High quality (111)B GaAs, AlGaAs, AlGaAs/GaAs modulation doped heterostructures and a GaAs/InGaAs/GaAs quantum well

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(Received 20 May 1991; accepted for publication 15 July 1991)

We report the successful growth of high quality molecular beam epitaxy (MBE) GaAs, AlGaAs, AlGaAs/GaAs modulation doped heterostructures and a GaAs/InGaAs/GaAs quantum well on GaAs (111)B substrates. Modulation doped heterostructures show a 77 K mobility of 145 500 $cm^2/V\,s$ with a sheet density of 5.0×10^{11} cm^{-2}. Photoluminescence of (111)B GaAs indicates a lower carbon incorporation than achieved on (100) substrates. The low growth temperature and high material quality obtainable in (111)B growth will provide advantages for laser diodes and heterostructure field effect transistors.

III-V compound semiconductors have been traditionally grown on (100) substrates because of the wide range of growth conditions which result in good epitaxial layer quality on this crystalline orientation. However, fundamental material properties, growth mechanisms, surface kinetics, and quantum well properties can be changed or improved on orientations other than (100).[1–3] It has been theoretically predicted and observed that coherently strained (110) or (111) layers will possess a large built-in in-plane or vertical-to-plane piezoelectric field, which leads to a new class of self electro-optic devices.[4] A novel two-dimensional electron gas (2-DEG) structure has already been proposed by using this effect.[5] Natural long range ordering has been observed on (110), where 2-DEG mobility exceeds the state-of-the-art value obtained on (100).[2] Quantum wells grown on (111) possess an enhanced optical transition, and a low-threshold (111) quantum well laser has been demonstrated.[1] It is rather difficult, however, to grow high quality material on (111) substrates. Either forced two-dimensional layer-by-layer migration enhanced epitaxy or a very high growth temperature ($\sim$700 °C)[1] are required to suppress microtwins and facet growth on (111). Here, we report the first growth of high quality, atomically smooth heterostructures on (111)B, over a wide range of growth conditions.

To achieve this goal, we have examined a variety of miscuts on (111)B. A few degrees of miscut can provide growth ledges to achieve two-dimensional step flow epitaxy, which was observed by reflection high-energy electron diffraction (RHEED) in miscut (110) growth.[2] It was found that if (111)B was miscut toward ⟨211⟩ instead of ⟨100⟩ and ⟨011⟩, a wide range of miscut angles (2°–4°) can generate a smooth growth.[6] These results were confirmed by recent growth on (111)B InP, with 1° miscut toward ⟨211⟩.[7] We have thus used this miscut to study material growth on (111)B. Although it was also found 0.5° miscut toward ⟨100⟩ can also achieve very high quality material,[1] we did not study this special miscut here, because exact 0.5° miscut is extremely difficult to control. The proper choice of miscut is the key to achieving high quality material on (111), over a wide range of growth conditions.

Our samples were grown in a Varian Modular GEN II molecular beam epitaxy (MBE) system. The samples were grown on (111)B GaAs at substrate temperature of 550–650 °C, with a group V/III beam equivalent pressure (BEP) ratio of 15–30. Typical growth rates for GaAs, $Al_{0.3}Ga_{0.7}As$, $In_{0.21}Ga_{0.79}As$ were 1.0, 1.43, and 1.27 $\mu m/h$, respectively. The growth temperature and BEP ratio were optimized separately for the different materials. A very sharp and strong RHEED pattern was observed in all the growth conditions mentioned above, after only ten monolayers deposition beyond oxide desorption; it lasts until the end of the growth.

The material quality of MBE GaAs, AlGaAs, and GaAs/InGaAs/GaAs quantum wells were characterized by low temperature (2.2 K) photoluminescence (PL), by using the 514.5 nm line from an Ar^+-ion laser. The $Al_{0.25}Ga_{0.75}As$/GaAs heterostructure was characterized by transport properties from Van der Pauw Hall measurements of modulation doped structures.

Before studying the heterostructures, we have first investigated the undoped GaAs and AlGaAs. Figure 1 shows the surface morphology of a 1.0 μm layer of GaAs grown on (111)B substrate at 600 °C. The surface morphology of a similar layer of $Al_{0.25}Ga_{0.75}As$ grown at 600 °C is nearly identical. In both cases, the surfaces are mirror smooth. This is a strong advantage to achieve mirror smooth surfaces at 600 °C grown on 1° off toward ⟨211⟩, as compared to near 700 °C growth temperature required for growth on 0.5° off toward ⟨100⟩.[1] The samples were examined further by PL.

