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Influence of substrate misorientation on the optical and structural properties of InGaAs/GaAs single strained quantum wells grown on (111)B GaAs by molecular beam epitaxy

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Abstract

A series of InGaAs/GaAs Single Strained Quantum Wells (SSQWs) with indium content ranging from 25% to 35% and 100 Å well thickness were grown on two different (111)B GaAs off-axis substrates under optimized growth conditions for simultaneous growth. Optoelectronic properties were studied in terms of low temperature photoluminescence (PL). Results indicate a PL emission dependence with the substrate used, this dependence being stronger for highly strained systems. In order to determine the source of this dependence, samples were studied by Planar View Transmission Electron Microscopy (PVTEM). Relaxation mechanisms seem to act in a different way regarding the misoriented substrate used. Although previous theoretical results have already reported this dependence, this is the first direct evidence of this phenomenon for SSQWs. The results of these two different techniques will be compared and discussed.

Keywords: Single strained quantum wells; Planar view transmission electron microscopy; Photoluminescence

1. Introduction

There is considerable potential for developing new optoelectronic devices within the wavelength region well beyond 1 μm using strained layers of $In_xGa_{1-x}As/GaAs$ Quantum Wells (QWs) on (111) GaAs. Growth studies on this orientation have gained much attention as it offers a number of advantages, such as larger heavy hole effective mass owing to its valence band anisotropy, the presence of a piezoelectric field in the wells because of strain and a larger e1–hh1 oscillator strength. In addition, some groups have reported a larger Critical Layer Thickness (CLT) for this orientation with respect to (001) [1,2]. This would allow InGaAs/GaAs devices to reach wavelengths beyond 1.1 μm, the limit for those grown on (001) GaAs [3]. Device applications already studied are improved high mobility transistors, microwave mixers [4,5] and self-electro-optic effects devices (SEEDs) [6].

When growing on (111) GaAs, there are two possible types of substrates: (111)A and (111)B. The first one refers to those wafers whose dangling bonds on the surface are gallium type, while in the second one they are the arsenic type. Growth on (111)A results in poor quality epilayers under growth conditions similar to those used for (001) epitaxy, whilst growth on (111)B is difficult without the precise choice of substrate or growth conditions. Epitaxial films grown on exact (111)B usually show a pyramidal surface morphology [7], though successful growth of control layers free of pyramids has also been reported [8]. The use of (111)B GaAs substrates with a slight miscut seems to be a pre-requisite for the successful growth of good quality (In)GaAs epilayers at low enough substrate temperature to avoid desorption of Indium and optimize optical properties of the layers. Besides the larger CLT reported for this orientation, some optical and transport studies of InGaAs/GaAs (111)B off-axis were published [9,10]. Unfortunately, the spread of these data concerning CLT for InGaAs layers on GaAs (111)B inhibits us to properly predict the CLT exact value. These different data come from various laboratories using different (111)B substrates

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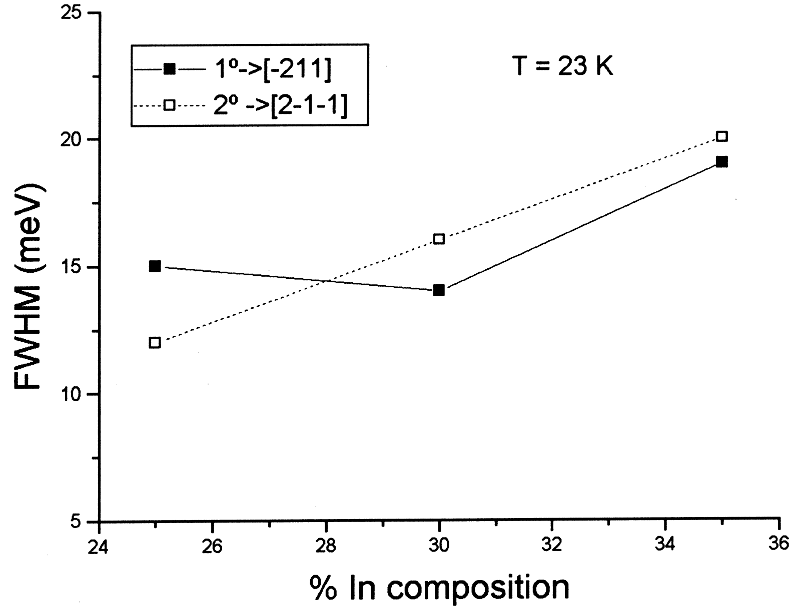

