

# Intersubband Transitions in Narrow InAs/AlSb Quantum Wells

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**Abstract.** We have investigated intersubband transitions (ISBTs) in InAs/AlSb multiple quantum wells with well widths from 2.1 to 10 nm. The ISBT energy increased with decreasing well width and temperature. To explain these well width and temperature dependences, we computed the band structure using an 8 band  $\mathbf{k} \cdot \mathbf{p}$  theory taking into account many-body effects. We have observed the effects on ISBTs of the QW interface type, the substrate type, and Si doping in the well. For wells in which the photoluminescence (PL) energy is less than the predicted ISBT energy, we observe only PL.

## 1. Introduction

The family of III-V semiconductors with lattice constants around 6.1 Å (InAs, GaSb, and AlSb) is a promising system for intraband wavefunction engineering due to the large conduction band offset between InAs and AlSb ( $\sim 2.1$  eV). Many intraband devices for infrared generation have been demonstrated in AlGaAs systems, such as difference frequency convertors [1], quantum cascade lasers [2], and optically pumped lasers [3]. Compared to AlGaAs systems, the 6.1 Å heterostructures offer greater flexibility in designing all-optical intraband devices with a short-wavelength pump [4].

We have investigated intersubband transitions in InAs/AlSb multiple quantum wells (MQWs) of 20 periods with well widths ranging from 2.1 nm to 10 nm. The wells' room temperature electron densities and mobilities were  $10^{12}$  cm $^{-2}$  and  $10^3$ - $10^4$  cm $^2$ /Vs, respectively, and the lowest subband was populated. The absorption was measured in a multipass geometry using a Fourier transform infrared spectrometer (FTIR). The absorption energy increased with decreasing well width and decreasing temperature, and the absorption linewidth showed a weak dependence on temperature. To explain these well width and temperature dependences, we computed the band structure of the quantum wells using an 8 band  $\mathbf{k} \cdot \mathbf{p}$  theory, taking into account the temperature dependence of the bulk bandgaps and of the strain effects due to the different thermal expansions of the well and barrier materials, as well as many-body effects. We also investigated the dependence of the ISBT on the heterointerface type, substrate type, and Si doping in the well. We find that ISBTs and photoluminescence (PL) are mutually exclusive.

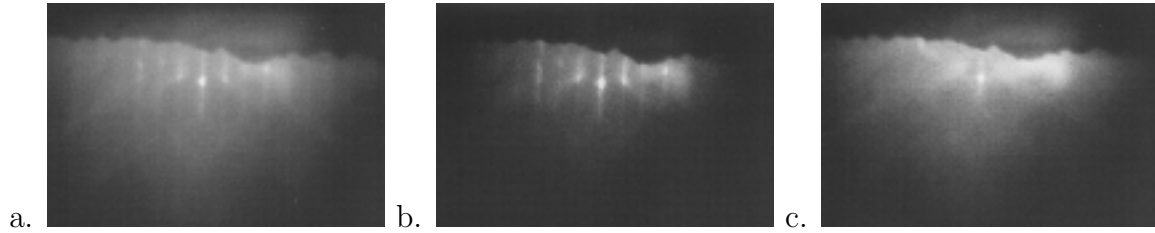


Figure 1. The RHEED patterns along  $[1\bar{1}0]$  during the growth of an InSb-like interface, as described in the text. The RHEED pattern is (a)  $(1\times 3)$  during AlSb growth, (b)  $(1\times 3)$  during InSb growth, and (c)  $(2\times 4)$  during InAs growth.

## 2. Sample Growth and Experimental Methods

The samples were grown by solid-source molecular beam epitaxy (MBE). Before growth, the GaAs substrates were thermally cleaned at  $630^\circ\text{C}$  for 30 min in an  $\text{As}_4$  atmosphere. Buffer layers consisting of 10 nm AlAs, 1000 nm AlSb and 15 periods of GaSb (6 nm)/AlSb (6 nm) SLs were grown at  $550^\circ\text{C}$ . These buffer layers are used to change from the lattice constant of GaAs (0.56 nm) to that of GaSb (0.60 nm). After the growth of buffer layers, InAs (2.1 to 10 nm)/AlSb (10 nm) MQWs were grown at  $420^\circ\text{C}$ . Finally, GaSb was grown as a cap layer.

The InAs/AlSb MQW interface types can be controlled by the growth sequence and are expected to affect the band structure [5]. Both the group III (In, Al) and group V (As, Sb) atoms change across the InAs/AlSb interface. Two types of interface are possible: InSb-like and AlAs-like. Yano et al. have reported that the low temperature PL intensities of InAs/AlSb QWs with InSb-type interfaces were much stronger than those with AlAs-type [6]. From these results, two types of interfaces were grown for this study: (1) InSb-like on both sides of the QW, and (2) AlAs-like from InAs to AlSb and InSb-like from AlSb to InAs.

