Microelectronics Journal 30 (1999) 467–470

Microelectronics Journal

New relaxation mechanisms in InGaAs/GaAs (111) multiple quantum well

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Accepted 6 November 1998

Abstract

A study by planar view transmission electron microscopy (PVTEM) of crystalline defect types in InGaAs/GaAs MQW grown on GaAs(111)B substrates is presented. The In-content of $In_xGa_{1-x}As$ layers was increased from $x = 0.1$ to 0.3. The relaxation in structures with low In-content ($x < 0.2$) occurred mainly through the formation of a triangular network of misfit dislocations (MDs) along each one of the three $\langle 1\bar{1}0\rangle$ directions contained in the interface. However, for In-contents above 22%, a new configuration of MDs as three-pointed star-shaped is observed. These star dislocations were formed by arms parallels to the $\langle 11\bar{2}\rangle$ directions contained in the growth plane. The interaction between two or more star dislocations worked as a new dislocation multiplication source. These new star dislocations often changed their dislocation lines turning towards the usual $\langle 1\bar{1}0\rangle$ directions. The characterization of this new dislocation configuration demonstrated that its Burgers vector lay on the growth plane with a strain-relieving component larger than the habitually considered. This result may modify the expectatives of a larger critical layer thickness for InGaAs/GaAs(111)B heterostructures with high In-content.

Keywords: Misfit dislocation; Star dislocation; Burgers vector

1. Introduction

In the last few years, the possibility to grow on substrates with a different orientation than the typical (001) has opened new possibilities for the design and fabrication of new optoelectronic devices [1]. The main reason for this is the strain-induced piezoelectric field (PF) caused by the distortion of the angles of the cubic unit cell for different polar orientations, which are not present in (001) systems [2]. Among all the polar orientations, the (111) growth presents the highest PF component perpendicular to the layers theoretically predicted and experimentally verified [3]. This constitutes a powerful tool to alter in a significant way the electrical and optical properties in strained heterostructures. Moreover, for PF application devices, one of the most important design parameters is the critical layer thickness (CLT). Above this CLT, the layer begins the plastic relaxation diminishing the elastic deformation useful for the PF effect. In this sense, a larger CLT for InGaAs layers grown on (111) orientation with respect to the ones grown on (001) substrates has been reported by a number of groups [4,5]. For these reasons, the InGaAs/GaAs(111) system would offer us some enormous expectations for optoelectronic device design with wavelength operation beyond 1.1 μm [6].

In the literature, there are many studies of optical and electronic transport properties evaluations of InGaAs/GaAs (111)B heterostructures. However, the relaxation mechanism of misfit strain has not been systematically investigated and details are not well documented in the scientific literature [7–9]. In this work, we carry out a study by PVTEM of different InGaAs/GaAs PIN structures with an In-content between 12% and 30%. The results allow us to establish that in heterostructures with larger In-content the relaxation mechanism has changed. This fact has not been reported in the bibliography to date. The consequences in the strain relaxation and the CLT will be discussed.

2. Experimental details

We study InGaAs/GaAs strained layers grown by MBE on (111)B substrates misoriented 1° towards $[\bar{2}11]$ direction and 2° towards $[2\bar{1}\bar{1}]$ one. The growth conditions were described elsewhere [10]. The heterostructure consisted of

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0026-2692/99/$ - see front matter
PII: S0026-2692(98)00154-2

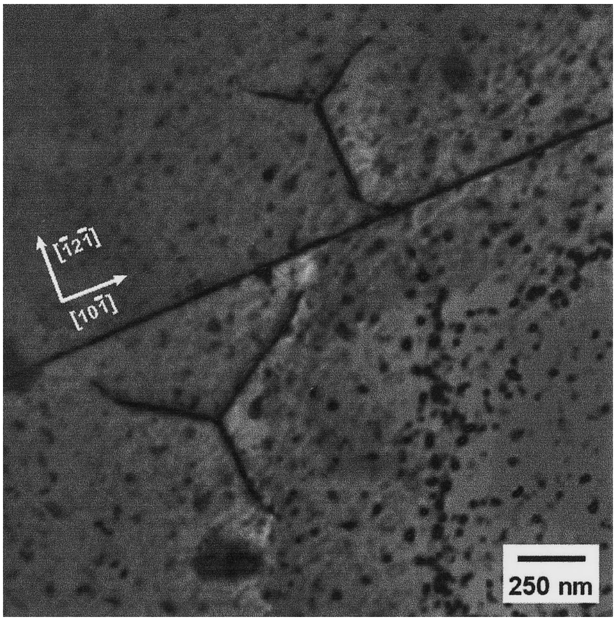


Fig. 1. PVTEM micrograph under 220 reflection of $In_{0.15}Ga_{0.85}As$ MQWs showing a three-pointed star-shaped dislocation with dislocation lines parallels to $\langle 11\bar{2} \rangle$ directions.

