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High resolution X-ray diffraction study of InAs layers grown with and without bismuth flow on GaAs substrates by metalorganic vapor phase epitaxy

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ABSTRACT

InAs layers were grown with and without bismuth flow by atmospheric pressure metalorganic vapor phase epitaxy on exactly oriented, 2° and 10° misoriented (1 0 0) GaAs substrates. Structural analysis was carried out using high resolution X-ray diffraction. Without bismuth flow, only InAs layers grown on 10° misoriented substrates exhibit a mosaic structure. Layers grown on exactly oriented and 2° misoriented substrates show large full widths at half maxima of their diffraction rocking curves. Growing InAs under bismuth flow leads to the reduction of this full width indicating a clear improvement of their structural quality. Particularly for samples grown on 10° misoriented substrates, a complete disappearance of the mosaic structure was obtained. The crystalline quality improvement is attributed to the contribution of Bi nanodots in relieving strain.

1. Introduction

The epitaxial growth of InAs layers on GaAs substrates is of particular interest due to their application in several electronic devices specially in infrared detectors and lasers [1–3]. However, InAs on GaAs is highly lattice-mismatched system (~7%) leading to a high dislocation density at the heteroepitaxial interface. To overcome such problems, several technical methods were suggested. A two step method using InAs prelayer grown under In rich environment [4], or a graded buffer layer (InGaAs, InAlAs, GaInAlAs) [5,6], or a Te covered GaAs surface [7], have showed a clear improvement of the physical properties of active InAs layer. Substrate orientation and growth parameters were found to change the energy of surface reconstructions, the kinetics of adsorption, migration and desorption of adatoms [8–12]. Indeed, growth at lower temperatures or under low V/III ratio eliminated the multiple tilting of InAs crystal planes giving rise to InAs films aligned with their substrates [13]. Many studies using misoriented GaAs substrates were also carried out to evaluate the microstructure and development of defects in epitaxial InAs films [14–16]. On the other hand, the use of surfactants in such mismatched systems as Te [17] and Sb [18] and Bi [19] provides a layer by layer growth mode, increases the critical layer thickness and ameliorates the surface quality. Bismuth solubility in III–V compounds is very low and reaches approximately 0.025% in InAs [20]. Due to its large size, bismuth segregates on the surface and does not incorporate easily in InAs matrix [19,21]. When growing InAs quantum dots by metalorganic vapor phase epitaxy (MOVPE) on (1 0 0) GaAs substrates, Bi was used as surfactant [22], but there is still no report indicating Bi effect on crystalline quality of InAs epilayers.

In this paper, the structural characterization of InAs layers grown by atmospheric pressure MOVPE on exactly oriented, 2° and 10° misoriented (1 0 0) GaAs substrates with and without Bi flow is reported. The effect of Bi on the structural quality and on the surface morphology of InAs layers is discussed.

2. Experimental methods

The epitaxial InAs layers were deposited simultaneously on different (1 0 0) GaAs substrates by atmospheric pressure MOVPE. These substrates are (1 0 0) exactly oriented and misoriented by 2° and 10° towards [1 1 1]A direction. Trimethylindium (TMI) and pure arsine (AsH_3) were used as source materials. The carrier gas was Pd-diffused H_2. The substrate temperature was measured by a thermocouple inserted into the graphite succeptor. In order to remove the native surface oxide layer the substrates were first ramped in a mixture flow of H_2 and AsH_3 at 700 °C for 10 min. After, the temperature was decreased till 450 °C and stabilized to grow InAs layers at a fixed V/III ratio of 18. Under these conditions another set of InAs layers were grown on GaAs substrates under trimethylbismuth (TMBi) flow (TMBi/AsH_3 = 0.005). High resolution X-ray diffraction (HRXRD), analysis were performed with a diffractometer using $\lambda_{CuK\alpha1}$ = 1.54056 Å radiation from a Discover D8 (40 KV, 55 mA) high

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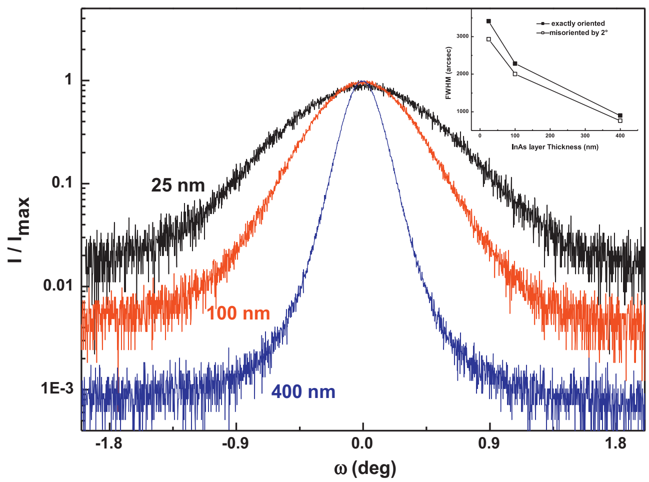

Fig. 1. (0 0 4) normalized RC of InAs layers with different thicknesses grown on exactly oriented (1 0 0) GaAs substrates. The inset shows the FWHM variation versus thickness.

power X-ray generator. Surface analysis was carried out using a scanning electron microscope (SEM).

