Comparison of high quality (111)B and (100) AlGaAs grown by molecular beam epitaxy

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State-of-the-art quality $Al_{0.3}Ga_{0.7}As$ was achieved on both (111)B and (100) GaAs by molecular beam epitaxy. Low-temperature photoluminescence linewidths of 2.9 and 2.4 meV were obtained for (111)B and (100) $Al_{0.3}Ga_{0.7}As$, grown at 650 and 700 °C, respectively, with nearly equivalent integrated luminescence intensity. This is the narrowest linewidth ever reported for (111) AlGaAs. The low growth temperature and high material quality of (111)B $Al_{0.3}Ga_{0.7}As$ is expected to be an important factor to the future development of both electronic and optical heterostructure devices.

The performance of many AlGaAs/GaAs, AlGaAs/InGaAs heterojunction photonic and microwave devices depends on the carrier confinement, and injection properties of AlGaAs. Due to the strong chemical reactivity and slow surface migration velocity of the aluminum adatom, very high growth temperatures and low V/III flux ratios are essential to achieving high quality AlGaAs material.[1] These growth conditions reduce the deep trap concentration,[2] which can reduce the free-carrier concentrations and behave as efficient nonradiative recombination centers.[3] These conditions can also smooth heterostructure interfaces and increase carrier mobilities. Until recently, AlGaAs has generally been grown on (100) GaAs substrates. However, fundamental growth mechanisms and surface kinetics may be changed and improved on other crystal orientations. Also, the (111) orientation has some intriguing properties that follow from the strain induced piezoelectric effect. It is rather difficult, however, to grow high quality material on (111) substrates. Although high performance laser diodes have been demonstrated on (111),[4] high growth temperature (720 °C) were required to suppress microtwins and facet growth. Such high growth temperature is not suitable to grow most electronic devices. Also no AlGaAs material study has been reported on (111).

In this letter, we present the first study comparing bulk AlGaAs grown by molecular beam epitaxy (MBE) on 1.0°-misoriented (111)B and (100)GaAs substrates. Mirrorlike smooth surface morphology and atomically smooth heterostructures can be obtained on this substrate orientation.[5] The material quality of AlGaAs is characterized by low-temperature photoluminescence (PL). PL was measured at 2.2 K by excitation of 514.5 nm radiation from an Ar^+-ion laser with a low excitation intensity of 30 mW/cm^2. Bound exciton linewidth as sharp as 2.9 meV is achieved, which is among the narrowest ever reported for AlGaAs grown on (111).

Our samples were grown in a Varian Associates Modular Gen II MBE system that was carefully baked and outgassed to reduce background impurities. After a few days of bakeout and cooling down, the chamber pressure is lower than the x-ray limited reading of the Bayard–Alpert ion gauges (1×10^{-11} Torr). The careful outgas procedure and low ambient pressures of CO, H_2O, and O_2 molecules are important to achieve high quality AlGaAs with low concentrations of nonradiative recombination centers.[6]

The typical epitaxial structure studied consists of a 0.2-μm GaAs buffer layer and a 1.5-μm undoped $Al_xGa_{1-x}As$ layer with $0.28\leqslant x\leqslant0.33$. The growth rate for GaAs was 1.0 μm/h and 1.33–1.49 μm/h for $Al_xGa_{1-x}As$. The V/III beam equivalent pressure ratio ranged between 15 and 30, depending on the growth temperature. Four substrate temperatures, 600, 650, 700, and 725 °C, were chosen for layers grown on (100). At the growth temperature of 600 °C, a minimum V/III ratio is chosen to achieve a (2×4) reflection high energy electron diffraction (RHEED) pattern during the growth on (100). At 650 °C, a (3×1) RHEED pattern starts to appear, and begins to fade out at 700 °C. At 725 °C, the RHEED pattern is translated to (2×1), which indicates an arsenic-deficient growth condition. Three substrate temperatures, 600, 650, and 725 °C were chosen for layers grown on (111)B. A distinct RHEED pattern was observed in all the growth conditions after only 10 monolayers of deposition and lasted until the end of the growth. For direct comparison, layers were grown at 600 and 725 °C on (100) and (111)B substrates mounted side-by-side on the same molyblock. PL spectra of $Al_xGa_{1-x}As$ grown at different substrate temperatures are shown in Figs. 1 and 2, for layers grown on (100) and (111)B, respectively, with compositions calculated by the equation derived by Stringfellow and Linnebach.[7] The PL transition energy shifts to higher energy as growth temperature is increased. This is due to the re-evaporation of surface gallium adatoms. The relative PL intensities, for different substrate temperatures, are carefully measured in a similar measurement condition for comparison.

