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Overcoming Ehrlich-Schwöbel barrier in (1 1 1)A GaAs molecular beam epitaxy

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A B S T R A C T

In this work, we first study the effect of different growth parameters on the molecular beam epitaxy (MBE) growth of GaAs layers on (1 1 1)A oriented substrates. After that we present a method for the MBE growth of atomically smooth layers by sequences of growth and annealing phases. The samples exhibit low surface roughness and good electrical properties shown by atomic force microscopy (AFM), scanning electron microscopy (SEM) and van-der-Pauw Hall measurements.

1. Introduction

In recent years new results on spin transport in [1 1 1]-oriented GaAs quantum well structures gave rise to the interest in growth on [1 1 1]-oriented GaAs substrates again. Effectively tuning spin lifetimes by applying electrical fields across the (1 1 1) direction was shown lately [1–3]. Besides, [1 1 1]-oriented surfaces were used for droplet epitaxy, generating quantum dots with strongly reduced fine structure splitting for the exciton and biexciton states [4–5]. These recent results were all achieved with samples MBE grown on misoriented substrates to enable higher layer quality and smooth inter- and surfaces. For the case of spin transport, this means an additional contribution adds to the spin-orbit interaction, limiting the spin lifetimes [1]. To overcome the need of miscut wafers, we investigate growth conditions for (1 1 1)A-oriented substrates like arsenic species, substrate temperature and As:Ga ratio which finally lead to atomically smooth surfaces and high crystal quality. MBE growth is typically done on the (0 0 1) – 2×4 reconstructed surface, which shows a unique nucleation process [6]. The 2×4 reconstruction only occurs after a minimum island size is reached, preventing the nucleation of new layers on small islands. This results in smooth, well ordered layers over a wide range of growth conditions compared to other orientations which show a more common two-dimensional island growth [6]. Instead, the (1 1 1)A surface shows a 2×2 reconstruction under a wide range of parameters [7]. It is already shown by *Yamaguchi* et al., that InAs layers of high quality can be grown on (1 1 1)A GaAs surfaces due to strain relaxation after about 2 nm [8]. Recently, *Esposito* et al. published a study on the growth of AlGaAs and identified a high Ehrlich-Schwöbel barrier to be the driving force behind the 3D island growth on (1 1 1)A-oriented substrates. By carefully adjusting the growth parameters to low growth rates and high arsenic fluxes, they were able to grow atomically smooth 100 nm thick $Al_{0.3}Ga_{0.7}As$ layers [9]. We follow this approach for GaAs homoepitaxy with significant lower V/III ratio, i.e. higher growth rates and lower arsenic pressures, and still overcome the Ehrlich-Schwöbel barrier thermally by introducing growth interrupting annealing steps.

2. Experimental setup

Epitaxial growth is performed in a RIBER III-V Epineat MBE System on semi-insulating GaAs(1 1 1)A substrates without

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intentional miscut. The wafers are degassed at 150 °C in the preparation chamber before transfer to the growth chamber where deoxidization takes place at 650 °C under arsenic atmosphere. The substrate temperature is measured with an IRCON infrared pyrometer aimed at the substrate center. Arsenic is supplied at different cracker temperatures from a valved cracker cell. The arsenic valve is set to a flux beam equivalent pressure (BEP) of 1.3×10^{-5} Torr measured at a cracker temperature of 500 °C. This is done for all samples to take account of the fact that our flux gauge is sensitive to the arsenic species. The As:Ga BEP is measured by an ion gauge and controlled by variation of the growth rate found on a GaAs (0 0 1) substrate using reflection high-energy electron diffraction (RHEED) intensity oscillations. The surface has then been ex-situ imaged by scanning electron microscopy (SEM) and the surface roughness is measured by atomic force microscopy (AFM). Hall measurements are taken with a self-build van-der-Pauw Hall setup on a 3×4 mm^2 device with In contacts soldered to the corners.

3. Experiments and results

Samples with 500 nm thick GaAs layers are grown under the following different growth parameters to investigate the effects on the surface morphology. Three samples are grown under different V/III-ratios, three at different substrate temperatures and three for different cracker temperatures, i.e. different arsenic species (see Table 1). For a cracker temperature of 500 °C we expect a nearly pure As_4 flux and for 900 °C a nearly pure As_2 flux. A cracker temperature of 700 °C results in the highest carrier mobilities of about 5×10^6 cm^2/Vs at 4.2 K. These mobilities are achieved on one-sided modulation-doped GaAs/$Al_{0.34}Ga_{0.66}As$ heterostructures on (0 0 1) substrates. The heterostructure consists of a quasi-two-dimensional electron system in GaAs 125 nm below the surface. The following layer sequence consists of a 40 nm undoped $Al_{0.34}Ga_{0.66}As$ spacer layer, 80 nm of $Al_{0.34}Ga_{0.66}As$ with a silicon doping density of 2×10^{18} cm^{-3} and a 5 nm GaAs cap.

