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1.798μm Intersubband Transition in InGaAs/AlAs Pseudomorphic Quantum Well Structures

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The well-width dependence of intersubband transition energies in InGaAs/AlAs pseudomorphic quantum well structures has been studied, and the shortest intersubband wavelength reported to date, 1.798 μm, has been observed for 6 monolayer wells. Both transverse electric (TE) and transverse magnetic (TM) optical polarizations are absorbed, with an energy splitting of 67 meV between them. The possibility of 1.55 μm intersubband transitions using this material system is also discussed.

1. INTRODUCTION

Since intersubband transitions in quantum well structures were first observed,[1)] there have been many reports on this topic related to large oscillator strength, large optical nonlinearity, and fast carrier relaxation time. A key issue pertaining to the utilization of intersubband transitions in practical devices is operation wavelength. Transition wavelengths in the range 4-10 μm are covered by GaAs/AlGaAs,[2)] GaAs/AlAs[3)] and InGaAs/InAlAs[4),5)] material systems. Intersubband absorptions in the range 2-4 μm appropriate for ultra-low-loss fiber communications have also been realized. An absorption wavelength of 2.4 μm was reported for the InGaAs/AlAsSb system,[6)] and a 2.1 μm absorption was reported for a 2.8 nm well in the InGaAs/InAlAs system.[7)]

Because of its applicability to current 1.55 μm optical communication systems, realization of 1.55 μm intersubband transitions in quantum wells would be interesting. Very fast relaxation times and large optical nonlinearities, which are useful for advanced 1.5 μm photonic devices such as high speed photonic switches, are expected. InP based material systems such as InGaAs/AlAs are thought to be among the most suitable systems for this purpose because of the large conduction band offset of AlAs on $In_{0.53}Ga_{0.47}As$. However, there has so far been no report on intersubband transitions at wavelengths shorter than 2 μm. Here, we report observation of intersubband absorption in this material system at 1.798 μm, the shortest wavelength value reported to date.

2. SAMPLE STRUCTURES

For our experiments, a number of samples with different well-widths were fabricated by molecular beam epitaxy (MBE) on Fe doped semi-insulating InP substrates. The band diagram for Samples A and B which had two, 1.8 nm-wide (2.9 nm-wide), $In_{0.53}Ga_{0.47}As$ quantum wells is shown in Fig.1. In order to increase the barrier height, pseudomorphic AlAs barrier layers were employed. Each AlAs layer is 9 monolayers thick. The lattice-mismatch between $In_{0.53}Ga_{0.47}As$ and AlAs is 3.7 %. The growth was monitored by in-situ, reflection high-energy electron diffraction (RHEED) intensity oscillations. Intensity oscillations are clearly observed, for the InAlAs upper cladding layer as well as for the quantum well region. The InGaAs well was highly doped at 10^{19} cm^{-3}. Samples C through F have similar structures as Samples A and B but have slight differences. Samples C, D, E, F have single quantum wells with thicknesses of 4.3, 5.0, 6.6, 7.6 nm, respectively. The composition of the wells for Samples C, D, E is $In_{0.7}Ga_{0.3}As$ instead of $In_{0.53}Ga_{0.47}As$. Sample F has 9 nm $In_{0.7}Al_{0.3}As$ strain compensation layers between the AlAs barrier layers and the $In_{0.52}Al_{0.48}As$ cladding layers.

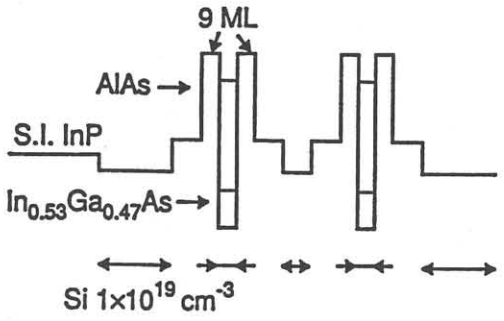

Fig.1 Band diagram for InGaAs/AlAs double quantum well structure.

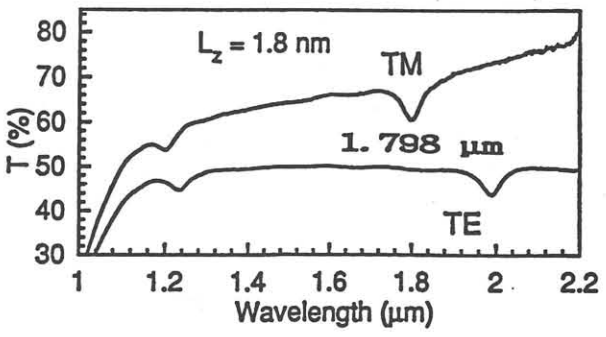

Fig.2 Polarization-resolved absorption spectra for InGaAs/AlAs double quantum wells measured by conventional absorption measurement system.

3. MEASUREMENTS

A conventional optical absorption measurement system with a PbS detector[5] was used for measuring room temperature absorption in the wavelength region less than 2 μm. A Fourier-transform infrared (FTIR) spectrometer with a glowbar source and a mercury cadmium telluride (MCT) detector was used for the wavelengths longer than 2 μm.[7] The backsides of the samples were polished by a bromine-methanol solution. The sample was sandwiched between a pair of parallel aluminum plates and light was focused upon the cleaved sample edge.[7] The light propagates in a total-internal-reflection mode between the polished sample surfaces, and a polarizer was used to separate TE and TM polarizations.

