Room-temperature excitons in 1.6-μm band-gap GaInAs/AlInAs quantum wells

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The first observation of strong and well-resolved exciton peaks in the room-temperature absorption spectra of infrared band-gap multiple quantum well structures (MQW's) is reported. Assignment of the optical resonances in the absorption spectra of GaInAs/AlInAs MQW's yields the material parameters of this new heterojunction. The discontinuities of the conduction and valence bands are found to be $\Delta E_c = 0.44$ eV and $\Delta E_v = 0.29$ eV, respectively.

Recently the physical properties of semiconductors in very thin layers (e.g., 100 Å) have attracted much attention, both for fundamental reasons and for their potential applications. A most interesting property of GaAs/AlGaAs multiple quantum well structures (MQWS) is the observation in their room-temperature absorption spectra of sharp, well-resolved exciton peaks.[1] Consequently the large resonant enhancement of optical properties that is observed at very low temperature in bulk crystals can be seen and exploited in GaAs/AlGaAs MQWS under more convenient conditions. This is at the origin of the very large nonlinear optical effects[2] and strong electroabsorption[3,4] shown at room temperature by these MQWS. Recently, partial recovery of absorption saturation has been observed on a 300-fs timescale associated with the ionization of excitons by phonons.[5] Room-temperature excitonic effects in GaAs MQWS have already been applied to high-speed optical modulation,[6,7] diode laser mode locking,[8] gates for optical logic,[9] linearized optical modulators, and optical level shifters.[10]

Because of the technological interest for the medium infrared in the domain of maximum transmission of optical fibers, it is important to develop new MQWS with small band gaps in which effects similar to those presented by GaAs MQWS can be exploited. In the present letter we report the first observation of room-temperature excitonic resonances at $\lambda \sim 1.6\,\mu$m in GaInAs/AlInAs MQWS.

Excitonic resonances are observed at room temperature in GaAs MQWS because of the conjunction of two factors. In MQWS the confinement of carriers in the well significantly reduces the average electron-hole separation which increases the binding energy E_x compared to the bulk,[11,12] whereas the exciton longitudinal optical (LO) phonon interaction that governs the temperature broadening of the exciton peak is only slightly modified[2]; hence the binding energy exceeds the broadening even at room temperature. Furthermore, the product of the bulk exciton Bohr radius and binding energy is independent of the band gap E_g; therefore, although narrower gap semiconductors have smaller E_x, for wells of the same thickness the effect of the reduction of E_g on E_x is to a large extent compensated for by the increase of the confinement enhancement. These trends should also apply to other III-V infrared semiconductors.

The semiconductor alloy $Ga_{0.47}In_{0.53}As$ can be grown lattice matched on an InP substrate and is a material with potential for applications in 1.55-μm optoelectronics. To the best of our knowledge, the only intrinsic excitonic behavior reported to date has been a small bump observed in the absorption of bulk material at low temperature.[13,14] Since the compound is also lattice matched to the larger band-gap $Al_{0.48}In_{0.52}As$ alloy, MQWS can be grown using the two materials.[15,16] GaInAs/AlInAs MQW lasers have been demonstrated[17] and the first study of the optical properties of modulation-doped MQWS has just been reported.[18]

Our samples were grown by molecular beam epitaxy (MBE) on S-doped, *n*-type InP substrates. The substrate preparation included chemical etching and oxide passivation as described earlier.[19] The oxide was desorbed in the MBE chamber just before deposition to ensure an atomically clean substrate. The growth of lattice-matched $Al_{0.48}In_{0.52}As$ and $Ga_{0.47}In_{0.53}As$ on InP substrates requires precise control in the Al, Ga and In beam intensities. These beam fluxes were measured with a nude ion gauge placed at the substrate position prior to growth. The epitaxial growth temperature was 580 °C. The growth starts with a 0.5–1-μm-thick $Al_{0.48}In_{0.52}As$ buffer layer, followed by 50 periods of alternate AlInAs and GaInAs layers and a 1-μm AlInAs cap layer. Six samples were grown and studied, with quantum well thicknesses varying from 85 to 165 Å. For some samples, in order to form a *p-i-n* diode[4,6] the first AlInAs layer was doped with Si to give $n = 10^{17}\ \mathrm{cm}^{-3}$, and the last AlInAs layer was doped with Be to give $p = 5\times 10^{18}$ cm^{-3}. A final 150-Å-thick Be-doped $Ga_{0.48}In_{0.52}As$ layer was grown on the top of these samples for ohmic contact.

The room-temperature absorption spectrum of one of our samples is shown in Fig. 1. At least three plateaus are seen. They correspond to the transitions between the $n = 1$, 2, and 3 valence and conduction subbands.[20] A clear heavy hole (hh) exciton peak is seen, well resolved from the plateaus of the $n = 1$ and $n = 2$ subband transitions.[20] At low temperature the light hole (lh) emerges clearly from the $n = 1$ continuum and the various edges steepen. The very strong excitonic behavior visible in the MQWS absorption even at room temperature contrasts remarkably with the best low-temperature results reported so far for GaInAs.

