Short wavelength intersubband transitions in InGaAs/AlGaAs quantum wells grown on GaAs

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(Received 4 August 1993; accepted for publication 18 November 1993)

We have demonstrated intersubband transition energies as high as 580 meV (2.1 μm wavelength) in InGaAs/AlGaAs quantum wells (QWs) grown on GaAs substrates. The well width dependence of intersubband transition energies in both $In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ QWs and $In_{0.5}Ga_{0.5}As/AlAs$ QWs have been determined. Good agreement of the intersubband transition energies to a single band effective mass model with band nonparabolicity included is found. Experimental studies of buffer and QW growth parameters for optimized intersubband absorption have also been performed.

Intersubband transitions have been used for applications such as photodetectors, modulators, and nonlinear optics.[1–3] These intersubband applications, however, are restricted in wavelength of operation by the range of intersubband transition energies available. Intersubband transition energies in GaAs/AlGaAs QWs and InGaAs/InAlAs QWs lattice matched to InP have been, typically, limited to less than 300 meV ($\geqslant$4.1 μm wavelength), and only recently have intersubband energies of greater than 400 meV ($\leqslant$3.1 μm) been achieved by using more exotic materials (2.4 μm in InGaAs/AlAsSb QWs)[4] or strained QWs (1.8 μm in InGaAs/AlAs QWs on InP).[5] By using InGaAs and AlGaAs for the well and barrier materials, respectively, QWs can have large conduction band offsets ΔE_c and thus, large intersubband transition energies. The growth of these highly strained QWs on GaAs substrates are facilitated by the initial growth of a linearly graded InGaAs buffer.[6,7] We present here a summary of growth studies performed on these InGaAs/AlGaAs QWs, measurements of the well width dependence of intersubband transition energies in both $In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ QWs and $In_{0.5}Ga_{0.5}As/AlAs$ QWs, a theoretical model for predicting the intersubband energies, and results on large energy intersubband transitions.

All of the InGaAs/AlGaAs QW samples were grown by molecular beam epitaxy (MBE) in a Varian Gen-II system on semi-insulating GaAs substrates. These QWs were grown atop linearly graded InGaAs buffers which were graded at a rate of 16% indium/μm from GaAs up to a final buffer indium composition, usually near the average indium concentration of the QWs. In addition, all of the QW samples had an AlGaAs barrier width of 80 Å and were uniformly silicon doped n-type over the well regions. The indium concentrations of the InGaAs wells and buffers were verified to be within 3% indium composition of the target value by high-resolution x-ray diffraction (HRXRD) measurements on thick, relaxed InGaAs samples grown with the same conditions and in the same run as the QW samples. The intersubband absorption spectra from these samples were measured using a Fourier transform infrared spectrometer (FTIR) with the samples mounted at Brewster's angle to the linearly polarized light.

Growth studies of $In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ QWs with 40 Å wells were performed to minimize the intersubband absorption linewidth and maximize the integrated absorption fraction (IAF).[8] The optimal substrate temperature during the growth of the QWs was found to be between 350 and 400 °C for both As_2 and As_4 species. At higher temperatures the interface quality degraded, resulting in broad absorption linewidths, while at lower temperatures the material quality degraded, yielding much lower IAFs. By adding GaAs smoothing layers at the QW interfaces and ramping the substrate temperature to 600 °C for growth of the AlGaAs barriers, we observed that the linewidths and IAFs were significantly improved. The final indium composition y_b of the $In_yGa_{1-y}As$ buffer was also determined to be a critical growth parameter; the linewidth monotonically decreased with increasing y_b up to $y_b=0.3$, where the IAF dropped and the QWs became relaxed. Thus the optimal effective substrate lattice constant for this QW structure corresponded to that of an $In_{0.3}Ga_{0.7}As$ buffer. This optimal $y_b=0.3$ is larger than the average indium concentration of the QWs, $y_{avg}=0.17$. Using near optimized growth conditions, we were able to obtain full width at half-maximum (FWHM) linewidths of 34 meV for 1–2 transition energies of 350 meV. This linewidth corresponds to a relative linewidth (FWHM divided by the transition energy) of less than 10%; similar relative linewidths were observed in well doped GaAs/AlGaAs QWs. This FWHM is also comparable to that obtained in InGaAs/InAlAs QWs grown on InP with similar transition energies (29 meV for unstrained and 60 meV for strained).[9]

The dependence of the intersubband absorption on well width for both $In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ and $In_{0.5}Ga_{0.5}As/AlAs$ QWs was also determined. These samples each had 50 QWs and were doped at a sheet charge density per QW of 2.8×10^{12} cm^{-2} and 4.0×10^{12} cm^{-2} for the $Al_{0.45}Ga_{0.55}As$ and AlAs barrier samples, respectively. The samples were grown at a substrate temperature of 400 °C with As_4 for the $Al_{0.45}Ga_{0.55}As$ samples and with As_2 for the AlAs samples. The final buffer indium composition was targeted to be near the average indium concentration of the QWs for the AlGaAs samples and slightly higher than the average for the AlAs samples. As determined by our growth parameter studies, using a final buffer indium composition slightly greater than the average lattice constant of the quantum wells should help improve the material quality in the AlAs barrier samples; the $Al_{0.45}Ga_{0.55}As$ samples were grown before these growth studies were performed. The intersubband absorption peak energies for these QWs are

