs/GaAs MQW by cross-sectional transmission electron microscopy (XTEM). Low-temperature photoluminescence (PL) and absorption measurements were performed to ascertain the optical quality and built-in strain in the hetero structures.

II. EXPERIMENT

The $In_yGa_{1-y}As/GaAs$ ($y \leqslant 0.16$) quantum-well structures were grown on (001)-oriented Si-doped GaAs substrates in a Varian GEN II molecular-beam epitaxy (MBE) facility. Preparation of the system prior to growth was similar to previous work.[11] The growth rate of the GaAs was maintained at 0.8 μm/h. For the structures grown here the growth temperature was in the range 550 ± 10 °C. The group V to group III ratio was held at approximately 30 to maintain an arsenic stabilized surface for both GaAs and InGaAs. The reflection high-energy electron diffraction

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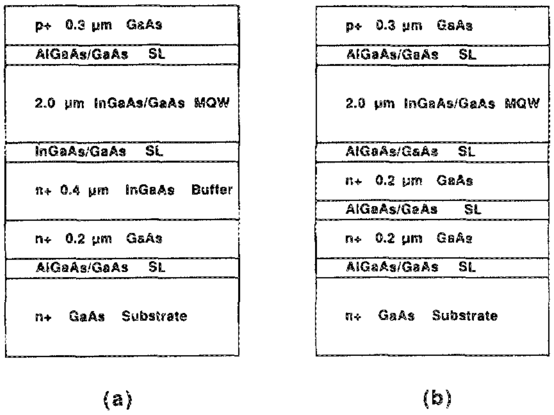


FIG. 1. Schematic diagrams of strained MQW structures grown by MBE (a) with and (b) without intermediate composition buffer.

(RHEED) patterns were extremely sharp during the growth of the GaAs. During the growth of the InGaAs wells, the arsenic stabilized lines faded but the pattern did not degenerate into spots up to the critical thickness, indicating a near two-dimensional (2D) layer-by-layer growth mode in this regime. A series of 2-μm MQW structures was grown for the present study. Some of these had an intermediate composition buffer layer between the substrate and the strained MQW, with an average composition x given by

$$x = (yL_Z)/(L_Z + L_B),$$

where L_Z and L_B are the well and barrier thicknesses, respectively. It should also be noted from Fig. 1 that "smoothening" AlGaAs/GaAs superlattices were incorporated in the buffer region. Growth was interrupted for 1 min while the temperature was reduced to 550 °C for growth of the active quantum wells, after the growth of the GaAs buffer regions at 600 °C

The fabrication of XTEM specimens was made by gluing together six 5×5 mm^2 GaAs wafers face-to-face with epoxy resin (only the center two were processed). The wafer blocks were sliced by a diamond saw on $\langle 110\rangle$ cleavage directions. The cross-sectional slices were polished, dimpled, and then ion milled to transparency. The specimens were examined in a JEOL 2000FX transmission electron microscope operating at 200 kV.

Low-temperature (15-K) photoluminescence measurements were made on the MQW samples to ascertain the optical quality of the quantum wells. The samples were photoexcited with an argon-ion laser (operating at $\lambda = 5145$ Å). The luminescence was analyzed with a 1-m Jarrell–Ash spectrometer and detected with a cooled photomultiplier tube. The spectra were recorded on a strip chart recorder after suitable amplification by a lock-in amplifier. Absorption measurements were made with halagon lamp excitation.

III. RESULTS AND DISCUSSION

Two types of structures were investigated, as shown schematically in Figs. 1(a) and 1(b). The essential difference between the two structures is the presence or absence of an intermediate composition $In_xGa_{1-x}As$ buffer layer between the GaAs substrate and the $In_yGa_{1-y}As$/GaAs MQW. Typical low-temperature photoluminescence data of both categories of MQW with 100-Å well widths are characterized by a dominant bound exciton transition with a linewidth of 1.5–2.5 meV. Furthermore, the Stoke's shift is also in the range of 1–2 meV, which is derived by comparison with low-temperature absorption data. These values, which are among the best reported to date, confirm the high quality of the quantum wells and heterointerfaces.

The cross-sectional TEM micrographs of 2-μm $In_{0.07}Ga_{0.93}As$/GaAs strained MQW growth with and without intermediate composition buffer layer are shown in Figs. 2(a) and 2(b), respectively. Figures 3(a) and 3(b) show the details of the MQW-buffer and MQW-GaAs interface regions, respectively. In the strained MQW with a lattice-matching intermediate buffer, a misfit dislocation network was generated at the interface between the 0.4-μm-thick $In_{0.023}Ga_{0.977}As$ buffer and GaAs. The strain in the $In_yGa_{1-y}As$/GaAs MQW matched to the $In_xGa_{1-x}As$ buffer depends on both the indium composition and the thickness ratio of the well and the barrier. Since each

