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Cathodoluminescence study of pyramidal facets in piezoelectric InGaAs/GaAs multiple quantum well pin photodiodes

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Abstract

A study of the optical and electrical activity of defects at the surface of InGaAs/GaAs multiple quantum well pin photodiodes was done on two different misoriented (111)B GaAs substrates: substrate A, misoriented 1° towards [$\bar{2}$11] and substrate B, misoriented 2° towards [2$\bar{1}\bar{1}$]. In this article, we report the existence of different faceted defects at the surface with the misorientation and their influence on the optical performance. The surface of photodiodes grown on substrate A shows inclined pyramids with two enhanced facets. The electron beam induced current measurements showed that these pyramids act as high efficient collector of the e-beam excited electron–hole pairs (e–h). This behaviour agrees with the reduction of the cathodoluminescence emission efficiency at the facets. In contrast, a different pyramid type with one enhanced facet is observed at the surface of diodes grown on substrate B. However, these facets have not shown either optic or electric activity. In these diodes, the dislocations localised at the active region degrade the device performance acting as non-radiative recombination centres.

Keywords: Cathodoluminescence; Photodiodes; InGaAs/GaAs multiple quantum well

1. Introduction

Piezoelectric pseudomorphic InGaAs/GaAs heterostructures grown on (111)B GaAs have demonstrated their advantages over those grown on (001) substrates in improving the performance of electronic and optoelectronic devices and in the development of novel applications [1,2]. To take full advantage of the potential of piezoelectric-field related band engineering, there is a critical need to improve the crystal quality [3,4]. There is no consensus about which substrate gives rise to the best quality of crystal grown. The existence of different faceted defects at the surface of InGaAs/GaAs multiple quantum well (MQW) heterostructures grown on different misoriented GaAs (111)B substrates was observed. In this sense, a comparative study of the electrical and optical activity of those superficial defects was carried out. Two (111)B off-axis substrates were used: substrate A, misoriented 1° towards [$\bar{2}$11] and substrate B, misoriented 2° towards [2$\bar{1}\bar{1}$].

The cathodoluminescence (CL) technique, owing to its high spatial resolution, is an excellent technique to characterise the optical and electrical activities of local defects at surface of semiconductor heteropitaxies. Thus, quantum wells (QWs) are suitable probes to analyse locally the growth conditions because the energy levels of QWs are sensitive to the Indium mole fraction, the thickness or the strain field. Moreover, in (111) substrates, these change the magnitude of the built-in piezoelectric field altering the luminescent properties of the material in turn. In this work, the discussion on the CL data are also supported by electron beam induced current (EBIC) measurements. The obtained data allow us to establish important differences in the opto-electronic behaviour of the defects observed for each one of the studied misorientations. These results imply that the defects observed do not only affect the planarity of the surface, but rather they deeply affect the electric and optic responses of the MQW.

2. Experimental

The InGaAs/GaAs(111)B MQW heterostructures were grown by MBE on (111)B n^+ GaAs substrates off-axis 1° towards [$\bar{2}$11] direction and 2° towards [2$\bar{1}\bar{1}$]. The heterostructures, in order of growth, consist of 0.3 μm of n^+ GaAs (Si, 3×10^{18} cm^{-3}), an intrinsic region of 0.57 μm where

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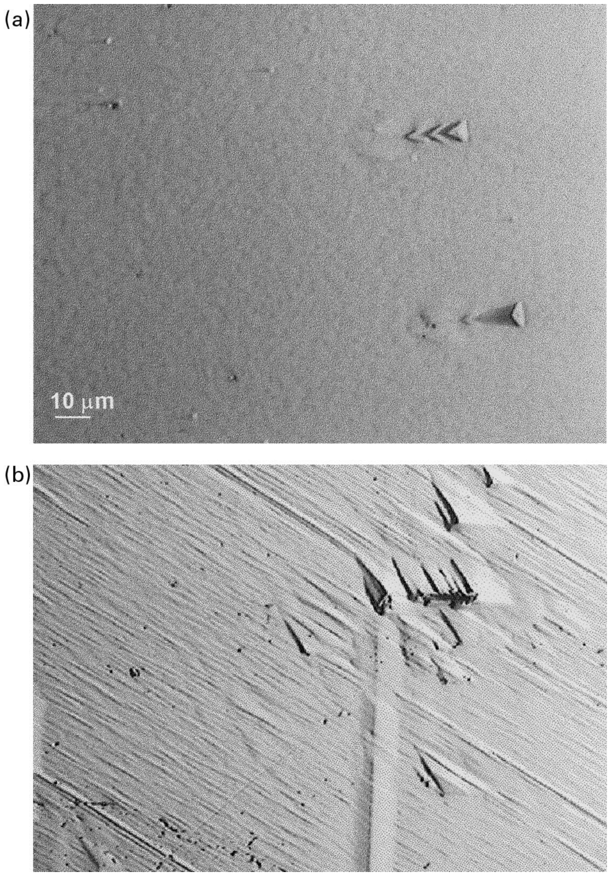