a 0.3 μm of n^+-GaAs layer followed by an intrinsic region of 0.57 μm-thick where 10 periods of $In_xGa_{1-x}As$(10 nm)/GaAs(20 nm) were embedded and finally other 0.3 μm of p^+ GaAs layer. The MQW In-content was 12%, 15%, 22%, 25% and 30% for both off-axis substrates.

Specimens were prepared for transmission electron microscopy (TEM) by mechanical thinning followed by chemical etching (H_2SO_4 + H_2O + H_2O_2) for the planar

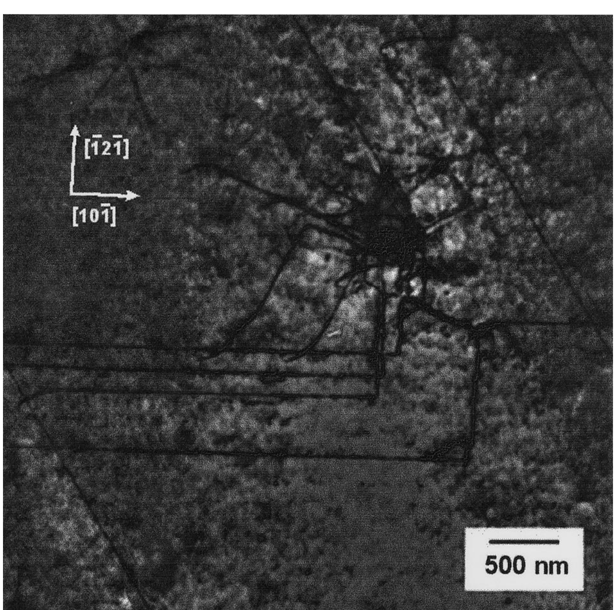
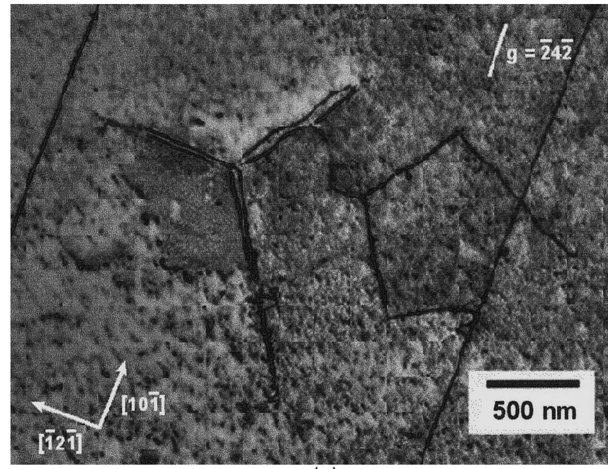
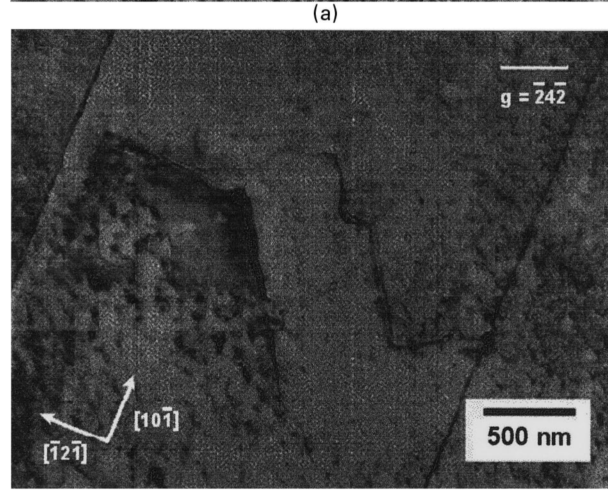


Fig. 2. New dislocation source by interaction of several star dislocations. The PVTEM image corresponds to a $In_{0.25}Ga_{0.75}As$/GaAs MQW sample with 220 reflection.



