ABSTRACT

Growth of (111)B oriented GaAs, GaInAs, and AlInAs by MBE was investigated through a study of surface morphology, RHEED patterns, and photoluminescence. Considering growth on both nominally oriented and 2° mis-oriented (111)B GaAs substrates, we have found that MBE growth in the (111)B direction proceeds quite differently than (100) growth. Except in the case of high substrate temperature growth on nominally oriented (111)B substrates, the growth of (111)B GaAs and GaInAs results in films which are characterized by macroscopically rough or faceted surfaces and by weak photoluminescence. We demonstrate that the surface morphology of these macroscopically rough films may be dramatically improved by growing with modulated Ga and In fluxes. Also, we find that AlAs and Al-containing alloys grow much more smoothly than GaAs on the (111)B surface. We report an AlAs/Al0.5In0.5As strained MQW structure which exhibits both good surface morphology and good photoluminescence spectra. Growth mechanisms which may explain the observed differences between (111)B and (100) MBE growth are proposed.

INTRODUCTION

Recently, there has been considerable interest in (111) oriented zinc-blend semiconductor structures[1],[2],[3]. It was reported that quantum wells grown in the [111] direction possess an enhanced optical transition, and a low-threshold (111) quantum well laser has been demonstrated[1]. Also, it has been theoretically predicted that coherently strained (111) layers will possess large built-in electric fields through the piezoelectric effect, an effect that vanishes in (100) oriented strained layers due to symmetry constraints[2]. The existence of such strain-induced built-in electric fields can lead to a whole new class of self-biased optical and electronic devices; enhanced nonlinear optical structures[4] and a novel 2-D electron gas structure[5] have already been proposed. Critical to the exploitation of these and other novel (111) structures is an understanding of (111) crystal growth mechanisms, and of the related optimal growth conditions and materials necessary for the attainment of high quality (111) layers.

Previous experimental work in the area of (111) epitaxy has concentrated on the growth of GaAs and GaInAs layers by Molecular Beam Epitaxy (MBE). Vina and Wang found that while MBE growth of GaAs on nominally oriented (111)B GaAs substrates yielded poor material, improved quality GaAs could be obtained by growing on 2° misoriented (111)B substrates[6]. However, Hayakawa et.al. found that optimal GaAs growth took place on 0.5° mis-oriented (111)B substrates. Most recently, photoluminescence has been reported from both Si doped GaAs and undoped GaAs/GaInAs quantum wells which were grown on nominally oriented (111)B substrates[7],[8].

In the present work, we examine the question of optimal (111) growth conditions by considering the growth of GaAs and GaAs/GaInAs quantum well structures on both
nominally oriented and 2° mis-oriented (111)B GaAs substrates. Based on our observations of surface morphology, RHEED patterns, and photoluminescence, we propose new growth mechanisms which may explain the differences between (111) and (100) growth. We show that by modulating the Ga and In fluxes during growth, GaAs and GaInAs layers are obtained which are smoother than those obtained by continuous MBE growth. We also demonstrate that AlAs and high Al-content alloys grow more smoothly than GaAs in the (111)B direction. We present an AlAs/GaInAs MQW structure which exhibits good surface morphology and the best PL signal that we have yet observed from a (111) oriented MQW structure. Both this result and the improvement of GaAs/GaInAs morphology through modulation of the Ga and In fluxes are readily explained by our newly proposed (111) growth mechanisms.

RESULTS AND DISCUSSION

As pointed out by earlier workers[1],[6],[7], growth on the (111)B surface is quite different from growth on the (100) surface. We first investigated these differences by considering the growth of GaAs on a nominally oriented (111)B GaAs substrate using the same growth conditions that lead to high quality (100) GaAs growth in our Varian GenII MBE system; that is a substrate temperature of 610°C, an $\text{As}_4$ beam equivalent pressure (BEP) of $10^{-5}$Torr, and the Ga flux adjusted for a GaAs growth rate of 1µm/hr, as calibrated by RHEED oscillations on a (100) surface. The resultant growth is characterized by a very faceted or hillocked surface, and a corresponding RHEED pattern which shows both streaks and spots, as depicted in Fig. 1(a).

Next, again considering growth on a nominally oriented (111)B GaAs substrate, the substrate temperature was raised to 710°C and the Ga flux reduced, and a smooth GaAs layer was obtained, Fig. 1(b). As is usual with high substrate temperatures, the RHEED pattern is somewhat faint, but it does show streaks which remain approximately constant in terms of both width and intensity throughout the growth. The layer depicted in Fig. 1(b) is approximately 1.5µm thick and exhibits a photoluminescence signal with a full width at half max (FWHM) of 7meV at 77°K. If we can neglect the difference between nominally oriented and 0.5° mis-oriented (111)B substrates, this result seems to agree with the result of Hayakawa et.al. which reported high quality GaAs growth at a substrate temperature of 720°C on a 0.5° tilted substrate[1]. Although it seems this high substrate temperature regime is well suited to growing GaAs, unfortunately it is not an option for growing indium containing layers, as indium will re-evaporate at these high substrate temperatures.

Growth at lower substrate temperatures is considered next. We consider a substrate temperature of 510°C and a reduced GaAs growth rate of 0.25µm/hr. Unlike the situation at the higher temperatures, at the onset of growth we see a well defined, streaked RHEED pattern, Fig. 1(c). However, as growth proceeds the RHEED pattern fades, becoming more diffuse, and corresponding with the RHEED degradation is resulant rough surface morphology, Fig. 1(c). In this lower temperature regime, we have observed similar behavior on both nominally oriented and 2° mis-oriented substrates. We have also observed photoluminescence from GaAs/GaInAs quantum well structures grown in this regime, but it has been of weak intensity and relatively broad.

