Lateral-superlattice effects in very narrow strained semiconductor quantum wells grown on vicinal surfaces

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The existence of lateral-superlattice effects in narrow $In_xGa_{1-x}As/GaAs$ strained quantum wells grown on GaAs vicinal substrates is reported. The effects have been probed by photoluminescence excitation under magnetic field and compared to a theoretical model. Prior work indicates that strained epitaxial layers grown on vicinal surfaces may present a tilt angle between the substrate plane and the epilayer plane that depends on the lattice mismatch. This provokes strong lateral modulation of the potential induced by inhomogeneity of the built-in strain. Our results are consistent with strong lateral-superlattice effects.

In the past few years we have witnessed the development of much activity in the search for quantum-well wires (QWW) and quantum dots because of the expected technological applications as well as the interest in the fundamental physics involved. Two methods have mainly been used so far to obtain one-dimensional (1D) systems. The first, and most extended one, uses photolithographical techniques.[1] Unfortunately, it produces low-quality interfaces. The second one is based in the direct synthesis of QWW on high-index plane substrates.[2] Strain has also been used to fabricate QWW and quantum dots by deposition of carbon stripes on top of the quantum well (QW), which stresses it and locally modifies the band profile.[3]

Research on strained-layer nanostructures constitutes a very active area because the built-in strain in the layers introduces an additional parameter to optimize the optoelectronic properties of QW's. In this paper we show that, for very narrow strained $In_xGa_{1-x}As/GaAs$ vicinal QW's, coupled quantum wire states are formed. The evidence we present comes from photoluminescence excitation (PLE) experiments under magnetic fields. We show that the inhomogeneity of the built-in strain induces a large modulation of the lateral potential.

Two samples were used in this experiment, both being single 15-Å $In_{0.35}Ga_{0.65}As/GaAs$ strained QW's grown simultaneously on GaAs substrates (strain coefficient ϵ=0.024). One of them was grown in the [001] direction (nominal structure), whereas the other was grown on a (001) vicinal substrate 4° off toward the $[111]A$ direction (vicinal structure). Details on the growth and other experimental details can be found elsewhere.[4]

Figure 1 shows selected PLE spectra from the vicinal structure taken at different magnetic fields in the $\sigma^-\sigma^-$ scattering configuration ($\sigma^-\sigma^-$ refer, respectively, to the helicity of the incident and scattered light, which are circularly polarized). A PLE spectrum for the nominal sample at $B = 0$ is also included for comparison. For the vicinal sample, some of the features are easily identifiable as they correspond to the typical absorption spectrum of a QW (Ref. 6) and are also similar, in some aspects, to that of $In_xGa_{1-x}As/GaAs$ superlattices (SL's).[7] For zero magnetic field the peaks at energies of 1478 and 1501 meV correspond to the fundamental states of heavy- (hh_0) and light-hole excitons (lh_0), respectively, of the quantum well. Between the excitonic peaks a mesa structure ranging from 1486 to 1495 meV appears. This fea-

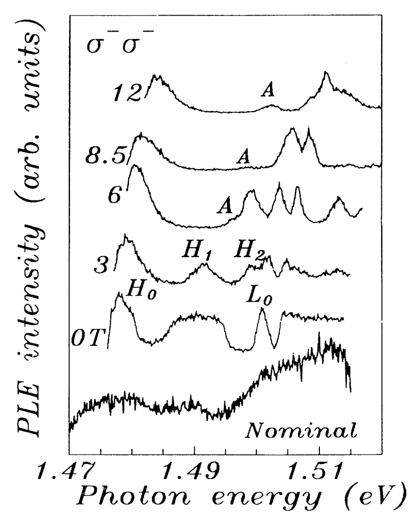

FIG. 1. Photoluminescence excitation (PLE) spectra at 2 K of a 15-Å-thick quantum well (QW) grown on a vicinal substrate for selected values of the applied magnetic field, B. Spectra have been offset vertically for clarity. A spectrum from the nominal sample at 0 T is also shown for comparison.

