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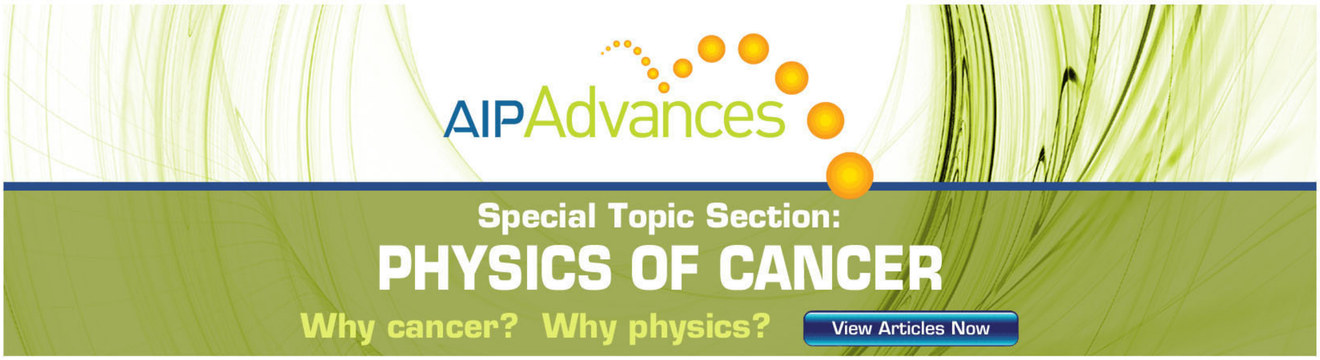

X-ray characterization of InAs laser structures grown by molecular beam epitaxy

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An x-ray interference effect was used to characterize a set of strained layer laser structures containing N monolayers of InAs ($N=1, 3, 5, 7$) conveniently distributed in the quantum well active region. A sample containing 100 Å of $Ga_{0.8}In_{0.2}As$ in the quantum well was also grown and characterized for comparison. Structural parameters such as thickness, chemical composition, and strain status of the different layers (cladding, waveguide, and quantum well layers) as well as the relaxation process and critical thickness due to increasing InAs content in the active region were studied. It was found that indium content was very close to the design values and that the whole structure is coherent with the substrate for 1 and 3 monolayers of InAs (and 100 Å of $Ga_{0.8}In_{0.2}As$) while the structure starts to relax by dislocation formation for 5 monolayers of InAs and is clearly relaxed for 7 monolayers of InAs. These x-ray results are in full agreement with transmission electron microscopy and characterization of the structures as laser devices.

Strained layer semiconductor structures have received considerable attention in the last few years. Although use of strain can, in principle, improve device performances (e.g., lower threshold current in quantum well lasers[1]), it is well known that design of strained structures is limited by the thickness at which the formation of dislocations becomes energetically favorable (critical thickness) and degradation of crystalline quality takes place.[2] More recently, single ultrathin strained layers of InAs as well as short period InAs/GaAs superlattices (with a 7.16% misfit) have been tried as an alternative for $Ga_{1-x}In_xAs$ alloys in order to obtain higher quality material. Recently several groups have reported results about devices using these kind of structures.[3,4] Simulation of x-ray diffraction is a well established method to characterize laser structures of unstrained $Al_xGa_{1-x}As/GaAs$[5] using dynamical theory of x-ray diffraction, and strained InGaAs/InGaAsP[6] using kinematic theory of x-ray diffraction. We used x-ray diffraction analysis combined with simulation using dynamical theory of diffraction as a post-growth means of evaluating the indium content, a key point in the design of these devices. We report on an x-ray interference effect study of critical thickness in a set of laser structures including highly strained 1, 3, 5, and 7 monolayers (MLs) of InAs, and 100 Å of $Ga_{0.8}In_{0.2}As$ in the quantum well using x-ray diffraction dynamical theory to fit the experimental diffraction patterns. To our knowledge this is the first study of the relaxation process using dynamical theory of x-ray diffraction applied to strained layer laser structures.

The structure of the samples is as follows: (001) GaAs:Si substrate, 0.5 μm n^+-GaAs buffer layer, 1 μm n^+-$Al_{0.6}Ga_{0.4}As$ ($n \sim 5\times10^{17}$ cm^{-3}) cladding layer, 1000 Å undoped $Al_{0.2}Ga_{0.8}As$ waveguide, 80 Å undoped quantum well that differs from sample to sample, 1000 Å of undoped $Al_{0.2}Ga_{0.8}As$, 1 μm of p^+-$Al_{0.6}Ga_{0.4}As$ ($p \sim 5\times10^{17}$ cm^{-3}) and 1500 Å p^{++}-GaAs ($p \sim 5\times10^{18}$ cm^{-3}) contact layer. The five different strained wells consist of 100 Å of $Ga_{0.8}In_{0.2}As$ (sample A), and N ML of InAs ($N=1, 3, 5, 7$) (samples B,C,D, and E) separated from each other by either 2 or 3 MLs of GaAs (Table I).