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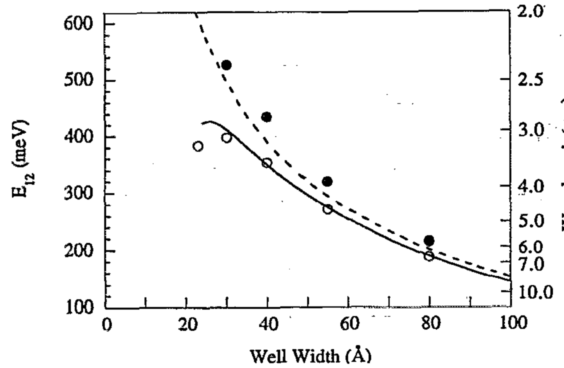

FIG. 1. Well width dependence of 1–2 intersubband absorption peak energies for $In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ (hollow circles) and $In_{0.5}Ga_{0.5}As/AlAs$ QWs (filled circles). Solid and dashed lines are calculated energies corresponding to the $Al_{0.45}Ga_{0.55}As$ and AlAs QW samples, respectively.

plotted in Fig. 1. The 1–2 transition energies for the narrow AlAs QWs are among the largest observed to date for intersubband transitions. For the $Al_{0.45}Ga_{0.55}As$ barrier samples, the 23 Å well had a 1–2 transition energy of 384 meV, lower than that for the 30 Å well. This indicates that the second energy level was near the top of the well so that narrowing the well width from 30 to 23 Å caused the ground state subband energy to increase more rapidly than the second subband energy.

The transition energies and dipole moments for these quantum wells were modeled with a single band effective mass model,[10] and band nonparabolicity was taken into account by using an energy dependent effective mass m^* given by[11]

$$m^*(E)=\frac{m_0^*}{1+(\alpha/E_g)(E-E_{c0})}, \tag{1}$$

where E is the electron energy, E_{c0} is the conduction band edge energy, α is the nonparabolicity factor,[12] and m_0^* is the effective mass at the bottom of the conduction band. The material parameters used for the calculation were a Γ-point band gap energy E_g of 0.755, 1.424, 1.985, and 3.018 eV for $In_{0.5}Ga_{0.5}As$, GaAs, $Al_{0.45}Ga_{0.55}As$, and AlAs, a conduction band offset ratio $\Delta E_c/E_g$ of 0.5 for $In_{0.5}Ga_{0.5}As$ to GaAs and 0.6 for GaAs to $Al_xGa_{1-x}As$, a m_0^* of 0.034 m_0, 0.098 m_0, and 0.141 m_0 for $In_{0.5}Ga_{0.5}As$, $Al_{0.45}Ga_{0.55}As$, and AlAs, respectively, and an $\alpha=-0.86$ for $In_{0.5}Ga_{0.5}As$. For energies less than 400 meV above the conduction band edge, the nonparabolic band parametrization given by Eq. (1) is used. However, for energies of more than 400 meV above the band edge, the fourth-order approximation to the band dispersion (energy E versus wave number k) becomes inaccurate for $In_{0.5}Ga_{0.5}As$ and in fact, approaches a maximum in E vs k so that the effective mass becomes infinite. In order to resolve this problem, we noted that the E vs k curves for InAs and GaAs, calculated using a pseudopotential method,[13] are nearly linear for energies high above the band edge around the Γ point. Thus, we assumed a linearized E vs k for energies of more than 400 meV above the conduction band edge with the E vs k curve and slope matched at 400 meV. The calculated energies using this method for both the

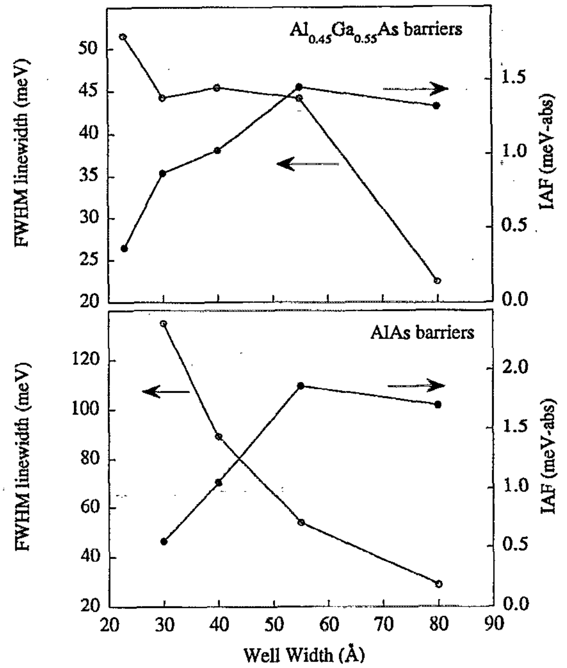

FIG. 2. Well width dependence of 1–2 intersubband absorption FWHM linewidth (hollow circles) and IAF (filled circles) for $In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ (top graph) and $In_{0.5}Ga_{0.5}As/AlAs$ QWs (bottom graph).

