Luminescence excitation spectroscopy on $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ quantum-well heterostructures

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We have performed low-temperature (5–30 K) photoluminescence excitation spectroscopy on $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ quantum-well heterostructures lattice matched to InP which were grown by molecular-beam epitaxy. Excitation spectroscopy using a tunable KCl:Tl color-center laser allows us to measure the energy shift of the first electron to heavy-hole subband transition in absorption for quantum-well widths down to 10 nm. In samples with well widths of 25 and 35 nm, higher subband transitions are also identified in the excitation spectrum. Comparison of the experimental subband energy shifts with calculated data shows good agreement for well widths down to 10 nm, when a finite square-well potential with conduction- and valence-band discontinuities of 0.5 and 0.2 eV, respectively, is assumed. This band offset is consistent with data determined by the C-V profiling technique.

Quantum-well heterostructures (QWH) made from $Ga_{0.46}In_{0.53}As$ and $Al_{0.48}In_{0.52}As$ lattice matched to InP are of considerable interest for basic research as well as device applications. The emission wavelength of the QWH can be varied in the range between 1.1 and 1.65 μm by changing the width of the $Ga_{0.47}In_{0.53}As$ potential well.[1–5] This wavelength range is important for the application in optical fiber communication systems based on silica fibers.

Photoluminescence excitation (PLE) spectroscopy and related techniques have been applied successfully to $GaAs/Al_xGa_{1-x}As$ QWH using tunable dye lasers.[6–9] Excitation spectroscopy was used to study, e.g., transitions between higher subbands. For PLE experiments on the $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ system we have employed a tunable KCl:Tl color-center laser covering the wavelength range from 1.42 to 1.59 μm.[10,11] In the present Brief Report we report PLE measurements on $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ QWH, which allow one to determine the shift of the first electron to heavy-hole subband transition (E_{1h}) as a function of the thickness (10–100 nm) of the potential well. We further identify higher subband transitions in the PLE spectra of samples with 25 and 35-nm well width.

The samples used in our study were $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single QWH grown by molecular-beam epitaxy (MBE). The lattice mismatch to the InP substrate was less than 10^{-3} at room temperature. The width L_z of the $Ga_{0.47}In_{0.53}As$ well was systematically varied from 100 down to 10 nm. For further details of the sample preparation see Ref. 5. To account for slight run-to-run variations of the composition of the $Ga_{0.47}In_{0.53}As$ layers within a lattice mismatch of 10^{-3}, which cause changes of a few meV in the $Ga_{0.47}In_{0.53}As$ band gap, a reference sample of 50-nm well width was grown in each growth run, which showed no detectable energy shift as compared to bulk-type $Ga_{0.47}In_{0.53}As$ epilayers. All transition energies are measured relative to the E_{1h} transition energy of the corresponding reference sample. The luminescence was excited by the tunable KCl:Tl color-center laser and dispersed by a 1-m grating double-pass spectrometer. The signals were detected by a liquid-nitrogen-cooled Ge photodiode.

The luminescence spectra of the $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single QWH are shown in Fig. 1. At 5 K the spectra are dominated by a transition 20 meV below the subband edge, which is due to a superposition of a band-to-acceptor (e,A^0) and a donor-to-acceptor (D^0,A^0) transition. The high-energy shoulder of the PL spectrum at 5 K in Fig. 1 is presumably due to a donor-to-band (D^0,h) transition. At higher temperatures (>50 K) the band-to-band transition (e,h) is the strongest feature in the luminescence spectra. This assignment of the emission peaks from $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single QWH, based on a detailed temperature-dependent PL study,[5] and a comparison with results of bulk-type epilayers (see for example Ref. 12), gets further support from the PLE data. By comparing PL and

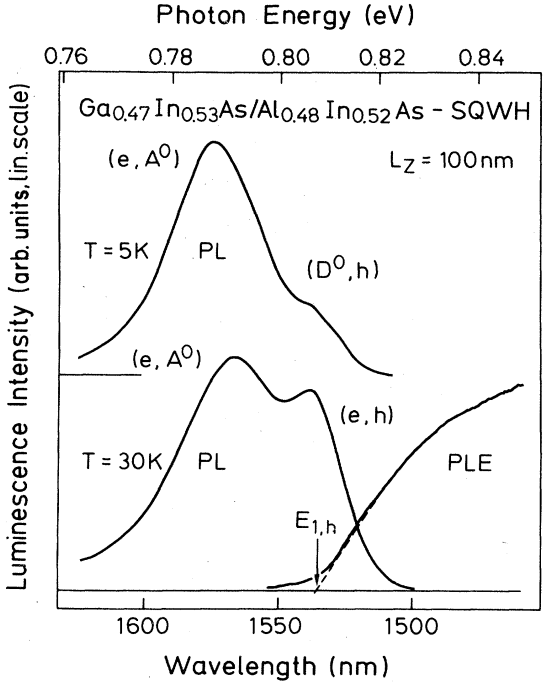

FIG. 1. PL (5 and 30 K) and PLE (30 K) spectra of a $Ge_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single QWH of well width $L_z = 100$ nm.

