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Extremely Flat Interfaces in $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ Quantum Wells Grown on (411)A GaAs Substrates by MBE

Tatsuya SAEKI[1], Takeharu MOTOKAWA[1], Takahiro KITADA[1], Satoshi SHIMOMURA[1], Akira ADACHI[2], Yasunori OKAMOTO[3], Naokatsu SANO[4], and Satoshi HIYAMIZU[1]

1. *Faculty of Engineering Science, Osaka University, Toyonaka, Osaka 560, Japan*
2. *Research Development Division, Nissin Electric Co. Ltd., Umezu-Takase-cho, Ukyouku, Kyoto 615, Japan*
3. *Research and Headquarters Kubota Corporation, Amagasaki, Hyogo 662, Japan*
4. *Faculty of Science, Kwansei-Gakuin University, Nishinomiya, Hyogo 662, Japan*

Effectively atomically flat interfaces have been achieved for the first time in pseudomorphic $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ (x = 0.04, 0.08) quantum wells (QWs) with well widths of 1.2 – 12 nm grown on (411)A GaAs substrates at 520 °C by molecular beam epitaxy (MBE). A single and sharp photoluminescence (PL) peak was observed for each QW at low temperatures. The linewidths for narrow QWs of L_w= 2.4 nm were 9 meV (x = 0.04) and 10 meV (x = 0.08) at 4.2 K which were about 30 % smaller than those of QWs simultaneously grown on (100) GaAs substrates.

1. Introduction

Atomically flat interfaces in a semiconductor heterostructure over a macroscopic area are very important for applications to quantum devices such as quantum well lasers or resonant tunneling diodes to achieve higher device performance. In our recent work [1,2], we have reported that $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells (QWs) grown on (411)A-oriented GaAs substrates by molecular beam epitaxy (MBE) show very sharp photoluminescence (PL) lines and effectively atomically flat $GaAs/Al_{0.3}Ga_{0.7}As$ interfaces [(411)A super-flat interfaces] are formed over a macroscopic area ($\sim 1\ cm^2$).

Pseudomorphic InGaAs/AlGaAs heterostructures have attracted much interest for electrical and optical device applications [3–5]. In the case of lattice-matched $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructures, the (411)A super-flat interfaces can be achieved as mentioned above, but it is not clear whether the super-flat interfaces can be also achieved in strained heterostructures or not, because formation of the (411)A super-flat interfaces is considered to relate to the growth mechanism on (411)A crystal plane. In this study, we investigate the interfaces flatness in pseudomorphic $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs with In contents of x = 0.04 and 0.08 grown on (411)A and (100) GaAs substrates by MBE.

2. MBE Growth of InGaAs/AlGaAs QWs

The (411)A-oriented GaAs substrates were degreased and etched by a sulfuric acid etchant solution. $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs (x = 0.0, 0.04, 0.08) with well widths (L_w) of 1.2, 2.4, 3.6, 4.8, 7.2 and 12.0 nm and a barrier width of 20 nm on a $GaAs/Al_{0.3}Ga_{0.7}As$ superlattice buffer layer (780

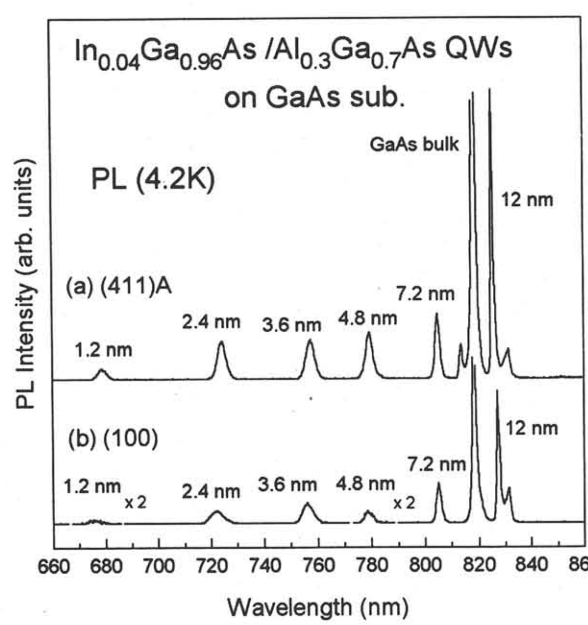

Fig. 1. Photoluminescence spectra at 4.2 K from $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs (x = 0.04) grown on (411)A (a) and (100) GaAs substrates (b)

