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Optical Anisotropy of Pseudomorphic (In, Ga)As Multiple Quantum Wells Oriented in the [110] Crystallographic Direction

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Zinc-blende semiconductors synthesized from group III and V elements of the periodic table exhibit a wealth of properties useful for the design of electronic and optoelectronic devices. Some of these properties depend on the crystallographic orientation of the synthesized thin film structures. This paper discusses some novel optical properties observed in strained heterostructures of (In,Ga)As and GaAs layers grown on (110) GaAs substrates. The fundamental photoluminescent emission from (In,Ga)As/GaAs quantum wells shows an intrinsic red-shift attributed to an internal strain-induced electric field. The luminescence intensity is also dependent on the relative polarization of the excitation source.

We report the successful growth, by molecular beam epitaxy, of device quality (In,Ga)As/GaAs strained-layer heterostructures on [110]-oriented GaAs substrates intentionally tilted by 6° toward the (111)B surface. We have discussed, in previous work, the details of why this particular vicinal orientation of the (110) GaAs substrate was chosen [1]. Briefly, it is found that the 6° tilt toward the (111)B plane is more conducive to growths with excellent surface morphologies. Photolumiscence characterization studies have been conducted on the structures grown on these substrates. The typical structure studied consisted of 5 quantum wells of $In_{0.2}Ga_{0.8}As$. Each well is 8 nm wide and is separated from its neighbor by a 10 nm GaAs barrier. The entire structure is sandwiched between two GaAs layers: a 500 nm buffer layer on top of the substrate and a 100 nm cap layer. The thickness of the $In_{0.2}Ga_{0.8}As$ quantum wells is sufficiently thin that the lattice-mismatch between these layers and the GaAs layers is accommodated by elastic strain—-hence the structure is pseudomorphic.

Most experimental studies on strained-layer (In,Ga)As material have been conducted on structures grown on the (100) GaAs surface. Recent theoretical studies, however, predict that new physical processes occur when orientations other than the conventional [100] are used for strained-layer heterostructures. These new processes are a consequence of the piezoelectric effects found in III-V compounds. In particular, lattice-mismatch induced strains are expected to generate polarization fields. For the (110) tilted substrates we are using, it is expected that the strained-layer structures should exhibit both a longitudinal electric field and a transverse polarization. A theoretical estimate of the longitudinal piezoelectric field gives a value of about 4.5×10^{6} Volts/m and a transverse polarization of $\sim 1.88\times10^{-3}$ C/m^2 in the structures studied here.

In this paper we report our experimental results which confirm the existence of the predicted processes in strained-layer (In;Ga)As quantum wells grown on [110]-oriented GaAs substrates. The photoluminescence experiments were conducted using an Ar^{+} ion laser as the excitation source. The emitted photoluminescence light is analyzed with a 0.5 meter scanning spectrometer before being detected and processed in a data acquisition system. For some of the experiments, the transverse directions of the crystal were aligned in a specific relative direction to the polarization of the laser. Our results show that the fundamental photoluminescence emission wavelength of the electron-to-heavy hole transition is blue-shifted for strained $In_{0.2}Ga_{0.8}As$ quantum wells grown on the (110) GaAs as the excitation intensity is increased. We explain this phenomenon by the screening effect of the photo-generated carriers on the internal strain-induced fields. As the excitation source intensity is increased, the photo-generated carriers screen out the effect of

