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GROWTH CONDITION DEPENDENCE OF RHEED PATTERN FROM GaAs (111)B SURFACE

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ABSTRACT

A 3-dimensional phase diagram is introduced to describe the dependence of the RHEED pattern from GaAs(111)B surface on growth conditions. The 2x2, transitional(1x1), and $\sqrt{19}$x$\sqrt{19}$ surface reconstructions correspond to different zones in the phase diagram. A equation is given for the planes that separate these zones, which fit experimental data well. Homoepitaxial films on GaAs(111)B grown in the 2x2 region generally have bad crystal quality as determined by the ion channeling, and growth in the $\sqrt{19}$x$\sqrt{19}$ region generally yields rough surface morphology. At higher substrate temperatures (~ 650 °C), featureless films with minimum ion channeling yields of less than 4% are achieved.

INTRODUCTION

Recently, more attention has been paid to the epitaxial growth on GaAs(111) substrates because the (111) orientation has several special properties. InGaAs/GaAs strained-layer superlattices (SLS) on GaAs(111) substrate have been predicted to have large linear electrooptic coefficients due to the strong piezoelectrically generated internal electric field.[1] Experimental studies on the optical properties of (100) and (111) oriented GaInAs/GaAs SLS have provided the evidence that agrees with the prediction.[2] In addition, Caridi et al. have fabricated p-i-n diodes grown on GaAs(111)B substrate by molecular beam epitaxy (MBE), with InGaAs in the intrinsic region. Photoconductivity spectra of such diodes show a blue shift of the quantum well band edge under reverse bias operation[3]. All this work indicates the possibility of fabricating novel electro-optical devices with a strong built-in electric field. High quality epitaxial films on GaAs(111) are crucial for turning this possibility into reality. Unfortunately, current understanding of epitaxial growth on the GaAs(111) surface, in comparison with that on GaAs(100), is poor and incomplete because only a limited number of studies have been done so far. Both homoepitaxial and heteroepitaxial films grown on GaAs(111)B, InAs(111)B, and InP(111)B usually show rough surface morphology, often exhibiting threefold pyramid, terrace, and other types of defects.[4,5,6,7] Hayakawa et al. have reported the achievement of specular surface on GaAs and AlGaAs films grown at 720 °C on 0.5° misoriented GaAs(111)B substrate at by MBE. Further, they showed that (111) oriented single quantum wells (SQW) have photoluminescence (PL) intensity about one order magnitude higher than (100) oriented SQW.[8] The threshold current density of the (111)B oriented quantum well laser is extremely low.[8,9] Most recently, Imaota demonstrated that AlGaAs layers with featureless surface morphology can be grown on on-axis (111)B oriented GaAs at temperatures as low as 500 °C by migration-enhanced epitaxy (MEE).[11] In this paper, we report the successful epitaxial growth of GaAs films with featureless surfaces on exactly (111)B substrates by MBE. The dependence of RHEED patterns of GaAs(111)B surfaces on the growth conditions is presented in a three-dimensional phase diagram. Ion channeling characterization is also presented.

EXPERIMENTAL

All film growth studies were done in a VG90 MBE system. Reflection high energy electron diffraction (RHEED) of 15keV was used. Growth rates were between 0.3 μm to 0.5 μm per hour. The thickness of all deposited films was about 0.5 μm. Initially, an As_4 source was used for the RHEED pattern studies and the low temperature (from 480 °C to 560 °C) growth studies. Afterwards, an As_2 source was installed into the deposition chamber. At a substrate temperature of 560 °C and As to Ga flux ratio of 40, no significant differences in film quality (in terms of surface morphology and ion channeling results) were found between the films grown with As_4 and As_2. Comparative studies of As_4 and As_2 for the (111) films at other growth condition are on going.