The samples were grown at low temperature (350 °C) by a development of the conventional molecular beam epitaxy (MBE) technique named atomic layer MBE (ALMBE).[7,8] The main feature of ALMBE is a periodic perturbation of the growing surface by means of the cyclic interruption of the molecular beam of As_4 which enhances two-dimensional growth kinetics.[8]

High resolution x-ray diffraction measurements were performed by means of a double crystal diffractometer around the (004) GaAs reflection. Experimental scans were compared with calculated diffraction patterns[9,10] using the dynamical theory of x-ray diffraction.[11,12] In this way we determined the structural parameters of the different layer such as thickness, chemical composition, and strain status. In these kinds of structures a characteristic modulation of the intensity (Pendellösung) due to the interference of x-ray waves inside the crystal is predicted by the simulation (Fig. 1). We observe that this modulation exists in the samples containing 100 Å of $Ga_{0.8}In_{0.2}As$ [Fig. 1(a)], 1 and 3 MLs of InAs [Figs. 1(b) and 1(c)] in the laser active region. For the sample with 5 MLs of InAs [Fig. 1(d)] this modulation is not observed and the background intensity is normal. In the sample with 7 MLs of

TABLE I. Composition of the strained quantum well for different samples.

Sample	Quantum well composition
A	100 Å $Ga_{0.8}In_{0.2}As$
B	$(GaAs)_{12}/InAs/(GaAs)_{14}$
C	$(GaAs)_8/3[InAs/(GaAs)_3]/(GaAs)_5$
D	$(GaAs)_3/5[InAs/(GaAs)_3]/(GaAs)_2$
E	$(GaAs)_3/7[InAs/(GaAs)_2]/(GaAs)_3$