PLE spectra taken at 30 K in Fig. 1, we find that the energy of the E_{1h} subband transition, as determined by PLE, coincides with the peak energy of the (e,h) emission in the PL spectrum.

The PLE spectra of $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single QWH with three different well widths are depicted in Fig. 2. The energy of the E_{1h} transition shifts systematically to higher energies with decreasing well width. The spectra have been recorded using the (e,A^0) emission as the monitor transition, but similar spectra are observed with the (e,h) transition as monitor. This confirms that we are probing intrinsic band-to-band transitions with PLE and no defect-related extrinsic absorption. The excitation or absorption spectrum reflects the steplike density of states in the two-dimensional system,[13] which is inhomogeneously broadened. In the single QWH samples studied here, no free exciton peaks are observed in the PLE spectra.

The excitation spectrum of a sample with 35-nm well width obtained at a temperature of 25 K is shown in Fig. 3. For the lower spectrum the (e,h) luminescence was taken as monitor, while the upper spectrum was recorded with the (e,A^0) emission, showing the coincidence of the onset of absorption. Two further steps can be identified in the lower spectrum, which are interpreted as the onset of transitions between higher subbands.

The transition energies resulting from the model of a finite square-well potential are indicated by arrows in Fig. 3. The solution of Schrödinger's equation for a finite square-well potential, taking the different effective masses of the well and the barrier material into account, leads to the following expressions for the allowed energy states in the potential well (Ref. 2, and references therein):

$$k_w \tan(k_w L_z/2) = k_b m_w/m_b \quad \text{for } n \text{ odd}\ , \tag{1}$$

$$k_w \cot(k_w L_z/2) = -k_b m_w/m_b \quad \text{for } n \text{ even}\ . \tag{2}$$

In Eqs. (1) and (2) $k_w^2 = (2m_w E_n)/\hbar^2 = [2m_b(V-E_n)]/\hbar^2$, m_b and m_w are the effective masses of the barrier and the well material, respectively, V is the depth of the potential well, and E_n is the energy of the corresponding subband. As input parameters we have used the (100) effective masses of $Ga_{0.47}In_{0.53}As$ ($m_e = 0.041$, $m_{hh} = 0.47$, $m_{1h} = 0.05$)[14–16] and $Al_{0.48}In_{0.52}As$ ($m_e = 0.075$,[16] $m_{hh} = 0.8$, $m_{1h} = 0.1$), and a conduction- and valence-band discontinuity of 0.5 and 0.2 eV,[17] respectively. The calculated E_{1h} and the first electron to light-hole (E_{1l}) transition for a well width of 35 nm are close together and not resolved in the experimental spectrum in Fig. 3, but their energy positions agree with the onset of absorption at 0.815 eV. The second electron–to–heavy-hole (E_{2h}) transition coincides with the step at 0.83 eV and the second electron to light-hole (E_{21}) transition with the step at 0.85 eV.

To determine the energy of the subband transition from the PLE spectrum, which reflects the broadened steplike two-dimensional density of states, the point of inflection in the spectrum should give the corresponding transition energy. Any excitonic effects are thereby neglected. However, the determination of the point of inflection from the present spectra is not that accurate. Therefore, we took the extrapolation of the steplike decrease in the PL intensity to zero intensity (indicated in Fig. 2) as a measure for the transition energy, noting that this gives energy values which are 5–10 meV smaller than the values one would obtain

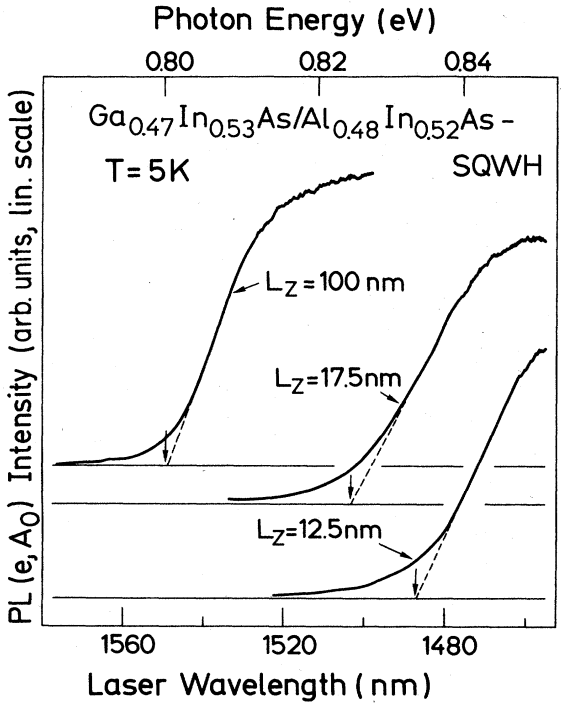

FIG. 2. PLE spectra of $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single QWH with different well widths L_z. The band-to-acceptor luminescence (e,A^0) was taken as monitor transition. The arrows indicate the extrapolated position of the first subband transition E_{1h} (see text).