RESULT AND DISCUSSION

The GaAs(111)B surface exhibits three types of reconstruction: 2x2, transitional(1x1), or $\sqrt{19}\times\sqrt{19}$, depending on the growth conditions. If a 3-dimensional phase diagram is constructed, with substrate temperature, arsenic flux, and Ga flux as the three parameters, then the 2x2, transitional(1x1), and $\sqrt{19}\times\sqrt{19}$ RHEED patterns will correspond to three distinct zones. The planes that separate the different surface reconstruction zones in the diagram (called separation planes here) can be approximately represented by

$$C_1F_{As_4} - C_2exp(-E/kT) - F_{Ga} = 0, \qquad (1)$$

where F_{Ga} and F_{As_4} are the Ga and As fluxes, respectively, E is the activation energy, k is Boltzmann's constant, and T is the substrate temperature. C_1 is the sticking coefficient, and C_2 is a coefficient that is related to As desorption. The equation was obtained by assuming that the separation planes are equi-arsenic-coverage planes. E, C_1, and C_2 can be determined experimentally. C_1 and C_2 are assumed to be related to the surface arsenic coverage by

$$C_1 = a(1-\theta), \qquad (2)$$

and

$$C_2 = b\theta, \qquad (3)$$

where θ is the normalized arsenic surface coverage, a and b are the constants. By choosing exp(E/kT), F_{As_4}, and F_{Ga} as the three variables for the phase diagram, Eq.(1) represents planes, as opposed to more complex surfaces. In Fig. 1, the lower plane represents the growth conditions at which the half integer lines (indicative of the 2x2 reconstruction) of the RHEED pattern just completely disappear, and the upper plane represents the growth conditions at which the lines that correspond to $\sqrt{19}\times\sqrt{19}$ reconstruction just appear. Although using a 3 dimensional diagram to illustrate the dependence of RHEED patterns on growth conditions is more involved than the conventional flux ratio versus substrate temperature plot[4,11], it gives a more complete description. In Fig. 2(a), we fitted the equation with our experimental data and found E=2.53eV. The values of C_1 and C_2 determined from other plots in Fig. 1 are 1.72×10^{-3} and $5.4\times10^{29}cm^{-2}s^{-1}$ respectively for the lower plane, and 3.6×10^{-3} and $1.5\times10^{29}cm^{-2}s^{-1}$ respectively for the upper plane. Furthermore, we calculated θ from the values of C_1 and C_2 by using Eq. (2) and Eq. (3). The value of θ is 0.9 for the lower plane and 0.75 for the upper plane. These values are close to the results of the studies by Auger

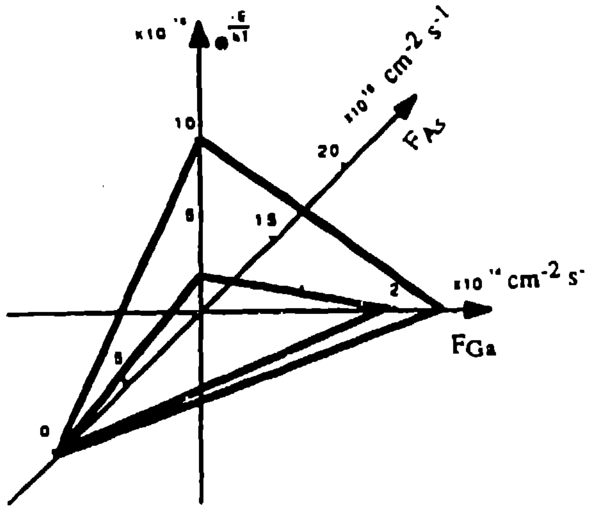

Fig. 1. The 3-D phase diagram describing the dependence of the RHEED pattern of GaAs(111)B surface on the growth condition. Above the upper plane, RHEED pattern shows √19x√19 reconstruction. Below the lower plane, RHEED pattern shows 2x2 reconstruction. The region between the two planes is a transitional region, in which RHEED pattern usually shows 1x1 reconstruction. The upper plane can be represented by equation

