High quality narrow GaInAs/InP quantum wells grown by atmospheric organometallic vapor phase epitaxy

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A series of GaInAs/InP quantum wells from 10 to 135 Å has been grown by atmospheric organometallic vapor phase epitaxy using pressure balancing techniques. These wells exhibit strong exciton peaks at 4 K and have quantized energy shifts of up to 326 meV. These energy shifts are compared with two simple finite well models (Kronig–Penney and envelope function approximation) using a conduction-band offset of $V_c \approx 40\% \, \Delta E_g$ (GaInAs) and are in close agreement with the latter model. The full width half-maximum linewidths indicate an average interface roughness of ≈ 1 monolayer.

The successful growth of thin abrupt interface quantum wells in the AlGaAs/GaAs system by molecular beam epitaxy (MBE) and organometallic vapor phase epitaxy (OMVPE)[1,2] has made possible lasers[3,4] and other devices[5,6] with unique properties. The GaInAs/InP system has many unique features with regard to the AlGaAs/GaAs system, such as high critical velocities for field-effect transistors and long emission wavelengths for optical communication systems. Consequently quantum wells in this system would also appear to be potentially attractive. However, these features do not come without a price, viz., the necessity to lattice match GaInAs to InP whereas GaAs and AlGaAs are nearly lattice matched. Lattice matching coupled with the difficulty of handling P in a MBE system and the difficulty of obtaining sharp interfaces and/or thin layers with vapor phase epitaxy (VPE) or OMVPE has made development proceed slowly.

Recently much progress has been made in this area. Quantum wells as thin as 30 Å grown by MBE,[7] 6 Å wells by chemical beam epitaxy (CBE),[8] 5 Å by gas source molecular beam epitaxy (GSMBE),[9] and an 8 Å well grown by low pressure OMVPE (LP OMVPE)[10] have been reported. In all these cases fairly narrow photoluminescence (PL) linewidths have been reported, with Tsang *et al.* observing an 8 meV full width half-maximum (FWHM) in the 4 K exciton line for a 10-Å well, which was estimated to be equal to a lattice "equivalent roughness" of $0.12a_0$. Up to now these results have not yet been duplicated by VPE or atmospheric OMVPE. DiGiuseppi *et al.*,[11] using a multibarreled VPE reactor, reported 100 Å wells with very broad linewidths ($\geqslant 50$ meV) and Skolnick *et al.*[12] have reported wells as thin as 75 Å grown by atmospheric OMVPE.

In this work we report the growth of quantum wells as thin as ≈ 10 Å grown by atmospheric OMVPE equaling the best LP OMVPE results and approaching the results reported by GSMBE (in regard to linewidth) and CBE (in regard to energy shift), while retaining the simplicity and ease of atmospheric OMVPE growth. These results were achieved by close attention to the pressure and switching of the OMVPE manifold and by increasing the carrier gas flow velocity to approach that of LP OMVPE region.

The quantum wells were grown at 760 Torr in an OMVPE system with a run-vent manifold with low dead volume three-way valves for gas switching. The pressure difference across the manifold was automatically maintained to within ± 0.2 mTorr as compared to 40 mTorr without automatic control. This feature prevents the transient pressures from rising to 100–200 mTorr upon gas switching, which can result in a transient 30% increase in the Ga/In ratio at the initial growth of the GaInAs layer. In Fig. 1(a) is shown an in-depth Auger profile of an InP/GaInAs/InP wafer. As

