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Measurement of the hole dispersion in a quantum well by hot-electron-acceptor luminescence

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We report quantitative measurements of the hole dispersion curves of a quantum well using hot-electron-acceptor luminescence in combination with band-edge luminescence. The directionally averaged heavy-hole and light-hole energies are determined for in-plane wave vectors between 3% and 7% of the Brillouin zone. Experimentally significant differences between quantum wells of different widths are observed.

The hole dispersion curves in quantum-confined semiconductor structures in which the holes can move freely only in a plane but are confined in the normal direction have been investigated theoretically in some detail.[1-4] Although a profound qualitative understanding has been achieved, the uncertainties in the Luttinger parameters[5] and the problem of matching the wave functions at the interfaces[6,7] result in a significant uncertainty when the hole dispersion is quantitatively calculated. Experimentally, Hayden *et al.* studied the hole dispersion in a GaAs/$Al_xGa_{1-x}As$ quantum well (QW) using magnetotunneling spectroscopy.[8] They were able to map out the in-plane dispersion of a large number of subbands in a plot of voltage versus magnetic field. In this work, however, both wave vector and energy can only be calculated using various approximations. In addition, the confining QW potential changes with applied voltage and is not clearly defined. Therefore only a qualitative comparison with theory is possible. In this paper we present quantitative measurements of the in-plane hole dispersion curves in a QW. We use the technique of hot-electron-acceptor luminescence, which was pioneered by Zakharchenya *et al.*,[9] who also applied the technique to QW's.[10] Recently hot-electron-acceptor luminescence was employed to determine scattering times[11,12] and to verify the band structure[13] in bulk GaAs.

Figure 1 shows how we can measure the hole dispersion in a QW by hot-electron-acceptor luminescence. We use p-type doped QW's with an acceptor level A^0 separated from the valence band edge by the acceptor binding energy E_A. At low temperatures most acceptors are neutral, i.e., have a hole bound to them. The band bending due to the doping is negligible in these p-type QW's, because the holes are not spatially separated from the acceptors. In our experiment an incoming photon of energy $\hbar\omega_L$ excites an electron from the lowest heavy-hole subband H_1 to the lowest electron subband E_1 creating a heavy hole and an electron both with wave vector k. The small photon wave vector can be neglected here. Most likely the hot electron will relax quickly by emission of LO phonons [the scattering time in bulk GaAs is $\cong$180 fsec (Ref. 14)]. With a small probability of $\cong 10^{-5}$, however, the electron radiatively recombines with a hole at a neutral acceptor before it can emit phonons. From the corresponding transition energy (e_H,A^0) we can determine one point on the heavy-hole dispersion curve as follows. From Fig. 1 we directly read the relations

$$H_1(k)=\hbar\omega_L-(e_H,A^0)-E_A\,, \tag{1}$$

$$E_1(k)=(e_H,A^0)-E_g^{QW}+E_A\,. \tag{2}$$

The QW band gap E_g^{QW} and the acceptor binding energy E_A can be measured separately using band-edge luminescence as discussed below. Then, Eq. (1) directly gives the heavy-hole energy $H_1(k)$. Equation (2) gives the electron energy $E_1(k)$, from which we will obtain the wave vector k. Other points on the dispersion curve with different wave vector and energy are obtained by varying the laser energy $\hbar\omega_L$. For each $\hbar\omega_L$ one observes luminescence not only from (e_H,A^0) but also from a second transition (e_L,A^0), as indicated in Fig. 1. The subscript L indicates that the hot electron has been excited from the light-hole subband in this case. The dispersion of the light-hole subband L_1 is determined from (e_L,A^0) in the same way as the heavy-hole dispersion is determined from (e_H,A^0).

The two samples used in this study are GaAs/$Al_xGa_{1-x}As$ multiple QW's grown by molecular-beam epitaxy. The well width L_Z, the barrier thickness, and x

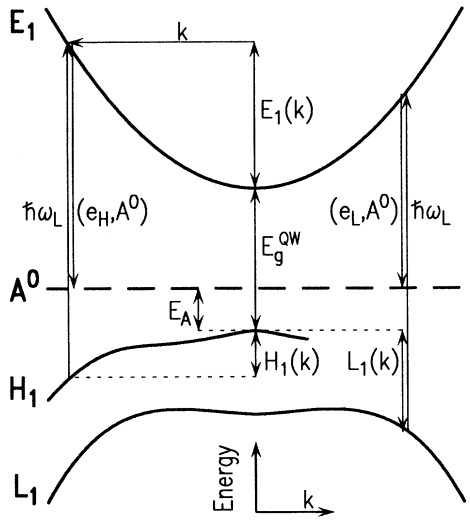

FIG. 1. Sketch of the energy levels vs wave vector in a quantum well. The arrows indicate energies involved in our measurement of the hole dispersion, as explained in the text.