Fig. 1. FWHM of the PL peaks at low temperature versus indium content.

in terms of amplitude and direction of the tilting angle [1,2]. To clarify the origin of this uncertainty, it is necessary to obtain layers on different off-axis substrates grown side by side and compare their characterization results.

To date, only few strain relaxation studies have been published. Dislocation structures in (111)B GaAs strained layers superlattices were studied by Mitchell and Unal [11]. The authors established that the CLT for misfit dislocation to be observed by TEM was almost twice than for (001). These results are in close agreement with the results of Anan et al. [2], who used RHEED techniques to determine the CLT on InGaAs/GaAs (111)B epilayers with a misorientation 2° towards [01−1] and indium contents in the 40%–60% range.

More recently, Sacedón et al. [12] have used photoluminescence (PL), Raman spectroscopy, and TEM techniques to investigate $In_xGa_{1-x}As$ epilayers on (111)B GaAs 1° towards [−211]. They showed that relaxation was very inhomogeneous and triangular arrays of misfit dislocations were observed along the three ⟨1−10⟩ directions. PL results indicated that macroscopic CLT for (111)B was higher than for (001) for low In-content, but seemed similar for $x > 22\%$. The influence of both the direction tilt and degree of misorientation on the value of CLT was studied theoretically by Colson et al. [13] who, based on pure geometrical considerations, performed the analysis of the Matthews and Blakeslee model taking into account these points. Edirishinghe et al. [14] have also indicated that changes in amplitude and direction of the misorientation may cause major differences in the nature of the defect structure and relaxation dynamics, though experimental information available came from samples grown on 2° towards [2−1−1], estimating the CLT in the range as that observed for (001) epilayers. The first direct evidence of this fact was pointed out very recently in PIN-MQW InGaAs/GaAs structures grown simultaneously on two different (111)B GaAs off-axis substrates [15]. However, no systematic comparison of relaxation mechanisms in InGaAs/GaAs structures simultaneously grown on different (111)B GaAs off-axis has been done up to now. This is of capital importance with regard to optoelectronic applications of InGaAs/GaAs structures in the wavelength region beyond 1 μm.

This article reports a PL and TEM investigation of $In_xGa_{1-x}As$/GaAs SSQWs structures grown *simultaneously* on the aforementioned two (111)B GaAs off-axis substrates. A comparison between both the techniques is given in order to estimate differences in relaxation mechanisms. Finally, possible repercussions in optoelectronic applications of the results are discussed.

2. Experimental details

InGaAs/GaAs SSQWs were grown by solid source MBE in a 2300 RIBER machine. Two different (111)B GaAs off-axis substrates were mounted side-by-side in the experiments. Referring to a (111)B stereographic projection, the misorientations used were: 1° towards [−211] and 2° towards [2−1−1]. Both orientations were reported in the literature to provide good quality InGaAs/GaAs growth, including structures such as PIN-MQW and lasers [16]. Surfaces were prepared by thermal annealing at near 630°C for 20 min, under As_4 flux. 0.3 μm GaAs undoped buffer layer was grown at 610–615°C with a growth rate of about 1.1 Å/s. Under these growth conditions, RHEED reconstruction pattern was kept in the $\sqrt{19} \times \sqrt{19}$ regime but very close to the $(1 \times 1)_{HT}$ one. This was followed by a transition layer of GaAs, during which the temperature

