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Calculations of the electric field dependent far-infrared absorption spectra in InAs/AlGaSb quantum wells

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Excitonic and band-to-band absorption spectra are calculated for vertical incident radiation for the InAs/AlGaSb multiple quantum well structures. Due to the special band lineup of this heterostructure, the absorption spectra can be tailored to respond in far infrared. The electric field dependence of the spectra shows blue shift and enhanced absorption in contrast to the situation in type I quantum wells. Applications to far-infrared detectors are discussed.

A variety of very important applications requires detection capability in the far infrared ($\sim 5\text{--}20\ \mu\text{m}$). Traditionally band-to-band spectra in HgCdTe and other small band-gap materials are used in semiconductor detectors.¹⁻⁴ However, the same material properties that yield small band gaps often also produce a "soft" material which is difficult to grow and process. This has led to increased interest in inter-subband absorption in multiple quantum well (MQW) structures.⁵⁻⁷ However, in such systems, the selection rules only allow absorption of electromagnetic radiation when the incident polarization is parallel to the growth (confinement) direction.⁷ This causes difficulties in detecting a 2-D image since radiation must come in a waveguide geometry.

The above problems are alleviated if one were to examine the InAs/Al_xGa_{1-x}Sb MQW structures where the conduction-band minimum occurs in the InAs region and the top of the valence band occurs in the Al_xGa_{1-x}Sb side.^{8,9} The conduction-band minimum to valence-band maximum energy separation can be altered by changing the Al composition. Experimentally the lineup occurs at Al fraction of 30%.⁹ Recently zero-field absorption spectra in such misaligned quantum wells have been reported experimentally.¹⁰

The behavior of this absorption in presence of a transverse electric field in this MQW system is expected to be quite different from the type I MQW structures like GaAs/AlGaAs. In type I quantum wells, the electric field separates the electron-hole pair and reduces the excitonic and band-to-band absorption with a red shift in the ground-state transition.^{11,12} However, in InAs/AlGaSb the opposite effect is expected, i.e., optical absorption is expected to increase together with a blue shift in the transition energies. In this letter we examine the electric field dependence of optical absorption spectra of this system and examine its potential as a vertical incidence far-infrared detector.

The band lineup of the InAs/AlGaSb system is critical in its use as a far-infrared imager. However, since this system is not very well studied, little is known about the precise lineup. According to simple electron affinity rules, the band lineup could be written as

$$\Delta E_c = 4.54 - [3.64x + 4.03(1 - x)], \quad (1)$$

where x is the Al content in AlGaSb. However, the electron affinity rules do not normally work in heterostructures due to charge transfer at the heterointerface. We know experimentally that the conduction band of InAs and valence band

of Al_{0.3}Ga_{0.7}Sb lineup.⁹ Based on this knowledge we introduce a parameter ΔE into Eq. (1) for the lineup:

$$\Delta E_c = 4.54 - [3.64x + 4.03(1 - x)] + \Delta E. \quad (2)$$

We find that $\Delta E = 0.471\ \text{eV}$. Further experimental work may alter this expression somewhat, but it allows us to calculate the kind of absorption strengths possible in the MQW system.

To calculate the absorption spectra, we first solve for the electron and hole problems in quantum wells:

$$\begin{aligned} -\frac{\hbar^2}{2m_{e(h)}} \nabla^2 \Psi_{e(h)}(\mathbf{k}, z) + V_{e(h)}(z) \Psi_{e(h)}(\mathbf{k}, z) \\ = E \Psi_{e(h)}(\mathbf{k}, z), \end{aligned} \quad (3)$$

where $V_{e(h)}$ is the potential barrier seen by the electron (hole), E is the electric field, and $m_{e(h)}$ is the electron (hole) mass. Hole mixing is ignored in this calculation although it is straightforward to account for it in our approach. However, since the Kohn-Luttinger parameters are not well known for this system we do not wish to introduce unnecessary complications at this point. The general particle solution is written as

$$\Psi_{e(h)}^n(\mathbf{k}, z) = f_{e(h)}^n(z) U_0(r) e^{ik_{\parallel} r}, \quad (4)$$

where $f^n(z)$ are the envelope functions, $U_0(r)$ is the zone center Bloch function for the bulk crystal, and k_{\parallel} is the in-plane momentum. The envelope functions are solved numerically by an eigenvalue technique. Details of the absorption from excitonic and band-to-band transitions have been published by us.¹³

