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Strong enhancement of the optical and electrical properties, and spontaneous formation of an ordered superlattice in (111)B AlGaAs

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Abstract

Strong enhancement in the luminescence intensity is observed in $Al_{0.22}Ga_{0.78}As$ epitaxial layers grown on misoriented (111)B GaAs as compared to those simultaneously grown on (100) GaAs. For a 1° misorientation the luminescence intensity is almost 10 to 1000 times that of the (100) layers, depending on the growth temperature. Room temperature electron mobility for 3° misoriented (111)B $Al_{0.18}Ga_{0.82}As$ is 19% higher than that for side-by-side grown (100). The strong luminescence associated with a large red shift of 90 meV and the 19% mobility enhancement are related to the long range composition ordering in (111)B AlGaAs, which is observed by cross-sectional transmission electron microscopy in a 280 Å $Al_{0.4}GaAs$ quantum well heterostructure with $Al_{0.7}GaAs$ barriers grown on (111)B GaAs substrates.

1. Introduction

Owing to the enhanced optical and electrical properties of improved quantum confinement and reduced alloy scattering, the spontaneous formation of ordered ternary compound semiconductors during growth has become a topic of increasing interest [1–4]. Most of these studies focused on GaInP [1,2] and InGaAs [3]; however, the growth of AlGaAs is particularly important for most opto-electronic and microwave devices applications. Unfortunately, the quality of AlGaAs strongly depends on the growth conditions. Furthermore, a high growth temperature of 700°C is generally required for (100) AlGaAs in order to improve the optical quality. The difficulties of AlGaAs can be overcome if the AlGaAs material is spontaneously ordered and forms a quantum confined microstructure. Owing to the high surface migration velocity of adatoms on the (111)B surface [5], fundamental growth mechanisms can be improved and possible phase separation can be formed if AlGaAs is grown on this orientation.

Here we report the first observation of long-range composition ordering in (111)B AlGaAs. A one to three order of magnitude enhancement of integrated photoluminescence (PL) intensity, and a large red shift of 90 meV PL peak energy are also observed in $Al_{0.22}Ga_{0.78}As$ grown on (111)B

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when compared to those on (100). The measured RT electron mobilities for (111)B exceed the (100) mobility values by 19%, with similar carrier densities.

2. Experimental procedure

Three sets of epitaxial structures were studied for optical, electrical, and structural characterization. For optical characterizations, PL was used to measure the optical properties of the undoped 2.0 μm thick $Al_{0.22}Ga_{0.78}As$ layers. Four substrate temperatures, 600, 630, 650, and 670°C, were chosen for layers grown on (100) and 1° misoriented (111)B. We also studied the degrees of misorientation effects on (111)B $Al_{0.22}Ga_{0.78}As$. For electrical characterizations, a 0.3 μm $Al_{0.18}Ga_{0.82}As$ buffer layer and a 3.0 μm Si doped $Al_{0.18}Ga_{0.82}As$ layer were grown at 630°C on (100) and misoriented (111)B GaAs substrates. Temperature dependent Hall measurement was used to characterize the electrical properties of the epitaxial layers and to analyze the scattering mechanism. For structure characterizations, cross-sectional transmission electron microscopy (TEM) was studied in a laser diode heterostructure. The layer structure consists of 0.75 μm Si or Be doped $Al_{0.7}Ga_{0.3}As$ barriers, and a 280 Å undoped $Al_{0.4}Ga_{0.6}As$ quantum well (QW). The growth temperature was 600°C for the $Al_{0.4}Ga_{0.6}As$ QW and 650°C for the $Al_{0.7}Ga_{0.3}As$ barriers.

3. Results and discussion

Fig. 1 shows the PL spectra for AlGaAs grown at 630°C. A full width at half maximum (FWHM) linewidth of 4.4 meV for the (100) $Al_{0.22}Ga_{0.78}As$ indicates the excellent quality of the AlGaAs layers. The (111)B AlGaAs layers show broad peaks without any resolvable fine structures. The peak energies decrease monotonically from 1.837 eV for (100) to 1.744 eV for the 3° (111)B layer. The 93 meV decrease of the PL peak energy resulting from the misorientation increase is related to the monotonic increase of 30 times PL integrated intensity. We believe that the PL is not due to impurity related transitions since the layers have a low impurity content, and the 2.0 μm thick AlGaAs is totally depleted during Hall measurement.