Fig. 1. Assessment of the InGaAs/GaAs(111) surface quality from optical micrographs.

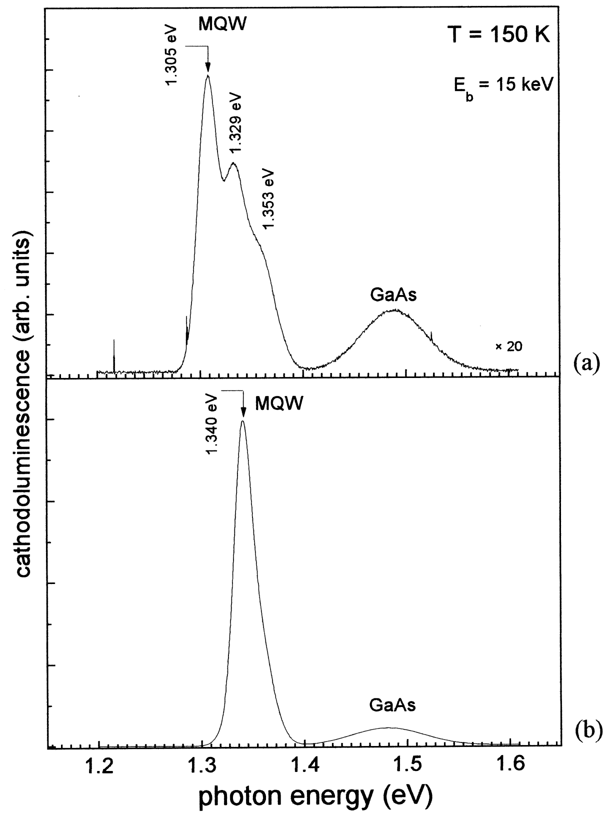

Fig. 2. Cathodoluminescence spectra ($T = 150$ K) at $E_b = 15$ keV and $I_b = 3.5$ nA over a region where the pyramidal facets emerge (a) and over a defect-free region (b). The MQW-related luminescence splits into three peaks (approximately 20 meV spaced between them) on the pyramidal facets growth area with the main peak shifted to lower photon energies.

$In_{0.15}Ga_{0.85}As$ (100 Å)/GaAs (200 Å) quantum wells (×10) were incorporated, and 0.3 μm of p^+ GaAs (Be, 2×10^{18} cm^{-3}).

To carry out the EBIC and CL measurements, these (111) diodes were mounted on an adapted holder of a JEOL-JSM820 scanning electron microscope in the planar-collector configuration, scanning the surface with the e-beam to access the faceted defects. The EBIC was measured using a head amplifier to a low input impedance amplifier (Matelect ISM-5A). A Faraday cup measured the e-beam current. The EBIC set-up allows us to apply a d.c. external bias voltage to the photodiode. The CL experiments were carried out at $T = 120$–300 K and electron beam energies (E_b) between 5 and 25 keV. CL is collected using a semi-parabolic mirror attached to an optical guide. A cryogenic CCD (Photometrics SDS9000) is attached to an Oriel 77400 Spectrograph/Monochromator for spectroscopic measurements. A CTI-Cryogenics 22C/350C Helium closed-circuit cryostat attached to an anti-vibration system is used for low temperature measurements.

3. Results and discussion

The first assessment of the surface quality is carried out at the optical microscope. Fig. 1(a) shows pyramidal faceted defects at the surface of the (111) diodes grown on substrate A, whose edges with the growth plane follow the ⟨110⟩ directions. The crystallographic planes that configure the pyramidal facets were determined to be (225) and (445) from atomic force microscopy (AFM) measurements. In contrast, Fig. 1(b) corresponds to the surface of photodiodes grown on substrate B. The pyramidal facets change their morphology lengthening perpendicularly to the offcut direction. Hereafter, we will identify them as narrow pyramid and wide pyramidal faceted defects, respectively.

