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Optical properties of spontaneous lateral composition modulation in AlAs/InAs short-period superlattices

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The effect of lateral composition modulation, spontaneously generated during the epitaxial growth of an AlAs/InAs short-period superlattice, on the electronic band structure is investigated using phototransmission and photoluminescence spectroscopy. Compared with uniform layers of identical average composition, the presence of the composition modulation considerably reduces the band-gap energy and produces strongly polarized emission and absorption spectra. We demonstrate that the dominant polarization direction can selectively be aligned along the $[\bar{1}10]$ or [010] crystallographic directions. In compressively strained samples, the use of (001) InP substrates slightly miscut toward (111)*A* or (101) resulted in modulation directions along [110] or [100], respectively, and dominant polarization directions along a direction orthogonal to the respective composition modulation. Band-gap reductions as high as 350 and 310 meV are obtained for samples with composition modulation along [110] and [100], respectively. Ratios of polarized intensities up to 26 are observed in transmission spectra. © *2000 American Institute of Physics.* [S0003-6951(00)03438-0]

Lateral composition modulation (CM) is a periodic variation in alloy composition in a direction perpendicular to the growth direction. Lateral CM bears strong similarities with spinodal decomposition observed in bulk alloys, but it also has its own distinct features: since the periodic composition modulation occurs spontaneously, lateral CM falls under the class of self-assembled phenomena, see Fig. 1. A one-dimensional (1D) CM is characterized by its average composition and the amplitude, wavelength, and direction of the modulation. One method to induce lateral CM is by growing a vertical short-period strained-layer superlattice (SPS). CM in SPS structures had been first observed in GaP/InP SPS (Refs. 1 and 2) and later observed in GaAs/InAs[3] and AlAs/InAs SPS.[4] These structures show a large band-gap reduction and a strong polarization anisotropy with respect to a uniform alloy with a similar average composition. These two effects can be exploited for device design. In principle, the band gap can be decreased without increasing the lattice mismatch of the epitaxial layer with its substrate. In addition, the polarization dependence of the transition probability can be used in the design of polarization-sensitive devices. CM in GaP/InP has been successfully applied for device applications.[5]

A comprehensive understanding of the formation of lateral composition modulation in strained SPS has not yet been achieved. The spontaneous formation of the modulation is likely to result from concurrent effects related to growth, thermodynamics, strain, and surface kinetics. Very good reviews on this subject can be found in Ref. 6.

The periodic sequence of In- and Al-rich regions creates a lateral superlattice and results in carrier confinement in the In-rich regions. Compared with the band gap of an alloy with a similar average composition but without modulation, the lowest-energy confined state of the superlattice can be significantly lower. Along with the band-gap reduction, the transition probability becomes polarization dependent for photons absorbed or emitted along the growth direction. The absorption and emission associated with the lowest-energy transition is polarized along the direction perpendicular to the CM direction. The ratio of intensities of orthogonal polarization could, in principle, reach factors of more than 100.[7] The band-gap reduction and polarization anisotropy depend on the characteristics of the modulation and the band-gap difference between the two binary compounds used. Of the three alloy systems mentioned above, AlInAs is the one with the highest band-gap difference between the two binary compounds, therefore, it is expected to show the largest band-gap reduction.[7] Indeed, strong band-gap reductions have been reported.[8] These results on CM AlAs/InAs were based on low-temperature photoluminescence (PL) results. As it will be demonstrated, estimation of the band-gap reduction from PL can be misleading since the experimental spectra are often dominated by transitions originating below the gap or from localized regions with strong deviations from the average composition.

In this work, we report phototransmission (PT) and PL measurements on samples showing strong CM along [110] or [100]. The band-gap reduction is unambiguously determined by absorption measurements. Control over the direction of the dominant polarization of the emission/absorption process can be achieved by controlling the CM direction. A preferential CM direction was selected by growing the structures on slightly misoriented substrates.

The CM was induced by growing a SPS by molecular-beam epitaxy. The samples consist of a 100-period $(AlAs)_m-(InAs)_n$ superlattice grown on a 0.1-μm-thick $Al_{0.48}In_{0.52}As$ buffer layer lattice matched to the InP(001) substrate. *m* and *n* represent the number of monolayers