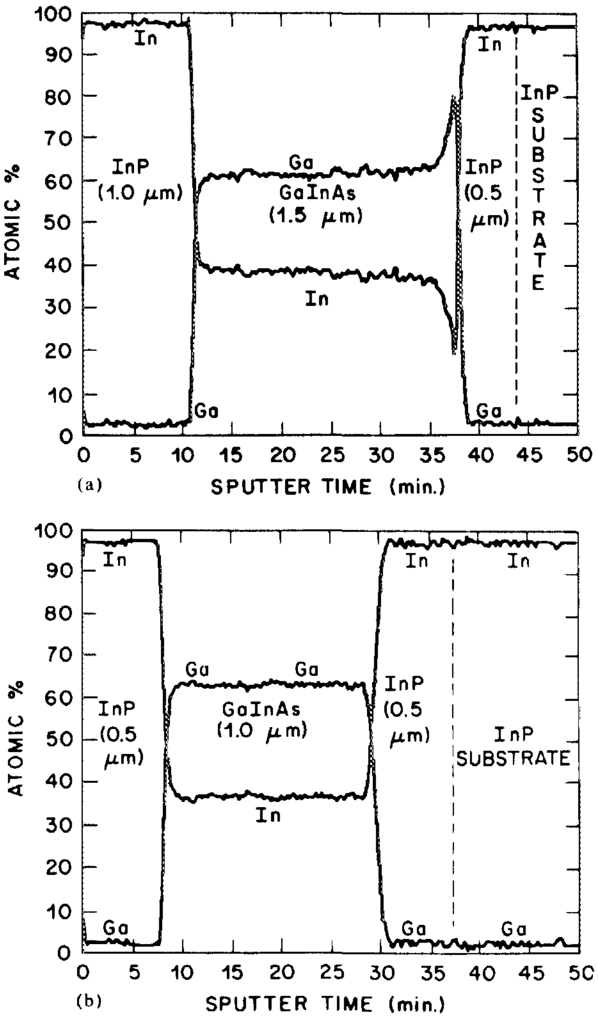

FIG. 1. In-depth Auger profile of two InP/GaInAs/InP wafers grown by atmospheric OMVPE. (a) Ga and In solid concentrations without pressure balancing, (b) with pressure balancing. The Auger resolution is ≈ 250 Å and the sputtering rate is ≈ 830 Å/min in InP.

can be seen at the start of the GaInAs growth there is a large transient in the Ga/In ratio. The resulting GaInAs layer would then be badly lattice mismatched within the first several monolayers with poor quality layers and interfaces. With automatic pressure balancing there was no detectable ($<2\%$) change of the Ga/In ratio at the interface [Fig. 1(b)] and high quality growth resulted.

The GaInAs/InP layers were grown using trimethylindium, trimethylgallium, AsH_3, and PH_3 at 625 °C. The carrier gas was H_2 and flowed through the reactor at 5000 sccm. Given the rectangular cross section of 3.75 cm^2 for the OMVPE reactor tube, the linear flow velocity was ≈ 22 cm/s approaching that of LP OMVPE reactors.[13] For the growth of GaInAs, it was found that a pause of 1 s in a PH_3 ambient between the GaInAs and InP layers gave the best results. This allowed the sweeping away of the AsH_3 before the start of the InP growth; previous results have shown us that As incorporates ≈ 100 times faster than P when both PH_3 and AsH_3 are present. The nominally undoped GaInAs layers were n type where $n \approx 2 \times 10^{15}\ cm^{-3}$ and had mobilities $\mu_{77} \approx 45\,000\ cm^2/V\ s$. The photoluminescence at 4 K for nearly lattice-matched thick epitaxial material exhibited a strong exciton line at 1.529 μm with a FWHM of 2.4 meV; a weak impurity band was also detected at 1.569 μm (see inset Fig. 2).