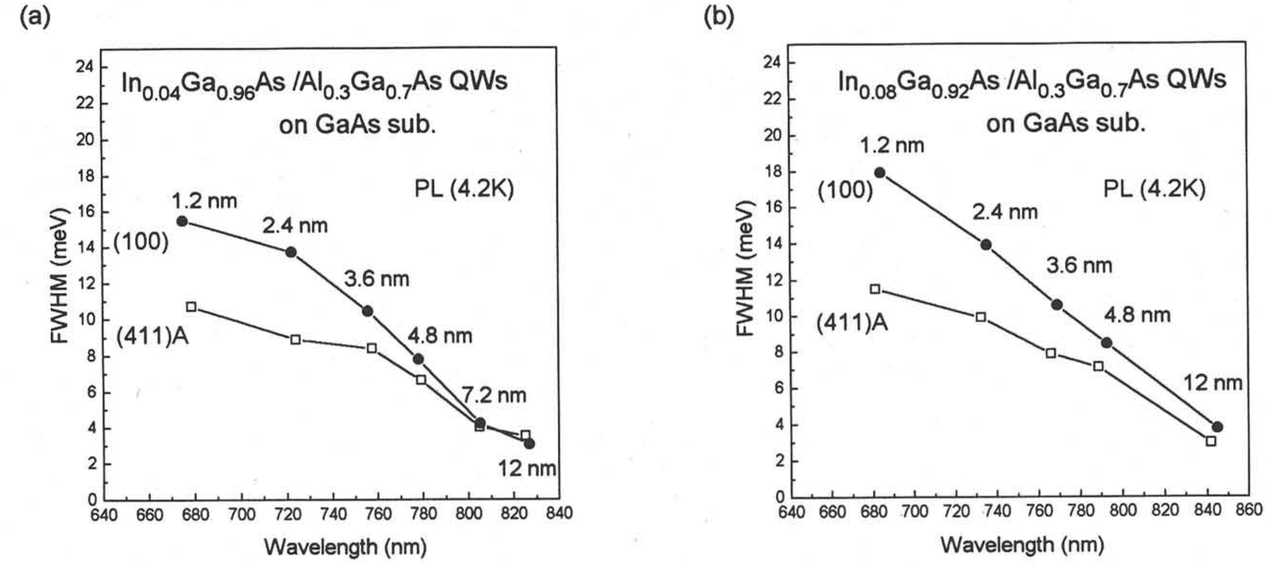

Fig. 2. FWHMs of PL peaks at 4.2 K from $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs with x = 0.04 (a) and x = 0.08 (b) grown on (411)A and (100) GaAs substrates.

nm in total) were simultaneously grown on (411)A and (100) GaAs substrates at a substrate temperature (T_s) of 520 °C by MBE. Growth rates of GaAs and AlAs were 1.0 μm/h and 0.43 μm/h, respectively. The beam equivalent pressure of As_4 was 4.5×10^{-7} Torr, or a V/III (As_4/Ga) ratio is 7.5. The substrates were rotated at 30 rpm during MBE growth.

3. PL Characteristics

Figure 1 shows PL spectra at 4.2 K from the $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs (x = 0.04) simultaneously grown on the (411)A and the (100) GaAs substrates. An excitation beam for PL measurements was focused on the sample surface in an area of about 200 μm diameter. Very sharp six peaks at wavelengths of 678.8, 724.2, 757.6, 779.4, 805.0 and 825.4 nm in Fig. 1(a) correspond to the luminescence from the $In_{0.04}Ga_{0.96}As$ QWs with well widths of L_w = 1.2, 2.4, 3.6, 4.8, 7.2 and 12.0 nm on the (411)A GaAs substrate, respectively. The peak at 818.2 nm comes from GaAs of the buffer layer. On the other hand, the luminescence peaks from the QWs on the (100) GaAs substrate [Fig. 1(b)] are observed at 675.2, 722.4, 756.0, 778.2, 805.2 and 827.0 nm. The most prominent characteristic feature is a much smaller linewidth of each luminescence peak observed for the (411)A QWs, indicating improved flatness of the (411)A $In_{0.04}Ga_{0.96}As/Al_{0.3}Ga_{0.7}As$ interfaces. In the range of narrow well width of 1.2 - 4.8 nm, a red-shift of the luminescence peaks was observed for the (411)A QWs compared with those of the (100) QWs, and a blue-shift was seen for the thick (411)A QW of L_w = 12 nm. This is probably due to the different strain components in pseudomorphic (411)A InGaAs/AlGaAs QWs from those of the (100) QWs. It is also worth noting that the integrated luminescence intensities of the (411)A QWs are higher than those of the (100) QWs, which suggests good optical quality of the (411)A QWs.

