Fully relaxed low-mismatched InAlAs layer on an InP substrate by using a two step buffer

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The strain relaxation in low mismatched $In_xAl_{1-x}As$ layers has been studied by triple axis x-ray diffraction, transmission electron microscopy, and photoluminescence. Using a two step buffer, a fully relaxed top layer has been grown by adapting the composition and thickness of a first "strained layer." The threading dislocation density in the top layer is below $10^6/cm^2$ and strain is relaxed at the substrate/first layer interface by misfit dislocations. This scheme is a promising method to limit the thickness of buffer layers and obtain fully relaxed pseudosubstrates. © *2010 American Institute of Physics*. [doi:10.1063/1.3275872]

The use of the large range of electrical and optical properties of III–V semiconductors is often impeded by the lack of a proper substrate material with the desired lattice parameter. For large lattice mismatch, metamorphic growth have been developed extensively for two decades but small lattice mismatch has not received so much attention although needs indeed exist, concerning for instance application to semiconductor optical amplifiers (SOA).

In a standard pseudomorphic SOA on InP,[1,2] a 0.1–0.15 μm thick InGaAs active layer is surrounded by a few tenths of microns thick InGaAsP layers. InGaAs is grown under a slight tensile strain (1.5×10^{-3}) in order to get a polarization independent amplifier. In this case, the maximum working wavelength is around 1.62 μm. With increasing simultaneously transmitted data, the extension of the useful spectral region is of interest with SOAs working at 1.7 μm or above. This achievement requires an increase in the indium composition of the InGaAs layer toward 56%–57%. Together with the requirement to keep a tensile strained active region, this leads to a lattice mismatch between the whole structure (more than 1 μm thick) and the InP substrate around 3.5×10^{-3}. This latter value is no more compatible with a pseudomorphic growth and appeals for a metamorphic approach. More precisely, there is a need for a pseudosubstrate whose lattice constant exhibits a 3.5×10^{-3} difference with the InP one, on which the amplifier structure can be grown in a pseudomorphic way. The aim of this work is to make such InP-based pseudosubstrates, i.e., to get a fully relaxed low-lattice mismatched layer on an InP substrate. For optical considerations due to the refraction index, the layer material cannot be InGaAs and we then choose InAlAs with a 58% In content, corresponding to a 3.5×10^{-3} mismatch with InP.

In highly mismatched structure ($\Delta a/a > 1.5\times10^{-2}$), fully relaxed InAlAs buffers have been achieved by the growth of graded layers in which the In content is gradually increased. This allows a progressive strain introduction which favors full plastic relaxation via misfit dislocations.[3–6] However, this kind of buffer layer [Fig. 1(a)] is useless in low mismatched structures. In the same way, an InAlAs layer with a constant 58% In content does not fully relax until large thickness, hardly compatible with standard growth. Indeed, in both cases, the driving force for the creation of misfit dislocations, i.e., the elastic energy stored in the growing layer increases too slowly with thickness.

In this work, we show that by using a buffer composed of two InAlAs layers, with two different indium compositions [Fig. 1(b)], plastic relaxation can be greatly enhanced by the first high-indium content layer. The desired thickness of this first layer must be such that the corresponding partial relaxation leads to an in-plane lattice parameter which is the

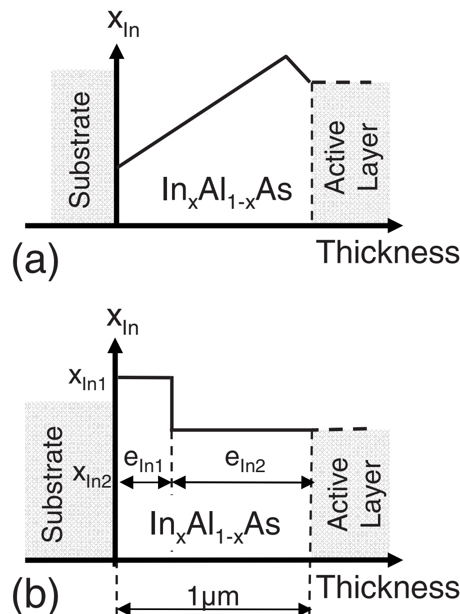

FIG. 1. Schematics of the variations in indium composition in metamorphic InAlAs buffers on InP(001): (a) graded ones and (b) two-step ones (this study).

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TABLE I. Lattice parameter relaxation and indium composition deduced from TA-XRD measurements on two 1 μm thick $In_xAl_{1-x}As$ homogeneous buffer grown on a InP(001) substrate.

Indium composition	Lattice parameter relaxation	
	[110]	$[1\bar{1}0]$
0.58	0.32	0.34
0.62	0.57	0.53

relaxed one of the 58% In top layer. In this way, the following growth of the 58% In layer will be strain-free leading to a fully relaxed layer.

