RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 39, NUMBER 8 15 MARCH 1989-I

Symmetry of conduction states for GaAs-AlAs type-II superlattices under uniaxial stress

P. Lefebvre, B Gil, and H. Mathieu
Groupe d'Etudes des Semiconducteurs, Université des Sciences et Techniques du Languedoc, Place E. Bataillon, 34060 Montpellier CEDEX, France

R. Planel
Laboratoire de Microstructures et Microélectronique, 196 Avenue H. Ravera, 92260 Bagneux CEDEX, France
(Received 22 November 1988)

We report the determination of the symmetry of conduction-band states for type-II superlattices under on-axis and in-plane uniaxial stress. From their stress dependence, the symmetry of the electron states is labeled in terms of X_z or $X_{x,y}$ conduction states. In some structures X_z is the conduction ground state and the ordering between X_z and $X_{x,y}$ is reversed by in-plane stress. In others, this situation is reversed and an explanation of the results needs to take into account lattice matching of AlAs slabs to GaAs. The shear tetragonal deformation potential of X states in AlAs is obtained.

The study of the electronic properties of GaAs-AlAs short-period superlatices (SPSL's) is of recent interest.[1-6] In contrast to the more classical GaAs-$Ga_{0.7}Al_{0.3}As$ system, the "barrier" material AlAs is of indirect forbidden gap, with lowest conduction band of X_6^c symmetry. The relative ordering and spacing of each pair of extrema (Γ_6^c and X_6^c) in the bulk materials, together with the magnitude of the valence-band offset between GaAs and AlAs acts in such a way that both type-I and type-II SL's can grown, depending on the relative thickness of the GaAs and AlAs slabs. In type-I SL's, both electrons and holes are confined in the GaAs slabs. However, in type-II SL's, the GaAs is the barrier for the electrons and the well material for the holes. In this latter case, the electron wave function is now built up from bulk states of X_6^c symmetry. An interesting theoretical problem also occurs: At least three bulk zone-boundary extrema, X_z, X_x, and X_y have to be considered to calculate the conduction band of the SL. Some tentative calculations in the literature gave results which varied with the theoretical approach used (see a recent discussion in Ref. 6). This question has also been addressed experimentally through the problem of exciton localization.[7] The envelope function approach (EFA) always predicts that X_z-like states lie at lower energies, due to the mass anisotropy of X minima.[1] On the other hand, Ihm[8] claimed that this situation could be reversed in very-short-period superlattices. Last, taking a precise account of the AlAs lattice matching on the GaAs substrate may be of importance in this question. As a matter of fact, using the average value $E_2=5$ eV for the X deformation potential of AlAs, which we determine in this work, we may estimate the associate splitting between X_z and $X_{x,y}$ as ~ 15 meV. This value is opposite to the EFA splitting, which is thus reduced or inverted, depending on the SPSL parameters.

In this Rapid Communication an examination of the indirect luminescence band is made for some type-II SL's under uniaxial stress. [110]- and [001]-oriented stresses were applied on SL's grown by molecular beam epitaxy (MBE) along the [001] direction. The perturbation of the X_6^c bulk conduction states depends on the orientation of the stress axis as shown in Fig. 1; the magnitude of the stress splitting is considerable and can be easily measured.[9] Thus, uniaxial stress is an ideal perturbation to investigate the symmetry of zone-boundary electronic states in type-II SL's. In this paper, we determine for the first time the symmetry of the conduction state to which each luminescence line is related. The different stress behavior of the X_z and $X_{x,y}$ states may also influence the shape of the luminescence spectra because the lifetimes are expected to be different for X_z- and $X_{x,y}$-related transitions.

We first discuss the case of sample 1, a SL with a period of 9.5 nm, of which 65% is the AlAs layer. Some typical luminescence spectra obtained under [110] stress are

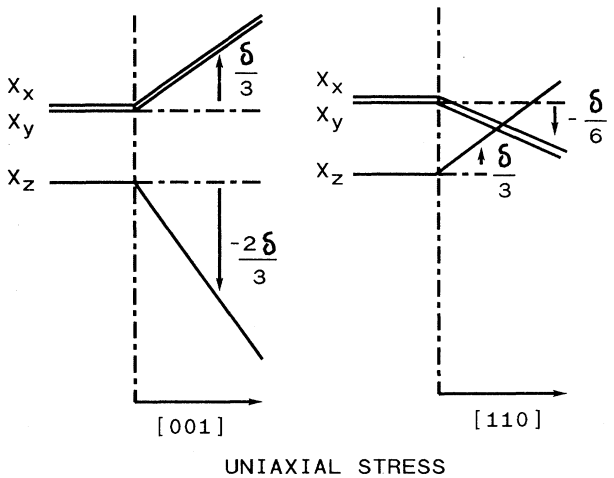

FIG. 1. Schematic behavior of the three zone-edge-related X_6^c conduction bands under both directions of the stress. The presented zero-stress ordering of the conduction minima is consistent with the effective-mass approach. $\delta=E_2(S_{11}-S_{12})$, with S_{ij} the elastic constants and E_2 the shear tetragonal deformation potential of X_6^c conduction states.