Figure 2 shows PL spectra of side-by-side grown 1.0 μm GaAs on (100) and (111)B, at a growth temperature 570 °C. The principal spectral features for GaAs grown on (100) are neutral donor bound (D^0,X) and acceptor bound (A^0,X) exciton recombination lines and free electron-acceptor (e,A^0) and donor acceptor (D^0,A^0) transitions. However, only the neutral donor bound exciton transition can be observed for the layer grown on (111)B. This is also true at other laser excitation intensities. Note that the peak intensity of donor bound exciton for (111)B and (100) are comparable. The acceptor related transition for (100) is due to carbon incorporated into GaAs from MBE background carbon -related species such as CO, CH_4, etc. This can be confirmed by the 26.4 meV C acceptor binding

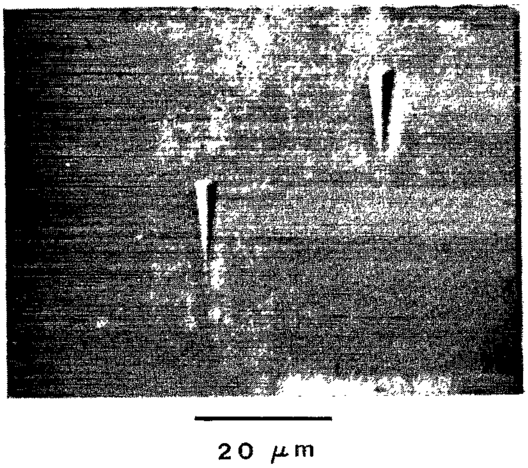

FIG. 1. Surface morphology of 1.0 μm layer of GaAs grown on a (111)B substrate at 600 °C.

energy. The donor related transition is difficult to identify by PL, because silicon or sulfur donors in GaAs lie too close together; it is generally accepted to be sulfur for high quality MBE GaAs at low growth temperatures.[8] Low C acceptor incorporation in (111)B GaAs can be understood based on the number of dangling bonds.

While the (100) surface always has two double dangling bonds available for both Ga and As surface adatoms, the (111)B surface has either one or three dangling bonds available for Ga or As, respectively. The larger number of dangling bonds available to As on (111)B increase the As sticking coefficient and reduce surface lifetime for As adatoms. Thus the probability for carbon incorporation is much decreased. This is one of the advantages for material grown on (111)B. Low carbon incorporation in GaAs should improve the material transport properties. Hall measurements were not possible on these samples; the entire layer was depleted due to the extremely low concentration of background impurities. Further work on electrical properties is in progress.

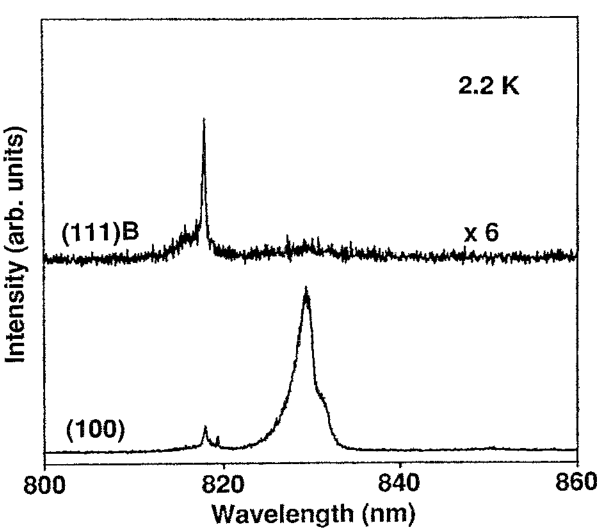

FIG. 2. 2.2 K PL spectrum of GaAs grown by MBE on (111)B and (100) GaAs substrates at 600 °C growth temperature.

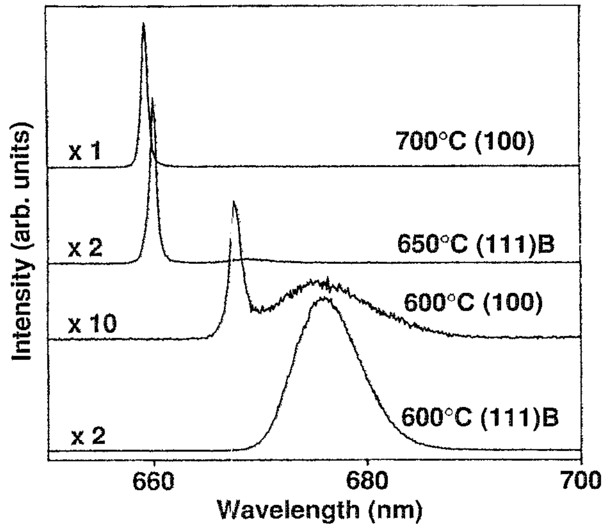

FIG. 3. 2.2 K PL spectrum of AlGaAs grown by MBE on (111)B and (100) GaAs substrates at different growth temperatures.