The MQW growth was monitored by reflection high energy electron diffraction (RHEED). Figure 1 shows the RHEED patterns along  $[1\bar{1}0]$  obtained during the formation of the InSb bonds. First Al and Sb are grown, and the RHEED displays a  $(1\times 3)$  pattern. Then the Al is turned off while the Sb is left on for five seconds. Then the Sb is turned off and after a wait of 1.4 seconds, the In is turned on. During the growth of InSb, the RHEED displays a  $(1\times 3)$  pattern. After growing one monolayer of InSb, the As is turned on and the RHEED displays a  $(2\times 4)$  pattern. These results indicate that the interface of InAs/AlSb can be controlled by the shutter sequence described.

We have investigated the following types of samples: well widths of 2.4, 2.7, 3.0, 3.3, 3.6, 4, 6, 7, 8, 9, and 10 nm with both interfaces InSb-like, not intentionally doped, on GaAs substrates; well widths of 2.1 and 7 nm with one interface InSb-like and one AlAs-like, both undoped and Si well-doped, on GaAs substrates; and well widths of 2.1 and 7 nm with both interfaces InSb-like, not doped, on GaSb substrates.

The ISBTs were measured in a parallelogram multibounce geometry using an FTIR (see inset to Fig. 2). This geometry enables the incident beam to couple to the ISBTs, which can be excited only by an electric field in the growth direction [9]. The QW surface of each sample was coated with 100 nm of gold to enhance the electric field in the growth direction at the QWs [7, 8]. The edges of the sample were polished at 45 degrees. The samples were 2.3 mm long, corresponding to 2.3 bounces. We performed polarization modulation spectroscopy using a holographic grating polarizer to select the ISBT active or inactive polarization,  $p$  or  $s$ .

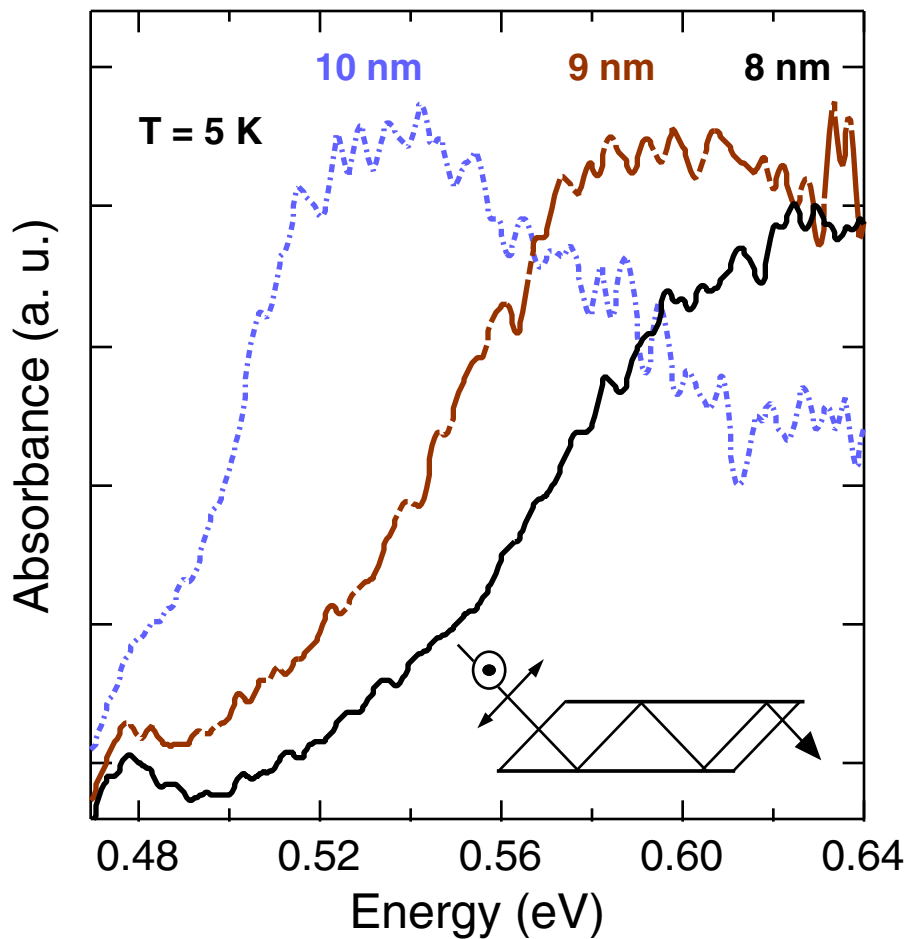


Figure 2. The  $s$  polarized interband spectra at 5 K are shown, normalized to a sample without quantum wells. The well widths are indicated in the figure. The interband absorption edge shifts to higher energy with decreasing well width. The  $p$  polarized interband spectra are similar. The inset shows the sample measurement geometry and possible polarizations of the incident light.