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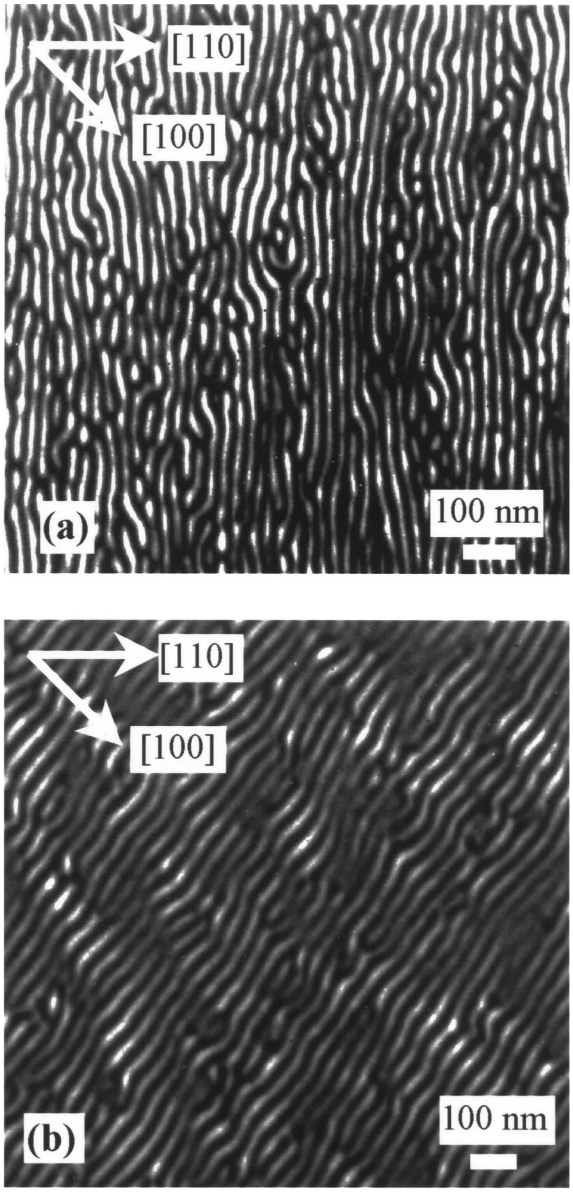

FIG. 1. TEM (200) dark-field micrographs of (a) CM [110] and (b) CM [100].

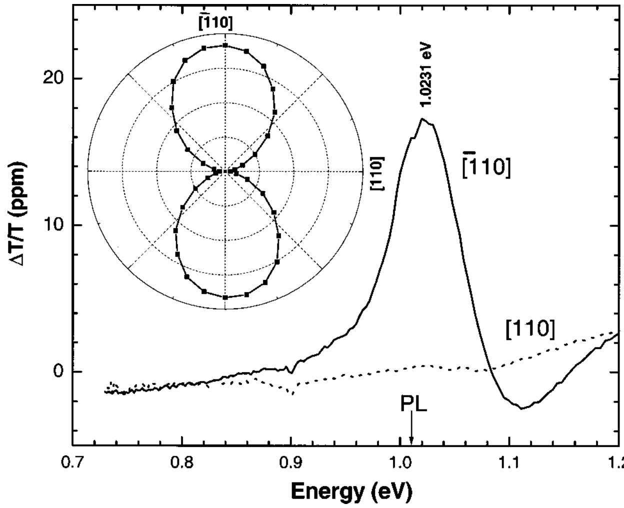

FIG. 2. Phototransmission (77 K) measured on CM [110]. The inset shows the PT intensity as a function of the polarization direction measured at an energy of 1.0231 eV.

grown for each component of the superlattice. For the work presented here, we used two samples grown under global compression. They are labeled using their respective direction of the CM, i.e., CM[110] and CM[100]. The values for (m,n) were (1.4, 2.0) and (1.5, 1.9), respectively. These samples were extensively characterized by techniques such as x-ray diffraction (XRD),[9] transmission electron microscopy,[10,11] and atomic-force microscopy. As determined by XRD, the average In composition of the SPS and the modulation wavelength were 58.5% and 252 Å for CM[110] and 54.8% and 329 Å for CM[100]. XRD can also be used to estimate the relative strength of the modulation.[9] The normalized integrated intensity of diffraction satellites along the modulation direction is, respectively, 2.31 and 3.37 for CM[110] and CM[100], indicating a 46% stronger modulation for CM [100].

PT was measured using a conventional setup by normalizing the change in transmission ΔT upon carrier injection by the absolute transmission T. The frequency-modulated transmission was induced with a frequency-doubled YAG laser (532 nm). The direction of polarization of the laser was fixed for all measurements. The transmitted light was detected with an InGaAs photodiode. The PT is approximately related to photoabsorption by $\Delta T/T = -d\Delta\alpha$, where d is the thickness of the absorbing layer.

When grown on on-axis (001) substrates, SPS-induced CM often occurs simultaneously in more than one direction, yielding a two-dimensional (2D) modulation.[10,12] As seen from transmission electron microscopy (TEM), these samples exhibit a relatively short wire-like structure in the growth plane. Samples under global compression grown on on-axis substrates result in two orthogonal modulation direction, [100] and [010]. A slight misorientation of the substrate can result in a unique modulation direction. In contrast to the 2D modulation, the wires are predominantly oriented along a unique direction and their average length can be increased significantly. This 1D modulation is advantageous since it results in samples with better-defined electronic properties. CM [110] and CM [100] were grown on substrates with a 2° miscut toward (111)A and (101), respectively. In the case of CM [100], the miscut results in a preferential selection of the [100] modulation direction, which is close to the miscut direction. In the case of CM [110], the miscut induces a new modulation direction. The modulations along [100] and [010] are reoriented along [110].[11]

Figure 1 shows the TEM (200) dark-field plan-view images for these two samples. The (200) diffracted beam is selected for its sensitivity to composition changes and the relatively low contribution of lateral strain to the image contrast. Clear and dark regions are associated to In- and Al-rich alloys, respectively. Cross-section micrographs showed that this modulation is strong already after the growth of ~20 periods of the SPS and extends quite uniformly to the sample surface, see Ref. 10 for more details.

