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Characterization of MBE grown GaAs/AlGaAs heterointerfaces with photoluminescence from quantum wells

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Abstract

Quantum-well heterointerfaces of AlGaAs on GaAs(1 0 0), (1 1 1)A, and (3 1 1)A were fabricated by molecular beam epitaxy (MBE) growth with interruption of Ga supply and then observed by photoluminescence (PL) measurements. The PL measurements showed that the interruption caused these heterointerfaces to roughen, and this roughening was proportional to the resulting increase in the quantum well widths. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The optical properties of gallium arsenide (GaAs) allow it to be used in a quantum well laser. In molecular beam epitaxy (MBE), superlattices of GaAs and aluminum gallium arsenide (AlGaAs) are easily made because GaAs and AlGaAs have almost the same lattice constant. However, the growth method influences the smoothness of the interface, which affects the properties of the resulting quantum well laser through electron mobility. High-index GaAs substrates are particularly useful for lateral devices.

Previously, we found that high-index GaAs substrates grown by MBE became smoother on (1 1 1)A and (3 1 1)A as the As pressure increased, whereas (1 0 0) surfaces had little dependence of roughness on As pressure [1–3]. In another set of experiments (unpublished), the height and steepness of hillocks on (1 1 1)A increased slightly with the increase of either time or growth rate. Also, the size of hillocks on (1 0 0) increased with growth time in spite of it being kept nearly at the same steepness (coarsening occurred) and the size of the hillocks on (1 0 0) decreased with an increased growth rate.

It is known that growth interruption tends to make smoother the GaAs surfaces provided that the net Ga flux is not changed. During this interruption time, molecules can migrate on to the substrate and find a more stable site. Likewise, we expect that growth of heterointerfaces should become smoother with growth interruption. To fabricate smooth heterointerfaces, the gallium (Ga) supply during MBE growth was interrupted at each GaAs/AlGaAs heterointerface after every

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GaAs or AlGaAs layer was fabricated. To understand better the effect of growth interruption, we studied the growth on GaAs surfaces with various indices of (1 0 0)A, (1 1 1)A, and (3 1 1)A. Instead we found that the growth interruption caused the growth to increase and produced rough surfaces.

2. Experimental procedure

The substrates were cleaned with Semico cleaning fluid, rinsed with distilled water, dried with N_2 gas, mounted on an indium-free Mo holder, and then put into a VG Semicon V80 H MBE machine. In the MBE machine, the substrates were outgassed at 450°C for 1 h in the preparation chamber. After moving the substrates to the growth chamber, the oxide film was removed by heating it to 680°C under an As_4 flux for 5 min.

Quantum wells were grown by MBE on GaAs(1 1 1)A, (3 1 1)A, and (1 0 0) substrates at a substrate temperature of 660°C, as determined by a pyrometer, and As pressure 1.2×10^{-3} Pa, as determined by the ion gauge current. By observing the RHEED oscillations, the growth rate was measured at 1.15 ML/s and 1.63 ML/s for GaAs and AlGaAs, respectively. The interruption time for the Ga supply was 30 or 120 s with constant As flux

Seven periods of the following quantum well structure were grown: GaAs (8 nm)/$Al_{0.35}Ga_{0.65}As$ (5 nm)/GaAs (14 nm)/$Al_{0.35}Ga_{0.65}As$ (5 nm)/GaAs (8 nm)/$Al_{0.35}Ga_{0.65}As$ (20 nm) (Fig. 1). Here, the wide well (WW) is the quantum well of GaAs (14 nm), and the narrow well (NW) is the quantum well of GaAs (8 nm).

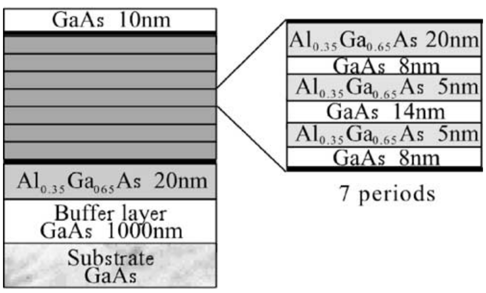

Fig. 1. Sample structure.

