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Influence of substrate misorientation on the structural characteristics of InGaAs/GaAs MQW on (111)B GaAs grown by MBE

M. Gutiérrez[a], D. González[a], G. Aragón[a,*], J.J. Sánchez[b], I. Izpura[b], M. Hopkinson[c], R. García[a]

[a]Departamento de Ciencia de los Materiales e Ingeniería Metalúrgica y Química Inorgánica, Universidad de Cádiz, Apdo 40, Puerto Real, 11510-Cádiz, Spain

[b]Departamento de Ingeniería Electrónica, E.T.S.I.T., Universidad Politécnica de Madrid, Ciudad Universitaria, 28040-Madrid, Spain

[c]Department of Electronic and Electric Engineering, University of Sheffield, Mappin Street, Sheffield S1 4DU, UK

Abstract

The dependence of the defect structure on substrate misorientation is investigated in InGaAs/GaAs(111) multiple quantum well heterostructures. Samples were simultaneously grown by molecular beam epitaxy on GaAs(111)B substrates misoriented 1° off towards [$\bar{2}$11] and 2° off towards [2$\bar{1}\bar{1}$] under optimized growth conditions for both off-axis substrates. For both substrate misorientations two different dislocation networks are evidenced: first, a triangular 60° misfit dislocation array with ⟨$\bar{1}$10⟩ directions and second, a new dislocation configuration seen for the first time with dislocation lines parallels to ⟨11$\bar{2}$⟩ directions. This latter can work as a dislocation multiplication source for In-content above 25% for the structure chosen being more active in 2° off substrates than in 1° off ones. The activation of this new dislocation source may drastically affect the optical properties of the multiple quantum wells. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Epitaxy; Gallium arsenide; Indium arsenide; Interfaces; Piezoelectric effect; Transmission electron microscopy

1. Introduction

There are considerable expectations of developing new optoelectronic devices within the wavelength region 1.1–1.3 μm using strained layers of InGaAs/GaAs quantum wells (QWs) on (111) GaAs. This orientation offers many advantages such as larger heavy hole effective mass due to its valence band anisotropy and the presence of a piezoelectric field in the wells due to strain. In addition, some groups have reported a larger critical layer thickness (CLT) for (111) orientation with respect to (001) [1–3]. This would alloy InGaAs/GaAs(111) devices to reach wavelengths beyond 1.1 μm overcoming the ones obtained for InGaAs/GaAs(001) [4].

The use of (111)B GaAs substrates with a slight miscut seems to be a pre-requisite for the successful growth of high quality InGaAs epilayers [5,6]. Although the growth on different (111)B substrate misorientations has been reported, little has been done until now in order to contrast the optoelectronic properties with the relaxation processes in InGaAs(111) strained layers [7–9].

In this work, a study of the influence of substrate misorientation and In-content on the QWs crystalline quality was done. A new defect structure observed for the first time may be related to the degradation of the PL spectrum for high In-content.

2. Experimental procedures

InGaAs/GaAs(111)B multiple quantum well (MQW) heterostructures were simultaneously grown by molecular beam epitaxy (MBE) on GaAs(111)B substrates misoriented 1° off towards [$\bar{2}$11] and 2° off towards [2$\bar{1}\bar{1}$] under identical optimized growth conditions [10]. The heterostructure consisted of a 0.3 μm of n^--GaAs layer followed by an intrinsic region of 0.57 μm-thick where ten periods of $In_xGa_{1-x}As$ (10 nm)/GaAs (20 nm) were embedded and finally 0.3 μm of p^--GaAs. The MQW In-content was 12, 15, 22, 25 and 30% for both off-axis substrates.

Specimens were prepared by mechanical thinning and chemical etching for plan view transmission electron microscopy (PVTEM). TEM observations were performed in a JEOL 1200EX.

Low temperature photoluminescence (PL) was carried out in a double-cycle He-flow cryostat. Excitation was performed using a He–Ne laser ($\lambda = 6328$ Å). The emission was dispersed through a Jobin–Yvon H25 spectrometer and

* Corresponding author. Tel.: + 34-956-83-08-28; fax: + 34-956-83-49-24.

