Extremely high quality $Ga_{0.47}In_{0.53}As/InP$ quantum wells grown by chemical beam epitaxy

W. T. Tsang and E. F. Schubert
AT&T Bell Laboratories, Holmdel, New Jersey 07733

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We have prepared by chemical beam epitaxy extremely high quality $Ga_{0.47}In_{0.53}As/InP$ quantum wells with thickness as thin as 6 Å. Emission as short as 1.09 μm at 2 K (1.14 μm at 300 K) was obtained. Very sharp intense efficient luminescence peaks due to excitonic transitions were obtained from all quantum wells. The photoluminescence (PL) linewidths at 2 K were the narrowest that have been ever reported for $Ga_{0.47}In_{0.53}As$ quantum wells grown by any technique. In fact, these $Ga_{0.47}In_{0.53}As$ quantum well linewidths are at least equal to the narrowest linewidths ever reported for the perfected GaAs/AlAs and $GaAs/Al_xGa_{1-x}As$ quantum wells. These linewidths indicate the "effective" interface roughness to be 0.12 lattice constant, which can be interpreted as that the quantum well was largely consisting of a big domain of the same thickness L_z perforated with a small fraction of small domains of $(L_z + a_0/2)$, where a_0 ($= 5.86$ Å) is the lattice constant. No broadening due to band filling from impurities was found. Alloy broadening in $Ga_{0.47}In_{0.53}As$ was limited to the intrinsic value of 1.3 meV. The PL energy upshifts measured in $Ga_{0.47}In_{0.53}As$ quantum wells were in excellent agreement with theoretical values.

$Ga_{0.47}In_{0.53}As$ lattice matched to InP has emerged as a very important semiconductor material. High electron mobility and peak velocity are attractive for ultrahigh speed devices. The band gap of 0.75 eV (1.65 μm) is ideal for photodetectors in optical communication systems in the optimum wavelength range of 1.3–1.6 μm. Furthermore, semiconductor injection lasers utilizing $Ga_{0.47}In_{0.53}As/InP$ quantum well structures[1,2] allow emission wavelength to be shifted from the 1.65 μm to the 1.3–1.55 μm region by having different well thicknesses. This not only circumvents the necessity of using homogeneous GaInAsP alloys as active medium, but also, as demonstrated in $GaAs/Al_xGa_{1-x}As$ system,[3] is expected to produce semiconductor injection lasers with significantly improved device performances not achievable by the bulk counterpart.

In comparison with GaAs/AlGaAs quantum wells, however, relatively few studies have been made on $Ga_{0.47}In_{0.53}As/InP$[4–10] or $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$[11–13] quantum wells thus far. Here, we report for the first time extremely high quality $Ga_{0.47}In_{0.53}As/InP$ quantum wells grown by a recently developed epitaxial technique, the chemical beam epitaxy[14] (CBE), and show that the present quantum wells are superior in quality to those published in literatures grown by organometallic chemical vapor deposition (OMCVD),[4,5] molecular beam epitaxy (MBE),[6–8,11–13] and chloride transport vapor phase epitaxy (VPE).[9,10]

For the growth of GaInAs/InP by CBE, the system described in Ref. 14 is employed. Arsine (AsH_3, 100%, Phoenix) and phosphine (PH_3, 100%, Phoenix) are used. The TEGa and TMIn flows were combined to form a single emerging beam. This single-beam nature automatically guarantees lateral spatial composition uniformity.[15] In CBE, thermal pyrolysis occurred entirely on the substrate surface. Continuous growth was employed at the interfaces by switching out and in the appropriate gas components.

Typical 2-μm-thick undoped InP layers were n type $\sim 5\times10^{15}$–1×10^{16} cm^{-3} with a 300-K mobility of $\sim$4500 $cm^2/V\,s$ and a 77-K mobility of $\sim$30 000 $cm^2\,V^{-1}\,s^{-1}$. Typical 2–5-μm-thick $Ga_{0.47}In_{0.53}As$ epilayers have mobilities of 10 000–12 000 and 40 000–57 000 $cm^2/V\,s$ at 300 K and 77 K with $n = 5\times10^{14}$–5×10^{15} cm^{-3}. Bulk $Ga_{0.47}In_{0.53}As$ epilayers also show a very intense efficient luminescence exciton peak with linewidths as narrow as 1.2 meV, which is equivalent to the calculated intrinsic (full width at half-maximum, FWHM) alloy broadening for $Ga_{0.47}In_{0.53}As$ (1.3 meV). Such linewidth is the narrowest ever measured for any alloy semiconductors including $Al_xGa_{1-x}As$ with $x > 0.1$.