were precisely determined from x-ray rocking curves.[15] The alloy composition x was confirmed by electron microprobe measurements. The samples have a well width $L_Z = 54$ (75) Å, 88 (142) Å thick $Al_xGa_{1-x}As$ barriers with $x = 0.25$ (0.32), 100 (30) periods, and are 3×10^{17} (2×10^{18}) Be-doped in the central 30 (10) Å of the wells. In addition, a growth interruption of 60 sec at all interfaces was used in the 75-Å sample. The hot luminescence, detected in cross polarization by a triple monochromator and an imaging photomultiplier, is excited using laser photon energies between 1.65 and 1.85 eV. The injected carrier densities are $\simeq 5\times10^9$ cm^{-2} per well. As expected, line shape and energy of the luminescence peaks are independent of the laser intensity in this intensity range. All measurements presented here were performed at a temperature of 2 K.

Figure 2(a) compares the hot-electron-acceptor luminescence spectra of bulk Be-doped GaAs and our 54-Å-wide QW for the same excitation energy. In the case of bulk GaAs we observe two peaks, which we identify[9] as (e_H,A^0) and $(e_H,A^0)-\hbar\omega_{LO}$. The latter peak is due to the acceptor transition of hot electrons which have already emitted one LO phonon. The same two peaks are observed in the QW sample, but they are each shifted by $\simeq 6$ meV to lower energy. According to Eq. (1), this energy shift arises from different hole energies and from different acceptor binding energies. Figure 2(a) also shows an additional peak in the spectrum of the QW at an energy between (e_H,A^0) and $(e_H,A^0)-\hbar\omega_{LO}$, which is due to the light-hole related transition (e_L,A^0). In the bulk, this transition occurs at much lower energy ($\simeq 1.61$ eV) and does not appear in Fig. 2(a).

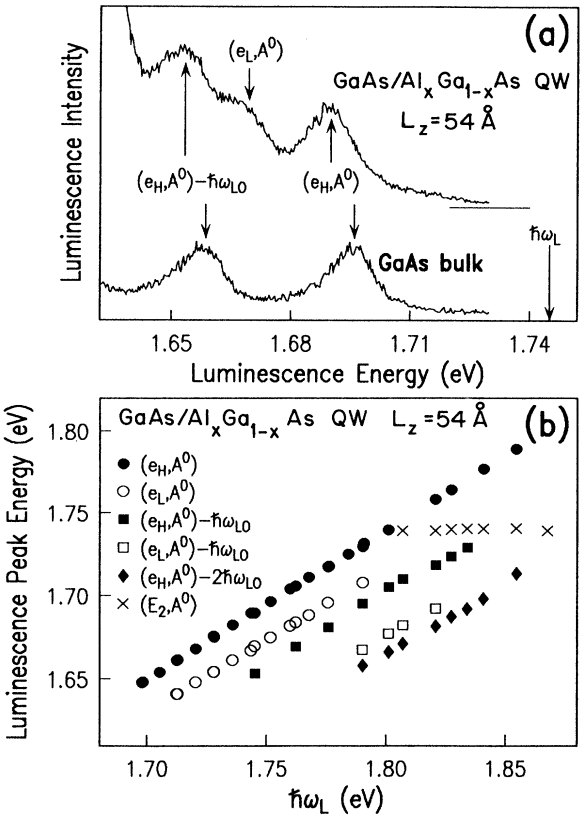

FIG. 2. (a) Comparison of the hot-electron-acceptor luminescence spectra in bulk and in a QW for $\hbar\omega_L = 1.745$ eV. The intensity scale is linear and the same for both samples as is the exciting laser intensity. (b) Peak energies of the hot-electron-acceptor luminescence vs laser energy for the same QW as in (a).

Figure 2(b) shows the energies of the luminescence peaks (e_H,A^0) and (e_L,A^0) as a function of laser energy $\hbar\omega_L$ for the 54-Å-wide QW. We also show the observed acceptor transitions from electrons which have emitted one or two LO phonons before recombining. For the determination of the hole dispersion, however, we only need to consider the zero-phonon transitions. The transition energies increase almost linearly with increasing laser energy. The slope of this increase is very similar for the heavy-hole and light-hole related transitions. This is in contrast to the case of bulk GaAs, where the slope of the light-hole transition is only approximately half the slope of the heavy-hole transition.[13] This difference compared to the bulk originates in the different hole dispersion curves.