E-mail address: guillermo.aragon@uca.es (G. Aragón)

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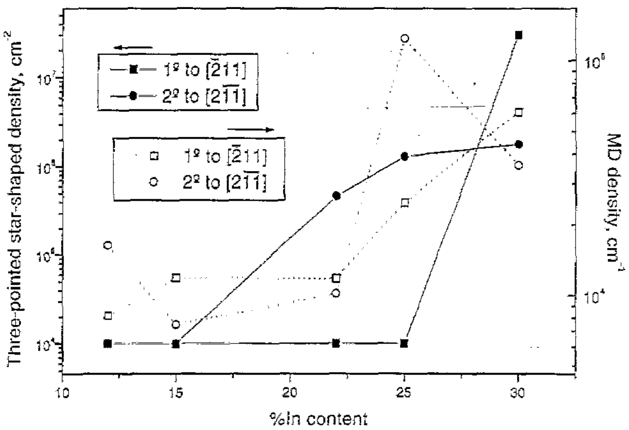

Fig. 1. MD density (right hand scale) and three-pointed star-shaped dislocation density (left hand scale) versus the In-content of InGaAs/GaAs MQWs for both misorientations.

detected by a photomultiplier S1-like and processed using lock-in techniques.

3. Experimental result and discussion

PVTEM observations are grouped in the next two sections depending on substrate misorientation. Finally, a comparison between the PL and TEM results is shown.

3.1. Substrates misoriented 2° off towards [2$\bar{1}\bar{1}$]

All samples revealed a triangular 60° misfit dislocation (MD) network located at the n^+-GaAs/MQW interface. These MDs were parallel to all three ⟨1$\bar{1}$0⟩ directions contained in the growth plane and it was always observed that one of these directions was favored. Moreover, the distribution of MDs was also inhomogeneous, i.e. different samples areas showed different dislocation density. The MD density remained very low below 22% In-content and went up above this In-content (Fig. 1). Furthermore, a new dislocation configuration as a three-pointed star-shape was found for all In-content (Fig. 2). These star-shaped dislocations with ⟨11$\bar{2}$⟩ line directions were located at n^+-GaAs/MQW

Fig. 3. PVTEM micrograph with 220 reflection of a complex three-pointed star-shaped dislocation for $In_{0.22}Ga_{0.78}As$ MQWs on 2° off substrates.

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

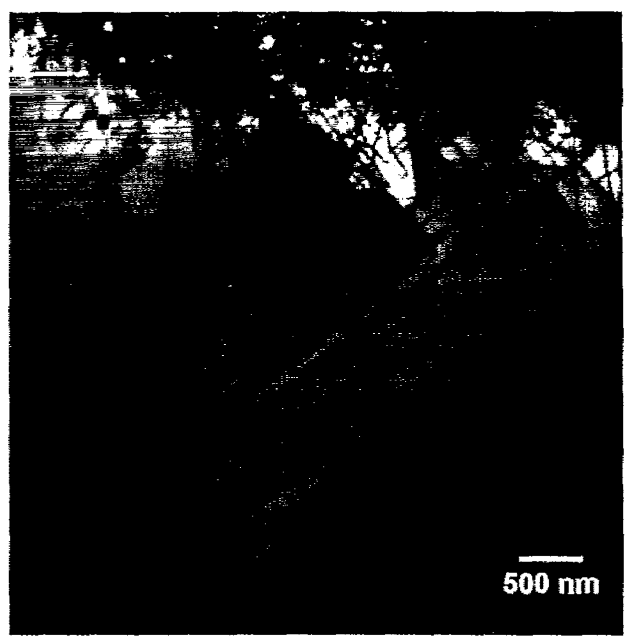

Fig. 4. PVTEM micrograph with 220 reflections of $In_{0.3}Ga_{0.7}As$ MQW on 2° off substrates. Note densely entangled islands separated by regions with a lower MD density.

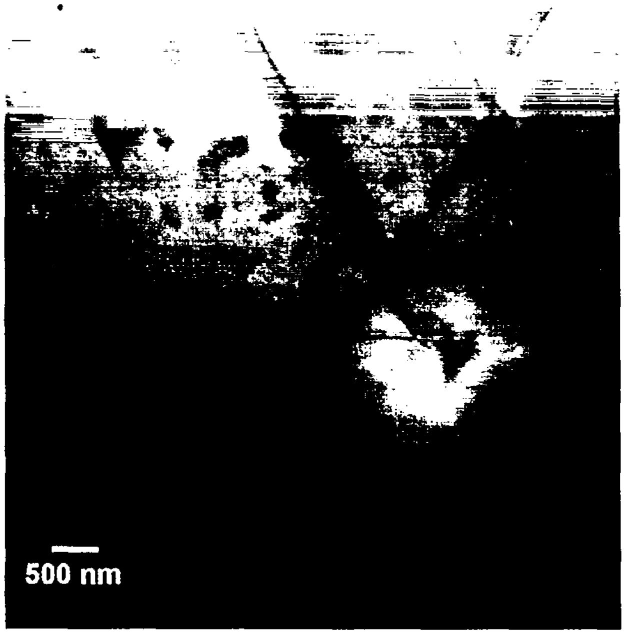

Fig. 5. PVTEM micrograph with 220 reflections of In$_{0.12}$Ga$_{0.88}$As MQWs on 1° off substrate. MDs lying along ⟨110⟩ directions and stacking fault tetrahedra are shown.