We point out, however, that the matrix element $\langle x | p_x | \mu \rangle$ between the atomic-like states is dependent on the semiconductor material under consideration. Values for some semiconductors are tabulated by Lawaetz.¹⁴ In this system since electrons and holes are in different materials, we use an average matrix element value. This is expected to be reasonable since the nature of the conduction-band states and valence-band states is similar in the two material systems. The matrix elements $p_{nm}(k_{\parallel})$ slowly vary with k and can be represented by the zone center value. The band-to-band absorption is then proportional to

$$\alpha(\hbar\omega, \hat{\epsilon}) \propto \sum_{n,m} |\hat{\epsilon} \cdot p_{nm}(k_{\parallel})|^2 \delta_{nm} \rho_{nm}(\hbar\omega), \quad (5)$$

where $\rho_{nm}(\hbar\omega)$ is the joint density of the states of the elec-

tron-hole system. Factor $|\hat{\epsilon} \cdot p_{nm}(k_{\parallel})|^2$ is a weighted matrix element for an electron (n band)—hole (m band) transition, which has anisotropic nature with respect to polarization. For simple parabolic bands

$$\rho_{nm}(\hbar\omega) = \sum_{nm} \frac{\mu_{nm}}{\pi\hbar^2} \Theta_{nm}(\hbar\omega), \quad (6)$$

where μ_{nm} is the reduced mass of electron subband n and hole subband m , and $\Theta_{nm}(\hbar\omega)$ is a step function.

For the calculation of the excitonic absorption coefficient one cannot treat $p_{nm}(k_{\parallel})$ to be independent of k_{\parallel} . However, it is found to be reasonable to take $p_{nm}(k_{\parallel})$ to be independent of the direction of $p_{nm}(k_{\parallel})$.¹⁵ The exciton absorption coefficient is given by

$$\alpha_{nm} = \frac{4\pi^2 e^2 \hbar}{\eta m_0 c W \hbar\omega} \left| \sum_{k_{\parallel}} G_{nm}(k_{\parallel}) \hat{\epsilon} \cdot p_{nm}(k_{\parallel}) \right|^2 \times \delta(\hbar\omega - E_{nm}). \quad (7)$$

Here the $G_{nm}(k_{\parallel})$ are the Fourier components of the exciton envelope function and are determined by the solution of the exciton problem. W is the effective well width of QW structure. The Dirac δ function has to be replaced by the broadening function since there is always a certain amount of linewidth in the exciton transition. If the width is due to inhomogeneous broadening, the appropriate replacement is

$$\delta(\hbar\omega - E_{nm}) = \frac{1}{\sqrt{1.44\pi}\sigma} \exp\left(-\frac{(\hbar\omega - E_{nm})^2}{1.44\sigma^2}\right). \quad (8)$$

Here σ is the linewidth (corresponding to the half width at half maximum).