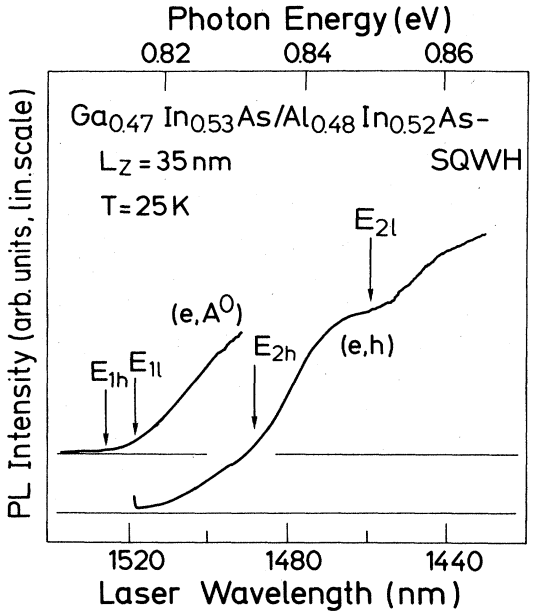

FIG. 3. PLE spectra of $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single QWH with 35-nm well width. The lower spectrum was recorded using the band-to-band (e,h) transition as monitor, the upper one with the band-to-acceptor recombination. The arrows indicate calculated energies for the first and second heavy- and light-hole subband transitions, respectively.

from the inflection point. But, as we measure all transition energies with respect to a reference sample, this energy shift cancels, provided that the broadening is the same in all spectra. As can be seen in Fig. 2 this assumption is justified for the present PLE curves.

The relative energy shift of the various subband transitions derived as described above are plotted versus well width L_z in Fig. 4. Also, the higher subband transitions in samples with 25- and 35-nm well width are shown. For samples with $L_z > 35$ nm, no higher subband transitions are resolved in the PLE spectra due to the small spacing between subbands and the broadness of the PL emission peak. Higher subband transitions for samples with well widths below 20 nm could not be observed in PLE due to the limited tuning range of the color-center laser.

The peak position of the low-temperature luminescence as a function of well width L_z is also plotted in Fig. 4. The scatter of these data with respect to the E_{1h} transition energy obtained from the PLE spectra is due to the fact that the 5 K PL spectra are not purely of (e,A^0) type. They contain a contribution of presumably a donor-to-band (D^0,h) emission on the high-energy side, which affects the PL peak position depending on the intensity relative to the (e,A^0) peak. This comparison of PL and PLE data shows the advantage of the PLE spectroscopy technique for the determination of subband transition energies in $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ QWH samples, because in our case PLE probes only intrinsic properties. Luminescence, in contrast, is sensitive to both intrinsic and extrinsic recombination. The comparison of the experimental and theoretical data obtained from the finite square-well model shows a good agreement for $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single QWH with potential well widths down to 10 nm.

In conclusion, we have applied the PLE spectroscopy technique to $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ single QWH using a tunable color-center laser. From the excitation spectra we were able to determine the energies of the first (E_{1h}) and higher (E_{2h},E_{2l}) optical subband transitions for potential well widths from 100 down to 10 nm. For well widths down to 10 nm the experimentally detected subband-energy shifts

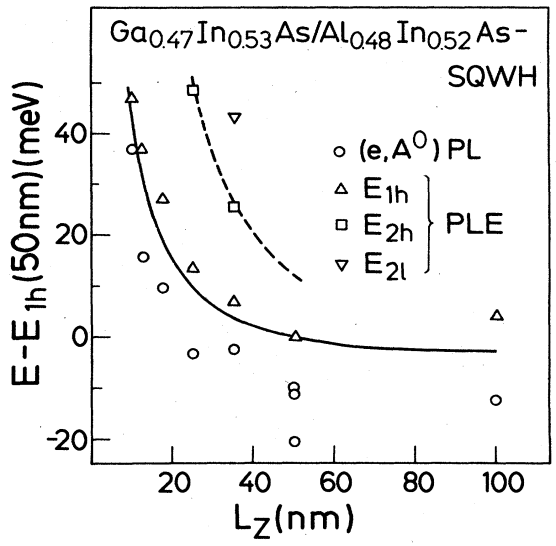

FIG. 4. Experimental subband transition energies measured relative to the E_{1h} transition energy of a single QWH of 50-nm well width. Also shown are the calculated subband transition energies for the E_{1h} (solid line) and E_{2h} (dashed line) transition and the positions of the luminescence peak emission (open circles).

are in good agreement with data obtained by a simple finite square-well model using the effective masses of bulk $Ga_{0.47}In_{0.53}As$ and $A_{0.48}In_{0.52}As$ epilayers.

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