Opt Quant Electron (2016) 48:428
DOI 10.1007/s11082-016-0698-4

# Molecular beam epitaxial growth and characterization of InAs layers on GaAs (001) substrate

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Received: 23 June 2016 / Accepted: 8 August 2016 / Published online: 13 August 2016

**Abstract** High-quality InAs epilayers were grown onto GaAs (001) substrate by molecular beam epitaxy. The optimal growth conditions were examined over a wide range of substrate temperature, substrate offcut orientation, and $As_4$/In flux ratio. The surface morphology, electrical and structural properties were investigated by Nomarski optical microscopy, Hall effect measurement, and X-ray diffraction, respectively. It is worth noting that InAs layers grown on GaAs (001) substrate with 2° offcut towards $\langle 110 \rangle$ have better crystalline quality and electrical properties than that grown on GaAs substrate without offcut. The results indicated that the layers grown at 400 °C, with a group V/III flux ratio of 8.5, yielded to the highest electrical quality, with a Hall mobility of 22,420 $cm^2/Vs$ at 80 K and 12,970 $cm^2/Vs$ at room temperature. It is found that the top part of 5 µm-thick InAs layer exhibits a high Hall mobility of 77,380 and 25,275 $cm^2/Vs$, at 80 and 300 K, respectively.

**Keywords** MBE · InAs · GaAs · Hall effect · X-ray diffraction

## 1 Introduction

Epitaxial InAs structures has attracted interest in several device applications. Some of its potentially useful attributes enclose high electron mobility, narrow band gap, as well as the feasibility of ohmic contacts of many metals with InAs (Trampert et al. 1995; Hooper et al. 1993; Kalem 1989, 1990; Fang et al. 1991). InAs films have been used into devices such as high electron mobility transistor (HEMT) (Popovic et al. 1996), Hall sensors (Yang et al.

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1996), photodetectors (Kuan et al. 1996) and avalanche diode (Maddox et al. 2012). InAs devices have been impeded by the absence of an appropriate lattice-matched substrate. Traditionally, InAs epilayers are grown on GaAs substrates. However, it is tough to obtain high-quality InAs layers due to the large lattice mismatch (7.2 %) between these two materials. A high density of dislocations takes place in the interface, some of which may thread into the epilayers, which causes the degradation of performance of the device (Kim et al. 2002). A huge number of these defects are located in the first few tenths of µm of InAs layer. These dislocations notably pass away for a distance greater than a critical thickness ($\sim$0.2 µm) (Hooper et al. 1993; Yamamoto et al. 1997). Hitherto, several types of buffer layer techniques have been developed in order to grow high quality InAs layer (Bolognesi et al. 1994; Yasuda et al. 2000; Ballet et al. 2001). However, these buffer layers are time consuming and are not cost-effective.

In this paper, we report on the effect of growth temperature, group V/III flux ratio, and substrate misorientation on the electrical, structural and surface morphology properties of InAs layers grown directly on GaAs substrates by molecular beam epitaxy.

## 2 Experiment

The samples studied in this work were grown on GaAs (001) substrate and on GaAs (001) substrate with 2° offcut towards $\langle 110 \rangle$ by a solid source RIBER COMPACT 21 DZ molecular beam epitaxy system, equipped with valved arsenic cracker. For temperature measurement, the manipulator thermocouple was used. Growth temperature was calibrated from the GaAs substrate deoxidization temperature. After thermal desorption of oxide at 655 °C under $As_4$ overpressure, a 250 nm-thick GaAs layer was deposited at 655 °C to smooth the surface, with a growth rate of 1 µm/h. Four InAs epilayers have been deposited, under a wide range of growth temperature, from 380 to 560 °C, and a V/III flux ratio of 8.5. In order to investigate the effect of $As_4$/In flux ratio, we have grown four samples at 400 °C, and under various V/III flux ratio: 7.5, 8.5, 10.5 and 17.5. The growth rate of InAs layers is 0.75 µm/h, while the layers thickness is 2 µm. A 5 µm-thick InAs layer was grown to measure differential Hall. In situ RHEED (Reflection High Energy-Electron Diffraction) was used to monitor the growth process.