For $Al_xGa_{1-x}As$ grown on (100) at 600 °C, the PL spectrum is dominated by two peaks, as seen in Fig. 1. The high energy peak at 1.857 eV is due to bound excitons, as confirmed by intensity dependent PL measurements (not shown). The broad peak, centered at 1.834 eV, is a combination of electron to neutral carbon acceptor and neutral donor to neutral acceptor recombination. The observation of bound excitonic transition is an indication of high quality $Al_xGa_{1-x}As$, here obtained even at a growth temper-

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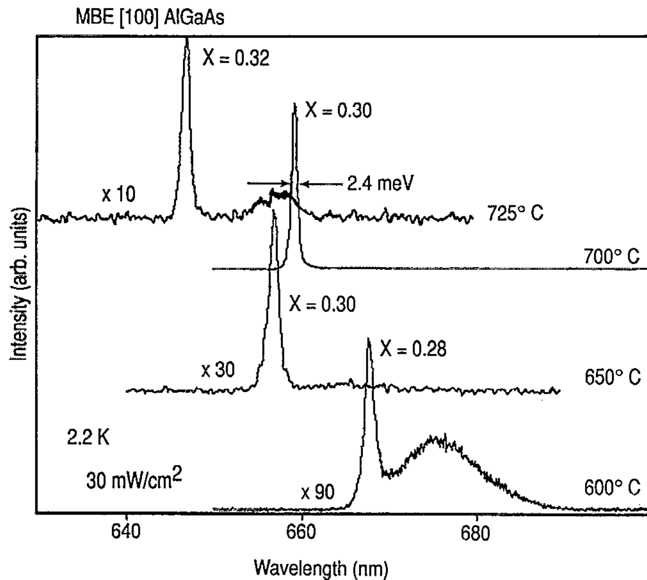

FIG. 1. 2.2-K PL spectrum of $Al_xGa_{1-x}As$ grown by MBE on (100) GaAs at different substrate temperatures.

ature as low as 600 °C. Also note that PL linewidth narrows with increasing growth temperature, but broadens above 700 °C, with the transition from (3×1) to the (2 ×1) As deficient growth condition. The improved PL linewidth at high growth temperature is believed to be due to an increasingly higher surface migration velocity of Al adatoms, which can effectively improve the material quality. Note that the PL linewidth for $Al_{0.3}Ga_{0.7}As$ grown at 700 °C is only 2.4 meV, which indicates the excellent quality of this material.

For $Al_xGa_{1-x}As$ grown on (111)B at 600 °C, only a broad transition can be observed. We find that carbon incorporation in (111)B GaAs is very low,[5] in agreement with others.[8] From the constant peak position and linearly

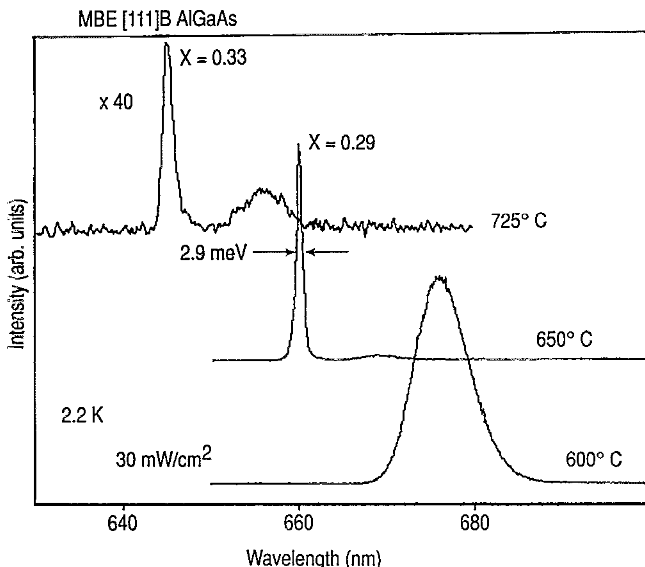

FIG. 2. 2.2-K PL spectrum of $Al_xGa_{1-x}As$ grown by MBE on (111)B GaAs at different substrate temperatures.