Samples used in this study were grown on 2 in. InP substrates by gas-source molecular beam epitaxy in a Riber 32P chamber. The arsenic flux was obtained by cracking arsine (AsH_3) through a high-temperature injector, whereas standard effusion cells were used for group-III elements. The fluxes were calibrated using reflection high energy electron diffraction (RHEED) specular beam intensity oscillations on GaAs and InAs substrates. Samples were deoxidized under phosphorus flux at 525 °C. Structures were grown at 510 °C, with a V/III ratio between 2 and 3 and we observed a streaky (2×4) RHEED pattern all along the growth. The samples have been characterized by triple axis x-ray diffraction (TA-XRD). We recorded reciprocal space maps around the (004) and the (224) Bragg reflection in two orthogonal [110] azimuth, which give us direct information on the strain and composition of the buffer. Room temperature photoluminescence (PL) measurements have been performed on different structures grown to estimate the crystalline quality of the active layer. To avoid absorption effects in the barriers of the structure, a yttrium aluminum garnet laser with a wavelength of 1064 nm (1.2 eV) was used, the detector being an InGaAs photodiode. Finally transmission electron microscopy (TEM) measurements have been achieved to localize the dislocations in the samples.

We have arbitrarily restricted the total thickness of the buffer layers under study to 1 μm. Considering the structure of Fig. 1(b), the parameters which must be adjusted are the indium composition and the thickness of the first layer. We started with the indium composition. In that purpose, we grew 1 μm thick InAlAs layers with 58% and 62% indium compositions, to estimate the layer relaxation. The results of the TA-XRD analysis on these samples are given in Table I. Both layers are far from fully relaxed after 1 μm. More precisely, the 62% In one exhibit a 55% relaxation which corresponds to an in-plane parameter of 5.89 Å, i.e., the relaxed lattice parameter of a 58% layer. These first results imply that, to promote plastic relaxation, the In composition of the first layer must be higher than 62%. On the other hand, for $\Delta a/a > 1.5\times10^{-2}$, i.e., for an In content above 75%, strain relaxation is no more plastic but elastic, characterized by a three-dimensional (3D) growth[7] mode that we want to avoid here. In order to be far away from this 3D growth mode limit and above 62% In content, we decided to use a 66% indium content for the first layer.

We have then grown two-layer buffers, 66% indium first layer, 58% indium top layer, varying the thickness of the first

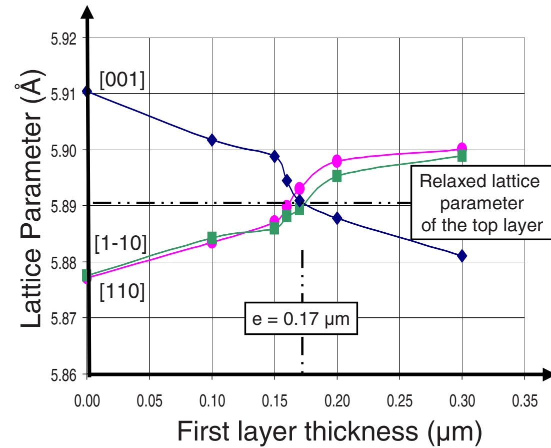

FIG. 2. (Color online) Evolution of the top layer lattice parameter relaxation in the [110], $[1\bar{1}0]$, and [001] directions as a function of the first layer thickness. The In composition of the first layer is 0.66 whereas that of the top layer is 0.58, the total buffer thickness being 1 μm. Full lines are guide for eyes.

layer and keeping the overall thickness to 1 μm. Results of the TA-XRD measurements on the top layer are given in Fig. 2. According to this study the optimal thickness for the first layer is 0.17 μm. This leads to a top layer thickness (0.83 μm) far larger than that of the first one, which is helpful to prevent any future evolution of the buffer structure upon further growth. Indeed, to test the stability of the buffer, we have extended the second layer thickness to 1.83 μm, without noticeable difference in the TA-XRD measurements. As regards the general shape of the curve in Fig. 2, the first part for thickness below 0.15 μm corresponds to the relaxation of the whole structure, once the growth of the second layer has already started. On the contrary, for thickness above 0.15 μm, the first layer starts to relax and since it exhibits the largest mismatch, this results in the observed rapid increase in the relaxation above 0.15 μm. Slight relaxation anisotropy can be observed between the [110] or $[1\bar{1}0]$ directions. The measured tilts remain below 0.3° on all samples. However, we have not found any clear correlation between the tilt direction and the relaxation anisotropy.

Considering the optimal parameters described above, a cross-section TEM measurement has been performed with the pattern oriented in the $\langle 1\bar{1}0\rangle_{InP}$ direction. Results given in the Fig. 3 bring to light the three different regions: the InP substrate, the $Al_{0.34}In_{0.66}As$ partially strained layer, and the relaxed $Al_{0.42}In_{0.58}As$ layer. By paying attention to the interfaces, dislocations appear at the interface between the substrate and the first buffer layer while the other one is free from any defects. It can be noticed that no threading dislocation can be found at a large scale, i.e., 10 μm wide in the [110] direction. According to these TEM observations, the density of threading dislocations is then below $10^6/cm^2$. The absence of defects at the interface between the two layers of the buffer confirms the TA-XRD measurements and that the second layer grows strain-free with the same in-plane parameter than the first one. We can also note that the density of misfit dislocations in the $\langle 110\rangle$ direction is around ten/micron. Considering the in-plane lattice parameter mismatch