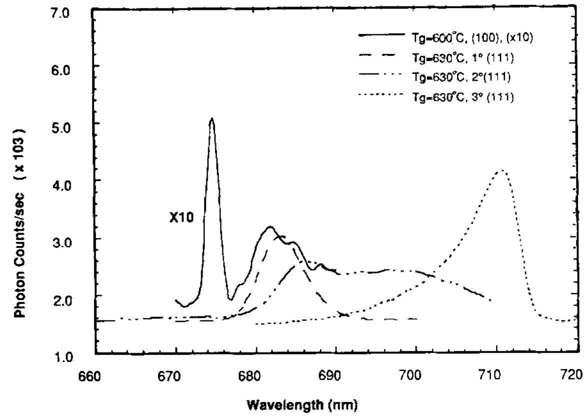

Fig. 1. Low temperature PL spectra of 2.0 μm thick $Al_{0.22}Ga_{0.78}As$ grown at 630°C on (100) and 1°, 2°, and 3° misoriented (111)B GaAs.

Fig. 2 shows the PL spectra for the AlGaAs grown at 670°C. There is little PL integrated intensity enhancement and peak energy shift for 670°C grown samples, as compared to layers grown at 630°C. The integrated intensity enhancement is about 1 to 4 times, while the peak energy shift is within 7 meV. The absence of any significant orientation dependence of the PL for

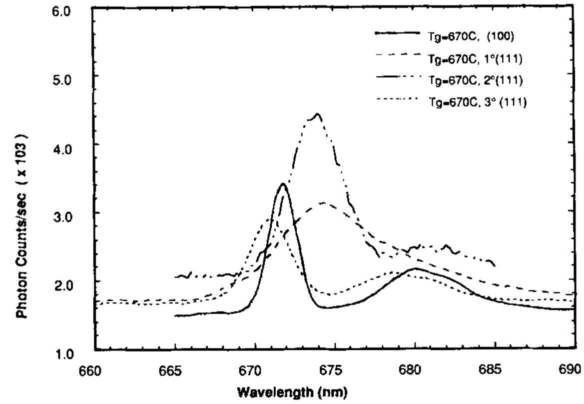

Fig. 2. Low temperature PL spectra of 2.0 μm thick $Al_{0.22}Ga_{0.78}As$ grown at 670°C on (100) and 1°, 2°, and 3° misoriented (111)B GaAs.

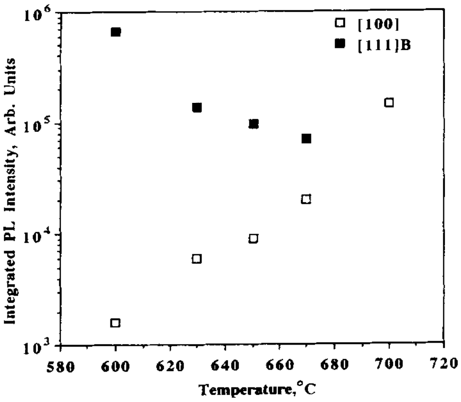

Fig. 3. Low temperature integrated PL intensity of $Al_{0.22}Ga_{0.78}As$ grown by MBE on both (100) and (111)B GaAs at different substrate temperatures.

Table 1
Electrical characterization of Si-doped (100) and misoriented (111)B $Al_{0.18}Ga_{0.82}As$

Orientation	μ_{RT} (cm^2/V·s)	μ_{77K} (cm^2/V·s)	n_{RT} (cm^{-3})	n_{77K} (cm^{-3})
0° (100)	2200	2800	1.04×10^{17}	0.95×10^{17}
1° (111)	2260	2820	1.10×10^{17}	0.94×10^{17}
2° (111)	2590	3140	0.98×10^{17}	0.95×10^{17}
3° (111)	2620	3220	1.00×10^{17}	0.94×10^{17}

the layers grown at 670°C is believed to be due to the high surface migration of both Al and Ga adatoms, which disorders the AlGaAs.

The dependence of the relative PL integrated intensity on growth temperature is shown in Fig. 3. A three orders of PL integrated intensity enhancement for (111)B AlGaAs, grown at 600°C, as compared to (100) AlGaAs, is very important to grow high optical quality AlGaAs at a low temperature of 600°C. The monotonic increase of PL integrated intensity with growth temperature on (100) AlGaAs is due to the reduction in the defect related non-radiative recombination centers. This is expected from higher surface migration velocities of adatoms and lower oxygen incorporation at higher growth temperatures. In contrast, a decrease in the PL integrated intensities for (111) AlGaAs as the growth temperature is increased cannot be explained by the above argument. It is believed to be due to the disordering effect as growth temperature is increased.