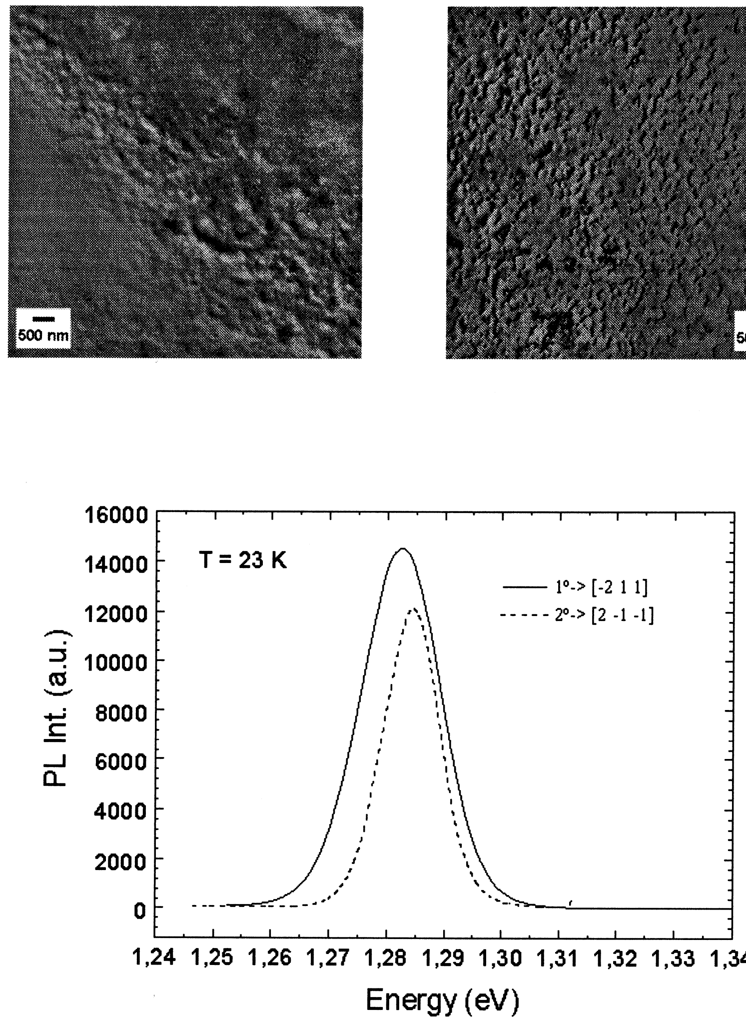

Fig. 2. PVTEM (upper graph) and PL spectra (lower graph) from the pair of SSQWs grown simultaneously with (a) $x = 25\%$, (b) $x = 30\%$, (c) $x = 35\%$. Concerning PVTEM images, those on the left are from samples grown on (111)B 1° towards [−211] and those on the right are from sample on (111)B 2° towards [2−1−1].

dropped to that used for the growth of InGaAs QW, 500°C during a period of 10 min. The beam equivalent pressure used was 30, which means an As/Ga flux ratio of about 1/3. These growth conditions for InGaAs/GaAs multilayers were reported as optimized for *simultaneous growth* on these two off-axis substrates [15]. Finally, 0.3 μm GaAs undoped cap layer was grown by increasing the temperature up to 610°C at the beginning of its growth.

PL studies were performed using a He–Ne laser ($\lambda = 6328$ Å) as an excitation power under normal incidence of the beam on the samples. The emission was dispersed through a Jobin–Yvon H25 spectrometer, detected by a photomultiplier S1 photocathode and processed using lock-in techniques.

Regarding TEM studies, specimens were prepared by mechanical thinning and chemical etching for Planar View Transmission Electron Microscopy (PVTEM). Observations were performed in a JEOL 1200EX microscope at 120 kV accelerating voltage.

3. Experimental results and discussions

Fig. 1 shows the 23 K linewidths (FWHM) extracted from PL measurements performed in the SSQWs with increasing In-content for both substrates. We can see a different behavior with increasing indium for samples on these substrates. When the wafer is (111)B 1° towards[−211], we notice that the FWHM keeps within the range 14–15 meV for 25% and 30%. We should remark that these values indicate good quality of these samples, as there is an intrinsic source of energy broadening because of the presence of the piezoelectric field in the strained wells, being important for wide wells with high indium contents. These variations in the transition energies are estimated to be about 11 meV in similar structures [17]. By contrast, when the indium content is as high as 35%, an increase up to 19 meV is observed. However, for samples on (111)B 2° towards [2−1−1], we notice a ''quasilinear'' increase in the FWHM values with indium content from 13 meV for