Hall measurement using Van der Pauw method was used to evaluate the electrical characteristics between 80 K and room temperature. This measurement was done by means of ECOPIA Hall Measurements System. Besides, the surface properties were assessed by Nomarski optical microscopy and high-resolution optical profilometry. A high-resolution X-ray diffractometer of PANalytical X'Pert was utilized to evaluate the crystallographic properties of the samples. The Cu $K\alpha_1$ radiation ($\lambda \sim 1.5406$ Å) originating from a line focus was used. The X-ray beam was monochromatized by four bounce, Ge (004) hybrid monochromator. The measurements were made in both $\omega$ and $2\theta$–$\omega$ directions.

## 3 Results and discussion

RHEED analysis exhibits that the first few InAs monolayers are consistent with the underlying GaAs buffer layer. After finishing the growth of GaAs, the RHEED is always (2 × 4), which signifies that the growth is always two-dimensional (2D). Then, the RHEED pattern changes to spotty one, indicating the onset of three-dimensional (3D) mode (island mode). After, the streaky pattern is re-established and a (2 × 4) diffraction pattern is evident (Fig. 1), pointing out a flat surface of InAs layers. This attitude confirms that InAs growth is a Stranski–Krastanov growth mode.

Figure 2 shows the surface morphology of InAs layers. As can be noticed from the figure, a shiny mirror-like was obtained with the use of GaAs (001) substrate with 2° offcut towards ⟨110⟩ (Fig. 2a). However, a lot of defects and hillocks have been obtained in the case of utilizing GaAs substrate without offcut (Fig. 2b). In terms of surface roughness (Rq), by using GaAs substrate with 2° offcut, it is four times smaller than using GaAs substrate without offcut. Those results are consistent with the works of Kim et al. (2002) and Yamamoto et al. (1997). This latter found out that the surface roughness increases as the misorientation of the substrate increases, and 2° offcut shows the best surface quality. The presented layers have been grown under optimized growth parameters (growth temperature of 400 °C and a V/III flux ratio of 8.5), if not, a rough (surface roughness of 206.5 nm) not mirror-like surface was obtained (Fig. 2c).

The comparison of the crystalline quality and electrical parameters of 2 μm-thick InAs epilayers on the GaAs substrate without offcut and that on GaAs substrate with 2° offcut towards ⟨110⟩ is shown in Table 1. Layers grown on the GaAs substrate with 2° offcut exhibit higher crystal quality and Hall mobility. For instance, the mobility in the case of GaAs substrate with 2° offcut is hugely higher than that in the case of that without offcut. Consequently, we consider further in this paper only the InAs layers grown on GaAs substrate with 2° offcut.

Owing to the nucleation sites along the surface steps, provided by offcut substrates, arrived atoms will occupy these sites and form small islands in each step, which is the characteristic of SK growth mode. The Schwoebel potential barrier at the step edges can significantly impede the surface diffusion of adatoms between the steps surfaces (Tersoff et al. 1994). On the other hand, growing on nominal GaAs (001) substrate, the islands formed by deposited material would coalesce, giving birth to large islands, which leads to higher number of dislocations.

Figure 3a exhibits the (004) X-ray diffraction curve of InAs layers. There are two peaks: that at the position $2\theta = 66.028°$, represents GaAs substrate peak, and that at the position $2\theta = 61.068°$ presents the InAs layer. Based on these XRD data, the lattice constant of InAs is 6.0647 Å, which is very close to the theoretical value ($a_{InAs} = 6.0583$ Å). In