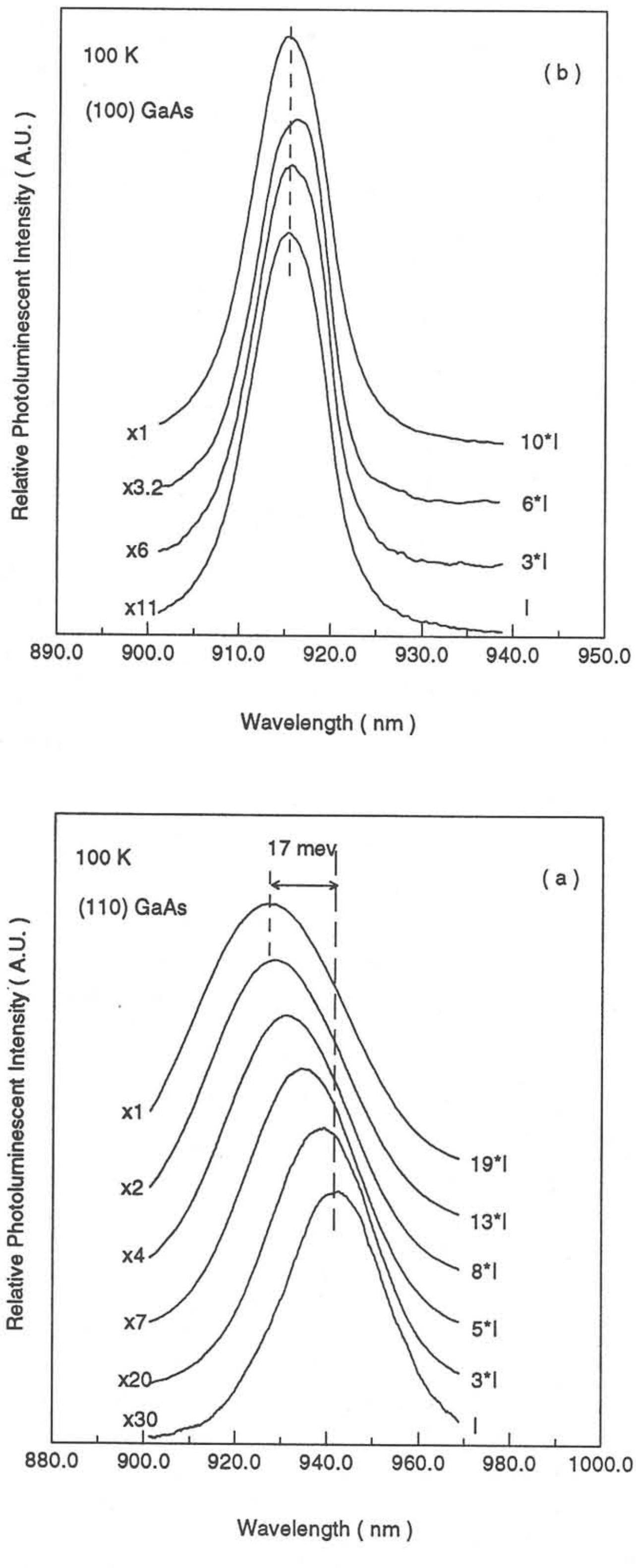

Fig. 1 Photoluminescence spectra of $In_{0.2}Ga_{0.8}As/GaAs$ multiple quantum well structures as a function of excitation intensity for layers on (a) (110) and (b) (100) GaAs substrates.