$$3.6E\text{-}3\ F_{As} - 4.5E29\ \exp(-E/kT) - F_{Ga} = 0,$$

and the lower plane can be represented by equation

$$1.7E\text{-}3\ F_{As} - 5.4E29\ \exp(-E/kT) - F_{Ga} = 0.$$

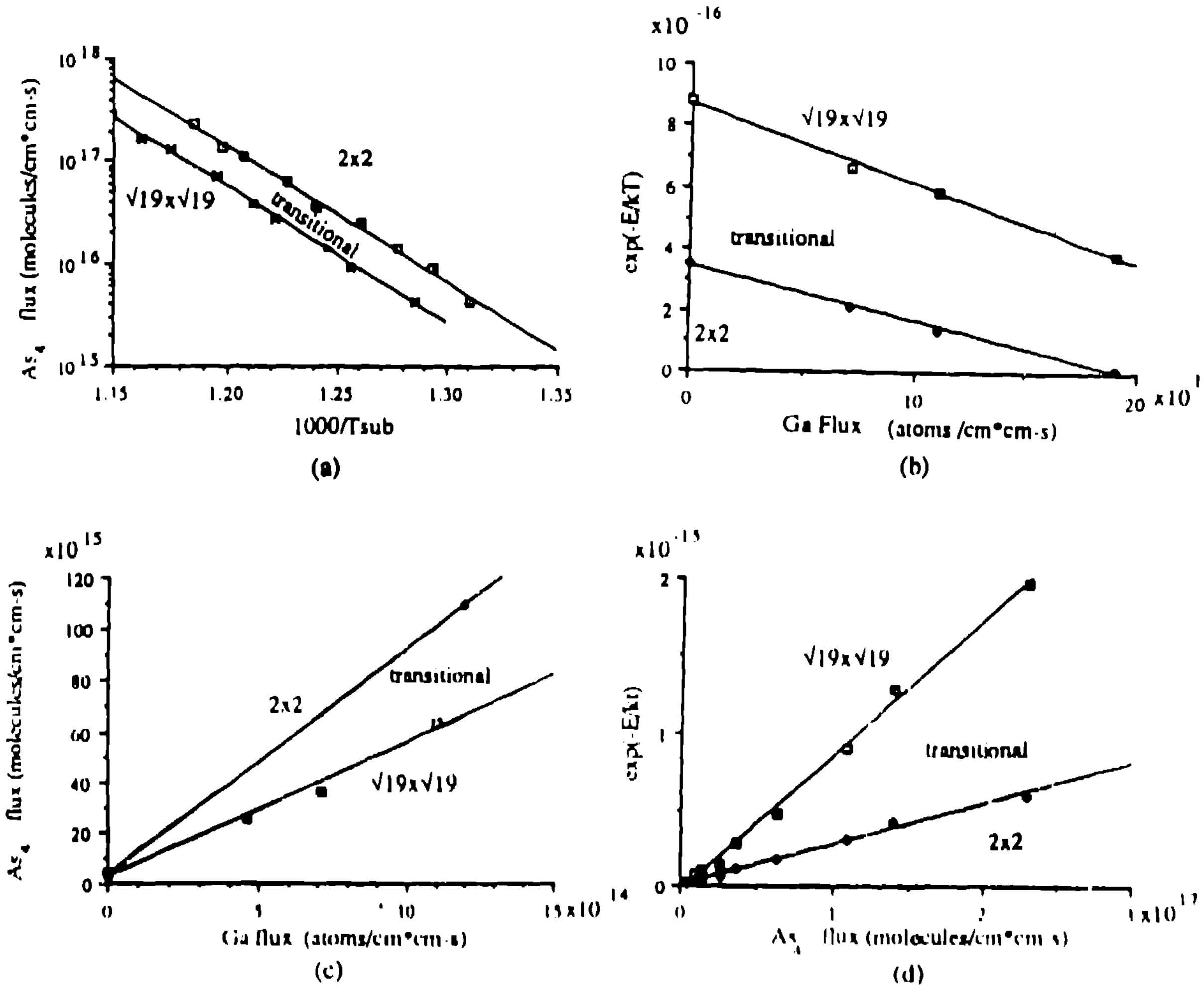

Fig. 2 Experimental data fitting to Eq. (1). From (a), the activation energy E is found to be 2.53eV. Plots in (b), (c), and (d) are actually the three perpendicular cross sections of the 3-D phase diagram in Fig. 1. C_1 and C_2 can be extrapolated from the plots.

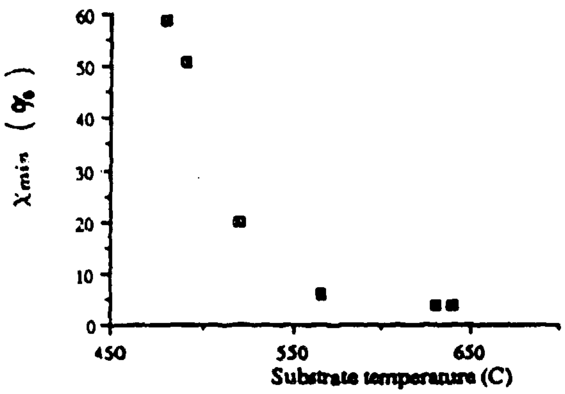

Fig. 3. The minimum ion channeling yield for the GaAs (111)B homoepitaxial films grown at different substrate temperatures.