Fig. 2 shows the CL spectra recorded for photodiodes grown on substrate A over a defect-free region and over a region where the narrow pyramidal facets get up. At 150 K, the 1.340 eV MQW-related luminescence splits off in three peaks (approximately 20 meV spaced between them) with the main peak shifted to lower photon energies. The relative intensity between areas with and without pyramids is 1:20. This feature remains invariable in an extension of several hundreds of microns around the narrow pyramids. The area affected by the facet growth is more extensive than expected initially as the CL results confirmed. These pyramidal facets were reported in GaAs/GaAs(111) homoepitaxy [5]. This fact suggests that these narrow pyramids may have begun on the terraces of the GaAs substrate 1° miscut towards

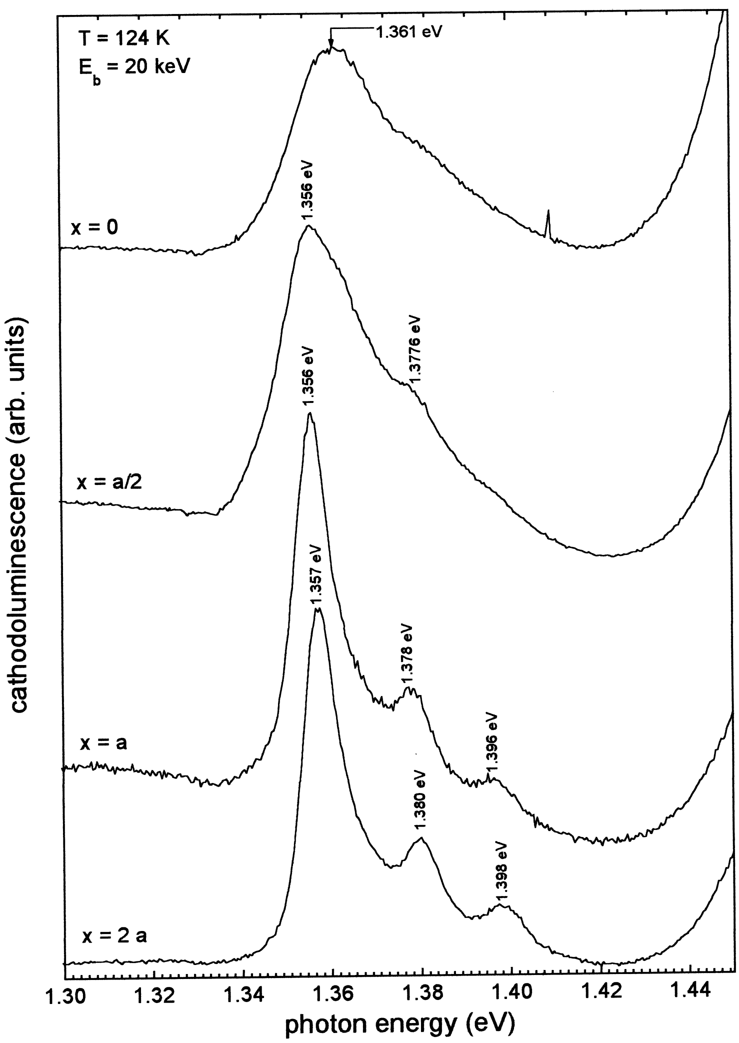

Fig. 3. CL spectra ($T = 124$ K and $E_b = 20$ keV) recorded on an isolated pyramid at different lengths ($x = 0$, $a/2$, a, $2a$). a is the distance between the vertex (the intersection between the (225) and (445) planes) and the end of the (225) facet as we schematically describe in the secondary electron (SE) micrograph of Fig. 4.

[$\bar{2}$11] and not in the strained InGaAs/GaAs heteroepitaxy. The superficial pyramids are the final result of the growth alteration of wide areas in the structure from the beginning of the growth.