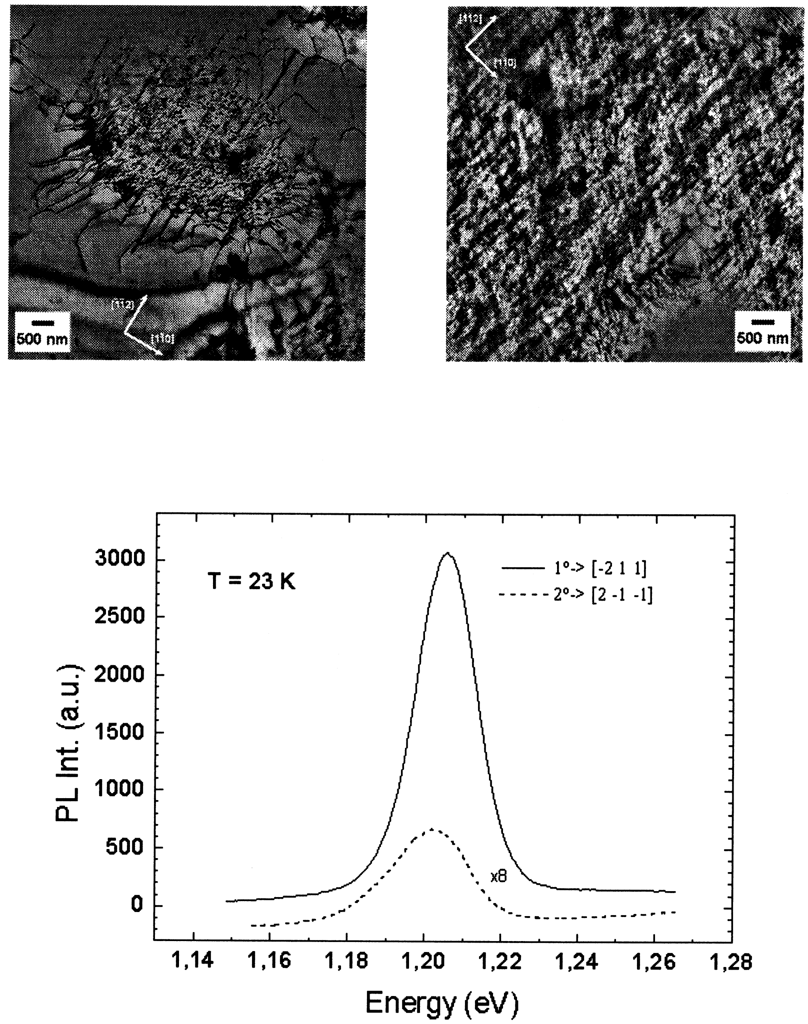

Fig. 2 (*continued*)

$x = 25\%$ up to 21 meV for an indium content as high as 35%. The degradation of the FWHM from InGaAs/GaAs (001) heterostructures when reaching the CLT, defined as the onset for plastic relaxation, is well known. According to the literature, two main mechanisms are said to be responsible for relaxation in the case of the (001) orientation: misfit dislocation generation in the epilayer/substrate interface and onset of 3D growth [18].

PVTEM observations of these highly strained samples revealed that the relaxation is through misfit dislocation (MD) at the epilayer/substrate interface. However, these MDs formed a network that was not a triangular 60° MD array, as expected for low strained InGaAs(111)B layers [11,12,14]. The new network in highly strained InGaAs(111)B layers consisted of a polygonal MD array with dislocation lines parallel to all three $\langle 11\bar{2} \rangle$ directions contained in the growth plane. This polygonal network can arise from the interaction among several three-pointed star-shaped MDs, with their arms parallel to all three $\langle 11\bar{2} \rangle$ directions and 1/2 $\langle 1\bar{1}0 \rangle$ Burgers vectors contained both in the (111) growth plane [19]. Fig. 2a–c show PL measurements of the three pairs of structures grown simultaneously, together with their PVTEM micrographs. It can be seen from them that the CLT is 100 Å in InGaAs (111)B for $25 < x \leq 30\%$ In-content regardless of the substrate misorientation. In addition, the plastic relaxation occurs inhomogeneously through densely entangled islands surrounded by a low MD density region. As the In-content increases, the polygonal network becomes more developed. Moreover, for In-content larger than 30%, the plastic relaxation develops through a more extended polygonal MD network in samples grown on (111)B 2° towards $[2\bar{1}\bar{1}]$ than in the other off-axis substrate. This is one of the first systematic evidences of relaxation dependence with substrate miscut.