In order to facilitate the study of more than one quantum well simultaneously, multilayer structures consisting of a 0.5-μm InP buffer, a 0.2-μm $Ga_{0.47}In_{0.53}As$ control layer plus $Ga_{0.47}In_{0.53}As$ quantum wells of different thicknesses alternated with 700 Å InP barriers were grown on InP (Fe) substrates. The 0.2-μm-thick $Ga_{0.47}In_{0.53}As$ control layer (behaves as bulk material) served as a reference wavelength in the photoluminescence (PL) spectrum from which the energy upshifts of the quantum wells can be calculated precisely. The quantum well thickness was determined from the steady-state growth rate. In CBE, this process was found to be very reliable and reproducible from run to run.

Photoluminescence measurements were made at 2 K using the 647.1-nm line of a Kr-ion laser as the optical pump. The pumping power used typically ranged from 0.1 to 10 μW over a pumping area of 50 μm in diameter. Very sharp intense efficient luminescence peaks due to excitonic transitions in the quantum wells were obtained as shown by a typical example in Fig. 1. With the 10-Å well, the emission peak has been shifted from 1.57 μm (the bulk $Ga_{0.47}In_{0.53}As$ reference) to 1.17 μm. Note that with a growth rate of 3.6 μm/h employed in the present experiment the 10-Å well required a growth time of only 1 s. Yet, extremely sharp and intense luminescence was obtained indicating that the heterointerfaces were extremely uniform and smooth. Separate samples with 6-Å wells have also been successfully grown with similar luminescence quality with emission peak at 1.09 μm. Further, such results have been reproduced from run to run. The abrupt composition transitions achieved with CBE un-

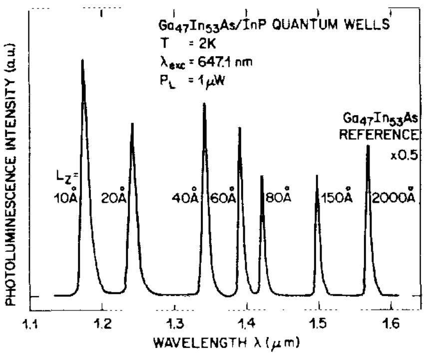

FIG. 1. Typical photoluminescence spectrum from a stack of quantum wells with different thicknesses separated by 700-Å InP barriers at 2 K. The pumping power is 1 μW and pumping area is ~50 μm diameter.

disputedly demonstrate the superiority of this technique over OMCVD[5] in producing high quality heterointerfaces. It should be pointed out that unlike the OMCVD results of Razeghi *et al.*[5] whose 25-Å (narrowest well reported) and 50-Å wells exhibited broad emission multicomponent in nature, all the CBE-grown wells exhibited a single sharp peak. The multicomponent nature is indicative of the participation of impurities in the recombination process (donor to valence band and donor to acceptor transitions) instead of excitonic transitions, while the broad emission is indicative of rough heterointerfaces.

Figure 2(a) represents a compilation of PL linewidths (FWHM) as a function of quantum well thickness for all (to the best of our knowledge) published $Ga_{0.47}In_{0.53}As/InP$[5-8] and $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$[11-13] quantum wells grown by either OMCVD or MBE. Since the exact thicknesses of the GaInAsP quantum wells were not given in Ref. 8, the thicknesses used here were estimated assuming ideal energy shift to well thickness relation. It is clear that the present quantum wells have significantly narrower PL linewidths than any previous $Ga_{0.47}In_{0.53}As$ quantum wells ever reported at all well thicknesses.

The low-temperature PL linewidths for $Ga_{0.47}In_{0.53}As$ single quantum wells are determined by three major contributions, i.e., alloy broadening,[12] due to geometric well width fluctuations,[12,16-20] and broadening due to an equilibrium concentration of carriers (band-filling effect) and defects associated with the heterointerfaces.[12] In $Ga_{0.47}In_{0.53}As/InP$ quantum wells, alloy broadening dominates for well thicknesses of $L_z > \sim 50$ Å and amounts to about 1.3 meV. Alloy broadening becomes reduced though not negligible in narrow wells because the electronic wave function spreads more into the InP cladding layer. A value of 1.2 meV was recently measured experimentally in extremely high quality $Ga_{0.47}In_{0.53}As$ bulk layers.[21]

The dashed curve shown in Fig. 2(a) was calculated by Welch *et al.*[12] for broadening due to an equilibrium number of carriers produced from impurities in the well and/or the barrier layers. A sheet carrier density of 2×10^{11} cm^{-2} was used. The dotted curve was the calculated linewidth broadening ΔE, due to a total (both heterointerfaces) geometric well width fluctuation L_z of one monolayer ($a_0/2 = 2.93$ Å) using the relationship $\Delta E = [d(\Delta E_{1h})/dL_z]\Delta L_z$.