In Fig. 1(d), we present the surface morphology and corresponding RHEED pattern for GaAs grown at higher substrate temperatures on 2° mis-oriented substrates. The main point of interest here is that the surface is once again faceted, but now the facet formations are smaller and directional, all lined up along the step edges. Also, this behavior is observed even at temperatures greater than 700°C, where we previously observed smooth growth on the untilted substrates, Fig. 1(b).
Fig 1. Surface morphologies and RHEED patterns of GaAs (a) $T_{\text{sub}} = 610^\circ\text{C}$, As BEP=10$^{-6}$Torr, nominally oriented (111)B, (b) $T_{\text{sub}} = 710^\circ\text{C}$, As BEP=3x10$^{-5}$, nominally oriented (111)B, (c) $T_{\text{sub}} = 510^\circ\text{C}$, As BEP=9x10$^{-6}$, nominally oriented and 2° mis-oriented (111)B, (d) $T_{\text{sub}} \geq 600^\circ\text{C}$, As BEP $\gtrsim 10^{-5}$Torr, 2° mis-oriented (111)B. (RHEED observed along [1\(\overline{2}\)1])
Considering, for simplicity, the unreconstructed (111)B and (100) GaAs surfaces, we note that each As atom on the (111)B surface possesses just a single dangling bond, while the As atoms on the (100) surface each have two dangling bonds. It is widely believed that As dimers on the (100) surface play a crucial role in both surface reconstruction and in the stable incorporation of Ga atoms into the GaAs crystal[9]. Basically, the interaction between a Ga atom and a single dangling As bond is quite unstable and short lived, while the interaction of Ga with multiple As bonds can yield much more stable surface configurations[9]. Based on these considerations, we suggest that Ga is less reactive with As and more mobile on the (111)B surface. If Ga is less reactive with As and more mobile on the (111)B surface, then the possibility of Ga clustering and the formation of Ga droplets should be considered. The presence of Ga clusters on the surface can in turn lead to the growth of higher index crystal planes around the clusters, as is the case with oval defect formations. This scenario can then provide an explanation for the observed facet formations, as in Fig. 1(a). Fig. 1(d) shows small facet formations directed along the step edges and can be interpreted as suggesting that the steps are favorable sites for Ga clustering. At much higher substrate temperatures, we further speculate that Ga atoms on a nominally oriented (111)B surface which are not quickly incorporated into the lattice may be re-evaporated before migrating far enough to cluster with other Ga, leading to smooth growth, as has been observed in Fig. 1(b). However, in the presence of frequent steps, Ga can congregate and stick at the step edges before re-evaporating, which would explain the high temperature faceted growth we observe on tilted substrates, Fig. 1(d).

We investigated these ideas further by first growing GaAs with the Ga flux being modulated. By delivering just enough Ga to the surface to construct one monolayer at a time, growth proceeding in a dose by dose fashion, the possibility of Ga clustering should be reduced. As is depicted in Fig. 2, a substantially improved surface morphology is obtained. This result has also been obtained for GaAs/GaInAs strained layer structures. However, we have not observed any photoluminescence from the layers grown by this modulated flux method.

Fig. 2. Surface morphology of (111)B GaAs grown with modulated Ga flux; \( T_{\text{sub}} = 600^\circ \text{C} \), As BEP = 10\(^{-6}\)
Accepting the premise that Ga is too mobile and unreactive with As on the (111)B GaAs surface, then it is also reasonable to consider Al for improved (111)B growth, since Al is known to be less mobile and more reactive than Ga on the (100) surface. Our experiments verify this supposition, as we find AlAs and the Al-containing alloys AlGaAs and AlInAs to grow much more smoothly than GaAs on the tilted (111)B surface, Fig.3. We further demonstrate the quality of Al containing (111)B layers by examining the PL spectra from an AlAs/Al_{5}In_{5}As multiquantum well structure grown on a 2° tilted semi-insulating GaAs substrate. The structure and its PL spectra are given in Fig.4. This PL peak is the narrowest that we have yet observed from (111)B strained quantum wells. After the initial AlAs buffer layer, a 3500Å Al_{5}In_{5}As layer was grown to establish a new lattice constant, so the lattice mismatch experienced by the Al_{5}In_{5}As quantum wells would be 1.2%. Based on this target lattice mismatch, we have calculated the strength of the piezoelectrically induced built-in electric field in each quantum well to be 2.4X10^{4}V/cm. The spectral position of the photoluminescence peak shown in Fig. 4 can only be explained if we include the red-shift effect of this large built-in electric field.

![Fig. 4. Photoluminescence spectra and cross-sectional structure of (111)B AlAs/Al_{5}In_{5}As MQW structure.](https://www.cambridge.org/core/terms). Downloaded from https://www.cambridge.org/core. IP address: 54.70.40.11, on 07 Dec 2019 at 11:40:43, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1557/PROC-198-265
CONCLUSION

In conclusion, we have found MBE growth in the (111)B direction proceeds quite differently than growth in the (100) direction. Based on our observations, we have proposed Ga clustering on the (111)B surface as a possible inhibitor of smooth GaAs and GaInAs growth. In agreement with this proposal, we have reported that smoother GaAs and GaInAs growth may be achieved by modulating the Ga and In fluxes. While this modulated flux technique leads to macroscopically smoother growth, we have yet to observe an appreciable photoluminescence signal from these layers; we are continuing work to better understand these findings. Also in agreement with our suggestion of Ga clustering, we have demonstrated that AlAs grows more smoothly than GaAs on the (111)B surface. An AlAs/Al\textsubscript{0.5}In\textsubscript{0.5}As MQW structure which exhibits both good surface morphology and good photoluminescence has been presented. We believe the ability to achieve high quality (111)B AlAs/AlInAs material can lead to many new electronic and optical devices.

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