4. RESULTS

Polarization-resolved absorption spectra for Sample A are shown in Fig.2. For Sample A, strong absorption for TM polarized light was observed at 1.798 μm (690 meV). For Sample B, the TM signal was observed at 1.942 μm (638 meV). These absorptions are attributed to the intersubband absorptions. The TE signals were observed at 1.990 μm (2.140 μm), and the splitting energy between TE and TM signals was 67 meV (60 meV) for Sample A (B). Similar splittings between TE and TM signals[7] were observed for samples with wider wells, as indicated below. Additional peaks at around 1.2 μm for Sample A may be due either to intersubband transitions from a confined subband level to virtual energy levels in the continuum or to impurity related transitions. Further study is needed to identify these signals.

Unpolarized spectra for Samples C, D, E with wider well-widths were measured. The FTIR was used for these measurements. For these samples, the well experiences a compressive strain because the well composition is $In_{0.7}Ga_{0.3}As$. The TE and TM signals were identified using the polarizer. The energy differences between the TE and TM signals are 70, 69, and 64 meV for Samples C, D, and E, respectively. The narrower wells produce wider separation between the TE and TM signals.

The well-width dependence of the intersubband transition energies between levels 1 and 2 is plotted in Fig.3. The transition energies increase with decreasing well-width.

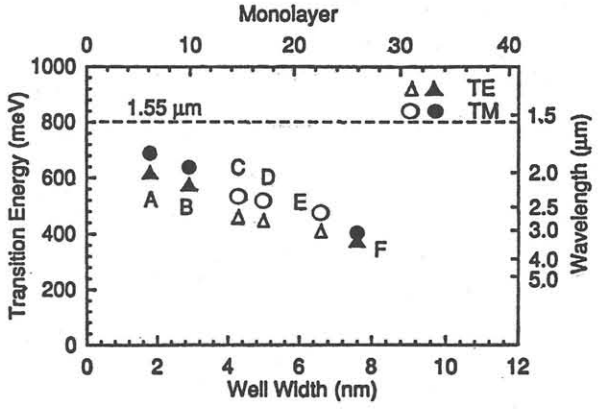

Fig.3 Well-width dependence of intersubband transition energies. Open (closed) triangles and circles are for $In_{0.7}Ga_{0.3}As$ ($In_{0.53}Ga_{0.47}As$) wells. Both TE (triangle) and TM (circle) are plotted.

5.DISCUSSIONS

Polarization selection rules are given in an envelope function approximation framework. The matrix element of an intersubband transition is approximately given as[9)]

$$\langle u'\varphi_f|V_p|u\varphi_i\rangle = \langle u'|V_p|u\rangle_{cell}\langle\varphi_f|\varphi_i\rangle + \langle u'|u\rangle_{cell}\langle\varphi_f|V_p|\varphi_i\rangle, \quad (1)$$

where V_p is the interaction potential, φ_i and φ_f are the envelope functions of the initial and final states, u' and u are the cell periodic functions. For interband transitions, the second term becomes zero because the cell periodic functions in conduction and valence bands are orthogonal. For intersubband transitions, the first term becomes zero because of the fact that the Hamiltonian used to obtain φ_i and φ_f is Hermitian. Therefore the matrix element is non-zero only for the TM polarized light in the case of intersubband transitions.[9)] However, our observation of both TE and TM signals with energy splitting contradicts this simple theory. Disagreement in selection rules and energy splittings between TE and TM signals have been explained by the D_{2d} tetragonal perturbation of the local crystal and strain field effects on the quantum well.[10)] It is noted that Sample F which had strain compensation layers showed a smaller splitting energy of 25 meV.

One method to achieve 1.55 μm intersubband transition might be to use transitions between levels 1 and 4. However, the oscillator strength for this transition is 30 times smaller than that of the 1 to 2 transition because the oscillator strength is approximately expressed by[1)]

$$f = m_e/m_{eff} \times 64/\pi^2 \times m^2n^2/(m^2-n^2)^3, \quad (2)$$

where m_e is free-electron mass, m_{eff} is effective mass and m, n are integers which stand for subband number. In our sample, no such transition was observed. Narrowing the well width is straightforward, although the first subband energy level in InGaAs may move above an X valley subband level in AlAs. A similar phenomenon was reported for GaAs/AlAs quantum well structures.[11)] The employment of In rich InGaAs including InAs in the well is promising. However, a careful design is needed because the band-to-band transition energy in the well may be smaller than the intersubband transition energy. In this case, the intersubband transition would be hidden by the band-to-band transition. The introduction of a multi-quantum barrier (MQB) to make the effective barrier height larger[12)] is also promising.

6.CONCLUSIONS

In conclusion, systematic study of intersubband absorption in very narrow InGaAs/AlAs quantum wells has produced the first reported absorption at wavelengths less than 2 μm. Both TE and TM optical polarizations are absorbed with an energy splitting between them of 67 meV.

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