Intersubband transitions in high indium content InGaAs/AlGaAs quantum wells

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We report the first observation of intersubband transitions in $In_yGa_{1-y}As(y=0.3,0.5)$/AlGaAs quantum wells. These quantum wells were grown on a GaAs substrate with a linearly graded InGaAs buffer to achieve strain relaxation before growth of the quantum wells. Measured intersubband transition energies of 316 and 350 meV are among the largest ever reported. Asymmetric step $In_{0.5}Ga_{0.5}As$/AlGaAs quantum wells designed for second harmonic generation measurements also demonstrate strong intersubband absorption at 224 meV corresponding to the 1-2 transition. With the large conduction band offsets (larger than 800 meV) available in this material system, extension to larger intersubband transitions energies for quantum well photodetector and nonlinear optics applications should be possible.

Large intersubband transition energies are essential for extending the operating wavelength of quantum well infrared photodetectors (QWIPs) and intersubband nonlinear optical frequency conversion devices.[1] QWIPs have recently been a topic of interest for applications in high speed detector arrays.[2] By using large energy intersubband transitions in quantum wells, the useful range of these QWIPs can be extended to the 3–5 μm atmospheric window. Also of interest is the application of large intersubband transition energies to nonlinear optical frequency conversion devices. With the demonstration of large nonlinear optical susceptibilities in quantum wells,[3] large intersubband transition energies would similarly extend the range of available frequencies for nonlinear interactions. Large intersubband transition energies have been observed in quantum wells of GaAs/AlAs ($E_{16}=434$ meV)[4] on GaAs as well as InGaAs/InAlAs on InP ($E_{12}=400$ meV for strained quantum wells and $E_{12}=295$ meV for lattice matched).[5–7] By using InGaAs/AlGaAs quantum wells, the conduction band offset ΔE_c is further extended. However, the lattice mismatch of InGaAs and AlGaAs limits the range of useful indium content for producing good quality material. Thus, prior to this work, intersubband transitions had only been observed in InGaAs/AlGaAs quantum wells of up to 15% indium concentration.[8] By using a linearly compositionally graded buffer, Lord *et al.*[9] demonstrated that high quality $In_{0.5}Ga_{0.5}As$/AlGaAs quantum wells could be grown on a GaAs substrate. Using this novel growth technique, we investigate intersubband transitions in InGaAs/AlGaAs quantum wells with high indium concentrations of 30% and 50%. We first present results on intersubband transitions in two square well samples before reporting on an asymmetric step multiple quantum well designed for future intersubband second harmonic generation measurements.

Two $In_yGa_{1-y}As/Al_{0.45}Ga_{0.55}As$ square multiple quantum well (MQW) samples were grown with well indium compositions of $y=0.3$ and 0.5. The targeted layer structures for these samples are shown in Fig. 1. These MQW structures were grown on semi-insulating GaAs substrates by molecular beam epitaxy (MBE) in a Varian Gen-II system using As_2 at a substrate temperature of 480 °C. The MQWs were grown atop an InGaAs buffer which was linearly graded at a rate of 16% indium/μm from GaAs to approximately the average indium composition of the MQWs. The indium compositions of the wells were measured by performing x-ray diffraction (XRD) on two thick, relaxed InGaAs samples grown in the same growth run and with the same growth rates as the MQW samples. The actual well compositions were determined to be $y=0.28$ and 0.51. The samples were doped n^+ in the well regions with measured Hall sheet charge densities per quantum well of $n=2.56\times 10^{12}$ and 5.56×10^{12} cm^{-2} for the $y=0.3$ and 0.5 samples, respectively.

The intersubband absorption was measured using a Fourier transform infrared spectrometer (FTIR) with the samples mounted at the Brewster angle to the TM polarized light. The FTIR spectra for the two square MQW samples are shown in Fig. 2. The measured absorption peaks for the 1-2 transitions were found to be 316 and 350 meV with full width at half-maximum (FWHM) linewidths of 37.5 and 52.9 meV for the $y=0.3$ and 0.5 samples, respectively. These intersubband transition energies are among the largest ever reported and are comparable to the theoretically calculated values of 330 meV for both the $y=0.3$ and $y=0.5$ samples. These values were calculated using a single band effective mass model[10] with nonpara-

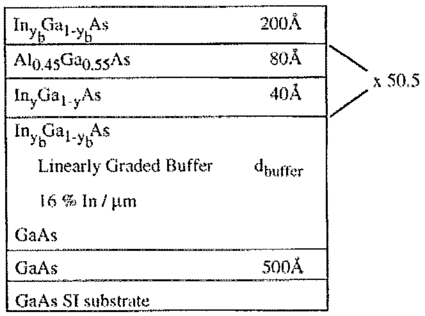

FIG. 1. Layer structure for $In_yGa_{1-y}As$/AlGaAs square MQWs with graded InGaAs buffer for (a) $y=0.3$ sample: $y_b=0.11$, d_{buffer} = 6000Å and (b) $y=0.5$ sample: $y_b=0.17$, $d_{buffer}=10\,000$ Å.