Fig. 4. RHEED pattern of GaAs (111)B film growing at 480 °C, 0.3μm/hour, and flux ratio 40.

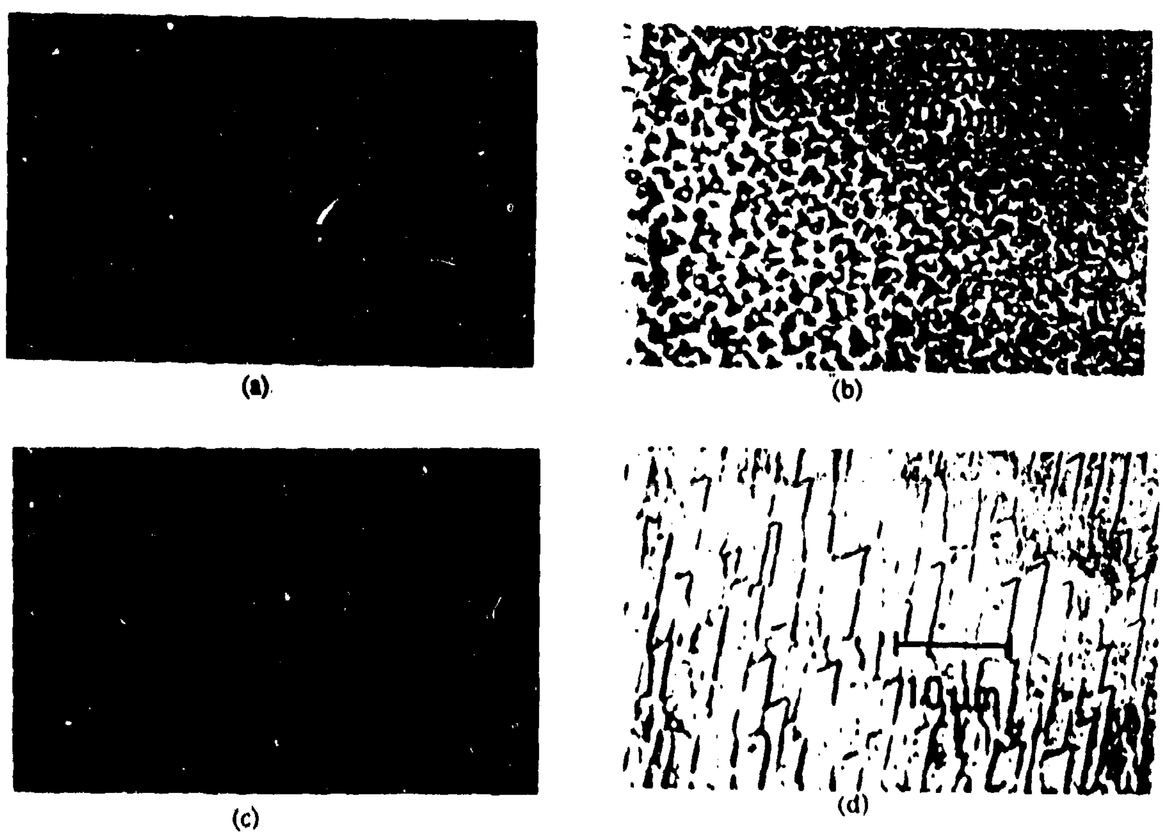

Fig. 5. Optical micrographs for the GaAs (111)B films grown at different temperatures and substrates. (a), (b), and (c) are the surfaces of films grown on on-axis (111)B substrates at 480 °C, 550 °C, and 590 °C respectively. (d) is the surface of the film grown on a (111)B substrate 4° off toward [1$\bar{1}$0] direction.

electron spectroscopy.[12]

Several undoped GaAs homoepitaxial films were grown at growth rates between 0.2μm and 0.5μm, flux ratios between 30 and 50, and substrate temperatures ranging from 480 °C to 650 °C. The minimum ion channeling yield χ_{min} at an ion energy 2 MeV, for samples grown at different substrate temperatures, is shown in Fig. 3.