### 3. Results

#### 3.1. Interband Absorption

Figure 2 shows the  $s$  polarized interband absorption spectra of samples with well widths of 8, 9 and 10 nm. These samples have both interfaces InSb-like, are undoped, and are grown on GaAs substrates. The interband spectra are the ratio of the sample transmission at one polarization to the transmission of a reference sample, grown without quantum wells, at that polarization. The figure shows  $-\log(\text{Transmission}_{\text{sample}}/\text{Transmission}_{\text{reference}})$ , i.e. absorbance, versus energy in eV.

The interband absorption edge shifts to higher energy as the well width decreases, mainly due to the increase in energy of the lowest quantized state in the well. Prevot et al. [10] have observed similar spectra in 6.5 to 8.5 nm InAs/AlSb wells. They also observe a difference between the shapes of the  $s$  and  $p$  polarized interband absorptions below the interband peak which is not present in our data.

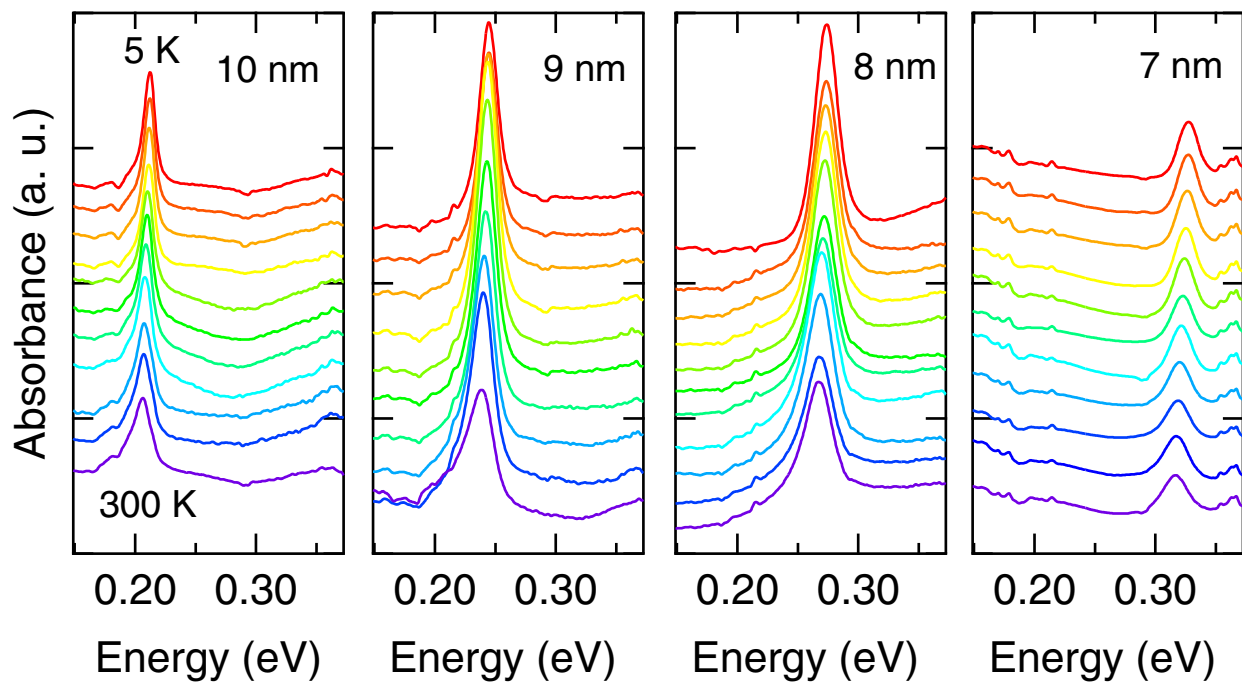


Figure 3. The intersubband absorptions of 10 through 7 nm wells as a function of temperature are shown. The  $p$  polarized spectrum is divided by the  $s$  polarized, and the traces are vertically offset for clarity. All traces are normalized to the same sample width so different samples are directly comparable. The resonance positions increase with decreasing well width and temperature, the linewidths narrow slightly with decreasing temperature, and the resonance intensity for the 7 nm sample is significantly smaller than the others.