3. Results and discussion

In order to study the crystalline quality of InAs layers grown on different GaAs substrates, we have performed (0 0 4) HRXRD analysis of samples having different thicknesses. Fig. 1 shows typical diffraction rocking curves (RC) of InAs layers grown on exactly oriented GaAs substrates without TMBi flow. The intensity is plotted in a logarithmic scale to show the behavior around the half width. This figure indicates that the breadth of these peaks decreases with increasing InAs thickness. The full width at half maximum (FWHM) of the X-ray diffraction RCs scans are shown in the insert as a function of InAs thicknesses grown on exactly oriented and 2° misoriented (1 0 0) GaAs substrates. The FWHM decreases with increase in film thickness. The reduction of FWHM can be caused by several phenomena, as well as defect and dislocation, grain size broadening, or strain fluctuation. The average dislocation density and the diameter of the particle size can be determined by the Eqs. (1) and (2) respectively [23]:

$$D = \frac{FWHM^2}{(4b)^2} \quad (1)$$

$$G = \frac{\lambda}{\cos(\theta_b)\,FWHM} \quad (2)$$

Where b is the Burgers vector, θ_b is Bragg angle and λ is the radiation wavelength. The dislocation density and grain size as a function of the layer thickness are shown in Fig. 2. We note that the particle sizes of the InAs layers increase, but the dislocation density decreases with increasing film thickness. The thick layer is formed of high particle size, that is to say, characterized by a better crystalline quality compared to other layers. SEM is used to estimate the dislocation density. Fig. 3 shows a SEM image of thick InAs layer (400 nm). Pits are observed at the surfaces which reveal the distribution of dislocations in the epitaxial layer. The density of pits calculated from the SEM images of three InAs layers is also presented in Fig. 2. However, the one-to-one correspondence between pits and dislocations provides a convenient method for estimating dislocation densities in these samples. Basing on the theoretical

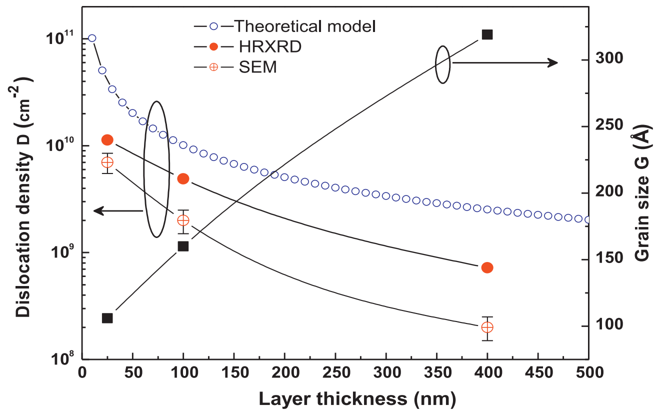

Fig. 2. Dislocation density (left axis) and grain size (right axis) as a function of epilayer thickness for InAs layers grown on exactly oriented (1 0 0) GaAs substrates.

model describing in ref. [24], the dislocation density is given by the following equation:

$$D = \frac{f\cos(\phi)}{16hb(1-\nu)} \ln\left(\frac{1}{4f}\right) \quad (3)$$

Where ν is the layer Poisson ratio, b is the length of the Burgers vector, f is the lattice mismatch, h is the layer thickness and ϕ is the angle between the threading segments and the interface. The theoretical dislocation density was then compared with the values obtained from the HRXRD and the SEM techniques. A notable difference was remarked. This discrepancy had several reasons. Indeed, the pits density appeared on the surface seem to be underestimated compared to the true dislocation density revealed in the entire layer by transmission electron microscopy. Another possible effect may stem from the depth dependence of the dislocation density. For each thickness, layers grown on 2° misoriented substrates exhibit FWHMs slightly lower than those grown on exactly oriented ones. This small decrease may be attributed to the presence of surface steps acting as a lattice distortion corrector. In order to analyze the thickness effect on the layer relaxation a qualitative calculation of (0 0 4) diffracted intensity of InAs for two thicknesses (25 nm and 400 nm) is calculated by using X-ray dynamical theory. In Fig. 4, we report the results of this calculation for strained and fully relaxed states of InAs layer. For comparison, the experimental data for these

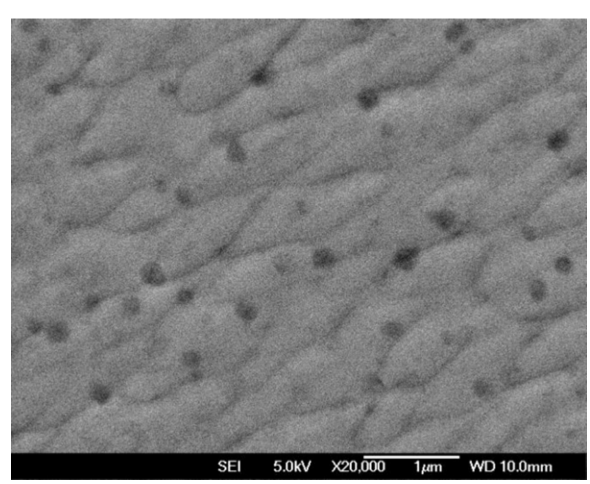

Fig. 3. SEM image of 400 nm InAs layer grown on exactly oriented (1 0 0) GaAs substrate.