# Intersubband absorption in strained $In_xGa_{1-x}As/Al_{0.4}Ga_{0.6}As$ ($0 \leqslant x \leqslant 0.15$) multiquantum wells

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We report, for the first time, temperature-dependent intersubband absorption data in doped pseudomorphic $In_xGa_{1-x}As/Al_{0.4}Ga_{0.6}As$ ($0 \leqslant x \leqslant 0.15$) multiquantum wells. In this composition range the absorption resonance varies in the range 6–7 $\mu$m for 50 Å wells, which agrees extremely well with theoretical calculations.

The possibility of realizing high-speed far-infrared detectors and modulators by utilizing carrier transition between the bound states in a quantum well has motivated the study of these transitions. West and Eglash[1] first demonstrated that the oscillator strength and dipole movement of such transitions, involving envelope states are very large in $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells. Since this report, other groups have made studies on $GaAs/Al_xGa_{1-x}As$[2–4] and $In_{0.53}Ga_{0.47}As/In_{0.52}Ga_{0.45}As$[5] quantum wells and novel detection and modulation devices have been proposed and demonstrated.[6,7] The use of pseudomorphic quantum wells can relax lattice matching requirements and provide additional tunability of the intersubband transition energy. We report here intersubband absorption studies in $In_xGa_{1-x}As/Al_{0.4}Ga_{0.6}As$ ($0 \leqslant x \leqslant 0.15$) quantum wells using Fourier transform infrared (FTIR) spectroscopy. The experiments have been made at room temperature and lower temperatures.

The device structures used in the FTIR measurements were grown by molecular beam epitaxy in a Varian Gen II system. The structures were grown on undoped semi-insulating GaAs, starting with a 0.3 $\mu$m Si-doped ($2\times10^{18}$ cm$^{-3}$) GaAs layer. This is followed by 50 periods of (50 Å) $In_xGa_{1-x}As$/(100 Å) $Al_{0.4}Ga_{0.6}As$ ($0 \leqslant x \leqslant 0.15$) multiquantum wells (MQWs). For the well thickness and compositions considered here, it is appropriate to assume that the wells are pseudomorphic and coherently strained. The quantum wells are doped in the middle 30 Å with Si to a level of $5\times10^{17}$ cm$^{-3}$. This is done to enhance the intensity of the absorption signal and to reduce built-in electric field effects. Finally a 0.3 $\mu$m Si-doped ($2\times10^{15}$ cm$^{-3}$) top layer is grown. The Si-doped layers were incorporated to include the possibility of applying a bias, which, of course, is not the subject of this study. Waveguides of lateral dimensions 1.0 cm$\times$0.7 mm were made from the wafers and polished 45° facets were made at the ends for proper light input and output. The multireflection waveguide geometry helps to increase the net absorption. Temperature-dependent FTIR measurements were made with a MATTSON Cygnus 100 system consisting of a Hg arc lamp source and a wideband HgCdTe detector. The resolution in our measurement is 4 cm$^{-1}$.

Figure 1 shows the intersubband absorption for an $In_{0.1}Ga_{0.9}As/Al_{0.4}Ga_{06}As$ sample at room temperature and lower temperatures. The position of the absorbance peak moves towards higher energies with the decrease of temperature accompanied by a linewidth narrowing, as expected. The linewidth decreases from 115.7 to 86.8 meV as the sample temperature is lowered from 300 to 8 K. The linewidth broadening can be used to calculate the transition time of carriers from the upper to the lower state, which in this case is 0.18 ps. Similar values have been reported for GaAs/AlGaAs,[1] which indicate that inhomogeneous line broadening mechanisms such as interface roughness and other spatial inhomogeneities do not play a serious role in the pseudomorphic quantum wells.

We have estimated the oscillator strength $f$ and matrix element $\langle z \rangle$ from the measured integrated absorption strength $I_A$ at 300 K using[1]

$$I_A = F\rho_s W(e^2h/4\epsilon_0 m_e c)(f/n_r^2\sqrt{n_r^2+1}) \quad (1)$$

and

$$\langle z \rangle = L_w(8/\pi^2)[mn/(m^2-n^2)^2], \quad (2)$$

where $m_e$ is the free-electron mass, $\rho_s$ is the two-dimensional electron density per well, $W$ is the number of wells, $n_r$ is the