displayed in Fig. 2. Consider first the zero stress pattern. The hot direct luminescence band, labeled e, is seen at 1800 meV. A reflectance structure was also observed at this energy. Lower in energy a strong luminescence peak (a) appears; some weak undulations (b,c,d) are also observed on its low-energy side, that may be attributed to phonon-assisted transitions from X states, involving three different phonon energies.[1-6] When the stress is applied, the intensity of the a transition collapses while the intensity of the phonon-assisted transitions is only weakly dependent on the stress. The e line shifts toward high energy, following the general trend for type-I $e_\Gamma(1)$-HH(1) features;[10] the remaining transitions show the opposite behavior. The stress shift of the a line is small (~ -0.4 meV kbar^{-1}) while the lower band shifts faster (~ -4.5 meV kbar^{-1}). The [001] stress dependence is rather different: Although hot direct luminescence with a strong positive shift is observed together with a shift to low energy of the indirect transitions, no drastic decreasing in the intensity of the a line is observed. The b, c, and d lines have a smaller slope than the a line. Thus, the a line and the "phonon-assisted" lines do not originate from the same states. To extract the conduction energy shifts from these experimental data, we subtracted the influence of the stress on valence states and the hydrostatic contribution. A preliminary study of type-I GaAs-AlAs samples convinced us that the situation for these states is well understood, in a way similar to GaAs-(GaAl)As quantum wells.[10] The electron shifts thus obtained for the a line on the one hand and for the b, c, and d lines on the other hand match the scheme of Fig. 1, with $\delta \sim 7.8$ meV kbar^{-1}. As a consequence, we assign the a line to the zero-phonon transition associated with the X_z levels (possibly impurity or defect related); and the b, c, and d lines to phonon-assisted transitions from the $X_{x,y}$ levels, lying at slightly higher energy at zero stress (the phonon emissions account for lower-energy radiations). The decrease of the intensity of the a line under [110] stress then results in the change of ordering of the conduction levels from $E(X_z) < E(X_{x,y})$ to the opposite in the range of stress less than 200 bars. On the other hand, no such sensitivity of the intensity is expected if X_z remains the ground state under stress, which is actually the case with [001] stress.

It should be pointed out that the $X_z - X_{x,y}$ zero-stress splitting should be in this case, smaller than 1 meV, a value to be compared to the EFA theoretical value of 20 meV without taking mismatch strain effects. Besides, from the experimental value of δ in this sample, we propose the following value for the X conduction-band deformation potential of AlAs $E_2 = 4.5 \pm 0.2$ eV.

The same type of experiment has been repeated on a 43.4-nm period sample (sample 2) in which the AlAs slabs constitute 60% of the period. Simple EFA calculations[1] suggest a $X_z - X_{x,y}$ splitting larger than in the case of sample 1. The luminescence spectra only exhibit one intense line in this sample; this may be related to poorer quality. The same experiments and data analysis provide conduction shifts shown in Fig. 3 for both stress orientations. Identifying these results with the theoretical sketch of Fig. 1, we deduce $\delta \sim 8.2 \pm 0.2$ meV kbar^{-1} and a zero-stress splitting between X_z and $X_{x,y}$-like states ~ 6.5 meV. The weak nonlinearities of the transition energy near the X_z-$X_{x,y}$ crossing can be easily reproduced if we introduce a mixing interaction of < 2 meV between X_z, X_x, and X_y states in a valley-orbit mixing-type approach. As possible origins for such a mixing potential we suggest interface roughness or impurities.

Results shown in Fig. 4 were obtained in an ultrathin short period SL, with period 1 nm and $x = 0.6$. In contrast to the results of sample 1, no noticeable change of intensities under stress is observed. The shifts of all the transi-

