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Optical studies of ultrashort-period GaAs/AlAs superlattices grown on (In,Ga)As pseudosubstrate

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We present studies of GaAs/AlAs ultrashort-period superlattices grown on (In,Ga)As pseudosubstrates. Piezomodulation spectroscopy is used for the identification of conduction- and valence-band states involved in optical transitions. This study shows how the lattice mismatch between AlAs and (In,Ga)As can be exploited for the unconditional obtaining of pseudodirect GaAs/AlAs superlattices, with a ground conduction subband of X_z symmetry. It is shown that GaAs/AlAs superlattices, with ultrashort periods (2–8 monolayers), which are indirect when grown on GaAs substrate, become pseudodirect when grown on (In,Ga)As pseudosubstrate. In addition, the first quantized light-hole subband is found to be the ground valence-band state, in good agreement with envelope-function calculations including the coupling between light-hole and spin-orbit split-off bands. [S0163-1829(98)51636-0]

Ultrashort-period $(\mathrm{GaAs})_m/(\mathrm{AlAs})_n$ superlattices (SL's) where m and n represent the number of monolayers in the GaAs and AlAs layers, respectively, have been intensively studied from both the experimental[1–11] and theoretical[12–21] points of view. Since the work by Finkman, Sturge, and Tamargo,[1] and Danan *et al.*,[2] the unanimity has been approved on the type-II nature of GaAs/AlAs ultrashort-periods SL's. This means that whereas the valence-band maximum is at the Γ point and is located in the GaAs layer, the conduction-band minimum is mainly derived from the X states of the AlAs layer. However, there has been some controversy about the X_z or X_{xy} nature of the fundamental conduction states. Due to the anisotropy of the effective-mass tensor near X valleys, the threefold degeneracy of the X-like subbands is lifted by the potential of the SL, which breaks the translational symmetry along the (001) growth axis, denoted the z axis. This splitting produces a doublet and a singlet, respectively denoted X_{xy} and X_z. Due to a larger effective mass (longitudinal mass) along (001), the first quantized subband arising from the X_z state should always remain the fundamental conduction subband of the structure. However, uniaxial stress experiments[3,4,7,11] and time-

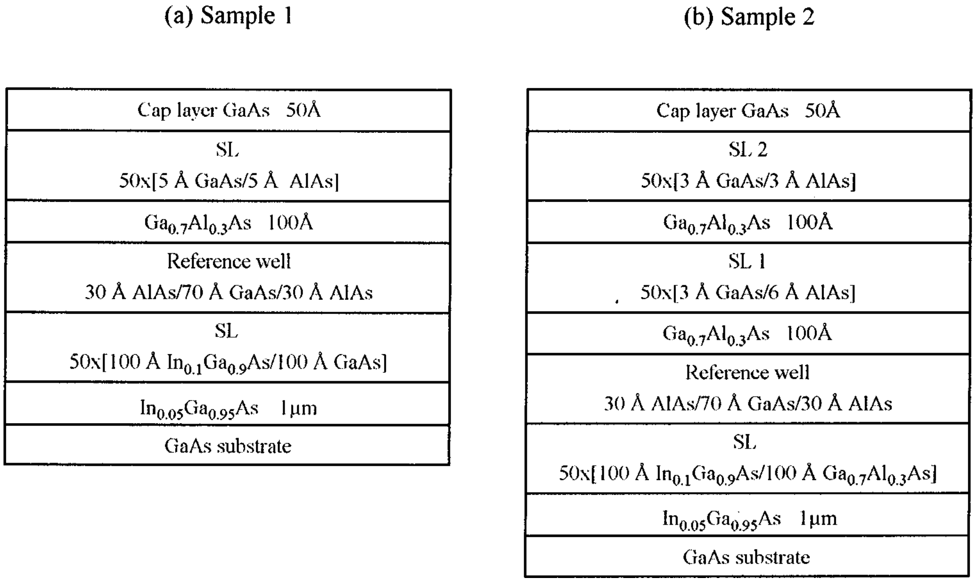

FIG. 1. Structure of the samples studied: (a) sample 1 and (b) sample 2. In both samples, the $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ pseudosubstrate is made up of the thick layer of $\mathrm{In}_{0.05}\mathrm{Ga}_{0.95}\mathrm{As}$ and the $\mathrm{In}_{0.1}\mathrm{Ga}_{0.9}\mathrm{As}$/GaAs (or $\mathrm{Ga}_{0.7}\mathrm{Al}_{0.3}\mathrm{As}$) superlattice.