In addition to the peaks due to hot-electron-acceptor luminescence we observe in Fig. 2(b) a transition at $\simeq 1.740$ eV for $\hbar\omega_L \gtrsim 1.805$ eV, which does not shift in energy when $\hbar\omega_L$ is varied. The exact energy of the H_2E_2 transition is 1.805 eV between the first excited heavy-hole and electron subbands as measured by photoluminescence excitation (PLE). Therefore we attribute the luminescence peak at 1.740 eV to the transition (E_2,A^0) of "cold" electrons at the bottom of the E_2 subband to an acceptor. This peak becomes stronger with increasing $\hbar\omega_L$. For $\hbar\omega_L \gtrsim 1.85$ eV it dominates the spectrum and prevents quantitative measurements of the hot-electron-acceptor luminescence. The lower limit of the accessible range of $\hbar\omega_L$ is determined by the high-energy tail of the band-gap luminescence. Its intensity increases exponentially with decreasing energy, and only hot-electron-acceptor peaks with an energy $\gtrsim 1.64$ eV can be quantitatively measured [Figs. 2(a) and 2(b)].

In order to obtain the hole dispersion curves from Eqs. (1) and (2) and the data of Fig. 2(b), we need to know the QW band gap E_g^{QW}, the acceptor binding energy E_A, and the dispersion $E_1(k)$ of the electron subband. To determine E_g^{QW} and E_A we studied the recombination of cold electrons and holes by luminescence and PLE. In the PLE spectra we observe not only the $1s$ ground state of the free exciton but also its excited $2s$ state. The QW band gap E_g^{QW} is the continuum of the hydrogenlike ladder of these excitonic states. Therefore we can take the small residual binding energy of the $2s$ state relative to the continuum from a calculation and add it to the measured energy of the $2s$-free-exciton transition to obtain E_g^{QW}. From Andreani and Pasquarello[16] we read a $2s$ binding energy of 1.8 meV for $L_z = 54$ Å and $x = 0.24$, which gives $E_g^{QW} = 1.6176$ eV. We note that our measured energy splitting of 9 meV between the $1s$ and $2s$ exciton states is also in very good agreement with the same theory.[16]

For a reliable determination of the acceptor binding energy E_A we use "selective luminescence" to measure the

energy difference between the $1s$ and $2s\Gamma_6$-like acceptor states, as suggested by Holtz *et al.*[17] Exciting "selectively" in resonance with the bound-exciton peak of the H_1E_1 transition we observe two sharp Raman transitions in the luminescence spectrum. The Raman shift of the higher-energy peak, which gives the energy difference between the $1s$ and $2s\Gamma_6$-like acceptor states,[17] is 29.3 meV in excellent agreement with theory.[18,19] If we add the residual binding energy of the $2s$ state given by theory,[19] we find a total binding energy $E_A=40.5$ meV.

Let us now discuss how we obtain the wave vector k from the energy $E_1(k)$. The task is to account for the deviation from a parabolic dispersion relation as precisely as possible. We do not know of any measurements of the in-plane electron dispersion in a QW for the energy range $50 \lesssim E_1(k) \lesssim 250$ meV. In bulk GaAs, the electron dispersion in this energy range has only been measured recently by Ruf and Cardona.[20] Their result can be expressed as $k^2(10^{-2}\times 4\pi^2/a^2)=c_1E+c_2E^2+c_3E^3$, with $c_1=1.41$ eV^{-1}, $c_2=1.02$ eV^{-2}, $c_3=0.116$ eV^{-3}, and the lattice constant $a=5.65$ Å of GaAs. Due to the lack of experimental data we must determine the electron dispersion in the QW by a calculation. We choose the approach of Lassnig,[21] because it is not restricted to small energies $E_1(k)$ and because it can be easily applied to bulk GaAs. Therefore we can fit the $\mathbf{k}\cdot\mathbf{p}$ parameters so that the calculation reproduces the bulk dispersion measured by Ruf and Cardona.[20] This fitting procedure eliminates the most important source of error in the calculation, namely the uncertainty in the $\mathbf{k}\cdot\mathbf{p}$ parameters.[22] For $Al_xGa_{1-x}As$ we use $E_0=(1.519+1.445x)$ eV as fundamental band gap,[23] $m_0^*/m_0=0.0665+0.084x$ as band-edge effective mass,[24] and the same $\mathbf{k}\cdot\mathbf{p}$ parameters as in GaAs.[25] We assume that 65% of the band-gap difference occurs in the conduction band.[26] The electron dispersion we calculate for the two QW samples can again be expressed as a development of k^2 in powers of E_1. We find $c_1=1.54$ (1.51) eV^{-1}, $c_2=1.05$ (1.03) eV^{-2}, and $c_3=0.137$ (0.173) eV^{-3} for the 54 (75) Å wide QW, respectively. As expected the nonparabolicity is stronger in a QW than in bulk and also becomes stronger with decreasing well width.