The electrical properties of (111) AlGaAs were further evaluated by Hall measurements. The measured Hall data are summarized in Table 1. Both room temperature (RT) and 77 K electron mobilities are higher for $Al_{0.18}Ga_{0.82}As$ grown on (111) than that grown on (100), and the mobility increases monotonically with the degree of misorientation. This is also consistent with the increased red shift of PL peak energy as degree of misorientation. Temperature dependent Hall mobility was also measured in order to probe the detailed scattering mechanisms. Fig. 4 shows the variation of Hall mobility with temperature in Si-doped (100), and 3° misoriented (111)B AlGaAs, respectively. The room temperature mobility is primary limited by polar optical and space charge scattering, while the low temperature or 77 K mobilities are mainly limited by the ionized impurity scattering. However, these two mobility limiting mechanisms are related to both effective mass and Al composition. From the calculated and measured mobility data, the Al composition of (100) AlGaAs is determined to be 18%, which is consistent with the measured RHEED oscillations data. However, for 3° misoriented (111)B AlGaAs, a good match between the total calculated mobility and experimental data can be achieved only if the Al composition is adjusted to be 14%. This can be explained by the higher electron mobility of (111)B AlGaAs, compared to

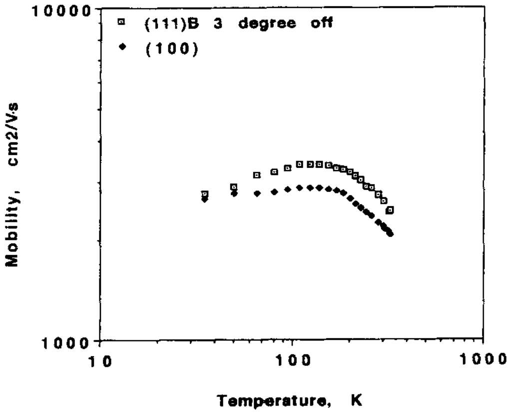

Fig. 4. Variation of Hall mobility with temperature in Si doped (100) and 3° misoriented (111)B $Al_{0.18}Ga_{0.82}As$.

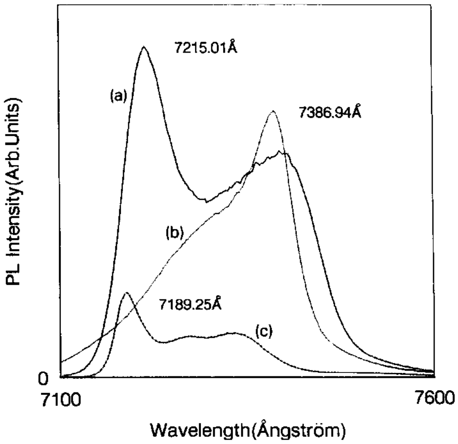

Fig. 5. Low temperature PL spectra of Si doped (100), 1° and 3° misoriented (111)B AlGaAs: (a) 1°(111)B; (b) 3°(111)B; (c) (100).

the (100) case, at similar carrier concentrations. In order to justify the lower effective Al composition in (111)B AlGaAs, we also measured PL of Si doped AlGaAs samples. Fig. 5 shows the measured PL spectra, at 10 K, of Si-doped (100), and 1° and 3° misoriented (111)B AlGaAs. The 46 meV red shift of the PL peak energy between (100) and 3° misoriented (111)B AlGaAs is equivalent to a 4% Al composition reduction, which is also consistent to the calculated Hall data.

TEM was used to investigate the microstructure of these samples and understand the red shift in PL peak energy. Figs. 6a and 6b show the cross-sectional (002) dark-field TEM images of a 280 Å thick $Al_{0.7}Ga_{0.3}As/Al_{0.4}Ga_{0.6}As$ single QW grown on (111)B and (100) GaAs, respectively. It is shown in Fig. 6b that the thickness of a QW heterostructure grown on (100) is rather non-uniform. This is expected from the relative low growth temperature of 650°C at the inverted $Al_{0.7}Ga_{0.3}As/Al_{0.4}Ga_{0.6}As$ interface. However, for the QW grown on (111)B, the well thickness is quite uniform and the inverted interface is very smooth. This is due to the much higher surface migration velocity of adatoms on (111)B than that on (100) orientation [5]. It is also noticed that there is a superstructure observed in the (111)B $Al_{0.4}Ga_{0.6}As$ QW, which consists of a modulation of bright (Al-rich) and dark lines (Ga-rich) in the well region. These Al-rich and Ga-rich AlGaAs