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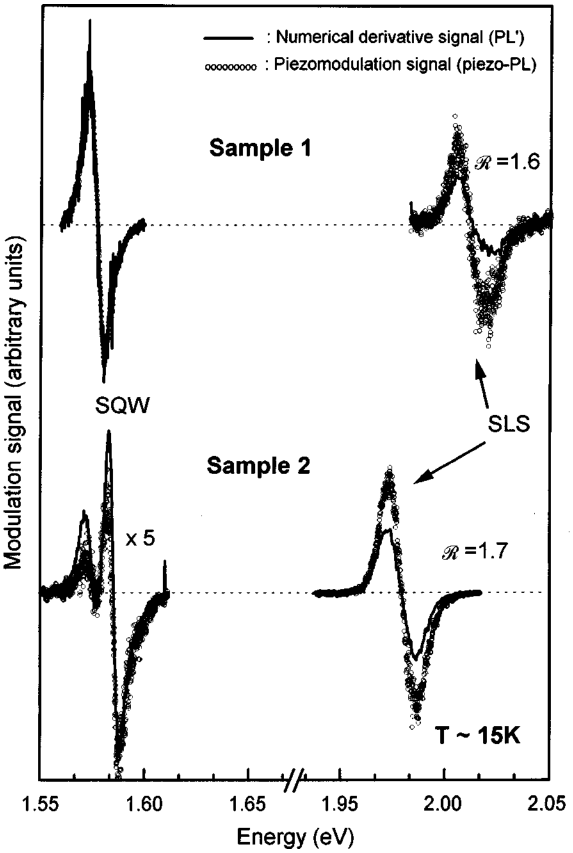

FIG. 2. Piezomodulation spectra of samples 1 and 2.

resolved luminescence[5,10] have contributed to determine a domain of *m* and *n* values for which the fundamental state of the SL is X_{xy}. Envelope-function calculations[4–7] have allowed us to assign this effect to the small lattice mismatch between AlAs layers and the GaAs substrate, which is capable of inducing a reversal of ordering of X states.

In a GaAs/AlAs structure grown on a GaAs substrate, the splitting of X states by the biaxial strain is about 15 meV, lowering the energy of X_{xy} states by 5 meV and increasing the energy of the X_z state by 10 meV, in competition with the confinement, the effect of which is opposite. Consequently, the symmetry of the fundamental state of the conduction band of GaAs/AlAs SL's depends on the thickness of the AlAs and GaAs layers.

The original idea of the growth of the GaAs/AlAs SL's on (In,Ga)As pseudosubstrate is based on the possibility of tuning the strain state of the ultrashort-period SL in order to modify the ordering of X-like states and to favor the pseudodirect transition between the X_z electrons confined in the AlAs layers and the holes confined in the GaAs layers. Indeed, for an indium concentration beyond 1.7%, the In$_x$Ga$_{1-x}$As substrate has a larger lattice parameter than AlAs. Thus, the AlAs layers of the SL undergo a biaxial tension that now induces a decrease of the energy of the X_z levels and an increase of that of the X_z levels. In this case, confinement and strain effects are complementary, and the fundamental conduction subband is of X_z symmetry, with no condition on the period of the SL.