We are now in a position to calculate the hole dispersion curves using Eqs. (1) and (2). The result is shown in Fig. 3, where the data for both QW's are included. The dispersions of both the H_1 and the L_1 subbands are always positive in the investigated range of k. We attribute this to the fact that the smallest wave vectors, for which we show data here, are already larger than the wave vector where the subbands H_1 and L_1 anticross. Because of the limited accessible range of $\hbar\omega_L$, we cannot provide quantitative data close to $k=0$ at this time. Comparing the hole dispersions of the two different QW's in Fig. 3, we find that the splitting between H_1 and L_1 is larger for the narrower QW. Because of the larger splitting, the anticrossing of H_1 and L_1 occurs at larger k, i.e., $H_1(k)$ increases up to a larger value of k before it is repelled by $L_1(k)$. Therefore, in the range of k investigated here, $H_1(k)$ should be larger for the narrower QW, as observed. We note that the hot-electron-acceptor luminescence comes from all directions in k in the QW plane. Therefore the luminescence peaks marked in Fig. 2(a) and the band structure shown in Fig. 3 represent an appropriately weighted average over all in-plane directions.[27]

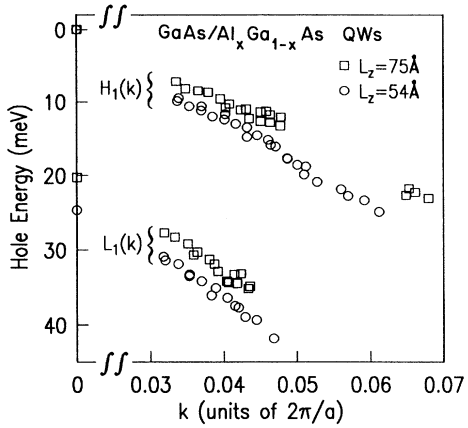

FIG. 3. In-plane dispersion of the lowest heavy-hole and light-hole subbands determined from the data of Fig. 2, along with the similarly obtained results for a second QW. Note that the zero of energy is defined as the top of the H_1 subband for both samples so that H_1 does not contain the confinement energy (Fig. 1). $L_1(0)$ is determined from PLE measurements assuming that the exciton binding energy is 2.8 meV larger for the light-hole exciton than for the heavy-hole exciton (Ref. 16). The lattice constant $a=5.65$ Å.

At present it is difficult to compare our experimentally determined hole dispersion with any calculated dispersion from the literature, because the well width and alloy composition of the barriers used in the calculations are not the same as in our QW's. To initiate a discussion we compare the splitting of 23 meV between H_1 and L_1 at $k=0.08\pi/a$ which we measure for $L_Z=75$ Å with values calculated for the same wave vector and similar L_Z. For example, Andreani, Pasquarello, and Bassani[4] find a splitting of 15 meV for $L_Z=78$ Å, and Batty *et al.*[28] calculate a value of 19 meV for $L_Z=70$ Å. The measured splitting appears to be somewhat larger than the calculated one, but this is partly because $x\simeq 0.2$ is used in the calculations, whereas $x=0.32$ in our QW.

Let us finally estimate the uncertainties in this measurement of the hole dispersion. For this purpose we first consider the errors involved in determining the quantities on the right sides of Eqs. (1) and (2). The random error in marking the energy (e_H,A^0) or (e_L,A^0) of the hot-electron-luminescence peak is estimated as ± 1.5 meV. The uncertainties in the experimental determination of E_g^{QW} and E_A are 0.5 meV and 1.5 meV, respectively. These uncertainties, however, cause only systematic errors in $E_1(k)$ and $H_1(k)$, i.e., they only correspond to a shift of all points in Fig. 3 to either smaller or larger values. Finally, the uncertainty in k calculated from $E_1(k)$ is only 5%, even if we allow for 50% error in calculating the conduction-band nonparabolicity. In addition, this error in k is only a systematic but not a random error. The total random (systematic) errors in the determination of energy and wave vector of the hole are ± 1.5 meV (± 2 meV)

and $\pm 1\%$ ($\pm 5\%$), respectively. We stress that for comparing the dispersion of H_1 with that of L_1 or the dispersions of the two QW's with each other, the systematic errors are much smaller, because they have the same sign and probably even similar magnitude. Therefore the observed differences between the two QW's are meaningful and the measured energy splitting between H_1 and L_1 is very accurate.

In conclusion, we have quantitatively measured the in-plane dispersion of the lowest heavy-hole and light-hole subbands in the wave vector range $0.06\pi/a \lesssim k \lesssim 0.14\pi/a$ for two $GaAs/Al_xGa_{1-x}As$ QW's with different well width. We find that the heavy-hole subband is more dispersive and the splitting between the heavy-hole and light-hole subbands is larger in the narrower quantum well. Because of the accuracy of the measurement of quantitative comparison of experiment and theory is now possible. For such a comparison the same well width and alloy composition of the barriers should be used in the calculation as in the experiment.

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