At low temperatures (from 480 °C to 520 °C), the RHEED pattern shows a 2x2 reconstruction. A few minutes after the deposition. several streaks that are not perpendicular to the shadow edge appear as shown in Fig. 4, indicating surface facet formation. If the sample is annealed at a temperature of ~600 °C, these facets lines will vanish. The surface looks shiny, but close inspection with optical microscope shows high density of surface defects of size ~1μm. as shown in Fig. 5(a). The χ_{min} for these samples is large and no excitonic peaks were observed in the photoluminescence (PL) spectrum.

In the substrate temperature range from 540 °C to 600 °C, the RHEED pattern shows $\sqrt{19}$x$\sqrt{19}$ reconstruction during the growth. Ion channeling results are much improved for this temperature range. Excitonic peaks are detected in the PL spectrum at 10 K, as shown in Fig. 6. However, the surfaces are very rough. The films exhibit three-fold pyramids on the surface, as shown in Fig. 5(b) and Fig. 5(c) which were also found in homoepitaxial InAs films[5]. The pyramids' bases, but not necessarily their heights, become larger as the substrate temperature goes higher. This could indicate that the pyramids are caused by insufficient surface mobility, instead of surface carbon contamination. as believed previously. The planes of the pyramids are no more than 8° tilted from the substrate surface. according to laser light scattering experiments, a phenomena also observed by Sugiyama[5]. The films grown on tilted substrates (1°. 2°, and 4° off toward [110], and 2° off toward [100]) exhibit saw-tooth wave morphology, as shown in Fig. 5(d).

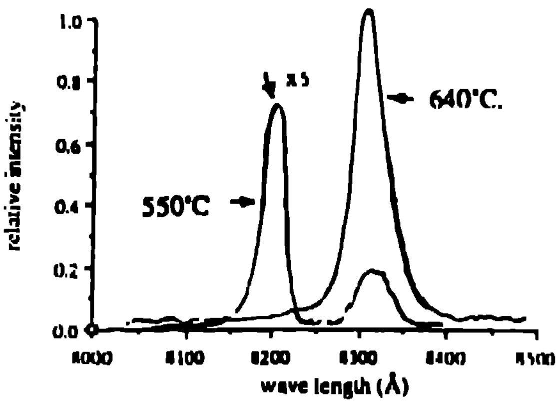

Fig. 6. Photoluminescence spectrum of the films grown at 550°C and 640°C.

At the substrate temperature ~ 640 °C, the RHEED pattern was $\sqrt{19}$x$\sqrt{19}$ before deposition and became faint after starting the deposition. The surface of the films grown at this temperature are featureless. This success is probably because the base size of the pyramids mentioned in the last paragraph becomes infinite at such a high growth temperature. The minimum ion channeling yield χ_{min} for the films grown at this temperature is always less than 4%. The PL spectrum at 10 K shows a peak that is probably related to the excitons bounded to carbon impurities. X-ray diffraction results also indicate good crystal quality. InGaAs films can not be grown at 640 °C because of the strong indium re-evaporation[13]. Even with high In flux during the growth, Rutherford back scattering (RBS) shows no indium concentration. However, the growth of GaAs at this temperature is confirmed by a specially designed experiment. In this experiment, the thickness of a GaAs film grown at 640 °C on a buried InGaAs layer is measured by RBS technique. The measured thickness indicates that the growth rate at 640 °C is not very much different from that at low temperature.

CONCLUSION

A new way of presenting surface reconstruction phase diagram has been introduced. The diagram gives a complete description of the dependence of the RHEED pattern on the growth conditions. The equations of the planes that separate different phase zones in the diagram are given. The planes are approximately equi-As-coverage planes. Growth in the 2x2 reconstruction region generally yield poor crystal quality (as indicated by ion channeling) even though surface of the epitaxial layer looks shiny. Growth in the $\sqrt{19}\times\sqrt{19}$ reconstruction regions yield pyramid surface morphology. By going to higher temperatures (~640 °C), good surface morphology along with high crystal quality are achieved.

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