(a)



(b)

Fig. 3. PVTEM micrographs with 220 (a) and 224 (b) reflections of a three-pointed star-shaped dislocation for $In_{0.22}Ga_{0.78}As$ MQWs. Note that one arm is invisible with one 224 reflection.

view orientation. TEM observations were performed in a JEOL 1200EX transmission electron microscope.

3. Results

PVTEM observations of low In-content ($x < 0.2$) samples presented a triangular network of MDs along each one of the three $\langle 1\bar{1}0 \rangle$ directions contained at the interface. These MDs are commonly associated with the growth on (111) substrates. The **g·b** analysis of MDs showed a Burgers vector of $\frac{1}{2}a\langle 101 \rangle$ type which is out of the growth plane [7,8].

For medium In-content ($0.20 < x < 0.25$), together with triangular MD network evolution, a new MD configuration was observed which has not been described in the bibliography so far. The structure of this new configuration consisted of isolated dislocation groupings as three-pointed star-shaped with a 120° angle between its arms. These arms

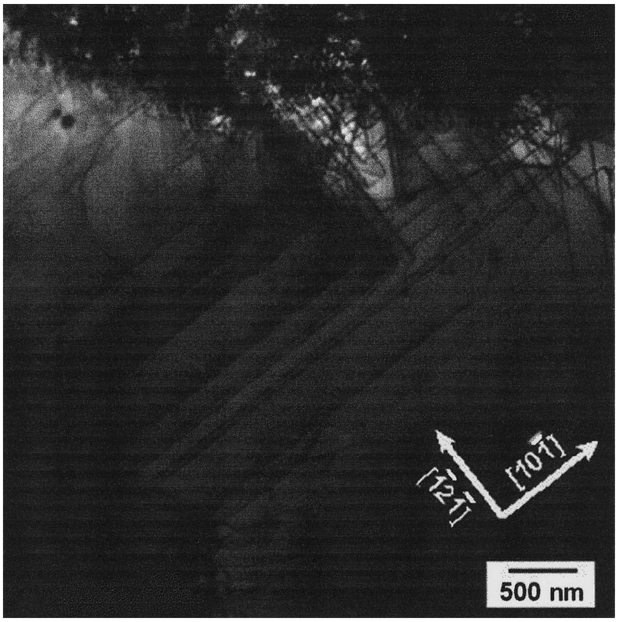


Fig. 4. PVTEM micrograph with 220 reflections of $In_{0.3}Ga_{0.7}As$ MQWs shows a densely entangled MDs islands separated by regions with a lower MDs density.

lay on $\langle 11\bar{2}\rangle$ directions contained in the growth plane as is shown in Fig. 1.

When the In-content was increased, the density of these star dislocations increased too. Moreover, a new configuration constituted by several star dislocations much closer appeared. The interaction among those stars produced a new dislocation multiplication source generating MDs parallels to the $\langle 11\bar{2}\rangle$ directions. These new dislocations often changed their dislocation lines from $\langle 11\bar{2}\rangle$ to $\langle 1\bar{1}0\rangle$ directions forming a right angle as is shown in Fig. 2.

Besides, the PVTEM study using 220 and 224 reflections revealed an outstanding characteristic as can be in Fig. 3. Under each 224 reflection, one of the star arms was invisible. This result was repeated for the other 224 reflections contained in the 111 pole finding invisibility for each arm. The **g·b** analysis lead us to deduce that Burgers vectors of this new MD configuration were $\frac{1}{2}a\langle 1\bar{1}0\rangle$ type contained in the (111) growth plane forming a 30° angle with the dislocation lines. Therefore, when these MDs changed from $\langle 11\bar{2}\rangle$ to $\langle 1\bar{1}0\rangle$ directions they kept the same Burgers vectors. A simple geometry study showed that these vectors formed 60° angle with the $\langle 1\bar{1}0\rangle$ dislocation lines. Thus, the growth plane was the active glide plane for these dislocations generated by this new dislocation source contrary to habitually suggested [7]. The new dislocation configuration has a Burgers vector and dislocation line coplanar to growth plane that is also a glide plane in III–V semiconductors.

This star configuration which was quickly developed became the predominant dislocation source for high In-content. Hence, for 30% In-content we observed a large-tangled centers with lots of arms on $\langle 11\bar{2}\rangle$ directions which rotated 90° forming a network on $\langle 1\bar{1}0\rangle$ directions as is shown in Fig. 4. The samples presented a large entangled island structure separated by an MD network parallel to the $\langle 1\bar{1}0\rangle$ directions whose Burgers vectors lay on the growth plane different to what it was observed in low In-content samples.