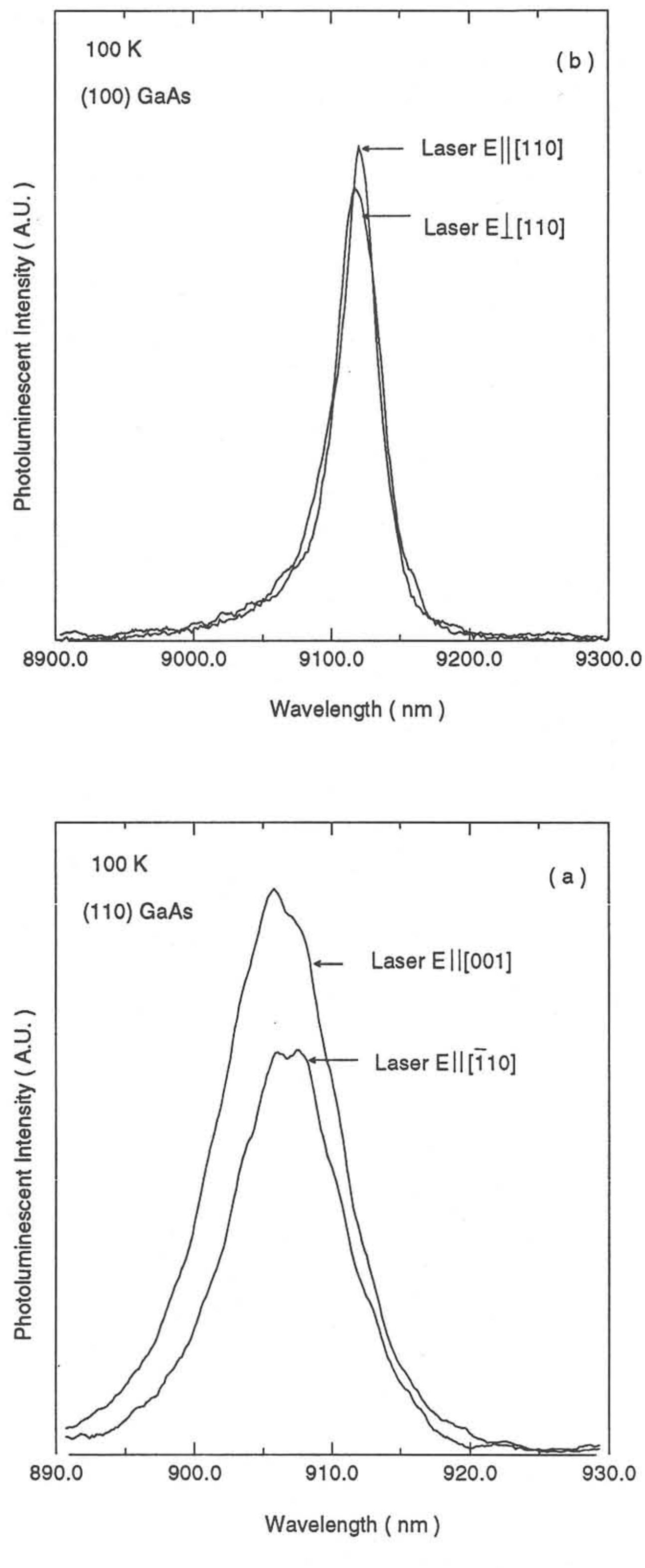

Fig. 2 Photoluminescence spectra of $In_{0.2}Ga_{0.8}As/GaAs$ single quamtum well structures grown on (a) (110) GaAs and (b) (100) GaAs. The polarization of the excitation source is aligned along two primary crystallographic orientations.

the strain-induced field on the fundamental optical transition. Higher excitation intensities with correspondingly large charge densities tend to blue-shift the fundamental transition. This trend is clearly evident in Fig. 1(a) where we illustrate the fundamental photoluminescence transition as a function of excitation intensity. A similar experiment conducted on a similar structure grown on a (100) GaAs substrate shows no blue-shift. It is clear that the presence of the internal field initially shifts the bound states in the quantum wells to lower energies—-a process analogous to the quantum-confined Stark effect [2, 3]. As the internal field is screened by the photo-generated carriers, the bound states shift to higher energies, toward the zero-field condition. This leads to the observed blue-shift in the photoluminescence spectrum. Since the quantum-confined Stark effect was originally observed in structures with externally applied electric fields, this suggests that it could be referred to as the *external* quantum-confined Stark effect. It would naturally follow then that the blue-shift in the pseudomorphic heterostructures with internal strain-induced fields exhibit a kind of an *internal* quantum-confined Stark effect.

Additional photoluminescence experiments on the [110]-oriented strained quantum wells show that the intensity of the emitted light is orientation-dependent. This dependency is related to the direction of linear polarization of the incident excitation source and its relative alignment to the natural crystallographic edge of the sample. We find, for example, that for an excitation of a given intensity polarized parallel to the [001] edge of the sample, the emitted photoluminescent intensity is higher than when the same source intensity has its polarization aligned along the natural $[\bar{1}10]$ edge of the crystal. This experiment was performed on a single quantum well structure. Figure 2(a) shows the polarization-dependent emission of the sample. Theoretical calculations indicate that this anisotropy is to be expected for layers of this kind grown on the (110) GaAs surface. We have used an eight band **k.p** model to perform our calculations. Similar experiments on a single strained quantum well grown on the (100) surface show no significant anisotropy. This effect is therefore attributed to the properties of the low symmetry (110) GaAs surface. It is important to understand the fundamental physics of the strained-layer (In,Ga)As layers on the (110) GaAs surface for the engineering of novel optical devices. These effects could be useful in the design of a new generation of lasers with reduced threshold current densities and in the design of polarization-controlled optical devices.

Acknowledgment

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