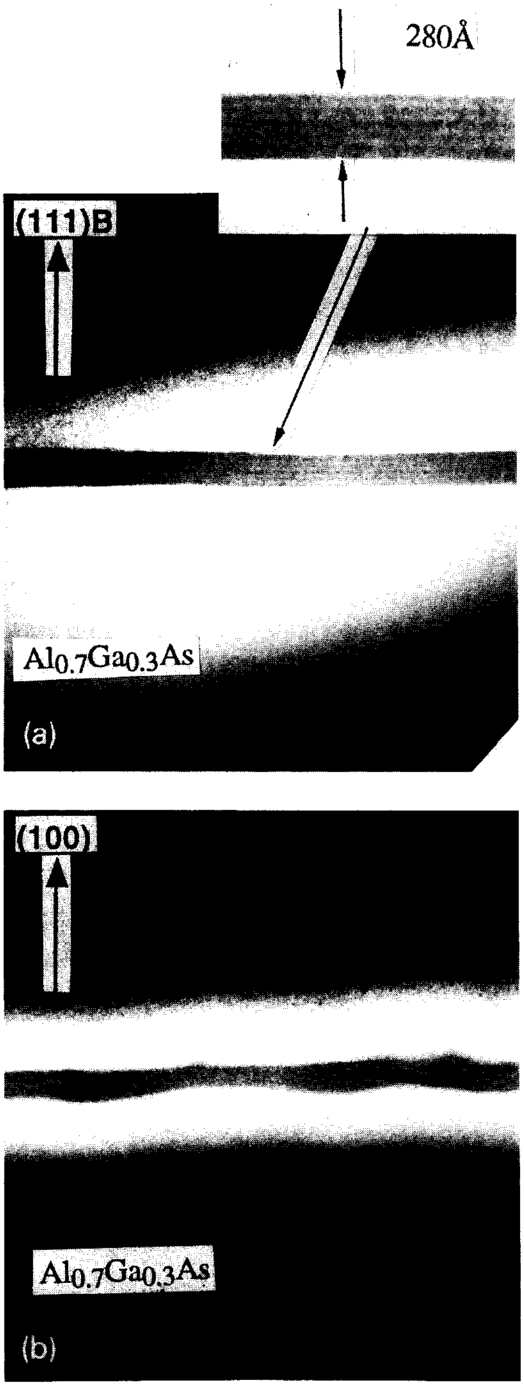

Fig. 6. Cross-sectional view, dark field TEM image of 280 Å thick $Al_{0.4}Ga_{0.6}As$ quantum well for (a) (111)B and (b) (100) orientation. The $Al_{0.4}Ga_{0.6}As$ quantum well and $Al_{0.7}Ga_{0.3}As$ barrier were grown at 600 and 650°C, respectively.

superlattice layers were parallel to the interface of the QW and were separated by approximately 55 Å. In contrast, no such superstructure is observed in the side-by-side grown (100) QW. This result indicates that the superstructure is formed spontaneously during MBE growth, and is only formed on the (111)B orientation. To our best knowledge, this is the first reported long-range ordering, and spontaneous formation of Al-rich and Ga-rich $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ superlattice in AlGaAs. There is no such superstructure in the $Al_{0.7}Ga_{0.3}As$ barrier due to the high growth temperature, which disorders the AlGaAs.

4. Conclusions

We have shown that a strong enhancement in the luminescence intensity of one to three orders can be obtained in misoriented (111)B $Al_{0.22}Ga_{0.78}As$ epitaxial layers. The room temperature electron mobility for 3° misoriented (111)B $Al_{0.18}Ga_{0.82}As$ is 19% higher than that for side-by-side grown (100). The strong luminescence associated with a large red shift of 90 meV, and the 19% mobility enhancement are related to the long range composition ordering in (111)B AlGaAs, which is observed, by cross-sectional TEM, in a 280 Å $Al_{0.4}GaAs$ QW heterostructure with $Al_{0.7}GaAs$ barriers, grown on (111)B GaAs substrates.

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