interface. The $g \times b$ analysis suggested Burgers vectors of 1/2⟨1$\bar{1}$0⟩ type lying on the (111) growth plane and forming a 30° angle with their dislocation lines. In addition to this star-shaped dislocation, a more complex dislocation configuration was also found for In-content above 22% (Fig. 3). This dislocation configuration consisted of a tangled center and many dislocations coming from this center parallel to all three ⟨11$\bar{2}$⟩ directions. The interaction between close three-pointed star-shaped dislocations is suggested as a possible formation mechanism of this complex configuration that operates as a MD multiplication source within the interface. We note that many dislocations coming from the source were changing over from ⟨11$\bar{2}$⟩ directions to ⟨1$\bar{1}$0⟩ ones in the (111) growth plane. For 30% In-content these complex, star-shaped dislocations appeared completely developed forming large tangled islands separated by regions with a low MD density (Fig. 4). In Fig. 1, the displayed MD density of 30% In-content corresponds to the MD density between tangle islands because of the difficulty in measuring the MD density inside of these islands.

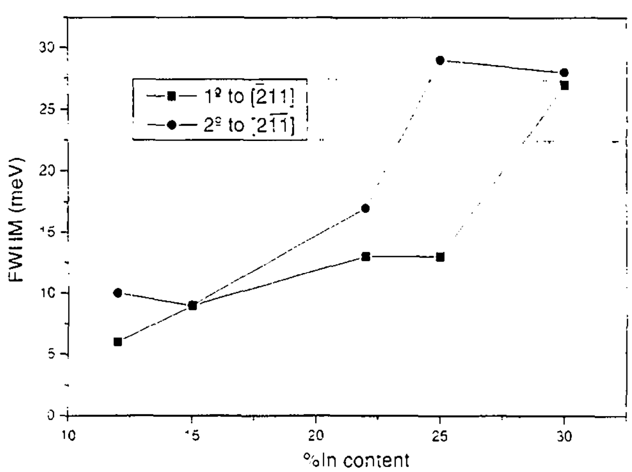

Fig. 6. FWHM measurement from low temperature PL spectra of InGaAs/GaAs MQWs grown on both misorientations as function of In-content.

3.2. Substrates misoriented 1° off towards [$\bar{2}$11]

Samples showed also a triangular 60° MD network and three-pointed star-shaped dislocations. However, complex star-shaped dislocations have only been observed in 30% InGaAs MQWs. As consequence, the MD density in 1° off substrates had risen more slowly than 2° off ones (Fig. 1). Additionally, stacking fault tetrahedra (Fig. 5) whose vertices leaned on MQW were found for low In-content (12, 15 and 22%) but they disappeared for high one (25 and 30%).

3.3. PL measurements.

The peak full width at half maximum (FWHM) from PL as function of In-content is displayed in Fig. 6. The FWHM of all samples grown on 2° off substrates was lightly broader than those grown on 1° off ones. However, the most important point is the previous worsening of the optical properties in 2° off substrates regarding 1° off ones. The FWHM rose up steeply on 22 and 25% for 2 and 1° off substrates, respectively. Finally, the optical properties of MQWs grown on both off-axis substrates became comparable for In-content up to 30%. This behavior led to establishment of a relation between the FWHM (Fig. 6) and the defects density (Fig. 2). Nevertheless, complex three-pointed star-shaped dislocations seem more harmful for optical properties than the triangular 60° MD network. This hypothesis can explain the delay in the optical properties worsening observed in 1° off substrates

4. Conclusions

PVTEM has been used to investigate the structural properties of InGaAs/GaAs MOWs grown on GaAs (111)B substrates misoriented 1 and 2° towards [$\bar{2}$11] and[2$\bar{1}\bar{1}$], respectively. The relaxation was brought about by two MD network types in both substrate misorientations: a triangular network with dislocation lines parallels to ⟨110⟩ directions and a new three-pointed star-shaped dislocation configuration parallel to ⟨112⟩ directions. This star-shaped dislocation configuration can work as a powerful dislocation source for high tensile strain. This new multiplication seems to operate at lower thicknesses in 2° off substrates. This fact coincides with the previous worsening of the PL spectra observed in these substrates. A relation between FWHM of MQWs PL spectra and the new complex dislocation configuration was suggested. Further work is needed to investigate the role of this three-pointed star-shaped dislocation in the relaxation and the PL spectrum of MQWs with high In-content.

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