4. Discussion

The usual MDs that are considered for III–V semiconductors are located along the intersection of the glide plane and the interface plane. Their Burgers vectors are $\frac{1}{2}a\langle 101\rangle$ 60° type and they glide on {111} planes. The strain relaxation through MDs is proportional to the misfit-relieving component of its Burgers vector, b_r, calculated as the projection of b onto a line in the interface at right angle to the misfit dislocation. Next, we are going to determine the b_r of the different MD configurations in (001) and (111) substrates.

For (001) growth, all four {111} glide planes are equivalent and the misfit-relieving component of their Burgers vectors for a mixed dislocation b_r is:

$$b_r(001) = \left(\frac{-1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)\cdot\left(\frac{-1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)b = \frac{1}{2}b, \tag{1}$$

where b is the Burgers vector module.

In the (111) substrates, we can distinguish three possible cases from our PVTEM study. First, case a, MDs with Burgers vectors outside the growth plane. This case is habitually considered in the bibliography. Second case b, the new star-shaped dislocation with dislocation lines parallel to $\langle 11\bar{2}\rangle$ directions and third, case c, dislocations along the $\langle 1\bar{1}0\rangle$ directions coming from the three-pointed star-shaped dislocation. Keeping in mind this new panorama in the (111) orientation, we proceed to calculate the misfit-relieving component for each case. Thus, the relaxation component in the case a is as follows:

$$b_r(111)^a = \left(\frac{-1}{\sqrt{6}}, \frac{-1}{\sqrt{6}}, \frac{2}{\sqrt{6}}\right)\cdot\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)b = \frac{1}{\sqrt{12}}b. \tag{2}$$

Anan et al [4] using Matthews–Blakeslee equation [11] found that CLT would be three times larger in (111) substrates than (001) ones. However, the experimental results showed only a lightly higher CLT (1.3 times) between (111) and (100) substrates [12].

The new dislocation configuration with Burgers vector parallel to the growth plane observed for In-content above 20% modifies significantly the relaxation relationship. Thus, the relaxation component for the dislocations in star configuration (case b) is:

$$b_r(111)^b = \left(\frac{-1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)\cdot\left(\frac{-1}{\sqrt{2}}, 0, \frac{1}{2}\right)b = \frac{1}{2}b. \tag{3}$$

This result coincides with the misfit-relieving component of MDs on (001) substrates. As shown in Fig. 2, the star branches turn generally at right angles towards the $\langle 1\bar{1}0\rangle$

directions with Burgers vector in the growth plane. In this case *c*, the misfit-relieving component of these segments is much larger than the former considered cases:

$$b_r(111)^c = \left(\frac{-1}{\sqrt{6}}, \frac{-1}{\sqrt{6}}, \frac{2}{\sqrt{6}}\right)\cdot\left(\frac{-1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)b = \frac{3}{\sqrt{12}}b. \quad (4)$$

This result suggests that the bending of the star branches occurs because the change to higher relaxation components is energetically favorable.

From the above results, it is obvious that the relaxation is larger for case c than for cases a and b. Assuming the Matthews–Blakeslee equation [11], CLT is proportional to inverse of misfit-relieving component. So, for a larger relaxation component of MDs, a smaller CLT is expected. For high In-content ($x > 0.2$), better comparative experimental studies between both (001) and (111) substrates to find their CLT relationship are needed to verify this result.

5. Summary

A PVTEM study of the relaxation mechanisms of $In_xGa_{1-x}As$/GaAs MQW ($0.1 < x < 0.3$) were performed. For low In-content, the widely described triangular MD network with slip planes different to the growth plane was found. However, for In-content higher than 20%, a new dislocation configuration was observed as three-pointed star-shaped with dislocation lines parallel to $\langle 11\bar{2}\rangle$ directions. This new configuration constituted the predominant dislocation source for high In-content. The analysis by TEM showed that the new dislocations glided on the growth plane and presented a misfit-relieving component higher to those habitually considered for (111) substrates. As a consequence, it becomes necessary to revise the ideas about CLT of InGaAs on GaAs(111)B as they could be much smaller than it was considered previously.

Acknowledgements

This work was supported by the Andalusian Government (PAI TEP-0120) and the CICYT project TIC98-0826. This work was carried out at the Electron Microscopy Facilities of Universidad de Cádiz.

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