ture, which was never reported before, reflects the joint density of states (DOS) of the first electron and heavy-hole bands. As we will see later, this mesa structure is explained in terms of coupled QWW states produced by the periodic distribution of steps along with the inhomogeneity of the built-in strain. On the contrary, the light-hole to electron joint density of states (above 1504 meV) shows the typical steplike shape with no clear evidence of a decrease at higher energies, because the light-hole transition has a type-II character. The corresponding spectrum of the nominal sample presents such a large inhomogeneous broadening that the different features overlap each other. The poorer quality of nominal samples has already been reported.[5] However, a blueshift of about 2 meV can be observed for the hh_0 exciton transition of the vicinal sample with respect to the nominal one. This blueshift has been explained as due to the lateral potential produced by the periodic distribution of terraces.[6] In what follows we will concentrate on the vicinal sample.

As magnetic field increases, the mesa disappears and H_1 and H_2 magneto-excitons emerge, eventually crossing over the L_0 magneto-exciton at high magnetic field. Figure 2 summarizes the PLE peak positions as a function of the applied magnetic field for the vicinal structure.

On the high-energy side of H_0 (L_0) magneto-exciton a shoulder (a peak at 1504 meV for $B = 1$ T) appears. With magnetic field both of them behave as their partners do (see Figs. 1 and 2). Recently, Moore *et al.*[8] have detected similar features in $In_xGa_{1-x}As/GaAs$ multiple QW's, that have been explained in terms of the fluctuations of either alloy composition or well thickness.

Besides those peaks mentioned above, a lone peak builds up (see peak A in Fig. 1) from the mesa between hh_0 and lh_0 excitons as the field increases, which is absent in the reference sample. This peak lies at an energy between the light- and heavy-hole transitions and, as far

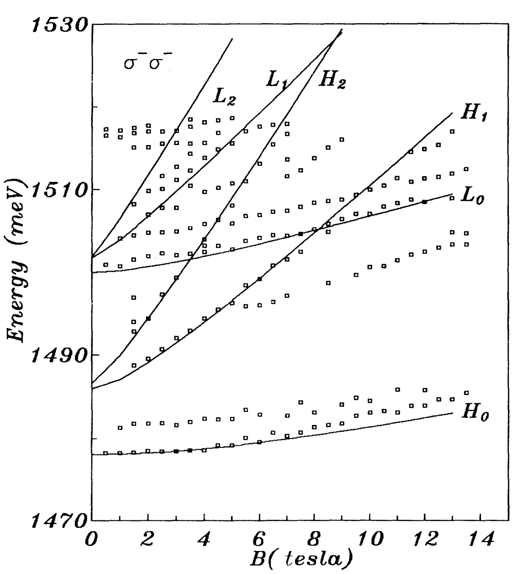

FIG. 2. PLE transition energies at 2 K as a function of magnetic field. Continuous lines fit the data to a two-dimensional hydrogenic magnetoexciton (see text).

as we know, has not been reported before.

Continuous lines in Fig. 2 show the fit of experimental data to a two-dimensional hydrogenic model.[9] From the fit one gets the exciton binding energy (E_b), its reduced effective mass (μ), and the band-to-band transition energy (E) as shown in Table I. Assuming that the effective mass for electrons in $In_xGa_{1-x}As$ is $m_e/m_0 = 0.0665 - 0.0435x$ (Ref. 8) we can get the in-plane heavy- and light-hole effective masses, $m_{\rm hh}$ and $m_{\rm lh}$, respectively.

With regard to the band-to-band transition energies, we have compared them with values calculated in a square QW using a model[10] that takes into account the strain, introducing the band parameters collected by Arent[11] and the accepted band offset ratio for high x ($Q_c = \Delta E_c/\Delta E_{gh}$=0.8)[12]. The results predict a type-II QW for the light holes. For a well width of 5 monolayers (ML) we get 1421 and 1459 meV for the hh and lh band-to-band transitions, respectively. The large difference between the calculated and experimental transition energies can be explained as due to the surface segregation of In atoms.[13,14] Atomic segregation modifies the potential profile and lowers the nominal width of the QW. A close agreement with the fundamental energy transition is obtained using a well width of 3 ML (1484 and 1492 meV, respectively).