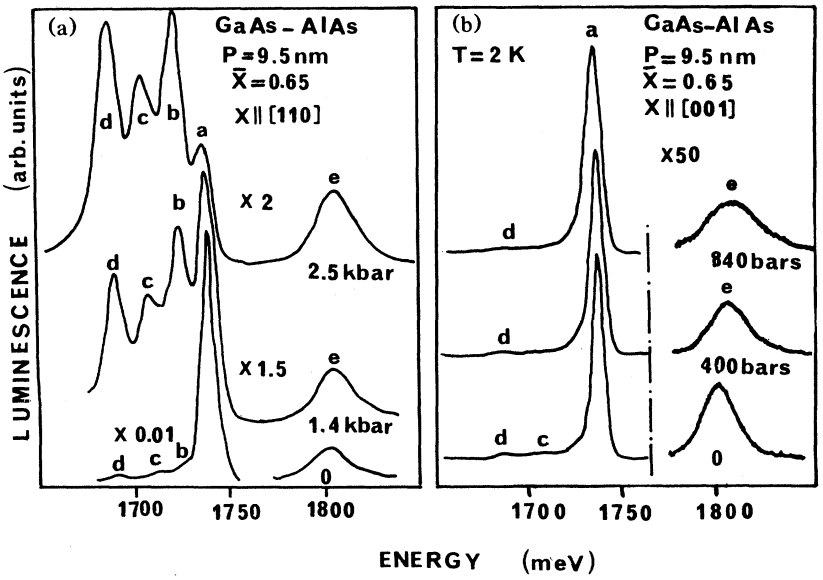

FIG. 2. Photoluminescence spectra of sample 1 under (a) [110] stress and (b) [001] stress. The identification of the lines is discussed in the text. x represents the thickness of AlAs measured in units of the period P.

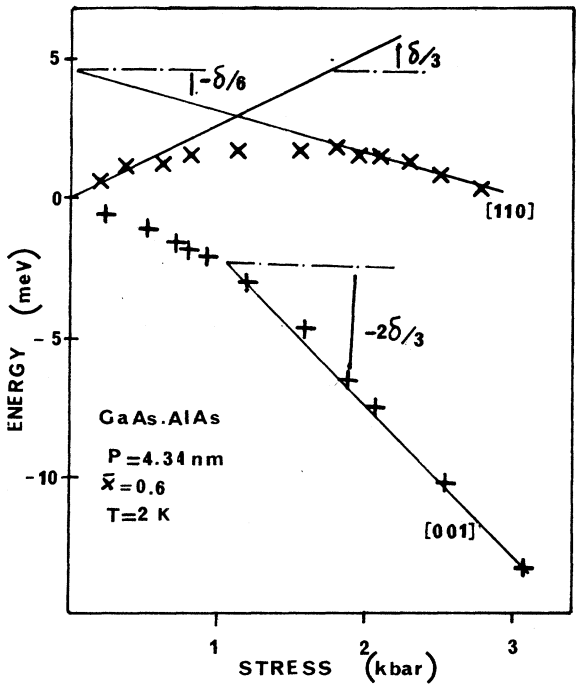

FIG. 3. Contribution of the shear part of the strain field on the conduction states for sample 2. Crosses for [110] stress and pluses for [001] stress.

tion lines are the same. They enable us, using the same data analysis, to identify the symmetry of the lowest conduction state as $X_{x,y}$. This is in contradiction with the predictions of EFA calculations if no lattice mismatch is taken into account. When lattice mismatch is included in an EFA calculation, we find $E(X_{x,y}) = E(X_z) - 5$ meV in qualitative agreement with the data. Two recent experimental works[11,12] reported an X_z symmetry from Stark shift[11] and optically detected magnetic resonance measurement.[12] In both these works, the authors only limit their study to one sample, which is not the case here.

In summary, we have presented piezospectroscopic properties specific to type-II SPSL's. Various periods have been selected which display: (i) a "nonphonon" line related to X_z conduction states and phonon assisted transitions related to $X_{x,y}$, (ii) a [110]-stress-induced reversal of the ground-state conduction level from X_z to $X_{x,y}$, (iii) the existence of an analog of the valley orbit interaction between X_z and $X_{x,y}$ produced by a localized potential, and (iv) the need to take into account lattice mismatch between GaAs and AlAs to explain qualitatively our results. Finally, we also propose the following average value for the X_6^c conduction states deformation potential E_2 of AlAs: 5.1 ± 0.7 eV. To conclude, it should be pointed out that the experimental situation is not yet fully understood: The influence of the structure parameters is clearly demonstrated, but the question of crystal quality is not easy to separate from it. It may modify the carrier localization and induce valley orbit mixing.