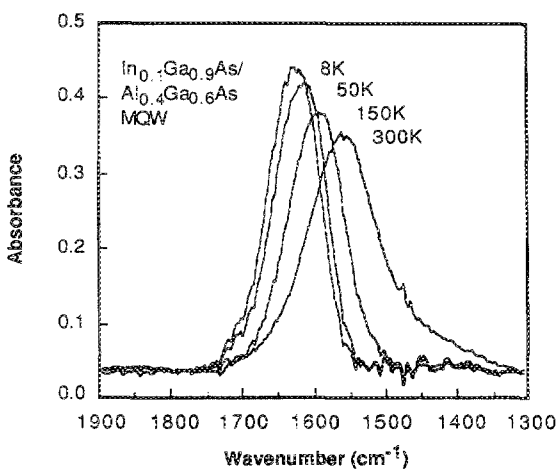


FIG. 1. Temperature-dependent intersubband absorption spectra of $In_{0.1}Ga_{0.9}As/Al_{0.4}Ga_{0.6}As$ MQWs with Si doping in the center of the wells. The sample is fabricated as a single-pass, multiple internal reflection waveguide with a wedge angle of 45°, a thickness of 0.466 mm, and a length of 9.5 mm.

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refractive index, and $F$ is a factor which takes into account the internal reflections at each boundary and changes in path the length of a single ray. $m$ and $n$ are integers denoting the initial and final states. For our samples $F \simeq 100$. The oscillator strength for the $In_{0.1}Ga_{0.9}As/Al_{0.4}Ga_{0.6}As$ MQW at 300 K is 4.24, which is comparable to those measured for GaAs/AlGaAs MQWs.[1]

Figure 2 shows the measured variation of the intersubband energy with In content in $In_xGa_{1-x}As/Al_{0.4}Ga_{0.6}As$ ($0 \leqslant x \leqslant 0.15$) MQWs. The transition energy increases with increase of $x$, as expected, and this primarily results from the decrease in band gap of the InGaAs and the accompanying increase in the conduction band offset due to alloying. The data were analyzed by considering a theoretical Krönig–Penney-type model, including the effect of strain on the band gap, and assuming a constant value of $\Delta E_c:\Delta E_v = 65:35$ in this composition range. This may not be entirely accurate as we have recent experimental evidence[8] that the ratio $\Delta E_c/\Delta E_v$ increases from 0.6 to 0.7 in the composition range of $In_xGa_{1-x}As$ from $x = 0$ to $x = 0.18$. However, the AlGaAs barriers in that experiment had an Al content of 15%. The solid line in Fig. 2 shows the calculated intersubband energies, and in spite of what has just been mentioned, the agreement with measured data is fairly good.

An observation made during the room-temperature measurements on quantum wells of varying In compositions should be mentioned. The peak of the absorbance moved to higher energies with increase of In, as expected, but at the same time the intensity of the transition monotonically decreased. In fact, it was difficult to do measurements beyond $x = 0.15$. This behavior was repeatable with different sets of samples grown at different times. We are in the process of understanding this phenomenon, but some explanations are as follows. Since the quantum wells are doped, it is possible that the doping efficiency is reduced with an increase of In content. Also, increasing strain may cause a lowering of the oscillator strength due to the tetragonal distortion. However, our data indicate that even in the range of $0 \leqslant x \leqslant 0.15$, a large tunability of the absorbance peak can be obtained, and this can obviously be enhanced by going to higher values of $x$ or by changing the well and barrier dimensions.

In conclusion, we report here the intersubband absorption in pseudomorphic $In_xGa_{1-x}As/Al_{0.4}Ga_{0.6}As$ quantum wells for the first time. It is seen that by going from $x = 0$ to $x = 0.15$, the absorbance peak can be shifted from 7 to 6 $\mu$m. The lifetime of the transitions is comparable to that in lattice-matched wells.

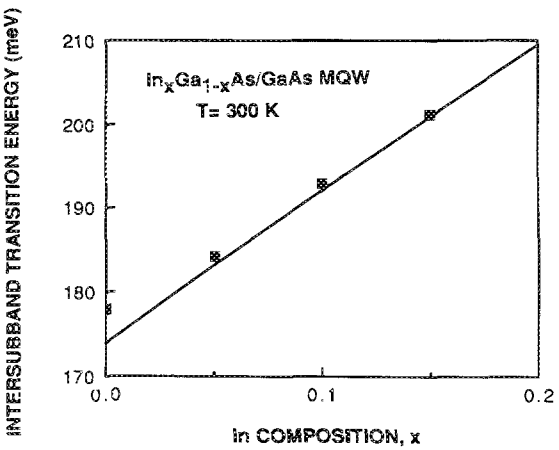


FIG. 2. Measured and calculated variation of the intersubband transition energy in $In_xGa_{1-x}As/Al_{0.4}Ga_{0.6}As$ MQWs as a function of In composition. The calculated values are obtained with $\Delta E_c:\Delta E_v = 65:35$ and a well width of 54 Å (nominal growth thickness = 50 Å).

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