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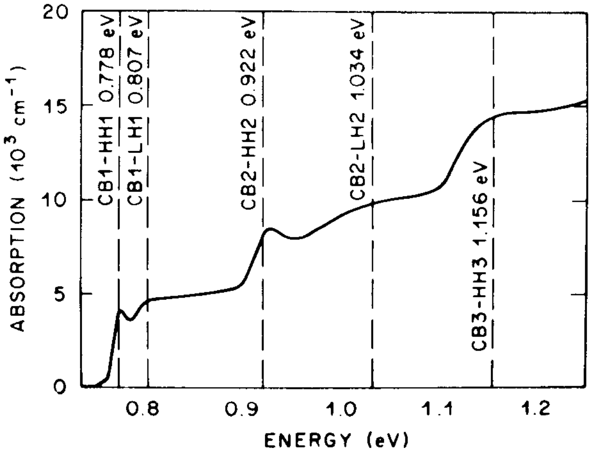

FIG. 1. Room-temperature absorption spectrum of an InGaAs/InAlAs heterostructure having a quantum well width of 110 Å. The dashed lines represent the exciton energies calculated using a finite square well model.

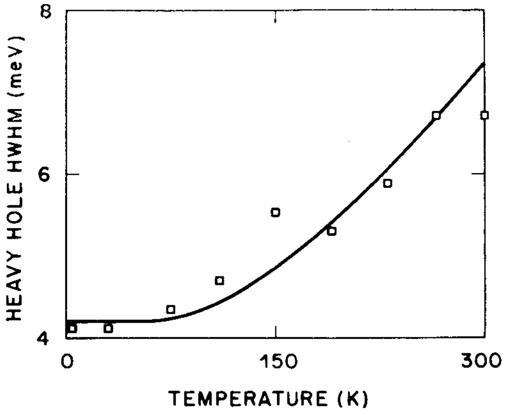

FIG. 2. Temperature dependence of the half-width half-maximum (HWHM) of the $n = 1$ hh exciton. The squares represent the experimental points for the 110-Å well width sample of Fig. 1. The solid curve is the theoretical exciton HWHM, which includes contributions from inhomogeneous broadening and scattering by optical phonons.

In order to deduce from these spectra the parameters describing the GaInAs/AlInAs system we have used the following procedure. From the electron effective masses in the two compounds[21] and the GaInAs valence-band Luttinger parameters[22] we determined the confinement masses $m_{\| h,l}$ and the exciton reduced masses $\mu_{h,l}$.[12] We used a variational procedure to calculate the excitons binding energies.[4] We estimated the hh exciton binding energy by fitting the line shape of the $n = 1$ absorption edge at various temperatures.[2] The estimated experimental binding energy $E_x = 6$ meV compares quite well with the variational value $E_x = 5.2$ meV. Finally, we solved for the unidimensional electron and hole motion normal to the layers in the usual manner.[23] The AlInAs band gap was fixed at 1.47 eV (Ref. 19) and the band discontinuities ΔE_c and ΔE_v were used as adjustable parameters. For the six samples the calculated positions of the exciton peaks were compared to the experimental spectra. The most consistent fits were obtained for $\Delta E_c = 0.44$ eV and $\Delta E_v = 0.29$ eV, corresponding to a band gap of $E_g = 0.74$ eV for the GaInAs. A typical fit is shown by the dashed lines in Fig. 1. The value of E_g is in satisfactory agreement with earlier measurements,[21,24] but the relative discontinuity in the conduction band is slightly smaller than previously reported.[25]

There is some uncertainty in the calculated exciton binding energy because the masses for the hole motion parallel to the layers are not well defined. It has recently been found that a large admixture of hh and lh occurs in GaAs/AlGaAs MQWS[26] implying a large valence subband nonparabolicity. Also, magneto-optical measurements have indicated much heavier hole masses than commonly supposed.[27] This could increase the calculated exciton binding energy.

In addition, it is worth mentioning that more accurate methods to determine the band discontinuities are optical studies based on more complicated structures such as parabolic wells or double quantum wells. Recently some of these structures have been fabricated in the GaAs/AlGaAs system. At the present time they are not yet available in the GaInAs/AlInAs system and our results should be considered as a first demonstration that indeed high quality microstructures can be fabricated in this system of ternary alloys.

The variation of the hh exciton half-width half-maximum (HWHM) with temperature is shown as the squares in Fig. 2. The temperature dependence is well described by the expression

$$\Gamma = \Gamma_0 + \frac{\Gamma_{\rm ph}}{\exp(\hbar\Omega_{\rm LO}/kT) - 1},$$

where Γ_0 is a constant inhomogeneous term accounting for interface roughness and alloy disorder and the second term represents the homogeneous broadening due to scattering by InGaAs LO phonons.[2] Taking the LO phonon energy to be $\hbar\Omega_{\rm LO} = 35$ meV (Ref. 28) and adjusting Γ_0 and $\Gamma_{\rm ph}$, the best fit is obtained with $\Gamma_0 = 4.2$ meV and $\Gamma_{\rm ph} = 9$ meV (shown as the solid line in Fig. 2), both of which are larger than the corresponding parameters for GaAs.[2] For the room-temperature excitons this corresponds to a mean ionization time by thermal LO phonons of 240 fs.[2,5]

In conclusion, we have demonstrated that ternary semiconductor alloy microstructures can be fabricated with high enough quality to exhibit excitons at *room temperature*. This is all the more remarkable since the corresponding bulk material barely shows excitons at low temperature.[13,14] This new achievement should allow the development of optoelectronic devices for the medium infrared wavelengths, such as diode laser mode lockers, high-speed light modulators, and optical switches similar to those that have already been demonstrated with GaAs MQWS.[6-10]

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