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In Situ Interface Control of Pseudomorphic InAs/InP SQWs Growth by Surface Photo-Absorption

Yasuyuki KOBAYASHI and Naoki KOBAYASHI
NTT Basic Research Laboratories
3-9-11 Midoricho Musashino-shi, Tokyo 180, JAPAN

The exchange reaction of group V atoms was monitored *in situ* on a submonolayer scale during MOVPE growth of a pseudomorphic InAs/InP heterostructure on (001) InP substrates by surface photo-absorption (SPA). About a 0.4 monolayer exchange reaction was observed after arsine was supplied at 0.2 µmol/s onto the In surface of InP at a substrate temperature (Ts) of 400°C. At a Ts of 350°C, the As/P exchange reaction was suppressed to less than 0.1 monolayer. We grew InAs/InP SQWs with 1-12 InAs monolayers and characterized them by TEM and photoluminescence.

Pseudomorphic InAs/InP single quantum wells (SQWs) have a significant potential for long-wavelength optoelectronic devices[1,2]. These structures have a heterointerface consisting of different group V atoms, and during growth, the surface P atom is easily exchanged with the impinging As atoms. The As/P exchange deteriorates the metallurgical interface abruptness due to the formation of short-range roughness[3]. This As/P exchange reaction depends on the growth conditions such as the substrate temperature and the group V source exposure time, so *in situ* monitoring of the atomic processes on the surface is necessary to control the heterointerface quality and to obtain an atomically abrupt interface.

This paper describes the *in situ* interface control during MOVPE growth of a pseudomorphic InAs/InP heterostructure on (001) InP substrates by surface photo absorption (SPA)[4]. SPA is based on the reflectivity measurement of p-polarized light incident at the Brewster angle. Under this condition, the reflectivity is highly sensitive to the surface as a result of minimizing bulk crystal contribution. SPA is used to monitor the As/P exchange reaction. To verify the positive effects of *in situ* control, we grew InAs/InP SQWs with 1-12 InAs monolayers (MLs) at the suitable condition for suppressing the As/P exchange reaction, and characterized their heterointerfaces by TEM and photoluminescence (PL).

Figure 1 shows the typical SPA reflectivity change when an As/P exchange reaction has occurred on the (001) InP surface. The surface reflectivity was measured at 470 nm wavelength and at [$\bar{1}$10] incident azimuth. The substrate temperature (Ts) was maintained at 400°C. After the formation of the In surface by P desorption from the InP surface, AsH_3 was supplied on the In surface to form the As surface on InP. Next, the AsH_3 supply was stopped, and then the In surface was formed again by As desorption. The reflectivity level

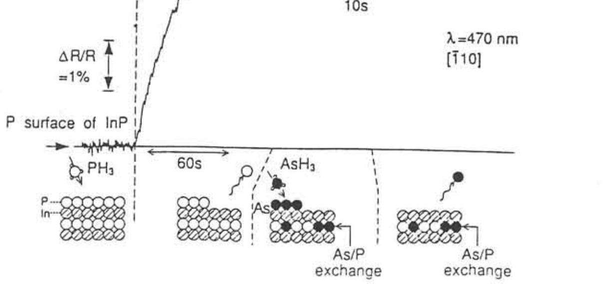

Fig.1 SPA reflectivity change showing As/P exchange reaction in InAs/InP system.

of the In surface differed before and after the AsH_3 exposure, indicating that a substitution from P to As atoms took place on the InP surface during the AsH_3 exposure. This reflectivity difference is caused by the refractive index change from InP to $InAs_xP_{1-x}$ in the surface penetration depth of the monitoring light.

From this SPA reflectivity measurement, we analyzed the As/P exchange reaction quantitatively. Figure 2 shows the Arrhenius plot of our estimated As/P exchange ratio. The substrate temperature was varied from 365°C to 400°C. Assuming that the As/P exchange occurs within only one monolayer of the surface, the exchange ratio can be approximately estimated by comparing the reflectivity of the following: the In surface of the $InAs_xP_{1-x}$ monolayer formed by the As/P exchange and the In surface of one InAs monolayer grown on InP at 350°C. At this temperature, the exchange reaction is negligibly small. Under the condition of a 0.2 µmol/s AsH_3 supply for 10 s on the InP surface, the exchange reaction proceeded to 44% at Ts=400°C. As the substrate temperature decreases, the exchange ratio decreases with an activation energy of 1.26 eV. The exchange reaction was suppressed to less than 10% at Ts=350 °C.

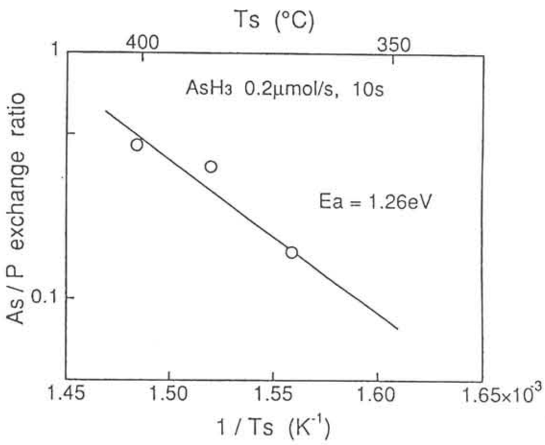

Fig.2 Substrate temperature dependence of estimated As/P exchange ratio.