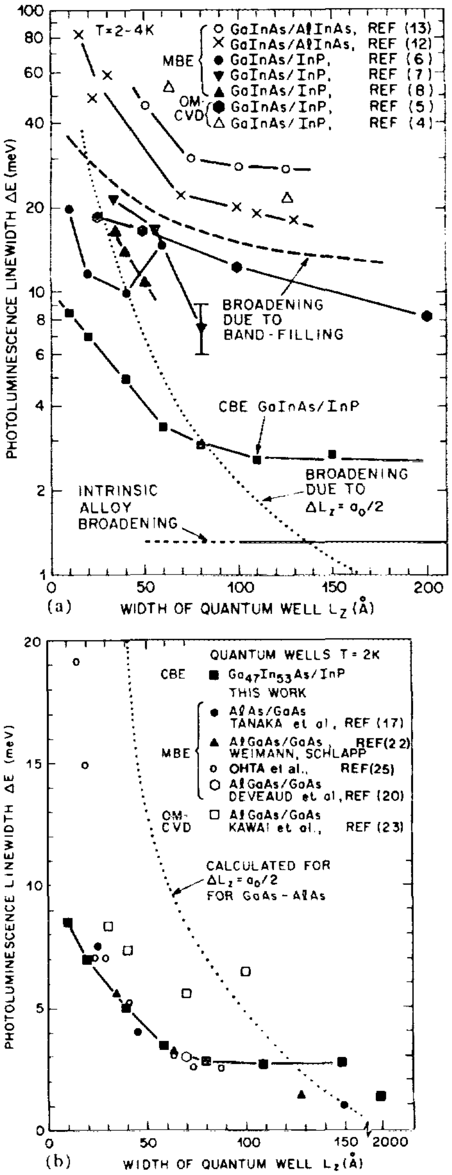

FIG. 2. (a) Represents a compilation of PL linewidths (FWHM) as a function of well thickness for all published $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ quantum wells grown by OMCVD and MBE together with present results grown by CBE. The dashed curve was calculated broadening due to band filling from impurities. A sheet carrier density of 2×10^{11} cm^{-2} was used. The dotted curve was calculated broadening due to "effective" interface roughness L_z of $a_0/2$ assuming finite-height barriers. (b) Represents a compilation of the narrowest PL linewidths (FWHM) of the GaAs/AlAs and GaAs/AlGaAs grown by MBE and OMCVD ever reported together with the present CBE-grown $Ga_{0.47}In_{0.53}As/InP$ quantum wells as a function of well thickness for comparison. In $Ga_{0.47}In_{0.53}As$ wells, intrinsic alloy broadening amounts to ~1.3 meV, which is not present in GaAs wells. The dotted curve was calculated for broadening due to $L_z = a_0/2$ for GaAs/AlAs wells assuming infinite-height barriers.

E_{1h} is the energy upshift due to quantum-size effect in wells with finite-height barriers. For narrow wells (~ < 50 Å) broadening due to well width fluctuation becomes very severe and is the dominant contribution to PL linewidths. Our linewidths are far significantly narrower than the calculated broadening. Similar situations were found by Tanaka *et al.*,[17] Weimann and Schlapp,[22] and Kawai *et al.*[23] for extremely flat MBE and OMCVD-grown GaAs/AlAs and GaAs/AlGaAs quantum wells recently, respectively.

Neglecting contribution due to alloy broadening in narrow wells, we estimated an "effective" interface roughness of $0.12a_0$, which can be interpreted as that the quantum well was largely consisting of a big domain of the same thickness

L_z perforated with a small fraction of small domains of $(L_z + a_0/2)$. From the above comparisons with previous published results[4–13] and theoretical calculations,[12] we conclude our quantum wells have extremely flat heterointerfaces, not band filling due to background impurities, and a minimal alloy broadening of ~ 1.3 meV for wells > 50 Å. This is further supported by the results of excitation spectroscopy[24] obtained from GaAs/AlGaAs quantum wells also grown with the same technique, which show an abrupt heterointerface smooth to within one monolayer.