### 3.2. Intraband Absorption

We observed ISBTs in 10, 9, 8, and 7 nm wells. Figure 3 shows the temperature dependence of the ISBTs for different well widths. These samples have both interfaces InSb-like, are undoped, and are grown on GaAs substrates. The ratios of the  $p$ -polarized to the  $s$ -polarized spectra for each sample are plotted in absorbance versus energy. The traces are vertically offset for clarity. The traces are normalized to the same sample width so that different samples are directly comparable. For example, the ISBT for the 7 nm well is significantly weaker than the others.

The energy of each ISBT increases with decreasing well width and increases with decreasing temperature by about 8 meV from room temperature to 5 K. The full width at half maximum (FWHM) decreases by a factor of about 0.7 from 300 K to 5 K. Specifically, the room temperature FWHM for the 10, 9, 8, and 7 nm samples is 167, 221, 224, and 188  $\text{cm}^{-1}$  (21, 27, 28, and 23 meV), and the FWHM at 5 K is 92, 144, 178, and 150  $\text{cm}^{-1}$  (11, 18, 22, and 19 meV). The temperature-insensitive linewidth and relatively high mobility ( $10^3$ - $10^4$   $\text{cm}^2/\text{Vs}$ ) indicate that interface roughness scattering is the major broadening mechanism for intraband absorption [8, 11]. The FWHM increases with decreasing well width because interface fluctuations are a larger fraction of the well width for narrower wells, and so interface roughness scattering is stronger.

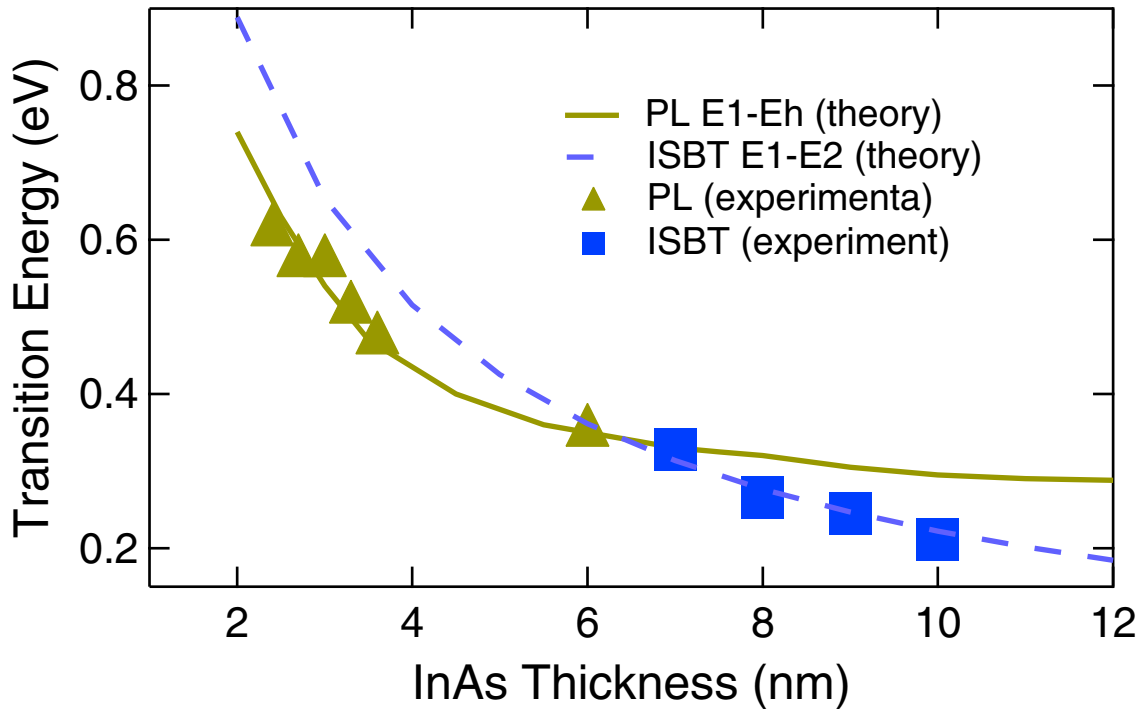


Figure 4. Transition energies as a function of quantum well thickness are shown. The solid curve is the predicted ISBT energy from a flat-band calculation, and the dashed curve is the PL prediction from the Kronig-Penny model. The squares and triangles are the measured ISBT and PL energies.