It is remarkable that the mesa structure mentioned above has not been shown in similar $Al_xGa_{1-x}As/GaAs$ unstrained samples (nominal and/or vicinal). From a purely two-dimensional joint DOS one should expect a steplike absorption shape. In a recent paper Yi, Dagli, and Coldren[15] have calculated the density of states for an array of QWW's with different degrees of coupling and for strong coupling they obtain a mesalike shape that evolves into a peak emerging from the high-energy side when the coupling is reduced, i.e., when approaching the isolated wire limit. It is easy to understand how inhomogeneity in the built-in strain present in these samples results in a system similar to that modeled by Yi, Dagli, and Coldren. Heterostructures grown on vicinal surfaces present a tilt angle α between the epilayer and the substrate lattice planes,[17] which depends on the lattice mismatch[17–19]. In our case the angle could reach a large value [$\alpha \gtrsim 0.1°$ (Ref. 18)].

Figure 3(a) shows the effect explained above. $In_xGa_{1-x}As$ cells at the terrace corner (zones labeled H) are under hydrostatic compression as they have to accommodate to the GaAs lattice parameter in the three directions, while cells close to the step edge (zones labeled B) are mainly under biaxial strain. Shear strain gives negligible effects. In order to calculate band energies at differ-

TABLE I. Fitted exciton parameters and in-plane effective masses (see text).

Parameters	hh	lh
E (meV)	1487	1502
E_b (meV)	9	2
μ/m_0	0.052	0.050
m_{hh}/m_0	$\gg$1	$\gg$1

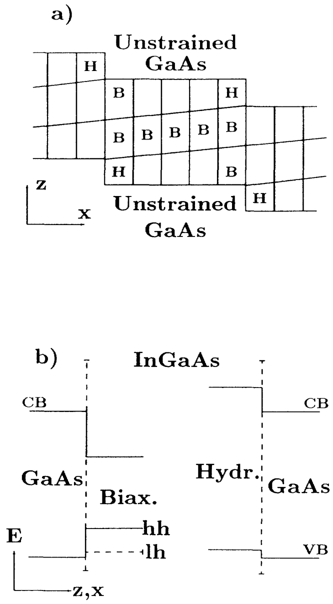

FIG. 3. (a) Schematic representation of the lattice deformation of an $In_xGa_{1-x}As/GaAs$ QW. The H and B mean zones under hydrostatic and biaxial strain, respectively. (b) Band lineup in the H and B zones.

ently strained $In_xGa_{1-x}As$ cells we have used the model of van de Walle[20] since it does not need any adjustable parameters. Figure 3(b) shows the band line up for $In_xGa_{1-x}As$ under biaxial (B) stress and under hydrostatic (H) stress. The calculated band offsets are given in Table II. Note that the band profile suffers dramatic changes depending on the lateral position of the cell under consideration. The lateral modulation of the conduction band for $In_{0.35}Ga_{0.65}As/GaAs$ vicinal QW's can be as large as 300 meV [i.e., $E_c(H) - E_c(B) = 301$ meV, where $E_c(H/B)$ is the energy of the $In_xGa_{1-x}As$ conduction band for cells under hydrostatic/biaxial stress]. This holds for every terrace so a large periodic modulation of the potential is achieved. In nominal samples the randomness in the island size distribution, due to monolayer fluctuations at the interfaces, prevents the formation of any periodic arrangements and the existence of any priviledged direction.