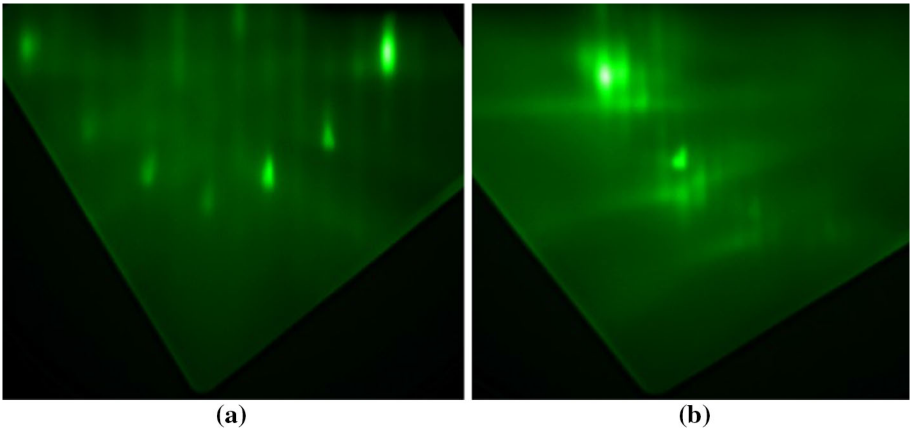


**Fig. 1** InAs layer RHEED pattern **a** (×2) pattern, **b** (×4) pattern

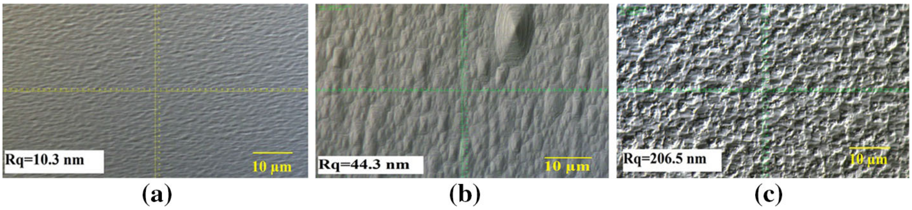


**Fig. 2** Nomarski optical microscopy pictures of 2 µm-thick InAs layer grown at 400 °C on GaAs (001) substrate with 2° offcut towards ⟨110⟩ (**a**) and GaAs (001) substrate without offcut (**b**) and GaAs (001) substrate without offcut under not optimized growth parameters (growth temperature of 530 °C and a V/III flux ratio of 12.5) (**c**)

**Table 1** Comparison of crystalline quality and electrical parameters of InAs layers grown on GaAs substrate and that on GaAs substrate with 2° offcut

| Substrate | InAs peak FWHM, arcsec | Concentration (300 K), $cm^{-3}$ | Mobility (300 K), $cm^2/Vs$ |
|---|---|---|---|
| Just GaAs | 347 | $-1.42 \times 10^{16}$ | 8487 |
| 2°-off GaAs | 233 | $-1.27 \times 10^{16}$ | 12,970 |

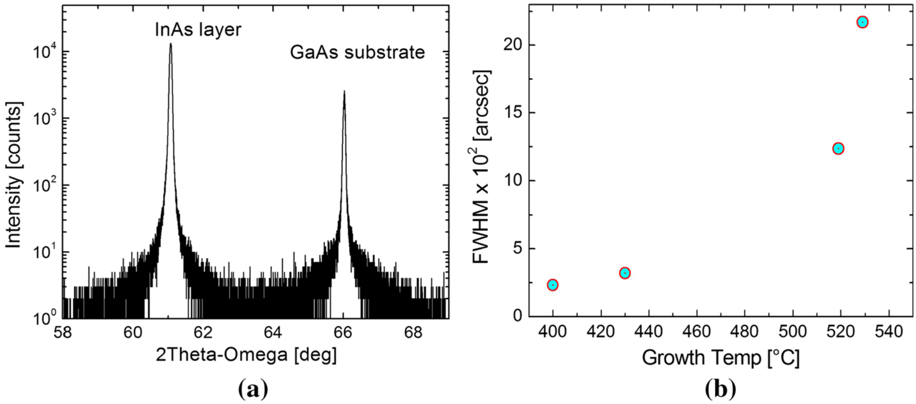


**Fig. 3** (004) X-ray scan in 2θ-ω direction (**a**) and InAs peak FWHM as a function of growth temperature (**b**) of 2 µm-thick InAs layers

addition, Fig. 3b illustrates the full width at half maximum (FWHM) of InAs epilayers measured in the ω direction, as a function of the substrate temperature. The FWHM increases significantly as the growth temperature increases. The same tendency was reported by Hooper et al. (1993). The best crystal quality was obtained for growth temperature of 400 °C, FWHM was 233 arcsec. For a thickness of 5 µm, InAs layer has a FWHM of 156 arcsec under the same substrate temperature. Przesławski et al. (2000) reported a FWHM of 170 arcsec for a 5 µm-thick InAs layer. The poor crystalline quality at higher growth temperature is *probably* due to the formation of extended defects due to the evaporation of arsenic from the surface.