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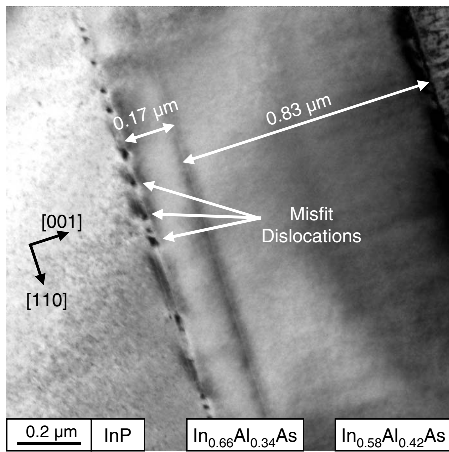

FIG. 3. TEM of the buffer layer revealing misfit dislocations at the layer/substrate interface. No threading dislocation can be observed.

between the buffer layer and the substrate (around 3.5×10^{-3}), full relaxation requires to relax 35 Å/μm along the interface. The above statements lead to a mean projection of the Burger vector in the interface plane of 3.5 Å. If we compare this value with the theoretical ones for 60° and the 90° misfit dislocations (respectively, 2.1 and 4.2 Å), it strongly suggests that the both types of dislocations are present at the interface.[8–10]

Finally, the interest of our buffer growth procedure for optical properties is demonstrated by the PL measurements in Fig. 4. For these measurements, three structures have been grown. The first one (curve A in Fig. 4) is a reference structure composed as follows: 0.5 μm InAlAs, 0.02 μm InP, 0.15 μm InGaAs, 0.02 μm InP, and 0.2 μm InAlAs, all alloys lattice-matched on InP. The two other structures are metamorphic ones with a tensile strained InGaAs well. The second structure (curve B in Fig. 4) makes use of a constant composition partially relaxed buffer layer: 1 μm $In_{0.62}Al_{0.38}As$, 0.02 μm InP, 0.15 μm $In_{0.565}Ga_{0.435}As$, 0.02 μm InP, and 0.2 μm $In_{0.62}Al_{0.38}As$. The third one (curve C in Fig. 4) uses the optimized buffer scheme: 0.17 μm $In_{0.66}Al_{0.34}As$, 0.83 μm $In_{0.58}Al_{0.42}As$, 0.02 μm InP, 0.15 μm $In_{0.565}Ga_{0.435}As$, 0.02 μm InP, and 0.2 μm $In_{0.58}Al_{0.42}As$. In each case, the InP thin layer is used to keep away the active InGaAs layer from Al-containing ones. First of all, we can confirm the correct wavelength of the structures above 1.7 μm. Then, a significant difference in PL intensity can be observed between the two metamorphic structures: it rises from 40% to 66% of the reference intensity when going from the constant composition buffer to the optimized one. This is a clear proof of the crystalline quality improvement in the active layer due to our optimized buffer scheme.

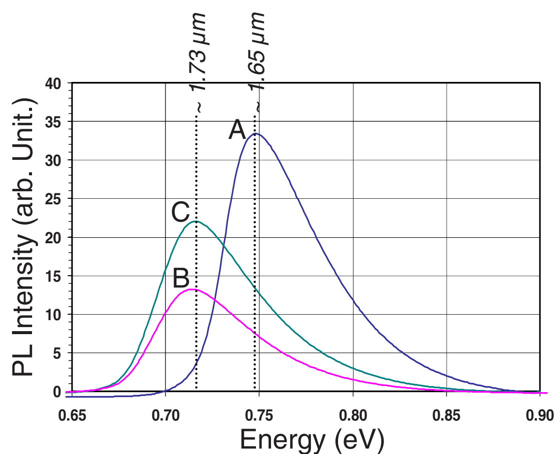

FIG. 4. (Color online) Influence of the buffer structure on PL measurements. Curve A is the PL response of a reference lattice-matched structure on InP. Curve B and C represent the PL measurement for a structure grown on a homogeneous $In_{0.62}Al_{0.38}As$ layer and on an optimized buffer, respectively.

As a conclusion, we propose a new structure to relax the strain in low-mismatched layers without growing thick buffers. The full relaxation of the top buffer layer can be obtained by adapting the lattice parameter and the thickness of a partially strained first layer, what has been achieved in this study by growing a 0.17 μm thick $In_{0.66}Al_{0.34}As$ layer before the growth of a fully relaxed $In_{0.58}Al_{0.42}As$ one. TEM and XRD measurements evidence that strain is confined in the first layer and especially at the interface between the substrate and the buffer layer. The strain seems to be relaxed by both 60° and 90° misfit dislocations at this interface. The threading dislocation density in the top layer is below $10^6/cm^2$ and the PL measurements prove a significant increase in the crystalline quality using this scheme. In a more general way, we believe that this kind of approach can be applied each time a low-misfit structure has to be relaxed.

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