To verify the suppression of the As/P exchange reaction and the formation of an atomically abrupt interface, we grew a pseudomorphic InAs/InP SQWs on (001) InP substrate at Ts=350°C. The InAs well layer was grown by atomic layer epitaxy (ALE) to control the well thickness precisely. Figure 3 shows TEM photographs of InAs/InP SQWs with 10 and 12 ML InAs wells. The measured well thickness agreed well with the nominal value determined from the growth cycles in ALE. An atomically abrupt and flat interface with dislocation free was observed for the 10ML SQW. This result shows that the low-temperature growth suppressed both the As/P exchange reaction at the lower interface and the strain-induced three-dimensional nucleation at the upper interface. In contrast, dislocations with small density ($\sim 10^8 cm^{-2}$) were observed for the 12ML SQW. This result indicates that the critical layer thickness in this system is 3.0-3.6 nm, which is compatible with the force balance model[5].

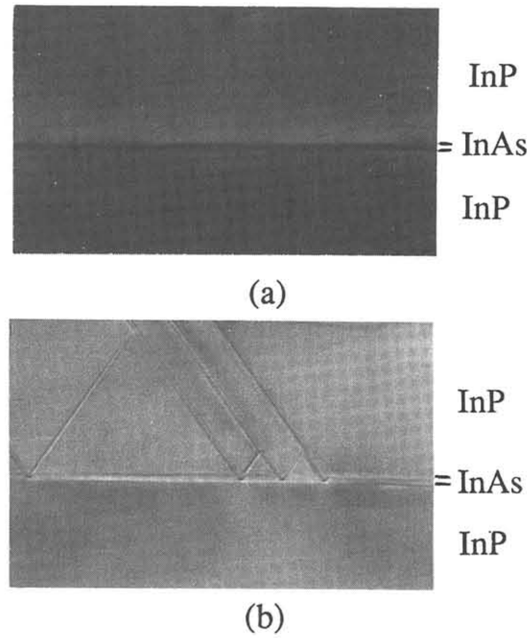

Fig.3 Cross sectional TEM image of InAs/InP with (a) 10ML and (b) 12ML well.

Figure 4 shows the 77K PL spectra of 1-12 ML InAs wells and also shows the dependence of PL emission energy on well thickness. Sharp and intense spectra with full width at half maximum (FWHM) of 17-37 meV can be observed . Multiple lines have been observed in PL spectra for InAs wells more than 4MLs in the case of high-temperature growth ($\sim$600 °C). These lines were attributed to the long-range roughness at the upper interface of InP on InAs, which is caused by strain-induced three-dimensional InAs nucleation. The present study, however, indicates that low-temperature growth at 350°C can suppress the three-dimensional InAs growth; Fig.4 shows a single peak for 2 to 12MLs of InAs. The PL intensity decreases drastically over 10MLs, because of the formation of misfit dislocations. This occurrence agrees with the TEM observation described before. The peak energy calculation used the Kronig-Penney model with a square well potential and considered the effect of strain. A good agreement was attained with a heavy-hole valence band discontinuity Ev of 460 meV.

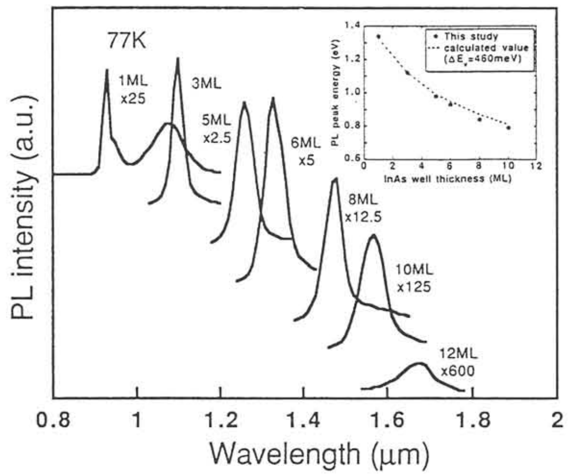

Fig.4 77K PL spectra of InAs/InP SQWs with 1-12 InAs ML.

In summary, the As/P exchange reaction was monitored *in situ* by SPA during InAs/InP MOVPE growth. The exchange rection was found to be strongly affected by the substrate temperature. So low-temperature growth at Ts=350°C to suppress the exchange reaction was performed, and produced metallurgically abrupt interface. Pseudomorphic InAs/InP SQWs with 1-12 MLs InAs well were grown at Ts=350°C; in this case, ALE was used for the InAs well growth. The low-temperature growth also suppressed the strain-induced three-dimensional nucleation of InAs on InP. The formation of high quality heterointerface up to 10MLs was verified by TEM and PL observation. Sharp and intense PL spectra with reasonable shifts due to the quantum size effect were also observed. Therefore *in situ* control enabled us to grow high-quality InAs/InP heterostructures available in the 1-1.5 μm wavelength range optoelectronic devices.

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