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Physica E 17 (2003) 561–563
PHYSICA E
www.elsevier.com/locate/physe

Misfit dislocations and surface morphology of lattice-mismatched GaAs/InGaAs heterostructures

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Abstract

A regular network of 60° misfit dislocations aligned along two orthogonal ⟨110⟩ directions at the (001) interface of GaAs/InGaAs heterostructures with a small lattice-mismatch has been revealed by means of transmission electron microscopy and electron-beam induced current mode in a scanning electron microscope. The network of misfit dislocations has been also reproduced, in a form of a well-defined cross-hatch pattern on the surface of the structures, with atomic force microscopy. Almost one-to-one correspondence between the structure of misfit dislocations at the interface and the surface morphology clearly demonstrate that the cross-hatch development results primarily from misfit-dislocation generation.

Keywords: Semiconductor heterostructures; Misfit dislocations; Surface morphology

1. Introduction

Lattice-mismatched GaAs-based heterostructures are of continual interest because of their application in high-speed and optoelectronic devices. They offer also a basis for fabrication of a variety of low-dimensional and mesoscopic systems being a subject of current studies in solid-state physics. Epitaxial growth of those heterostructures is accompanied by a strain in the epitaxial layer that results from a difference in lattice parameters between the substrate and the layer. If the thickness of the layer exceeds its critical value the strain is relieved by the formation of misfit dislocations. In heteroepitaxial semiconductor systems with zinc-blende structure and small lattice mismatch, grown on (001)-oriented substrates, orthogonal arrays of regular 60° misfit dislocations are formed at the interface. The misfit dislocations are accompanied by threading dislocations which propagate into the epitaxial layer. The presence of a network of dislocations often results in a characteristic undulating surface morphology known as cross hatch. Understanding of the formation mechanism of such a surface relief, which occurs in many lattice-mismatched semiconductor systems [1,2], is important for fabrication of low-dimensional devices based on those systems. Despite several models have been recently proposed to describe the cross-hatch development its origin remains controversial and unresolved [3].

In this communication we report results of investigations of the structure of misfit dislocations in GaAs/InGaAs heterostructures with a small lattice-mismatch by means of transmission electron

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1386-9477/03/$ - see front matter
doi:10.1016/S1386-9477(02)00871-8

microscopy (TEM) and electron-beam induced current (EBIC) in a scanning electron microscope. Additionally, atomic force microscopy (AFM) has been employed to investigate surface morphology of the epitaxial layers.

2. Experimental results

The investigated heterostructures, grown by molecular beam epitaxy on (001)-oriented *n*-type GaAs substrates, contained p-type InGaAs layers with the In content of 3% resulting in the lattice-mismatch of 0.25% between GaAs and the ternary compound. The InGaAs layer thickness, of 1 μm, exceeded a little the critical value for misfit dislocation formation, so the structures were partially relaxed.

A plan view TEM image of the heterostructure interface, shown in Fig. 1, revealed a regular network of 60° misfit dislocations aligned along two orthogonal ⟨110⟩ directions at the (001) interface. The same regular network of misfit dislocations has been also visualized, on a larger scale, by means of EBIC technique utilizing a p–n junction formed at the interface, as shown in Fig. 2. Here the misfit dislocations are visible as dark lines owing to enhanced recombination rate of electron-hole pairs generated by an electron beam. The network of misfit dislocations has been also reproduced with AFM in a form of a well-defined cross-hatch pattern, with undulations, of about 2 nm peak-to-valley amplitude, running along two perpendicular ⟨110⟩ directions, on the (001) surface of the structures, as shown in Fig. 3.

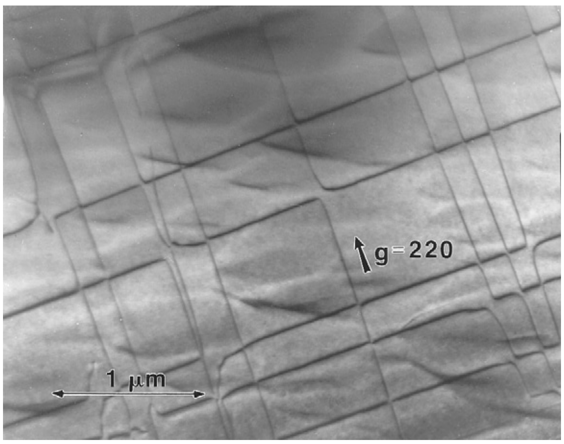

Fig. 1. TEM bright field image of misfit dislocations at the interface of GaAs/InGaAs heterostructure.

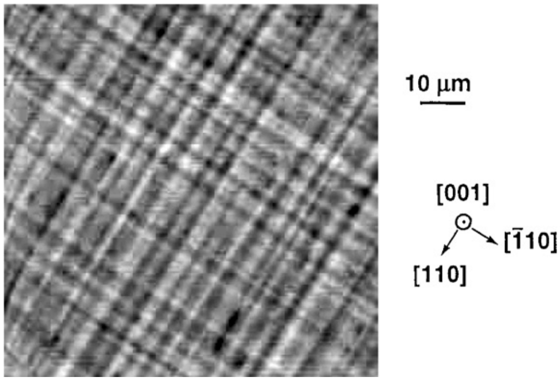

Fig. 2. Distribution of misfit dislocations at the interface of GaAs/InGaAs heterostructure visualized by means of EBIC technique in a scanning electron microscope.

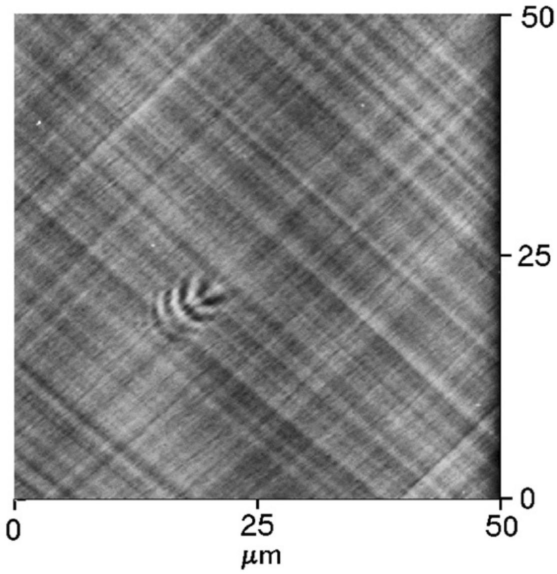

Fig. 3. Surface morphology of the same heterostructure as in Fig. 2 revealed by AFM showing a well-defined cross-hatch pattern reproducing the network of misfit dislocations. A characteristic feature visible on the structure surface probably reveals an outcrop of a threading dislocation lying on a (111) plane inclined to the (001) surface by the angle of 55°.

3. Discussion

Our present observations, which evidence almost one-to-one correspondence between the structure of misfit dislocations at the interface and the cross-hatch surface morphology, clearly demonstrate that the cross-hatch development is a consequence of misfit-dislocation formation. This is in agreement with the models in which the undulations result primarily from misfit-dislocation generation and glide processes [1,4]. Alternative explanations of the surface relief formation, either as originating from composition fluctuations in the layer of ternary compound [5] or as a result of enhanced growth over strain relaxed regions due to lateral mass transport by surface diffusion [2], should be excluded in view of our results.

In conclusion, a direct comparison of the results obtained with AFM and EBIC methods shows that atomically smooth but mesoscopically rough surface of the structures exhibits undulations, which are correlated spatially with the positions of the underlying misfit dislocations.

Acknowledgements

This work has been partly supported by the State Committee for Scientific Research of Poland under Grant No. 2P03B06319.

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