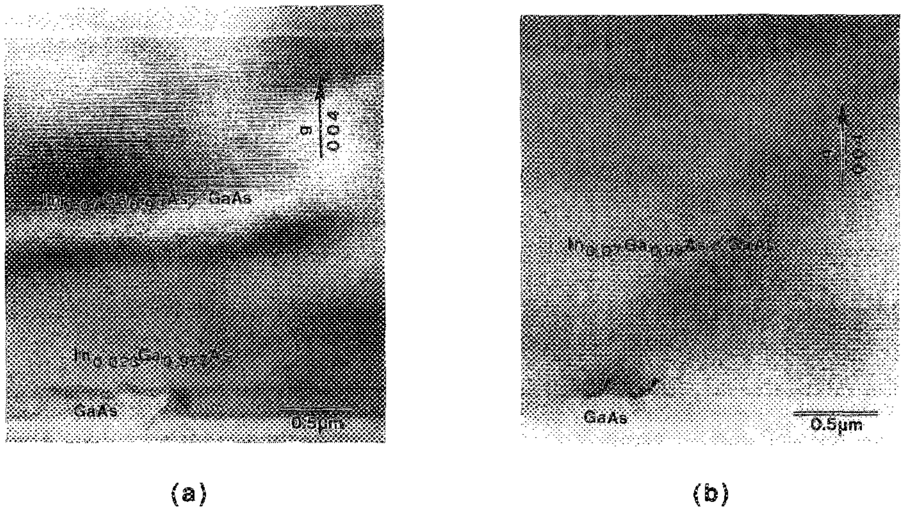
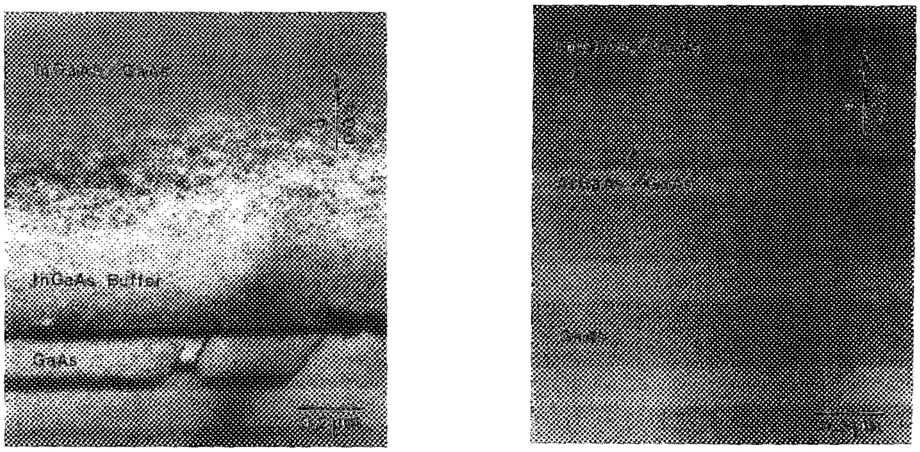


FIG. 2. XTEM micrographs of $In_{0.07}Ga_{0.93}As$/GaAs MQW (a) with and (b) without intermediate composition buffer.



(a) (b)

FIG. 3. XTEM micrographs revealing the interfacial details of the sample shown in Fig. 2.

strained layer (well or barrier) is thinner than the critical thickness, no new misfit dislocations are generated in the MQW region. On the other hand, it is interesting to note that very few or no misfit dislocations are seen by XTEM in the sample without the intermediate buffer [Figs. 2(b) and 3(b)]. Only a few small dislocation loops are observed close to the interface between the strained MQW and the GaAs buffer. These dislocation loops formed in regions of high local stress may grow under misfit stress to generate dislocation networks.[12] One can then assume that the directly grown MQW is predominantly in a metastable state in which the whole MQW remains coherently strained. To verify this assumption, the sample was annealed at 850 °C for 30 min. The XTEM micrograph of the annealed sample is shown in Fig. 4 where the generation of dislocations due to thermal activation is clearly visible at the top and bottom interfaces between the MQW and the bulk GaAs region. These misfit dislocations, which form as the result of strain relaxation, may be originated from the threading dislocations in the substrate or from the preexisting dislocation loops at the heterointerfaces. Some of the misfit dislocations also thread into the GaAs buffer region. This is not only because the mismatched extra half-planes are in the GaAs side, but also because the elastic strain energy on the MQW side of the interface expels the dislocations away from this heterojunction.[13]

FIG. 4. XTEM micrograph of the sample in Fig. 2(b) after post-growth annealing.