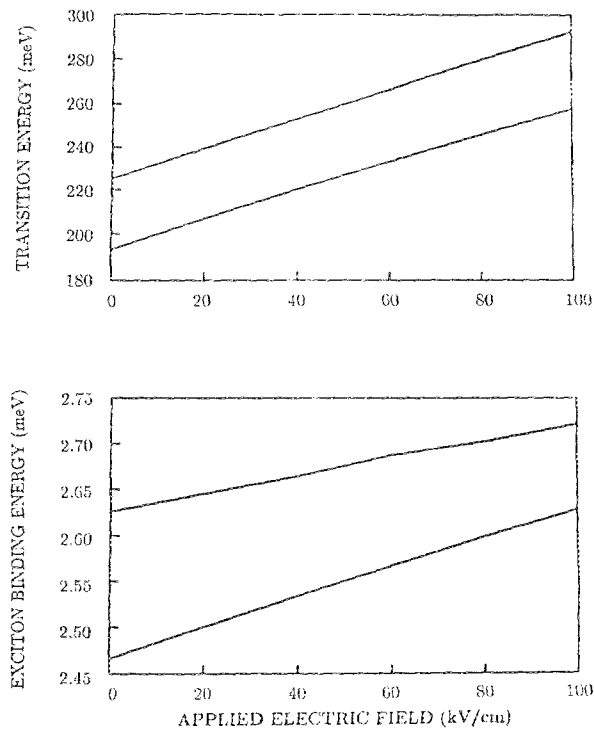


FIG. 1. (a) Variation of the HH1-CB1 (lower curve) and LH1-CB1 (upper curve) transition energies as a function of applied field; (b) variation of the HH1-CB1 exciton (lower curve) and LH1-CB1 exciton (upper curve) as a function of applied field.

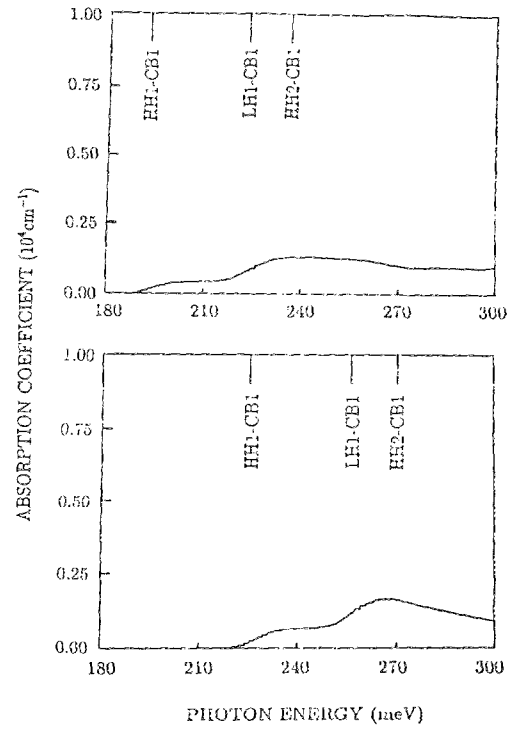


FIG. 2. Calculated absorption spectra for a 70 Å InAs/70 Å Al_{0.3}Ga_{0.7}AsSb quantum well structure for (a) $E = 0$ and (b) $E = 70$ kV/cm.

In Fig. 1 we show results for the (70 Å) InAs/(70 Å) Al_{0.3}Ga_{0.7}Sb system. Shown in Fig. 1(a) are the calculated ground-state heavy hole—electron (HH— E) and light hole electron (LH— E) transition energies as a function of electric field. Also shown in Fig. 1(b) are the exciton binding energy values. As can be expected, the exciton binding energy is much weaker than in type I quantum wells due to the electron-hole separation. For example, in a 70 Å GaAs/Al_{0.3}Ga_{0.7}As quantum well, the binding energy is \sim four times larger. However, the binding energy increases as the field increases. Choice of narrower quantum well size can increase the relative change even more. A detailed parametric study will be presented elsewhere.

In Figs. 2(a) and 2(b) we show the optical absorption spectra in the MQW structure at two electric fields of 0 and 70 kV/cm. The absorption coefficient is about eight times smaller than that in GaAs/AlGaAs quantum wells but it may be noted that about 5 μ m of the material should be able to absorb \sim 30% of incoming vertical incident light at \sim 0.2 eV (\sim 6 μ m). The absorption energy can easily be tailored by adjusting the quantum well dimensions and the electric field. Due to the weakly bound exciton, the exciton peaks are undistinguishable from the band-to-band transitions.

In summary, we have presented results of absorption coefficient calculations for the InAs/AlGaSb system under electric field. A number of parameters are still not known in this system, but our calculations indicate a good potential for vertical incident long-wavelength detection.

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