### 3.3. Photoluminescence

We observed PL in 2 to 6 nm wells, as shown in Figure 4. We could not observe PL in any of the samples which showed ISBTs; neither could we observe ISBTs in the samples which showed PL. It appears that whichever of these two transitions is lower in energy completely suppresses the other. We are currently investigating this situation theoretically. Moreover, the InAs/AlSb system offers the possibility of growing a sample in which the ISBT and PL are expected to occur at the same energy, accessing an unusual and interesting crossover.

### 3.4. Other Parameters

We have investigated several other sample parameters, including interface type (InSb or AlAs), Si doping, and substrate (GaAs or GaSb). GaSb is attractive because it is lattice matched to InAs and AlSb and therefore does not require the growth of a buffer layer. We are also studying couple double quantum wells. Theoretical work is in progress to elucidate our results in these situations. All of these results will be published in a separate paper.

## 4. Calculations

To obtain the band structure of the QW structure, an 8 band  $\mathbf{k}\cdot\mathbf{p}$  theory in the envelope function approximation is used. Strain effects are included according to the Bir-Pikus

description [12]. The Poisson and Schrödinger equations are solved self-consistently. The temperature dependence of the lattice constant is taken into account empirically according to a linear expansion expression. The temperature dependence of the band gap is included via the Varshni formula [13]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \quad (1)$$

The model successfully describes the well width dependence of the ISBT energy. Due to the high density of free carriers in the quantum well, however, many-body effects on the absorption need to be included. Preliminary theoretical results corroborate standard understanding for the ISBT. For example, in Fig. 4 the solid curve shows the transition energy versus the quantum well thickness from a flat-band calculation. In addition, the depolarization shift causes blue shift, the exchange correlation induces red shift, and the vertex correction leads to lineshape narrowing.

The model indicates the temperature dependence of the ISBT energy as follows: as the temperature increases, the decrease of band gap, which causes a blue shift, is compensated to certain degree by the increasing density and linewidth. Full modeling capability of type II QW structures and their optical properties with many-body interactions within the density matrix formalism is under development.

## 5. Conclusions

We have investigated intersubband transitions in narrow InAs/AlSb QWs. The transition energies increase with decreasing well width and decreasing temperature, and the linewidths decrease slightly with decreasing temperature. We have developed an 8-band  $\mathbf{k} \cdot \mathbf{p}$  model including many-body effects which successfully describes these well width and temperature dependences. We have observed interband absorption, and its energy increases with decreasing well width. We have observed that photoluminescence and intersubband transitions are mutually exclusive in these QWs.

## References

- [1] Sirtori S, Capasso F, Faist J, Pfeiffer L N, West K W 1994 Appl. Phys. Lett. **65** 445
- [2] Beck M, Hofstetter D, Aellen T, Faist J, Oesterle U, Ilegems M, Gini E Melchior H 2002 Science **295** 301; Faist J, Capasso F, Sivco D L, Sirtori C, Hutchinson A L, Cho A Y 1994 Science **264** 553
- [3] Gauthier-Lafaye O, Boucaud P, Julien F H, Sauvage S, Cabaret S, Lourtioz J M 1997 Appl. Phys. Lett. **71** 3619
- [4] Liu A and Ning C Z 2000 Appl. Phys. Lett. **7** 1984; Liu A and Ning C Z 2000 OSA Technical Digest 56
- [5] Brar B, Ibbetson J, Kroemer H, English J H 1994 Appl. Phys. Lett **64** 3392; Waldrop J R, Sullivan G J, Grant R W, Kraut E A, Harrison W A 1992 J. Vac. Sci. Technol. **10** 1773
- [6] Yano M, Okuizumi M, Iwai Y and Inoue M 1993 J. Appl. Phys. **74** 7472
- [7] Kane M J, Emeny M T, Apsley N, Whitehouse C R, Lee D 1988 Semicond. Sci. Technol. **3** 722
- [8] Warburton R J, Weilhammer K, Kotthaus J P, Thomas M, Kroemer H 1988 Phys. Rev. Lett. **80** 2185
- [9] Weisbuch C and Vinter B 1991 Quantum Semiconductor Structures: Fundamentals and Applications (San Diego: Academic)
- [10] Prevot I, Vinter B, Julien F H, Fossard F, Marcadet X 2001 Phys. Rev. B **64** 195318
- [11] Unuma T, Takahashi T, Noda T, Yoshita M, Sakaki H, Baba M, Akiyama H 2001 Appl. Phys. Lett. **78** 3448
- [12] Bir G L and Pikus G E 1974 Symmetry and Strain-Induced Effects in Semiconductors (New York: Wiley)
- [13] Varshni Y P 1967 Physica (Amsterdam) **34** 149