The effective conduction-band profile in a 5-ML thick vicinal QW with and without strain inhomogeneity, respectively, is shown in Figs. 4(a) and 4(b). Although an homogeneously strained structure like the one shown in

TABLE II. Calculated values of the conduction- (ΔE_c) and the valence- ($\Delta E_{\rm hh}$ and $\Delta E_{\rm lh}$) band offsets of an InGaAs/GaAs heterojunction for $In_{0.35}Ga_{0.65}As$ cells under hydrostatic (H) or biaxial (B) strain (Ref. 20). Band offsets are defined as $\Delta E = E(\mathrm{GaAs}) - E(\mathrm{InGaAs})$.

Strain	ΔE_c	$\Delta E_{\rm hh}$	$\Delta E_{\rm lh}$
Hydrostatic	-101	-14	-14
Biaxial	200	-140	-22

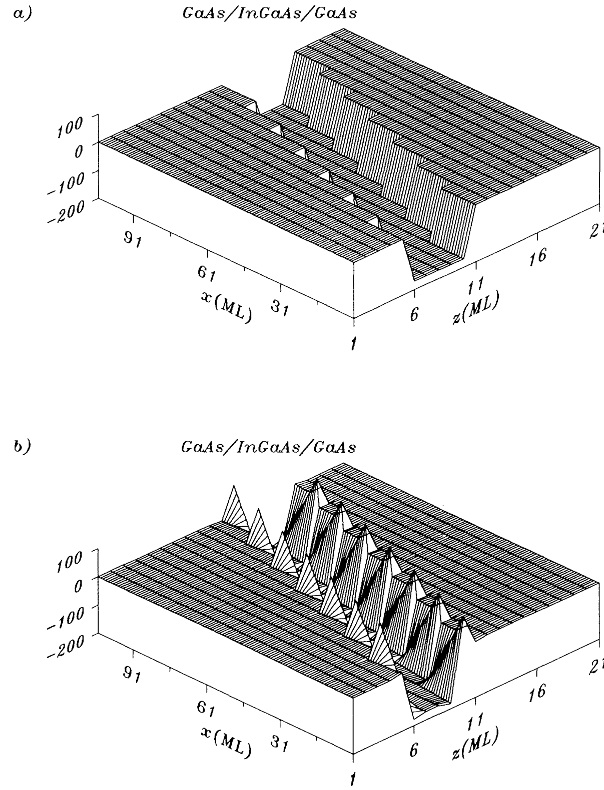

FIG. 4. 3D plot of the conduction-band profile, in the x, z plane, of a 15-Å thick InGaAs/GaAs vicinal QW with 40-Å long terraces taking into account (a) stepped interfaces and homogeneous biaxial stress whithin the well, and (b) including inhomogeneous strain. Each node in the plot represents a cell. The origin of energies has been taken at the GaAs barrier conduction band.

Fig. 4(a) could produce a lateral modulation if a high effective mass is assumed,[16] it is the inhomogeneity in the stress distribution [Fig. 4(b)], which creates a periodic set of straits in the vicinal $In_xGa_{1-x}As$ QW and assures a large modulation of the electron wave function. Therefore the density of states corresponds to that of strongly coupled quantum wires, explaining the observed mesalike structure in the PLE spectrum. The strain pattern also creates spikes 100 meV above the GaAs conduction band on every hydrostatically stressed cell, which strengthen the lateral modulation.

When the coupling between the QWW is reduced, the mesa structure should narrow and finally collapse into a single peak (see Ref. 15). This is the effect observed in Fig. 1 as the magnetic field increases. We think that this is due to the quantization of electron motion in the QW plane that enhances the lateral effects.

In summary, we report effects in the optical properties of narrow strained $In_{0.35}Ga_{0.65}As/GaAs$ quantum wells grown on GaAs vicinal substrates, which we attribute to the presence of lateral superlattice states. These have been probed by photoluminescence excitation under magnetic field and explained by the periodic inhomogeneous stress caused by the presence of ordered interface terraces in this sort of samples. Our results indicate that it is possible to make systems with coupled quantum wires with high-quality interfaces. More theoretical and experimental effort is needed in order to achieve the optimal parameters of In content, well thickness,, and terrace length to improve the lateral confinement in this type of microstructure.

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