For this experiment we grew a series of different thickness quantum wells of GaInAs nearly lattice matched to InP separated by 500 Å of InP. The well thicknesses were, from the top of the wafer down, 10, 21, 42, 63, 80, and 136 Å, plus a 2000-Å reference layer, each corresponding to growth times of 1, 2, 4, 6, 8, 12, and 154 s, respectively. The thicknesses of the wells were determined from an exact transmission electron microscope (TEM) lattice image of the 136-Å and 80-Å wells and then extrapolated to the other wells assuming a linear growth rate with time. Figure 2 shows the photoluminescence of the multilayer quantum well wafer (sample 2A052986) taken at 4 K. The thick 2000-Å layer luminescences at 1.627 μm instead of 1.529 μm, indicating a slight lattice mismatch in the $\Delta a/a_0$ positive direction. All quantum well energy shifts are measured relative to this peak. The amplitude of the peaks corresponding to each well is of arbitrary height and adjusted so as to be visible on one trace. As can be seen there are seven peaks corresponding to the seven grown layers; the maximum energy shift was 326 meV corresponding to the 10-Å well; the thicker wells had correspondingly smaller energy shifts. Figure 3 is a plot of the energy shifts versus well thickness shown in Fig. 2 as well as some additional single quantum wells grown by us. For comparison we also plot the narrowest quantum well CBE, GSMBE, LP OMVPE, and atmospheric OMVPE results. The dashed line in Fig. 3 is a theoretical plot of the well thickness versus energy using a finite well based on the Kronig–Penney[14] model where both the wave function and its derivative are continuous across the well-barrier interface. In this calculation we used a band offset of $\Delta V_c \approx 40\%$ E_g (GaInAs) as determined independently by Forrest *et al.* from *C-V* measurements.[15] As can be seen our results fall in line with other investigators' but the energy shifts seem slightly less than what this theory predicts. A more comprehensive theory which matches propagating envelope functions[16,17] at the well-barrier interface was used to calculate the solid curves in Fig. 3; here we plot $\Delta V_c = 20\%\ \Delta E_g$ (GaInAs) as well as $40\%\ \Delta E_g$ (GaInAs). Most of the data are in close agreement with these two curves which points to their validity, but it should be pointed out that upon closer examination of the data, it appears that for the narrow wells, the $\Delta V_c = 20\%\ \Delta E_g$ (GaInAs) fits best while the thicker wells fit $\Delta V_c = 40\%\ \Delta E_g$ (GaInAs) and for the thickest

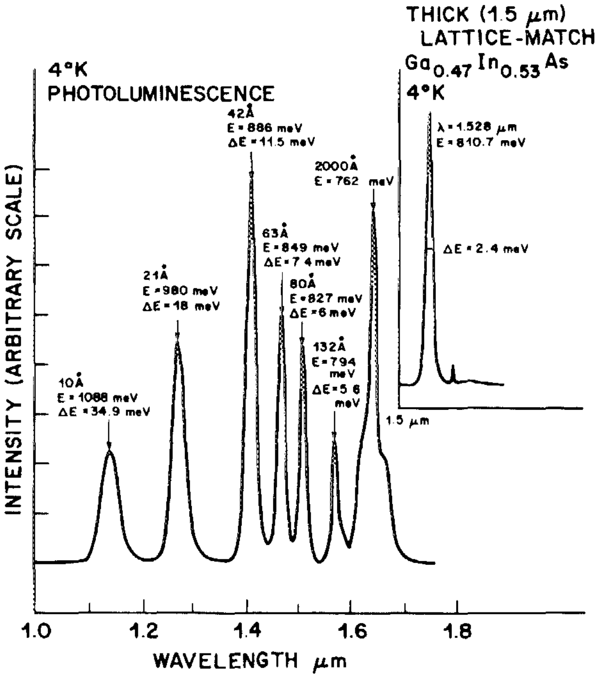

FIG. 2. 4 K photoluminescence spectra of the 6 quantum well wafer (sample 2A052986) grown for 1, 2, 4, 6, 8, and 12 s. The estimated thicknesses are indicated as well as the energy of each peak and its FWHM. The 2000-Å peak is used as the reference peak and shows a slight lattice mismatch in the positive direction with respect to a thick lattice matched GaInAs layer (see inset).