The energy positions and the energy separation between the heavy- and light-hole excitonic resonances in the optical absorption spectra of quantum wells are very sensitive to biaxial strain. We therefore performed low-temperature optical transmission measurements on the as-grown samples grown with and without the intermediate composition buffer layer. Biaxial compressive strain in the InGaAs wells increases both the fundamental band gap E_g, and the separa-

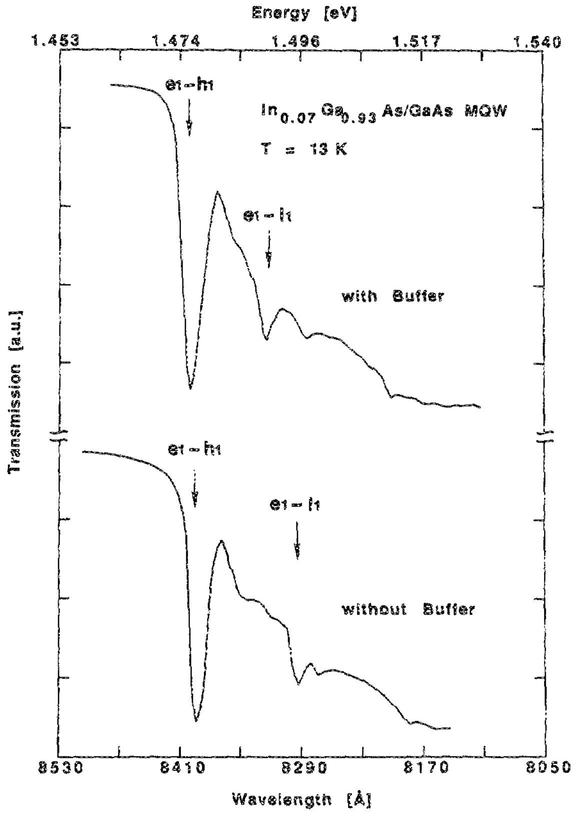
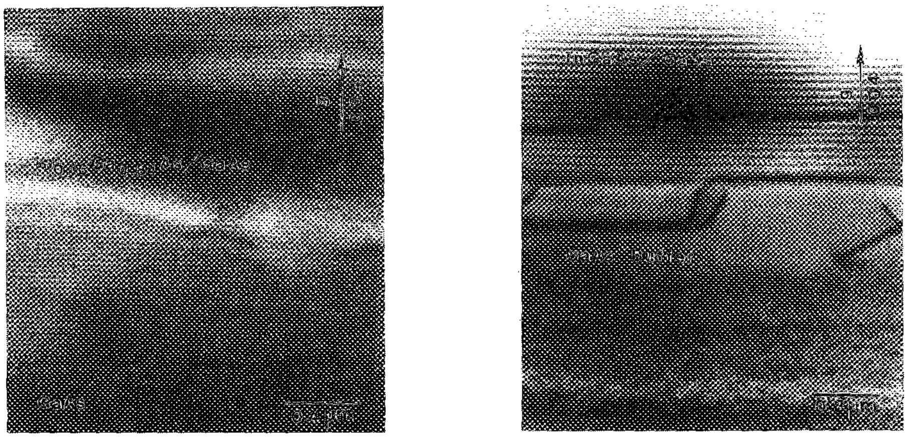


FIG. 5. Low-temperature absorption spectra of 2-μm $In_{0.07}Ga_{0.93}As$/GaAs MQW grown directly on GaAs, and on intermediate composition $In_xGa_{1-x}As$ buffer layer.



(a)

(b)

FIG. 6. XTEM micrographs of (a) 2-μm InGaAs/GaAs MQW and (b) the details of interfacial defects.

tion ΔE_0 between the heavy- and light-hole excitonic resonances. Both of these observations were borne out by the results, shown in Fig. 5. It is indeed seen that in the sample grown directly, both these energy values are higher than in the samples grown with the intermediate composition buffer. Growth in a metastable state therefore seems to be the only plausible conclusion.

We have also studied a 2-μm-thick $In_{0.16}Ga_{0.84}As$/GaAs strained MQW structure, with $L_B = 2L_Z = 250$ Å, grown directly on a GaAs substrate, and shown in Fig. 6. In this sample, the well thickness is above the calculated critical layer thickness for a single strained layer.[3,12] It is interesting to note that misfit dislocations were only found at the region close to the MQW/GaAs interface. Apparently, after the elastic strain in the first few quantum wells is relaxed, the MQW is no longer lattice matched to the GaAs substrate but is in a freestanding state. The average lattice constant of the MQW is now equal to that of $In_{0.053}Ga_{0.947}As$, and the thicknesses of both well and barrier regions are now below the calculated critical layer thickness for the particular alloy composition.[8] With the equal but opposite elastic strain fields in the well and the barrier, zero net strain results in the MQW.[14] Dislocations are also generated at several quantum wells above the heterointerface. This may be due to nonuniform strain relaxation at the heterojunctions and high local stress. The linewidth of the dominant excitonic transition in the photoluminescence spectrum is ~2.5 meV. It is therefore apparent that the high optical quality strained MQW with large misfit between well and barrier regions can be grown by MBE without the incorporation of intermediate composition buffer layers.

It is worth mentioning that recent theoretical calculations[15,16] indicate that in a strained layer SL, the thickness of the individual layers can be several times larger than that in a single heterojunction, before dislocations are generated. This result, coupled with our present experimental findings on the directly grown strained MQW, both with small and large misfits, indicates that large pseudomorphic regions without appreciable dislocation densities and with excellent optical properties can be realized by MBE.

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