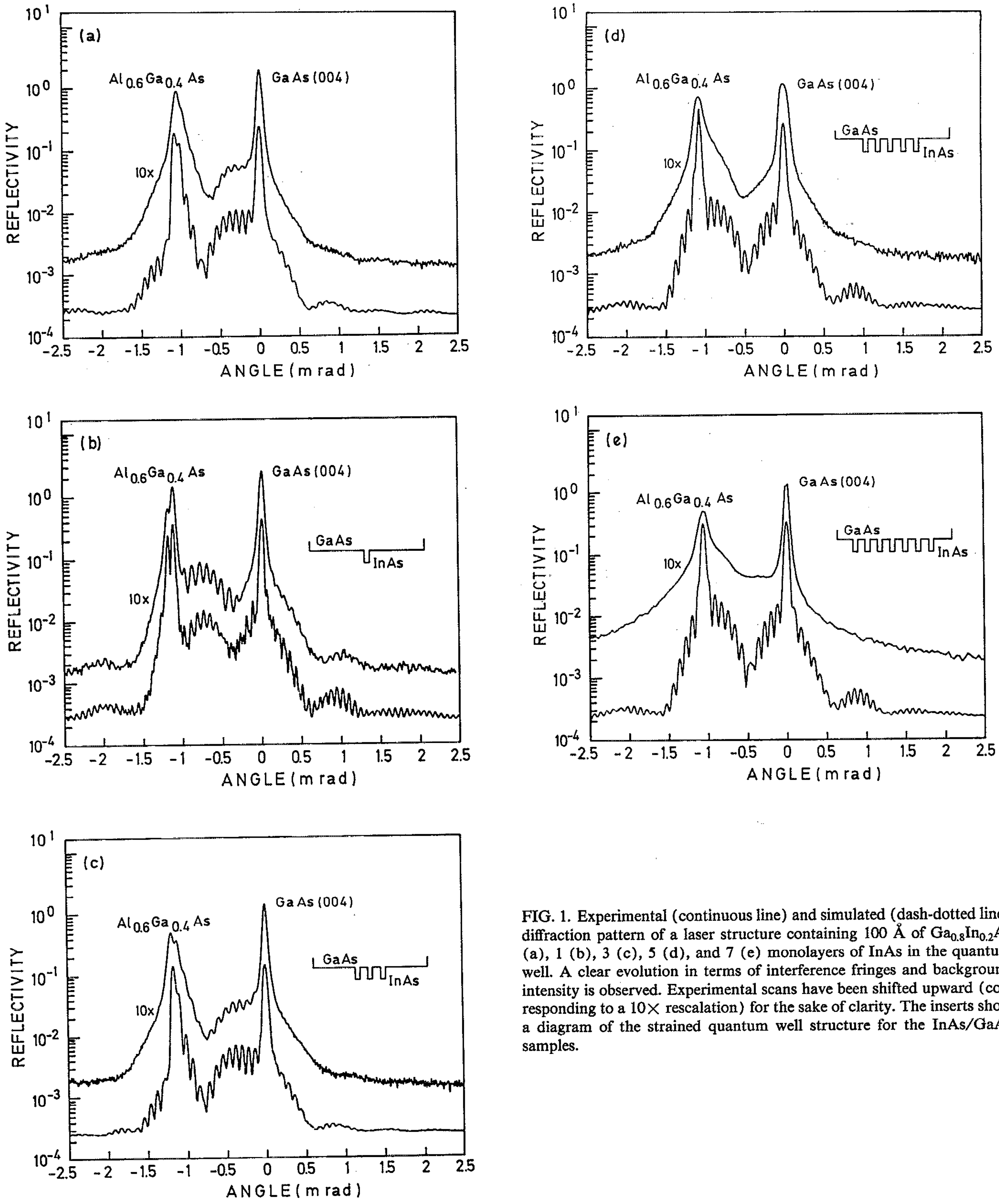

FIG. 1. Experimental (continuous line) and simulated (dash-dotted line) diffraction pattern of a laser structure containing 100 Å of $Ga_{0.8}In_{0.2}As$ (a), 1 (b), 3 (c), 5 (d), and 7 (e) monolayers of InAs in the quantum well. A clear evolution in terms of interference fringes and background intensity is observed. Experimental scans have been shifted upward (corresponding to a 10× rescalation) for the sake of clarity. The inserts show a diagram of the strained quantum well structure for the InAs/GaAs samples.

InAs [Fig. 1(e)] no Pendellösung is observed and the background intensity is much higher than normal. Chemical composition and thickness of the $Al_xGa_{1-x}As$ alloy layers, and InAs content found were very close to the design values. The good fit [see Figs. 1(a), 1(b), and 1(c)] between experimental and simulated diffraction scans for samples with 100 Å $Ga_{0.8}In_{0.2}As$, and 1, 3 MLs of InAs in the quantum well and the values of different parameters (thickness, chemical composition, and strain) used in the simulation indicate that these samples are coherent with the substrate, i.e., mean lattice parameter in the growth plane ($a_{\parallel}$) is the same of the one of the substrate, InAs layer is tetragonally strained to accommodate the in plane misfit. A lack of Pendellösung in the sample with 5 MLs of

InAs [Fig. 1(d)] and normal background indicate that relaxation process has started, thus damping the interference effect, but the dislocation density is not high. A large amount of dislocations would not only induce a disappearance of x-ray interferences, but also a high background due to incoherent scattering.[13] These two phenomena, no Pendellösung and high background, are clearly observed in the sample with 7 MLs of InAs [Fig. 1(e)] indicating that the structure is relaxed by appearance of misfit dislocations.

These results are in agreement with transmission electron microscopy[14] analysis. This shows that samples A, B, and C are free of dislocation, while sample D has a considerable density of dislocations and sample E has a much higher density of dislocations. Characterization of the samples as laser devices shows that samples A, B, and C have good laser characteristics (e.g., $J_{\mathrm{th}}=1.97\ \mathrm{kA\,cm^{-2}}$, $\lambda=884$ nm for sample B[15]) while sample D shows poorer performance and sample E does not lase as expected by the high density of dislocations in the active region.

In summary, we have used the x-ray interference effect to study the relaxation process occurring in laser structures containing 1, 3, 5, and 7 MLs of InAs and 100 Å of $\mathrm{Ga_{0.8}In_{0.2}As}$ in the active region. Samples with 1 and 3 MLs of InAs, and 100 Å of $\mathrm{Ga_{0.8}In_{0.2}As}$, were found coherent with the substrate. The sample with 5 MLs of InAs was found in an initial state of relaxation, and the sample with 7 MLs of InAs was found relaxed. Results are confirmed by transmission electron microscopy and characterization of the lasers, showing a strong degradation of the samples with 5 and 7 MLs of InAs.

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