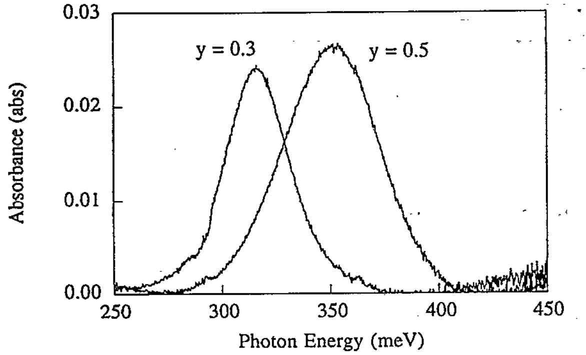

FIG. 2. FTIR absorption spectra of the $y=0.3$ and 0.5 square MQW samples.

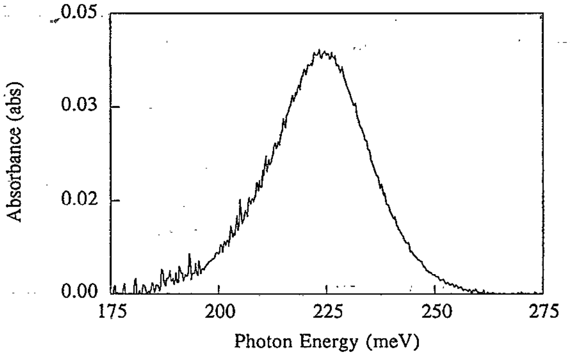

FIG. 4. FTIR absorption spectrum of the InGaAs/AlGaAs asymmetric step MQW sample.

bolicity included via an energy dependent effective mass derived from the conduction band dispersion. The calculated values for the two composition wells are approximately the same because the change in well depth is offset by differences in the effective mass and band nonparabolicity. The measured integrated absorption fractions, IAFs, were found to be 0.965 abs-meV and 1.489 abs-meV resulting in dipole moments[11] of 8.3 and 7.0 Å for the $y=0.3$ and 0.5 samples, respectively. The theoretically calculated dipole moments using the measured sheet charge densities are 12 Å for both samples.

An asymmetric step quantum well sample was also grown for future second harmonic generation measurements.[12,13] This sample, however, was grown using As_4 at a substrate temperature of 430 °C. The conduction band diagram for the asymmetric step quantum wells of this sample with theoretically calculated energy levels is shown in Fig. 3. This sample was doped n^+ in the 40 Å well regions only, resulting in a measured Hall sheet charge density of 2.94×10^{12} cm^{-2} per quantum well. The structure was similar to that shown in Fig. 1. However, the final buffer composition y_b was 0.19, and the buffer was graded at a rate of 8% indium/μm to further improve the material quality in the MQW region.[14] High resolution XRD measurements of a reference wafer grown in the same growth run and with thick relaxed InGaAs layers corresponding to the buffer and well determined that the actual well, step, and buffer compositions were 0.54, 0.24, and 0.20, respectively, instead of the targeted 0.47, 0.23, and 0.19.

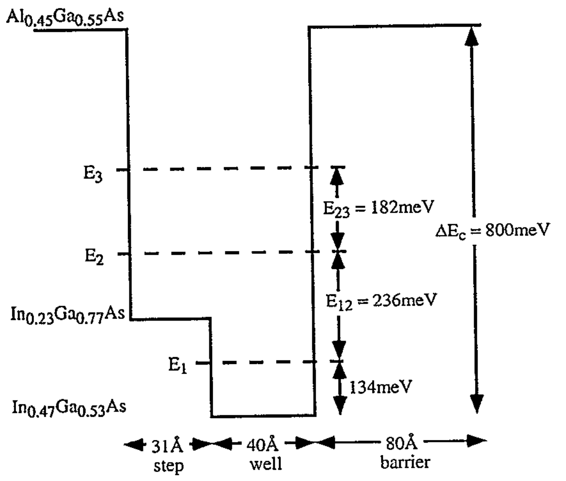

FIG. 3. Conduction band diagram of asymmetric step MQW sample with theoretically calculated energy levels

The absorption spectrum of the asymmetric step MQW sample was measured using FTIR, and the spectrum is plotted in Fig. 4. A strong intersubband absorption at 224 meV with a FWHM of 27 meV corresponding to the 1-2 transition is observed. The transition energy is close to the theoretically calculated value of 236 meV. The measured IAF is 1.26 abs-meV resulting in a dipole moment of 10.4 Å for this transition. This dipole moment is different from the calculated value of 15 Å.

In summary, we report the first observation of intersubband transitions in high indium content InGaAs/AlGaAs square and asymmetric step quantum wells. The intersubband transition energies of 316 and 350 meV measured for the $y=0.3$ and 0.5 square well samples, respectively, are among the largest ever reported. Intersubband absorption at 224 meV was also observed in an asymmetric step quantum well sample. The key element to the successful growth was the use of a linearly graded InGaAs buffer. Thus we have demonstrated that the strained InGaAs/AlGaAs system grown on a linearly graded InGaAs buffer is a material system that should prove useful for applications where extremely large conduction band offsets are needed. With the $In_{0.5}Ga_{0.5}As/Al_{0.45}Ga_{0.55}As$ quantum wells, there is a conduction band offset of 800 meV, and by further increasing the indium content in the wells and the aluminum content in the barriers, even larger conduction band offsets and intersubband transition energies are obtainable. Applications such as short wavelength quantum well photodetectors, resonant tunneling diodes, and near infrared intersubband nonlinear optical frequency converters should be possible.

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