To characterize the GaAs/AlGaAs heterointerfaces, photo luminescence (PL) from the quantum well structures was measured with an He-Ne laser (wavelength 633 nm) at 20 K. For comparison, we measured the PL of a sample with the interruption and also a sample without the interruption but for growth at the same thermodynamic conditions.

3. Results and discussion

The results of PL measurements are shown in Figs. 2–4. These figures show the results of PL with no interruption, with 30-s interruption, and with 120-s interruption, respectively. In each figure, the largest peak, at around 1.54 eV, is the PL signal from the WW. The peak energies on the interrupted-growth samples are at lower energies compared to the samples grown without interruption. This indicates that there was difference of quantum well width; the well width was broadened by the interruption of Ga flux.

The energy levels in a quantum well equal those from an infinite square well potential

$$E = \frac{\pi^2 \hbar^2}{2mL_z^2} n^2 \quad (n = 1, 2, 3), \tag{3.1}$$

where L_z is the well thickness. In the energy transitions of interest here, the electron also drops through the band gap energy. However, for the

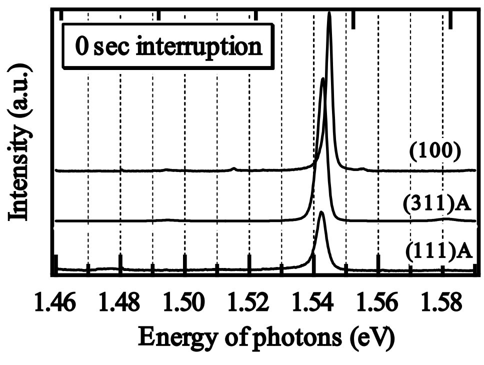

Fig. 2. Photoluminescence spectrum for samples grown with no interruption at the heterointerfaces.

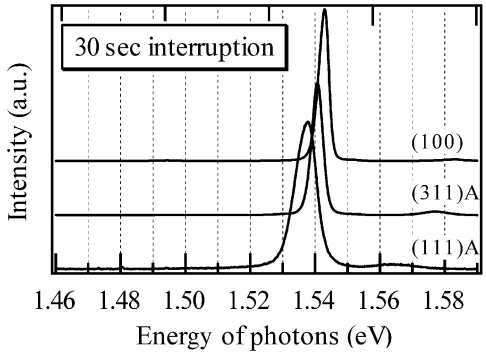

Fig. 3. Photoluminescence spectrum for samples grown with interruptions for 30 s at the heterointerfaces.

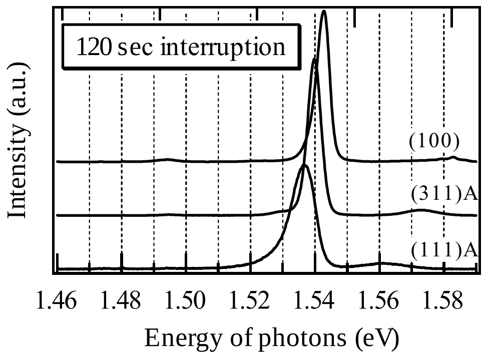

Fig. 4. Photoluminescence spectrum for samples grown with interruptions for 120 s at the heterointerfaces.

dependence of PL peak on well thickness, the band gap energy is ignored. Differentiating Eq. (3.1) by L_z,

$$\mathrm{d}E = \mathrm{d}E_\mathrm{e} + \mathrm{d}E_\mathrm{hh} = \frac{h^2}{4}\left(\frac{1}{m_\mathrm{e}^*} + \frac{1}{m_\mathrm{hh}^*}\right)\frac{1}{L_z^3}\,\mathrm{d}L_z, \qquad (3.2)$$

where m_e^* is the effective mass of the electron and m_hh^* is the effective mass of the heavy hole.