Hall effect measurements of InAs layers revealed *n*-type conduction. As follows from Fig. 4a, the carrier concentration weakly depends on the growth temperature. A Hall

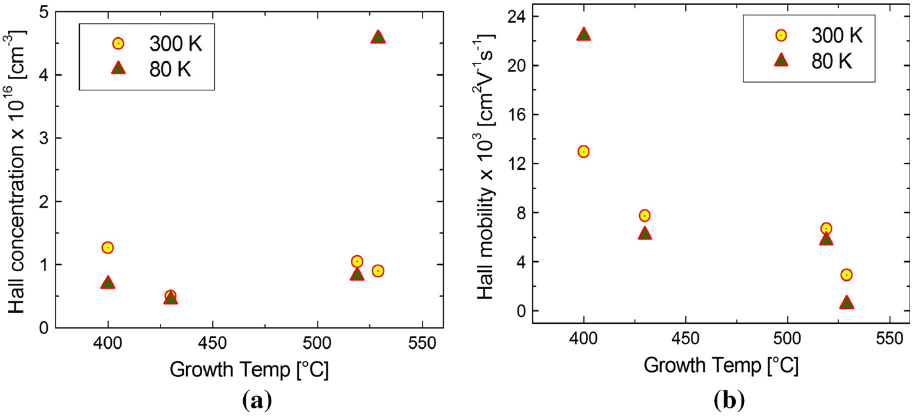


**Fig. 4** Hall concentration (**a**) and Hall mobility (**b**) of 2 μm-thick InAs epilayers as a function of substrate temperature measured at 80 K and at room temperature

concentration as low as $1.3 \times 10^{16}$ and $6.9 \times 10^{15}$ $cm^{-3}$ at 300 and 80 K, respectively, for a thickness of 2 μm.

As follows from Fig. 4b, the Hall mobility decreases rapidly as the growth temperature increases. This behavior is due to the point and extended defects generated at higher growth temperatures, which act as scattering centres. The evidence of this high concentration of defects is the high values of FWHM of InAs layers at higher temperatures. The peak values for a thickness of 2 μm are: 12,970 and 22,420 $cm^2$/Vs at 300 and 80 K, respectively, for a growth temperature of 400 °C. The Hall mobility trend is consistent with the work of Hooper et al. (1993), where they reported a room temperature mobility of 13,000 $cm^2$/Vs at a growth temperature of 300 °C. Also, Westwood et al. (1989) pointed out a room temperature mobility of 16,400 $cm^2$/Vs, for a 2.8 μm-thick InAs layer grown at 330 °C. For a 5 μm-thick InAs layers, a Hall mobility as high as 33,750 $cm^2$/Vs has been obtained at room temperature.

With the purpose of investigating the electrical parameters along the depth of the InAs layer, the differential Hall measurement has been carried out, and the results are presented in Fig. 5. At first, we perform Hall effect measurement for a 5 μm-thick InAs layer (whole

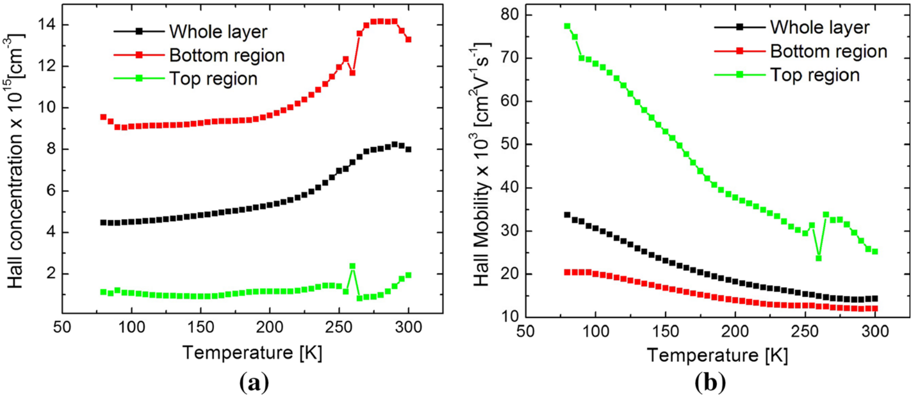
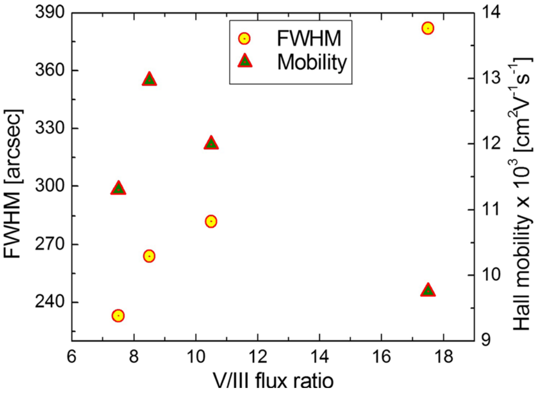