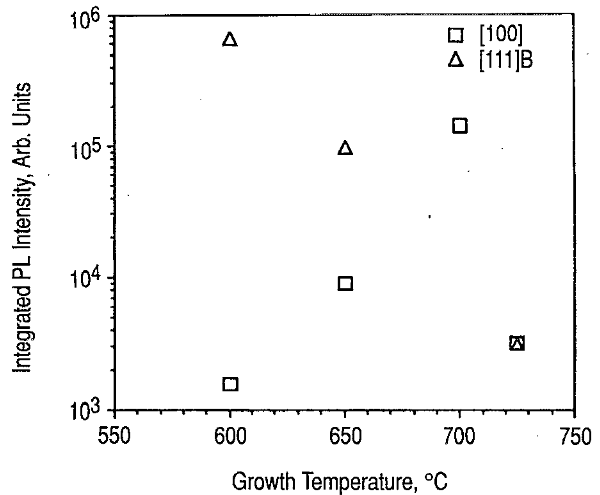

FIG. 3. 2.2-K PL integrated exciton intensity of $Al_xGa_{1-x}As$ grown by MBE on both (100) and (111)B GaAs at different substrate temperatures.

increased integrated PL intensity over two orders of excitation intensity, we believe this peak is a free-to-bound transition. The PL linewidth is minimized at 650 °C and rebroadened at 725 °C, which is believed to be due to the same As deficient growth conditions, as observed on (100). Note the PL linewidth for (111) growth at 650 °C is only 2.9 meV, which is comparable to our excellent result on (100) $Al_{0.3}Ga_{0.7}As$, 2.4 meV.

Another important factor to determine AlGaAs material quality is the deep trap related nonradiative recombination. To study this phenomenon, we have plotted the integrated PL intensity with growth temperature for (100) and (111)B, in Fig. 3. The integrated intensity for (111)B at 650 °C is almost comparable to that for (100) at 700 °C and is about an order of magnitude higher than that for 650 °C growth on (100). The integrated intensity of the (111)B $Al_xGa_{1-x}As$ actually rises when the growth temperature is dropped from 650 to 600 °C. The difference is primarily due to the free-to-bound transition for the sample grown at 600 °C, as compared to bound exciton dominated transition for other samples. It is likely that this peak is broadened, indicating an increased incorporation of shallow donors, which would increase the luminescence intensity. In any case, its overall strength affirms the reduced incorporation of nonradiative recombination centers, which kill the luminescence in (100) sample grown at the same temperature. Although the actual origin of deep traps is still not fully understood at this moment, the traps are probably not oxygen related, because the absorbed background oxygen molecules on (100) are as chemically reactive to aluminum as that on (111)B. Also the improvement is probably not due to substrate misorientation, because the 1° miscut is less than the ⩾3° miscut required to improve the surface morphology of MBE grown layers.[9,10] We believe it is due to the different growth mechanism and surface kinetics as mentioned above. The As atoms on the unreconstructed (111)B surface have only one dangling bond, as compared to two surface dangling

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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). The above discussion is verified by a recent RHEED oscillation study on (111)B,[11] which indicates that step flow is obtained on (111)B at significantly lower temperatures than (100). Thus, it is plausible that the densities of group III vacancy complex and antisite defects, which were assigned to the origin of deep traps, can differ between the two orientations.

In summary, extremely high quality $Al_{0.3}Ga_{0.7}As$ can be grown on both (100) and (111)B GaAs substrates. In our growth conditions, 2.4- and 2.9-meV PL linewidths can be obtained for (100) and (111)B $Al_{0.3}Ga_{0.7}As$, respectively, with comparable integrated PL intensity. At lower temperatures (600–650 °C) (100) growth results in degraded PL, most likely a result of a lower surface mobility of group III adatoms. This problem is substantially reduced for growth on (111)B. The achievement of high quality material at relatively low growth temperature on (111)B growth is believed to be due to the reduction of native defects, by a higher Al adatom migration velocity achieved through relatively weaker As-group III surface bond.

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