To resolve how the growth of the narrow pyramids affects the MQW luminescence, we have recorded a set of CL spectra on an isolated pyramid at different lengths ($x = 0$, $a/2$, a, $2a$) as shown in Fig. 3. We labelled a the distance between the pyramid vertex (the intersection between the (225) and (445) planes) and the end of the (225) facet following the [−110] direction (schematically described in Fig. 4(a)). Far from the pyramid ($x \geq 2a$), we found the three peaks in the spectra mentioned earlier (1.357, 1.380 and 1.398 eV), that is retain it even when the facets are reached. Only when the e-beam is localised at the middle of the (225) facet ($x = a/2$) merit-of-mention changes in the emitted luminescence were recorded: First, a reduction of the emission efficiency in one order of magnitude. Second, a 5 meV blue-shift at the vertex of the pyramid. Third, a broadening of the MQW luminescence spectrum. The full-width half-maximum (FWHM) of the tree peaks increases from 10 to 20 meV. These results are repeated in all the pyramids studied.

The decrease of the CL intensity at the pyramid can be correlated with an increase of the charge collection efficiency (CCE), as revealed by EBIC micrographs (see Fig. 4(b)) of isolated defects. An increase of the space-charge-region (SCR) width or a local diminishing of the built-in piezoelectric field could explain an enhanced CCE at the pyramids. The changes of the In-content or well thickness have a negligible effect on the CCE in the absence of the piezoelectric effect. To elucidate the responsible effect of the higher CCE, we have assessed the d.c. external bias voltage dependence of the EBIC contrast. For a wider SCR at the narrow pyramids, we would obtain higher or lower CCE applying an external bias voltage but an almost

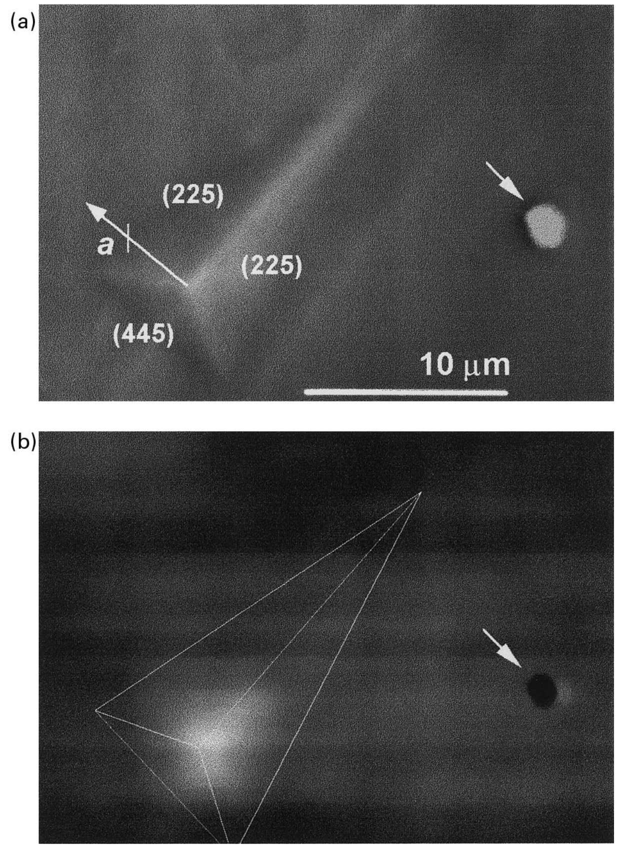

Fig. 4. SE (a) and EBIC (b) micrographs from an isolated pyramid. The EBIC micrograph was taken applying an external reverse bias voltage of 0.09 V. The reverse EBIC contrast at the dusty particle (indicated by arrow) shows that the contrast at the pyramid is not a geometric factor. The higher CCE at the pyramid is because of the reduction of the built-in piezoelectric field in the defect.

uniform EBIC contrast. However, we have found experimentally that the EBIC contrast at pyramidal facets is extremely sensitive with respect to the applied d.c. external bias voltage and this is probably owing to a piezoelectric field-related effect [1]. This behaviour is justified by a shift of the external bias voltage required for the transition from negative to positive electrostatic potential envelopes inside and outside the facets. Therefore, the higher CCE constitutes a direct evidence of the built-in piezoelectric field lowering close to the vertex of the narrow pyramids. Moreover, this fact would also explain the blue-shift of MQW luminescence observed at pyramid vertex. Finally, the broadening of the emitted CL could be justified by the geometrical changes of the MQW at the pyramid vertex.