**Fig. 5** Hall concentration (**a**) and mobility (**b**) of a 5 μm-thick InAs layer, 2 μm-thick top region, and 3 μm-thick bottom region. The layer was grown at 400 °C

**Fig. 6** FWHM and room temperature Hall mobility of 2 µm-thick InAs layers grown at 400 °C as a function of V/III flux ratio



layer). After, we etch 2 µm of this layer, and we make Hall effect measurement for this layer (bottom layer). Having done this, we calculate the electrical parameters for the 2 µm-thick etched layer (top layer). As can be seen in this figure, the bottom layer shows significantly higher carrier concentration than the top layer, which confirms that the dislocations density decreases from the interface to the layer surface. The top layer exhibits a low Hall concentration, $1.12 \times 10^{15}$ and $1.93 \times 10^{15}$ $cm^{-3}$ at 80 K and at room temperature, respectively. This result is almost equal to the intrinsic concentration of InAs at 300 K, which is $1 \times 10^{15}$ $cm^{-3}$. Besides, this top layer has a high carrier mobility, 77,380 and 25,275 $cm^2$/Vs at 80 and 300 K, respectively. This investigation confirms that the dislocations are virtually situated in the interface between GaAs substrate and InAs layer, and the dislocations distribution decreases as the thickness increases. The same outcome was observed by Chang et al. (1980), who reported a dislocation density of $\sim 3 \times 10^9$ $cm^{-2}$ for a 0.2 µm-thick InAs layers, but for a thickness of 2 µm, the dislocation density was one order of magnitude lower.

After investigating the effect of growth temperature, we studied the influence of V/III flux ratio on the InAs layer quality. As can be seen from Fig. 6, the FWHM of InAs layers increases drastically as the $As_4$/In flux ratio increases. On the other hand, below a V/III flux ratio of 8.5, the mobility increases to its maximum value of 12,970 $cm^2$/Vs, then, it decreases to 9756 $cm^2$/Vs as the V/III flux ratio increases from 8.5 to 17.5. Consequently, the $As_4$/In flux ratio of 8.5 leads to the best InAs epilayer quality.

## 4 Conclusions

In summary, we have investigated the effect of growth temperature, $As_4$/In flux ratio and GaAs substrate misorientation on the structural, surface morphology and electrical properties of InAs epilayer grown by molecular beam epitaxy. Shiny mirror-like InAs layers have been grown. It is found that this growth follows Stranski–Krastanov growth mode. In Addition, the growth on GaAs (001) substrate with 2° offcut has been demonstrated to exhibit higher layer quality than that without offcut. The high quality InAs layer has a carrier concentration (mobility) of $1.3 \times 10^{16}$ $cm^{-3}$ (12,970 $cm^2$/Vs) and $6.9 \times 10^{15}$ $cm^{-3}$ (22,420 $cm^2$/Vs) at 300 and at 80 K, respectively. Differential Hall measurements revealed a high carrier concentration and low mobility in the first-to-grow layers, which is due probably to the high concentration of dislocations. Besides, the top layer exhibits a high Hall mobility (77,380 $cm^2$/Vs at 80 K) and low Hall concentration ($1.1 \times 10^{15}$ $cm^{-3}$ at 80 K). This confirms the high quality of top part of InAs layer, which can be viable in infrared detectors as defect-free buffer layer.

**Acknowledgments** This paper has been completed with the financial support of the Polish National Science Centre, Project: UMO-2015/17/B/ST5/01753.

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