We have studied two samples, grown by molecular-beam epitaxy, which are sketched in Fig. 1. Apart from the type-II superlattice and a ''reference'' single quantum well (SQW), special care had to be taken of the growth of the In$_x$Ga$_{1-x}$As pseudosubstrate. As a matter of fact, the structural quality of this layer has a significant influence on the properties of the GaAs/AlAs SL. In particular, pseudosubstrates made up of a simple thick layer of In$_x$Ga$_{1-x}$As generate a large number of dislocations. In order to get round this problem, we have made a pseudosubstrate consisting of a 1-μm-thick In$_{0.05}$Ga$_{0.95}$As layer, which is expected to be relaxed, followed by a superlattice 100×[100-Å In$_{0.1}$Ga$_{0.9}$As/100-Å GaAs (or Ga$_{0.7}$Al$_{0.3}$Al)]. Each layer thickness is well below the critical thickness for avoiding the generation of new dislocations. So the SL, which is, as a whole, lattice matched, promotes the recombination of dislocations by curving them, due to alternating strains in the two types of layers.[22]

The reference SQW is obviously type I, considering the thicknesses of the GaAs and AlAs layers, with a fundamental optical transition involving Γ-like conduction and valence states. This transition is thus used as a reference and test of reasonable sample quality, in the piezomodulation experiments described below, in order to identify the symmetry of the states involved in the fundamental transition of the type-II SL's. Ga$_x$Al$_{1-x}$As barriers ensure the decoupling between the SQW and the GaAs/AlAs SL, and between the two GaAs/AlAs SL's (in the case of sample 2).

The two samples have been studied by photoluminescence (PL), reflectivity (RE), and piezomodulated PL (piezo-PL) at liquid helium temperature. But the unambiguous assignment of experimental optical transitions cannot be achieved by standard RE or PL experiments. In order to check whether the ordering of conduction-band states is modified by the In$_x$Ga$_{1-x}$Ga pseudosubstrate, we have thus used the piezomodulation technique,[23,24] since the application of elastic stresses has proven to be useful for solving such questions.[4,7] This method consists in applying a small, alternating, in-plane, biaxial stress by gluing the sample onto a piezoelectric ceramic, driven by an alternating voltage. The stress-induced variations of the emitted or reflected signal are detected synchronously with the driving voltage. The applied stress is essentially similar to that induced by the

TABLE I. Supermodulation ratios $\mathcal{R}$ calculated from the shifts of the various energy bands under a given biaxial stress. We note that $\mathcal{R}>0$ for X_z states and $\mathcal{R}<0$ for X_{xy} states.

Ratios calculated from the X_z states	$\frac{\Delta(X_z\mathrm{HH})}{\Delta(\Gamma\mathrm{HH})}=+0.33$	$\frac{\Delta(X_z\mathrm{HH})}{\Delta(\Gamma\mathrm{LH})}=+0.15$	$\frac{\Delta(X_z\mathrm{LH})}{\Delta(\Gamma\mathrm{HH})}=+1.59$	$\frac{\Delta(X_z\mathrm{LH})}{\Delta(\Gamma\mathrm{LH})}=+0.71$
Ratios calculated from the X_{xy} states	$\frac{\Delta(X_{xy}\mathrm{HH})}{\Delta(\Gamma\mathrm{HH})}=-1.75$	$\frac{\Delta(X_{xy}\mathrm{HH})}{\Delta(\Gamma\mathrm{LH})}=-0.77$	$\frac{\Delta(X_{xy}\mathrm{LH})}{\Delta(\Gamma\mathrm{HH})}=-0.27$	$\frac{\Delta(X_{xy}\mathrm{LH})}{\Delta(\Gamma\mathrm{LH})}=-0.12$

TABLE II. Experimental transition energies deduced from photoluminescence and reflectivity for samples 1 and 2, and theoretical energies of the X_{xy} and X_z transitions. The theoretical energies were calculated taking into account the strain effect due to lattice mismatch between the GaAs/AlAs system and $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ pseudosubstrate. X_zLH transition energy is calculated by including the coupling between the light-hole and the spin-orbit bands (Γ_8^1-Γ_7). The X_zLH column gives the values of the fundamental transition energies in the GaAs/AlAs SL of the two samples.