The implication of this result in optoelectronic applications of InGaAs/GaAs heterostructures on (111)B GaAs for wavelengths beyond 1 μm is quite clear. From the point of view of growers, the use of off-axis substrates to alleviate the tight growth conditions for growth on (111)B seems more suitable. However, in order to obtain useful structures

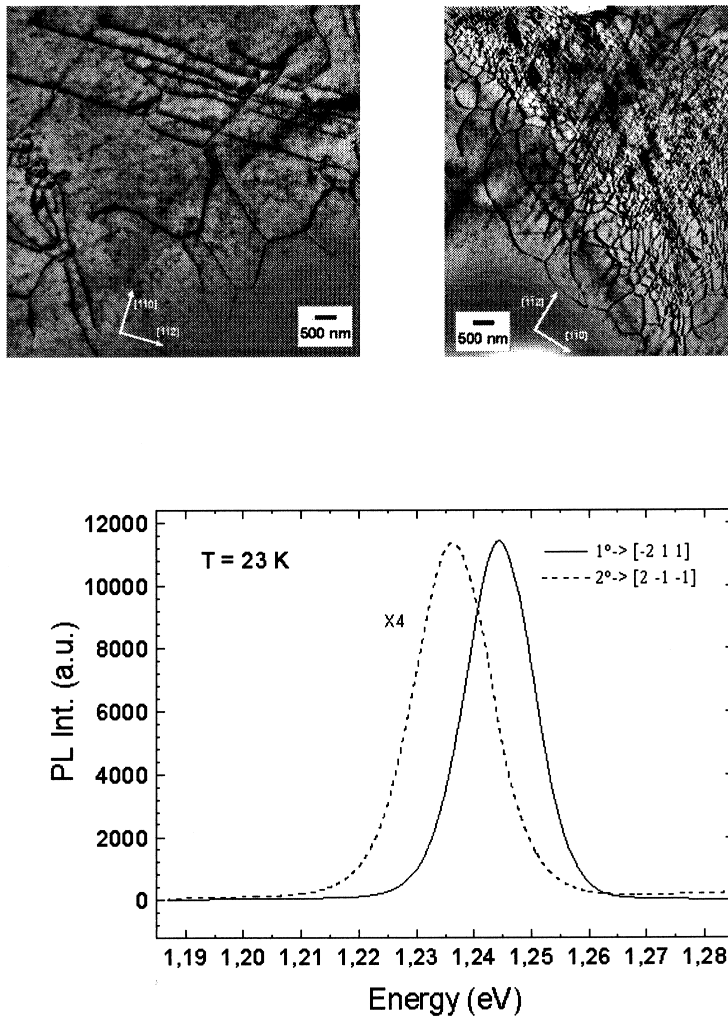

Fig. 2 (*continued*)

from the optoelectronic viewpoint, one has to keep in mind the dependence of the relaxation mechanisms with the substrate miscut used, as we have evidenced here for at least two specific off-axis substrates. Following this argument, the use of (111)B GaAs 1° towards [−211] substrates seems more suitable for device purposes in the wavelength region close to 1.1 μm.

4. Conclusions

A comparison of the optical and structural properties of highly strained InGaAs/GaAs SSQWs simultaneously grown on two different (111)B GaAs off-axis substrates was done. Results show a dependence of relaxation dynamics on the tilted substrate used, as was theoretically predicted before. However, this is the first experimental observation of this phenomenon in SSQWs. Implications for optoelectronic applications beyond 1 μm lead us to consider more suitable growths of highly strained InGaAs/GaAs systems on (111)B GaAs 1° towards [−211] than on 2° towards [2−1−1].

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