Eq. (3.2) gives the energy-peak shift of PL from the quantum wells as the sum of the energy shifts from electron and hole from a change in the well width. In this calculation, we used a conduction-to-balance band offset ratio of 65:35, a well width of $L_z = 14$ nm, and the following effective masses: $m_\mathrm{e}^* = 0.067m_0$ for electrons and for the heavy hole masses, $m_\mathrm{hh}^* = 0.95m_0$, $0.54m_0$, and $0.34m_0$ for (1 1 1)A, (3 1 1)A, and (1 0 0), respectively. Here m_0

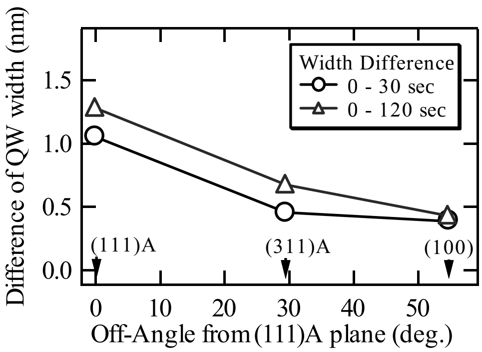

Fig. 5. Calculated change of QW width due to growth interruption as a function of the substrate orientation. For example, the line 0–30 s indicates the difference of WW width between the interruption time 0 s and 30 s.

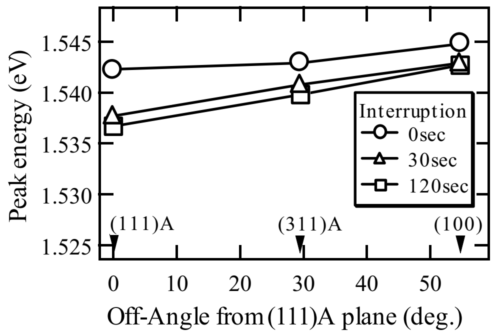

Fig. 6. The PL peak energy from the WW as a function of the substrate orientation. At every index, the energy peak shift of the sample with 30 s interruption and 120 s interruption is less than 1 meV.

is the free electron mass. According to this equation, our PL spectra indicate energy peak shifts of growth-interrupted samples which are 2–7 meV lower than those without interruption. This difference of the WW quantum well width is equivalent to about 0.4–1.6-nm change in thickness (Fig. 5). On the other hand, the energy peak shifts of the samples with 30 and 120 s interruption differed by less than 1 meV (Fig. 6). Thus, either the duration of 30 s is sufficient to affect the well widths, or the effect is primarily due to the interruption and not the duration of the interruption.

The PL full-width at half-maximum (FWHM) of the sample with interruption time at each heterointerface was broader than the one without

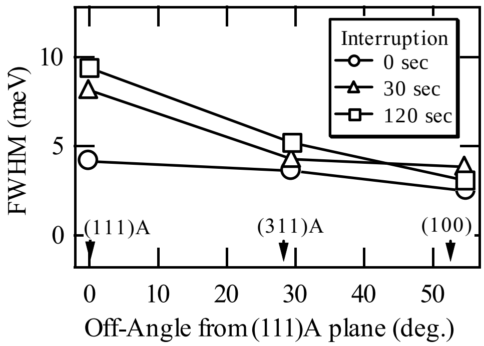

Fig. 7. FWHM as a function of the substrate orientation and duration of growth interruption.

interruption time (Fig. 7). Smaller FWHMs indicate smoother interfaces; thus, the results indicate that growth interruption roughened the heterointerfaces macroscopically. This is consistent with our AFM measurement of the (1 1 1)A and (1 0 0) surfaces. We found that both surfaces roughened with increasing growth time, although the growth times in the AFM studies were 30 min and longer. Nevertheless, increasing roughness with growth time is a general feature of many growth models that predict roughening. In support of this, the orientation dependence of the FWHM in Fig. 7 is qualitatively the same as the orientation dependence of the increase in well width in Fig. 5.

4. Conclusions

To fabricate smooth heterointerfaces, interruption time at each heterointerface was studied. The samples with growth interruption had lower-energy peaks in their PL spectra. This indicates that growth interruption made the wells larger by 0.4–1.6 nm. This difference is less at high index substrates such as (3 1 1)A and (1 0 0), compared to low index ones such as (1 1 1)A. The difference of the peak energies between the sample with 30 s interruption and with 120 s interruption was less than 1 meV. This indicates that the increase of well width is related to the interruption process instead of the interruption duration. For samples grown with an interruption time, the FWHM became broader than the samples without an interruption time. Our results indicate that growth-interrupted surfaces roughened macroscopically for high index surface because they had greater net flux.

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