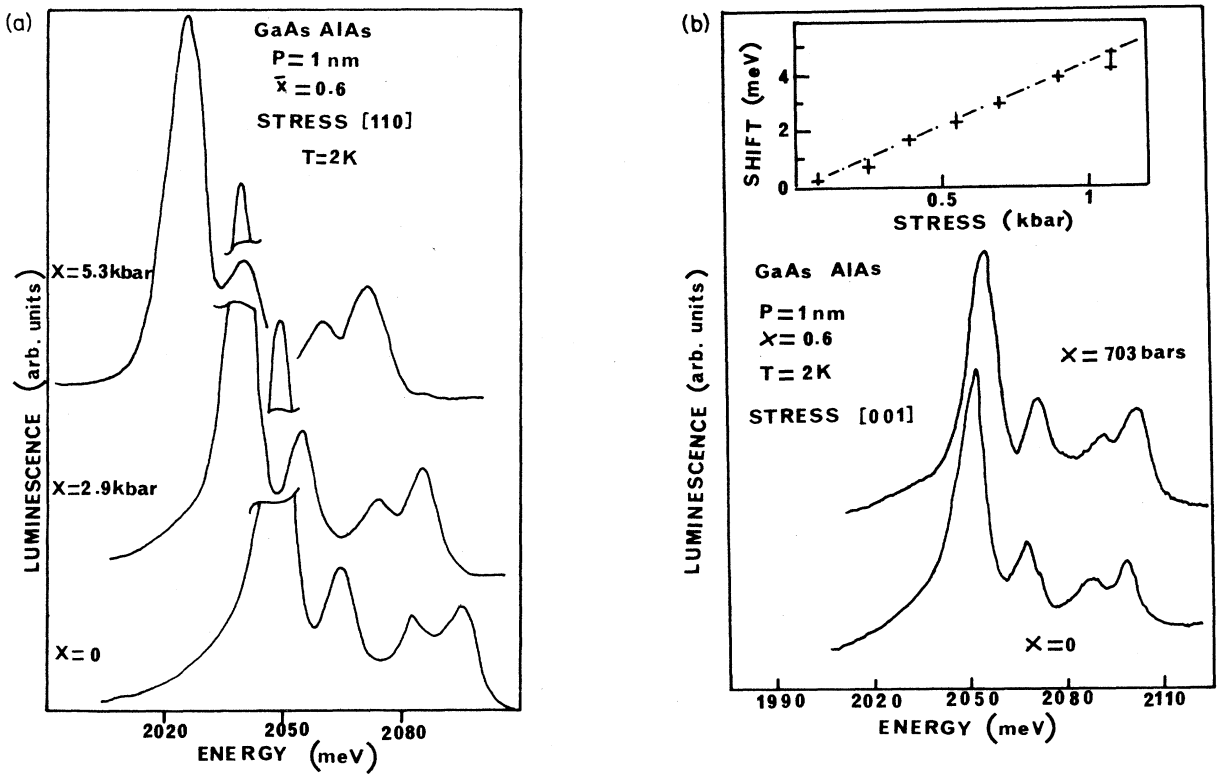

FIG. 4. Luminescence spectra of the ultrathin short-period SL under (a) [110] and (b) [001] stress. Here the intensities do not depend on the magnitude of the stress and all peaks shift with the same slope characteristic of an electronic contribution of $X_{x,y}$ origin.

We thank C. Benoit à la Guillaume and F. Mollot for fruitful discussions.

[1]G. Danan, B. Etienne, F. Mollot, R. Planel, A. M. Jean-Louis, F. Alexandre, B. Jusserand, G. Leroux, J. Y. Marzin, H. Savary, and B. Sermage, in *Proceedings of the Eighteenth International Conference on Physics Semiconductors, Stockholm, 1986,* edited by Olaf Engstrom (World Scientific, Singapore, 1986), p. 719; Phys. Rev. B **35**, 6207 (1987).

[2]E. Finkman, M. D. Sturge, and M. C. Tamargo, Appl. Phys. Lett. **49**, 1299 (1986).

[3]K. J. Moore, P. Dawson, and C. T. Foxon, J. Phys. (Paris), Colloq. **48**, C5-525 (1987).

[4]J. Nagle, M. Garriga, W. Stolz, and K. Ploog, J. Phys. (Paris), Colloq. **48**, C5-495 (1987).

[5]E. Finkman, M. D. Sturge, M. H. Meynadier, R. E. Nahory, M. C. Tamargo, D. M. Hwang, and C. C. Chang, J. Lumin. **39**, 57 (1987).

[6]B. A. Wilson, IEEE J. Quantum Electron. **24**, 1763 (1988).

[7]F. Minami, K. Hirata, K. Era, T. Yao, and Y. Masumoto, Phys. Rev. B **36**, 2875 (1987).

[8]J. Ihm, Appl. Phys. Lett. **50**, 1068 (1987).

[9]D. N. Mirlin, V. F. Sapeya, I. Ya. Karlik, and R. Katilius, Solid State Commun. **61**, 799 (1987).

[10]B. Gil, P. Lefebvre, H. Mathieu, G. Palatero, M. Altarelli, T. Fukunaga, and H. Nakashima, Phys. Rev. B **38**, 1215 (1988).

[11]M. H. Meynadier, R. E. Nahory, J. M. Worlock, M. C. Tamargo, J. L. De Miguel, and M. D. Sturge, Phys. Rev. Lett. **60**, 1338 (1988).

[12]H. W. Van Kesteren, E. C. Cosman, F. J. A. M. Greidanus, P. Dawson, K. J. Moore, and C. T. Foxon, Phys. Rev. Lett. **61**, 129 (1988).