Figure 2 shows PT spectra measured at 77 K on CM [110] along and perpendicular to the CM direction. The PT signal shows a clear maximum at 1.023 eV. The energy of this transition, produced by the lateral superlattice, corresponds to a band-gap reduction of 0.350 eV compared to a

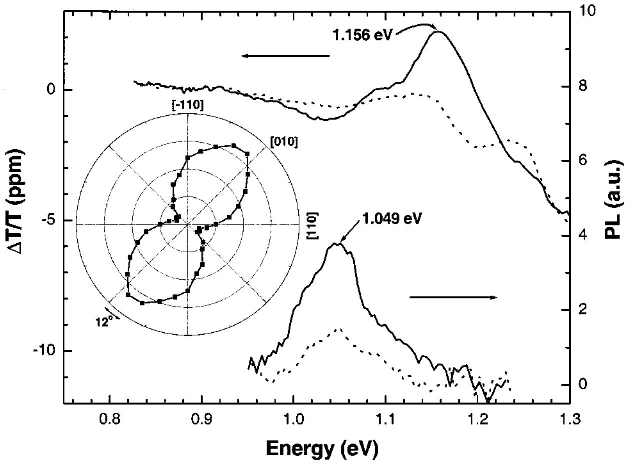

FIG. 3. Phototransmission and photoluminescence measured at 77 K on CM [100]. The solid and dotted curves represent the [010] and [100] polarization directions, respectively. The inset shows the PT intensity as a function of the polarization direction measured at 1.156 eV.

uniform alloy with the same average composition compressively strained to InP. The inset shows the angular dependence of the polarization of the PT measured at 1.023 eV. The signal is strongly polarized in the [$\bar{1}$10] direction and weakly polarized parallel to the CM. The measured maximum ratio of polarized intensities is equal to 26. Polarized PL spectra measured at 77 K revealed a similar transition located approximately 15 meV lower (see the arrow in Fig. 2). Even though the ratio of polarized intensities measured from the PL was only 3.9, the PT and PL features are likely to share the same origin. The absolute amplitude of the composition modulation is not known, it is, therefore, difficult to compare the experimental results with theoretical calculations. However, it is possible to estimate the amplitude of the modulation from the band-gap reduction. Using the theory developed by Zhang and Mascarenhas[7] and taking into account the In-rich average composition of the SPS, a band-gap reduction of 350 meV corresponds to a modulation amplitude of approximately 13%. As predicted by Zhang and Mascarenhas,[7] for given modulation characteristics, the band-gap reduction can be larger for the AlAs/InAs SPS than for the InAs/GaAs (~100 meV) and GaP/InP SPS (~300 meV).

Figure 3 shows PT and PL spectra measured at 77 K on the second sample, CM [100]. The PT shows a polarized feature at 1.156 eV. This energy is associated with the band gap of the lateral superlattice. The PL spectra measured at 77 K have a single feature located at 1.049 eV. The PL yields a transition significantly lower in energy than the signal observed from the PT. Low-temperature PL spectra can be dominated by radiative transitions below the band gap, originating from defects or from local deviations of any of the modulation characteristics and, therefore, do not provide an accurate estimate of the band-gap energy. The inset of Fig. 3 shows the direction dependence of the polarization of the PT measured at 1.156 eV. The angle of maximum intensity is tilted by 12° towards [$\bar{1}$10]. Assuming that the direction of maximum intensity always occurs perpendicularly to the CM modulation, the PT data indicate a tilt of the modulation towards [110]. Transmission electron diffraction revealed that the net CM direction is slightly tilted by approximately 10° towards the same direction. The direction of the dominant polarization is very sensitive to the orientation of the CM. The band-gap reduction observed in this sample is 310 meV. Compared to CM [110], the relative quality of CM [100], as judged from the strength of the optical signal, is inferior. Using only PL to estimate the band-gap reduction would have led to a much higher, but erroneous, value.

The band-gap reduction is higher for CM [110] even though the modulation amplitude for CM [100] estimated from XRD is higher. Assuming that the difference in modulation wavelength has a relatively small effect,[13] it is possible that the orientation of the modulation has a relatively important effect on the band gap of the structure. No theoretical calculations have been published to date for a [100] modulation.

In summary, we have reported the band-gap reduction, the dominant polarization direction, and the ratio of polarized intensities from AlAs/InAs short-period superlattices showing a strong lateral composition modulation. The modulation was induced by the growth of a vertical short-period strained-layer superlattice. In these compressively strained samples, the modulation direction could be selected with the choice of the right substrate miscut.

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