In fact, the PL linewidths of these CBE-grown $Ga_{0.47}In_{0.53}As/InP$ quantum wells are at least equal to the narrowest linewidths reported[17,20,22,25] for the extremely flat all binary GaAs/AlAs quantum wells recently grown by MBE using a specially controlled interrupted growth technique[17] and phase-locked epitaxy.[25] Figure 2(b) gives a compilation of the best GaAs/AlAs and GaAs/AlGaAs quantum wells grown by MBE[17,20,22] and OMCVD[23] that have shown a single sharp exciton peak together with the present results for comparison. Note that in GaAs/AlAs quantum wells, there is no broadening due to alloy fluctuations. Thus, for narrower $Ga_{0.47}In_{0.53}As$ wells, where the electronic wave functions spread farther into the InP cladding layers, the PL linewidths are similar to those of GaAs/AlAs obtained by Tanaka *et al.*[17] even though there are still some contributions from alloy broadening. On the other hand, for thicker $Ga_{0.47}In_{0.53}As$ quantum wells, where the electronic wave functions are tightly localized within the wells, intrinsic alloy fluctuations (~ 1.3 meV)[24] broaden the PL linewidths in comparison with GaAs wells. If a value of 1.3 meV is subtracted for the $Ga_{0.47}In_{0.53}As$ wells having thicknesses > 100 Å, the resulting linewidths become equal to those of extremely flat GaAs wells with thicknesses > 100 Å. The dotted curve was calculated for broadening due to $L_z = a_0/2$ for GaAs/AlAs quantum wells assuming infinite-height barriers from which Tanaka *et al.*[17] concluded that their PL linewidths correspond to an "effective" interface roughness ΔL_z of ~ 0.19 atomic layer. This value underestimates the "effective" interface roughness because of the assumption of infinite-height barriers. Such comparison in Fig. 2(b) undisputedly shows that the interface quality of the CBE-grown $Ga_{0.47}In_{0.53}As/InP$ quantum wells is at least equal to even the best GaAs/AlAs and GaAs/AlGaAs quantum wells grown by MBE. Note that both the GaAs and $Al_xGa_{1-x}As$ materials and the MBE growth of these materials and heterostructures have been extensively studied and perfected by now. Note also that the growth of $Ga_{0.47}In_{0.53}As/InP$ also involves a complete replacement of As with P and vice versa at the heterointerfaces. Comparing with OMCVD-grown GaAs quantum wells,[23] the present $Ga_{0.47}In_{0.53}As$ quantum wells are still significantly better [see Fig. 2(b)].

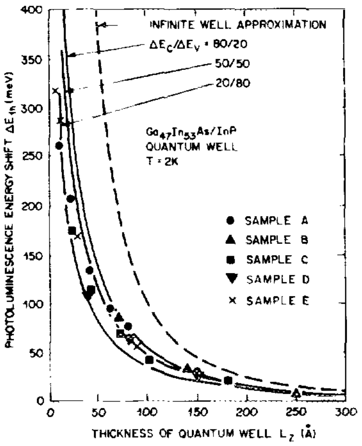

FIG. 3. Measured PL energy upshifts of five different $Ga_{0.47}In_{0.53}As/InP$ quantum well samples each having stacks of quantum wells of different thicknesses as a function of well thickness. The three solid curves were calculated with different ratios of $\Delta E_c/\Delta E_v$. The $Ga_{0.47}In_{0.53}As$ dispersion relation was taken to be of parabolic shape.

In Fig. 3 we show the measured PL energy upshifts ΔE_{1h} of five different $Ga_{0.47}In_{0.53}As/InP$ quantum well samples each having stacks of quantum wells of different thicknesses as thin as 6 Å as a function of well thicknesses. The three solid curves were calculated with different ratios of conduction-band-edge differences to valence-band-edge differences, $\Delta E_c/\Delta E_v$. For the first time, experimental values fall within the theoretical curves. All previous results[4–8,10–12] lie below the theoretical curves. Further, the extreme consistence and well-behavedness of the various different samples prove the reliability of the data and the reproducibility of the growth technique. Basing on the present data alone, it is difficult to determine the actual $\Delta E_c/\Delta E_v$ ratio.

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