$In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ and $In_{0.5}Ga_{0.5}As/AlAs$ QWs are also plotted in Fig. 1. Good agreement between the calculated and measured energies is observed.

The FWHM linewidths and IAFs for the $In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ and $In_{0.5}Ga_{0.5}As/AlAs$ QWs samples are shown in Fig. 2. The measured IAFs are approximately half of the theoretically calculated values for all of the samples except the narrowest well samples for both series for which the IAF dropped significantly below 50% of the theoretical value. The IAFs are calculated by using dipole moments obtained from our theoretical model and by using the targeted dopant concentration for the carrier concentration.[14] We have observed this 50% experimental to theoretical IAF ratio, even for GaAs/AlGaAs QW samples. The reduced IAFs in the narrowest wells may be due in part to the high dopant concentrations in these narrow wells required to achieve the same sheet charge density as the wider wells. The linewidths follow a generally increasing trend with narrower well width. Many linewidth broadening mechanisms contribute to this well width dependent linewidth, including increased impurity and interface scattering with decreased well widths and increased transition energies. The broad linewidth for the narrowest well may be due to Γ-X scattering in the AlAs barrier, since according to our model, the second energy level is above the AlAs X valley.

To obtain even larger transition energies, we have investigated samples with higher indium concentrations. Three $In_{0.6}Ga_{0.4}As/Al_xGa_{1-x}As$ QW samples with 50 QWs and aluminum compositions of $x=0.45$, 0.67, and 1.0 were grown with a final buffer indium composition of 0.3 and well doping concentration of 1.9×10^{19} cm^{-3}. The intersubband absorption spectra for these three samples are shown in Fig.

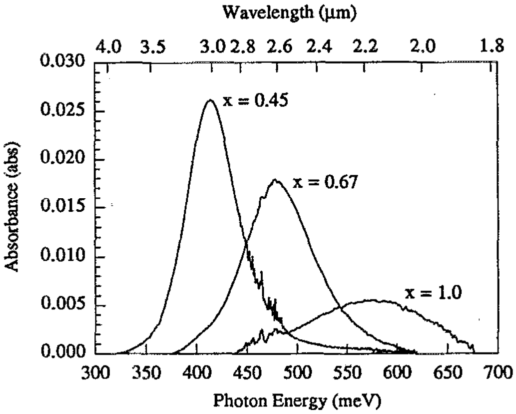

FIG. 3. Intersubband absorption spectra for $In_{0.6}Ga_{0.4}As/Al_xGa_{1-x}As$ QWs with 30 Å wells for $x=0.45$, 0.67, and 1.0.

3. The AlAs barrier sample has a transition peak energy of 580 meV (2.1 μm wavelength). The relative linewidths for these samples are 14%, 17%, and 25% for the $x=0.45$, 0.67, and 1.0 samples, respectively. The broad linewidth for the AlAs barrier sample is mainly attributed to band nonparabolicity; the same QW structure grown with a lower doping concentration of 3×10^{18} cm^{-3} exhibited an intersubband absorption peak at 600 meV with a relative linewidth of only 12.5%.

To summarize, we have demonstrated intersubband transitions in high indium content InGaAs/AlGaAs QWs grown on GaAs using a linearly graded InGaAs buffer. Growth studies were performed to optimize growth conditions for minimum intersubband absorption linewidth with maximum IAF. The well width dependence for both $In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ and $In_{0.5}Ga_{0.5}As/AlAs$ QWs was presented, and good agreement to a single band effective mass model with band nonparabolicity included was obtained. A peak intersubband transition energy as high as 580 meV (2.1 μm wavelength) was observed in $In_{0.6}Ga_{0.4}As/AlAs$ QWs. The large transition energies observed in these InGaAs/AlGaAs QWs should be useful for short wavelength intersubband applications in the near-infrared where compact diode laser based sources are available.

H. C. Chui acknowledges fellowship support from the Office of Naval Research (ONR), and E. L. Martinet, from ONR and Lockheed. This work was supported by ONR under Contract No. N00014-91-J-0170 and Contract No. N00014-92-J-1903 and by ARPA under Contract No. N00014-90-J-4056. FTIR measurements were performed on a Bruker FTIR at the Stanford Free Electron Laser facility.

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