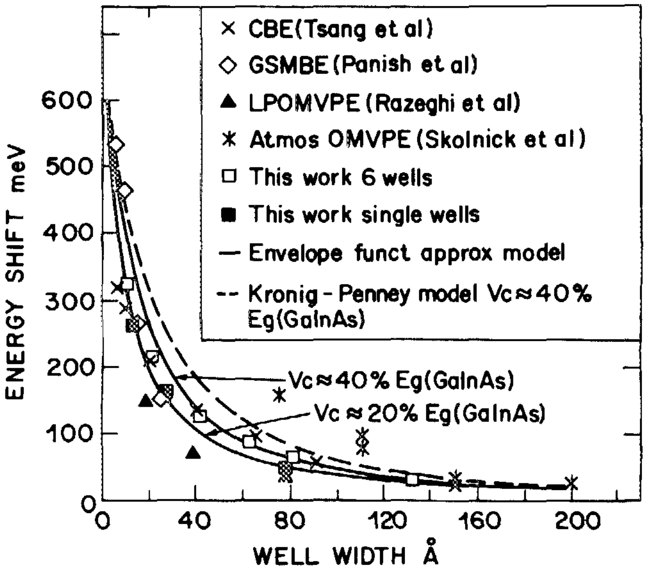

FIG. 3. Photoluminescent energy shift of GaInAs quantum wells with respect to thick GaInAs vs well thickness. Shown here are our results for the 6-well sample (2A052986) and single well samples compared to results by other growth methods including recent atmospheric OMVPE data. The dashed and solid lines are finite well theoretical models (Kronig–Penney and envelope function approximation—see text).

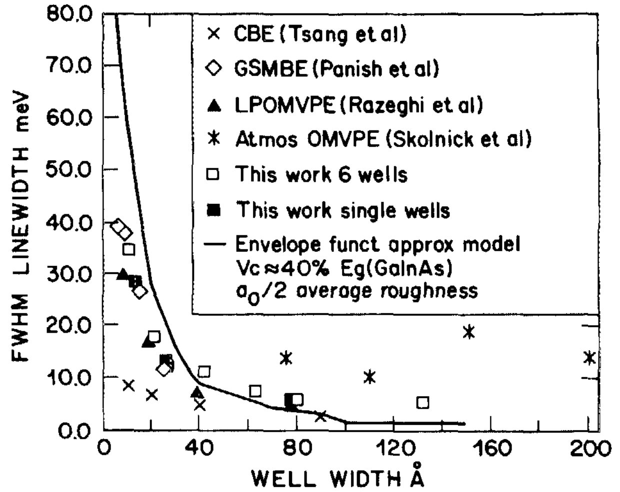

FIG. 4. Photoluminescent FWHM vs well thickness using the data from Fig. 3. The solid line is the expected FWHM for an average interface roughness of one monolayer ($a_0/2 = 2.93$ Å) based on the envelope function model discussed earlier.

wells we found that $\Delta V_c = 50\%\ \Delta E_g$ (GaInAs) gave the best fit. At present we have no explanation for this apparent change of conduction-band offset with well thickness. To see if this is a real effect would require precise TEM thickness measurements for all the layers and several growth runs under varying conditions, which will be the subject for a future study.

A figure of merit for the sharpness of the interfaces is the FWHM of the photoluminescence versus well thickness which we plot in Fig. 4 along with those references of Fig. 3 for comparison. Except for the results reported by Tsang *et al.*, our FWHM are about as small or smaller than the other reported linewidths. The theoretically expected linewidth for an average roughness of a single monolayer ($\Delta L_z = a_0/2$) is also plotted using the envelope function approximation and a $\Delta V_c = 40\%\ \Delta E_g$ (GaInAs). It should be noted here that the photoluminescent linewidth due to alloy broadening for GaInAs lattice matched to InP is small[18] as compared to broadening caused by thickness variations of the quantum wells. For our very narrowest of wells the roughness, as compared to theory, seems to be less than $\Delta L_z = a_0/2$, but some of the thicker wells seem to indicate somewhat more roughness. It appears that this widening could be due to the slight lattice mismatch observed in this sample. It also has been suggested[12] that the photoluminescent linewidth may not be the best test of interface quality, especially for very narrow quantum wells. Clearly more work must be done to resolve this matter.

In conclusion, we have shown that it is possible to grow by atmospheric OMVPE, high quality quantum wells ≈ 10 Å having widths and interface sharpnesses equaling that of MBE, GSMBE, LP OMVPE, and approaching that of CBE. The ease of use and simplicity of atmospheric OMVPE can now be used to fabricate many devices which earlier were thought to be only within the realm of MBE, GSMBE, LP OMVPE, or CBE.

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