Wide pyramidal faceted defects arise in diodes grown on substrate B, as shown in Fig. 1(b). To analyse their influence over the device performance, we have carried out similar experiments over the narrow pyramidal facets. Fig. 5 shows (a) a secondary electron micrograph, (b) the pancromathic cathodoluminescence ($T = 150$ K) and (c) the EBIC ($T = 300$ K) distributions over the same pyramids. These wide

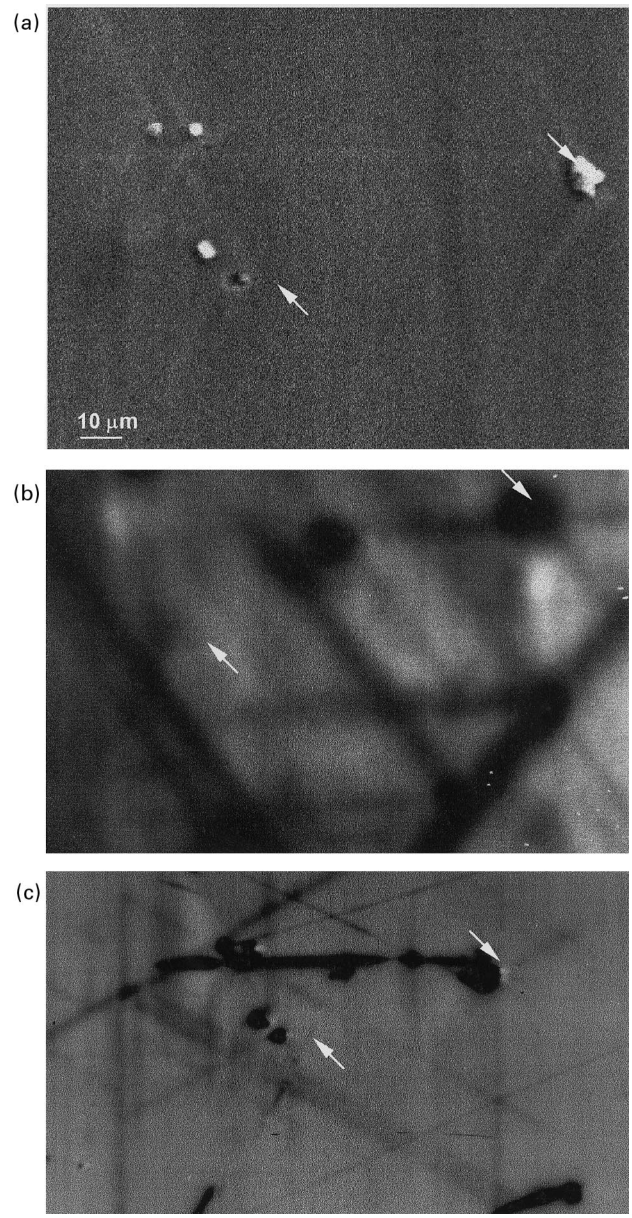

Fig. 5. (a) Secondary electron micrograph over wide faceted defects and their pancromathic CL (b) ($E_b = 20$ keV, $I_b = 3$ nA and $T = 150$ K) and EBIC (c) ($E_b = 20$ keV, $I_b = 500$ pA and $T = 300$ K). The arrows allow us to establish the correspondence between the micrographs. The EBIC and CL show the presence of dislocations acting as non-radiative recombination centres.

faceted defects have a negligible effect on the CL and EBIC efficiencies, contrary to that observed in the previous substrate. However, these pyramidal facets seem to be associated with the dislocation network of the InGaAs/GaAs MQW. Indeed, the EBIC/CL measurements revealed that dislocation network at the active region of these diodes acts as non-radiative recombination centres in the whole temperature range studied (from 300 to 150 K). Thus, both the CCE and luminescence efficiency is reduced by the dislocations.

4. Conclusions

We have studied by EBIC and CL the optical and electrical activities of different faceted defects that appear in the MBE epitaxy on two different misoriented (111)GaAs substrates. For substrate A, a strong decrease of the QW luminescence in regions next to the pyramidal facets is observed. In addition, the pyramids act as centres of a high CCE, probably because of the built-in piezoelectric field reduction. In addition, the higher CCE was related with a lower CL emission efficiency. For substrate B, wide faceted defects are observed and they did not show either optical or electrical activity. In summary, the presence of superficial pyramids in substrate A implies growth conditions deterioration in wide areas in these types of diodes that degrades the QW luminescence, while these effects are not observed in substrate B.

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