Figs. 1–3 show SEM images of GaAs layers grown under different conditions. The root-mean-squared-roughness (RMS-R) ranges from 23.9 nm to 2.2 nm found for a BEP ratio of 116.6 and a substrate temperature of 550 °C. It should be noticed here that this result may still be optimized by adjusting the growth parameters. The trend of best sample quality on lowered substrate temperature and high III/V ratio is also reported by *Sato* et al. [10].

However, none of these surfaces is defect free and atomically smooth. The preferred 3D island growth is explained by a high Ehrlich-Schwöbel barrier on the step edges of growing 2D islands [9]. Instead of merging into step edges Ga adatoms tend to be reflected and find another adatom on the 2D island with which

Table 1
Samples grown for the growth parameter study. Sample #10 was grown at 550 °C and annealed at 650 °C for 5 min every *50* nm.

#	As:Ga [BEP]	Substrate temperature [°C]	Cracker temperature [°C]	Rms-roughness [nm]
1	30.4	600	500	23.9
2	58.3	600	500	7.4
3	116.6	600	500	5.0
4	116.6	550	500	2.2
5	116.6	650	500	7.1
6	116.6	600	700	4.0
7	116.6	600	900	6.9
8	116.6	550/650	700	0.3

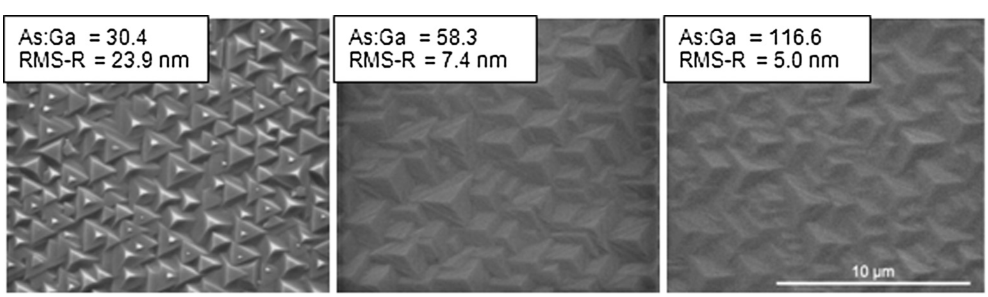

Fig. 1. SEM images of GaAs layers grown with different As:Ga BEP ratios 30.4, 58.3 and 116.6 (corresponding to growth rates of 0.72 µm/h, 0.36 µm/h and 0.18 µm/h) with rms-roughnesses 23.9 nm, 7.4 nm and 5.0 nm. Substrate temperature is set to 600 °C and cracker temperature to 500 °C.

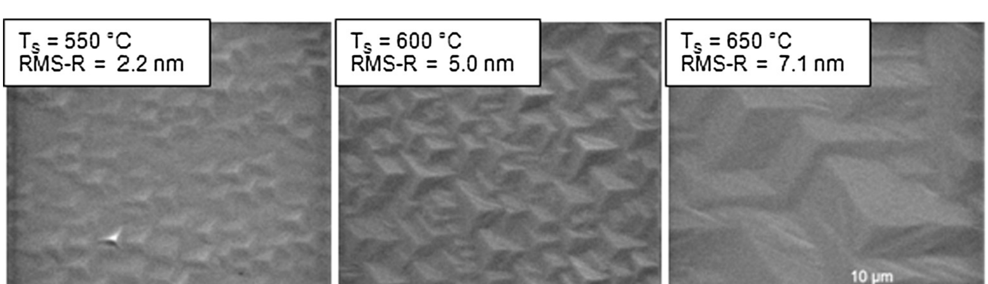

Fig. 2. SEM images of GaAs layers grown at different substrate temperatures 550 °C, 600 °C and 650 °C with corresponding rms-roughnesses 2.2 nm, 5.0 nm and 7.1 nm. As:Ga BEP is set to 116.6 and cracker temperature to 500 °C.