To take full advantage of the difference in the number of surface dangling bonds to As and group III atoms, we have studied the growth of AlGaAs on (111)B . For MBE grown AlGaAs on (100), a very high growth temperature ($\geqslant$700 °C) and low V/III flux ratios are essential to achieving high quality material. This is due to the strong chemical reactivity and slow surface migration velocity of aluminum adatoms However, there is only one dangling bond available for Al adatoms on (111)B, as compared to two dangling bonds on (100). Even after the surface is reconstructed, the surface migration mobility for Al adatoms is believed to be higher on (111)B than (100).

Figure 3 shows the growth temperature dependence of the PL spectra on (100) and (111)B AlGaAs. For comparison, layers grown at 600 °C from (100) and (111)B substrates were mounted side-by-side on the same molyblock. The PL linewidth for $Al_{0.30}Ga_{0.70}As$, grown at 650 °C, is only 2.9 meV, which is comparable to the state-of-the-art result 2.4 meV on (100), grown at 700 °C. Another important feature for layers grown on (111)B is that strong luminescence intensity can be reached even at growth temperatures as low as 600 °C, with an integrated intensity almost three orders of magnitude higher than that of the AlGaAs grown side-by-side on (100). The strong integrated PL intensity is believed to be due to the reduction of native defect-related deep level transitions; the defects are generated by slow-migrating Al adatoms. A more detailed study of growth and material characterization will be published in a separate paper.[9]

The interface quality and transport properties of AlGaAs/GaAs were evaluated by fabrication of modulation doped samples. The layer structure consists of a 1.0 μm undoped GaAs buffer layer, a 180 Å undoped $Al_{0.25}Ga_{0.75}As$ spacer, a 400 Å Si-doped (1×10^{18} cm^{-3}) $Al_{0.25}Ga_{0.75}As$ layer, and finally a 50 Å undoped GaAs cap layer. The measured room temperature and 77 K Hall mobilities for layers grown at 600 °C on (111)B are 7620 and

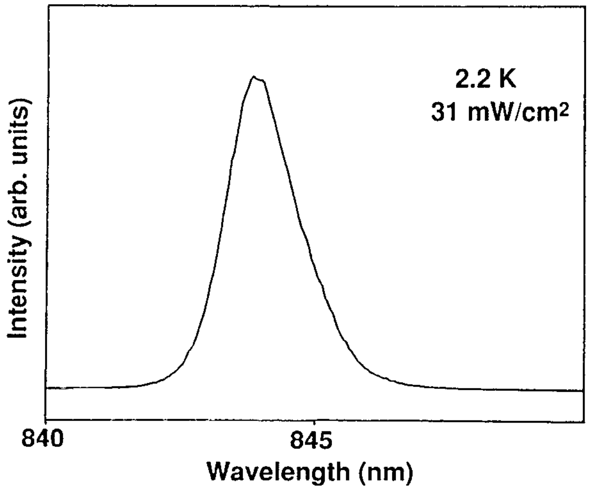

FIG. 4. 2.2 K PL spectrum of GaAs/InGaAs/GaAs quantum well grown by MBE on (111)B GaAs substrates.

145 500 cm^2/V s, respectively, with 2-DEG carrier densities of 5.2×10^{11} and 5.0×10^{11} cm^{-2}, respectively. To our knowledge, this is the first successful growth of a high mobility 2-DEG on (111) GaAs. For comparison, typical mobility values for $Al_{0.25}Ga_{0.75}As/GaAs$ layers grown at 600 °C on (100) GaAs are 5950 and 186 900 cm^2/V s, with sheet densities 8.8×10^{11} and 3.9×10^{11} cm^{-2}, for room temperature and 77 K, respectively. The slightly inferior mobility on (111)B compared to (100) may be due to a higher density of interface steps for 1° miscut (111)B samples.

Another sensitive test of interface is PL linewidth of quantum well structures. Figure 4 shows the PL spectrum of a GaAs/InGaAs/GaAs quantum well. The linewidth for a 20 Å $In_{0.21}Ga_{0.79}As$ quantum well, grown at 550 °C, is only 3.0 meV, which to our knowledge is the narrowest linewidth for quantum wells grown on (111).

In summary, we have established that excellent material and interfaces can be achieved for MBE growth of AlGaAs, GaAs, and pseudomorphic InGaAs on (111)B GaAs substrates. The low AlGaAs growth temperature and high material quality coupled with advantages unique to the (111) orientation will prove useful for a wide variety of devices.

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