	Theoretical transition energies (eV)				Experimental transition energies (eV)	
	X_{xy}HH	X_{xy}LH	X_zHH	X_zLH	PL	Reflectivity
Sample 1	2.107	2.063	2.066	2.026	2.005	2.029
Sample 2 SL 2	2.123	2.074	2.088	2.034	1.987	2.012

$\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ pseudosubstrate, but is much smaller in magnitude. The signal delivered by the lock-in amplifier is then proportional to the first derivative of the normal (PL or RE) spectrum. However, the modulation amplitudes of the various transitions observed are proportional to their respective stress-induced energy shifts. Since a given biaxial stress has selective effects on Γ, X_{xy}, or X_z conduction states and on heavy- and light-hole valence states, one gets a selective modulation of the different transitions observed.

Figure 2 displays the numerical derivative of the PL (denoted PL′) and the piezo-PL, of both the reference well and the GaAs/AlAs SL, for sample 1 (a) and sample 2 (b). We have matched the amplitudes of the PL′ and of the piezo-PL spectra, for the transition of the SQW. By doing so, we observe a ''supermodulation ratio,'' $\mathcal{R}$ of +1.6 (a) and of +1.7 (b) between the respective amplitudes of the piezo-PL and the PL′ for the SL's. This $\mathcal{R}$ ratio is also equal to the ratio between the energy shifts for the transitions involved in the SL and the SQW. However, the piezo-PL does not allow the identification of the transition involved in the GaAs/AlAs SL. We therefore calculate all the ratios between the energy shifts of the different transitions possible for the SL and the SQW. These energy shifts induced by the biaxial stress are easily calculated because the proper stiffness coefficients and deformation potentials are well known for GaAs and AlAs. Table I gathers the calculated values for $\mathcal{R}$, in each of the eight reasonable possibilities concerning the conduction and valence subbands involved. The Δ symbol represents the shift of the transition energy concerned. The denominator always refers to the zone-center transition for the reference well, but with both the cases of heavy- (ΓHH) and light-hole (ΓLH) states. The usual calculations actually predict that a heavy-hole exciton is concerned, even when the strain induced by the pseudosubstrate is included. The numerators run through the four possibilities for the type-II transition of the SL's. The comparison between the ratio $\mathcal{R}$ measured for the SL and the different values of Table I allows the identification of the observed transition for the SL. Clearly, the experimental ratios allow the unambiguous assignment of the PL from the strained GaAs/AlAs SL's in both samples to a recombination between X_z electrons and light holes, while the PL from the reference wells corresponds, expectedly, to a ΓHH transition. This result is not surprising: first, we demonstrate the expected ordering of *X*-like conduction subbands and, second, the fundamental light-hole state is simply another effect of the stress induced by the pseudosubstrate.

We have checked this last point by performing envelope-function calculations within a three-band model for zone-center states. A nonparabolic band structure was included, as well as the strain effects induced by the $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ pseudosubstrate. The energies of X_{xy} and X_z subbands and of the heavy holes were calculated by using the simplest parabolic model. The comparison between theoretical and experimental transition energies is shown in Table II. The discrepancy may be interpreted as an effect of the nonideal GaAs-AlAs interface quality, in particular roughness and graduality. Nevertheless, we confirm the necessity of including the coupling between the light holes and the spin-orbit bands (Γ_8^1-Γ_7)in order to avoid an important overvaluation of the confinement energy of the light holes. This is made particularly necessary by the very short periods of the present SL's, inducing very high confinement levels. The latter condition has been identified in previous works as a critical criterion for choice of a two-band or a three-band model.[25,26]

In summary, the growth of ultrashort period GaAs/AlAs SL's on $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ pseudosubstrates has proved to be very conclusive in achieving the switching of the lowest conduction band from X_{xy} to X_z without any condition on the thickness of the GaAs and AlAs layers. Consistent with the results of a three-band envelope-function calculation, we have demonstrated that this growth also results in the reversal of the ground valence-band state from the heavy hole to the light hole. The piezomodulation technique has proved its usefulness as an easy way for determining the symmetries of electronic states involved in optical transitions.

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