Figure 2 shows full widths at half maximum (FWHMs) of the PL peaks from the $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs with x = 0.04 (a) and x = 0.08 (b) grown on both (411)A and (100) GaAs substrates as a function of wavelength. For the narrow QWs with L_w = 1.2 - 2.4 nm, the FWHMs of PL peaks from the (411)A InGaAs/AlGaAs QWs with x = 0.04 are about 30% smaller than those of the (100) QWs [Fig. 2(a)]. In the case of wide QWs of L_w = 7.2 - 12 nm, the FWHMs of the (411)A QWs are almost equal to those of (100) QWs. The (411)A QWs with x = 0.08 show smaller FWHMs than those of the (100) QWs in all well widths [Fig. 2(b)]. Luminescence from the QW (x = 0.08) with L_w = 7.2 nm overlaps with that from GaAs buffer layer. These FWHMs (3 $\sim$ 4 meV) of the (411)A QWs and the (100) QWs with L_w = 12 nm are better than reported value (6.7 meV at 4.2 K) for a $GaAs/In_{0.11}Ga_{0.89}As/Al_{0.23}Ga_{0.77}As$ QW (L_w = 15 nm) on the (100) GaAs substrate [6].

Figure 3 shows FWHMs of the luminescence peaks from the $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs (x = 0.0, 0.04, 0.08) with the well width of L_w = 2.4 nm grown

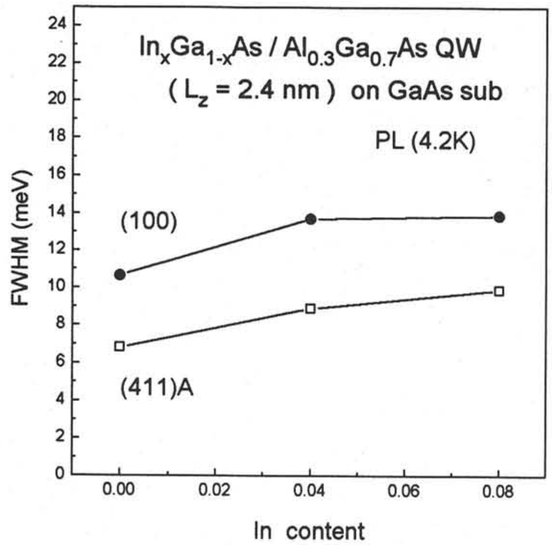

Fig. 3. FWHMs of PL peaks at 4.2 K from $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs (x = 0.0, 0.04, 0.08) with the well width of $L_w = 2.4$ nm grown on (411)A and (100) GaAs substrates as a function of In contents.

on (411)A and (100) GaAs substrates as a function of x. In the case of x = 0.0, FWHM (6.8 meV) at 4.2 K of the (411)A QW is slightly worse than that previously reported value (5.4 meV at 4.2K) of GaAs/AlGaAs QWs on (411)A GaAs substrates [1]. This is probably due to the lower growth temperature (520 °C) compared with the optimized temperature of 580 °C [1]. FWHMs of the (411)A QWs are almost 40% smaller than those of the (100) QWs in the range of $x \leq 0.08$. In the pseudomorphic InGaAs/AlGaAs QWs, a FWHM of PL is mainly determined by alloy disorder of an InGaAs well layer and interface roughness. Interface roughness is more crucial for QWs with reduced L_w. So, the difference between FWHMs for the (411)A QWs with $L_w = 2.4$ nm and the (100) QWs with $L_w = 2.4$ nm is considered to be due to difference in the interface roughness. Moreover, each QW on the (411)A substrate shows only one sharp luminescence peak, indicating that effectively atomically flat interfaces over a macroscopic area of the laser excitation (200 μm diameter) are also realized in pseudomorphic $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs with low In contents ($x \leq 0.08$) grown on the (411)A GaAs substrates similarly to the lattice-matched case of $GaAs/Al_{0.3}Ga_{0.7}As$ QWs on the (411)A GaAs substrates [1, 2].

4. Conclusion

In contents (x) in pseudomorphic $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ quantum wells (QWs) grown on the (411)A GaAs substrates could be successfully increased up to 0.08 while keeping their super-flat InGaAs/AlGaAs interfaces over a macroscopic region (about 200 μm diameter). A single and very sharp peak was observed in photoluminescence (PL) spectra at 4.2K from each of $In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As$ QWs (x = 0.0, 0.04, 0.08) with L_w = 1.2, 2.4, 3.6, 4.8, 7.2 and 12.0 nm grown on the (411)A-oriented GaAs substrates at T_s = 520 °C by MBE. These results are believed to be due to more stable two-dimensional MBE growth of $In_xGa_{1-x}As$ ($x \leq 0.08$) and $Al_{0.3}Ga_{0.7}As$ on the (411)A GaAs substrates. Hence, InGaAs/AlGaAs heterostructures grown on the (411)A GaAs substrates can be expected to have high potential for applications to quantum devices.

Acknowledgments

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