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DETERMINATION OF BINDING ENERGIES AND WAVE FUNCTIONS IN QUANTUM WELLS FROM RAMAN RESONANCE CROSS SECTION MEASUREMENTS

T. SUEMOTO*, G. FASOL** and K. PLOOG

Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-7000 Stuttgart 80, P.R.G.
*Tohoku University, Sendai 980, Japan
** Cavendish Laboratory, Madingley Road, GB-Cambridge CB3 0HE, Great-Britain


Abstract. We study the resonance profiles of LO phonon and hole intersubband Raman signals from p-type modulation doped AlAs - GaAs - AlGaAs quantum wells. The resonance profiles show very pronounced sharp peaks at electronic resonance energies. We show that the energies at which the Raman resonances occur are directly related to the electron subband energies in the conduction band well. We study quantum wells which are up to 745 Å wide. We determine the binding energy of bound levels in the conduction band well up to n = 18. We determine the conduction band nonparabolicity experimentally. The intensity at the Raman resonance peaks is modulated by an envelope function which is related to the overlap integral of the electron and the hole wavefunction. Thus we determine the Fourier components of the hole wavefunction in terms of the conduction band wavefunctions.

1. Introduction. The cross section of the Raman scattering by LO phonons and by hole intersubband excitations as a function of dye laser energy shows sharp and pronounced peaks. These sharp resonance peaks have been studied recently in several papers and they can be used to explore the electronic structure of quantum wells [1, 2, 3]. This method of exploring the subband structure of quantum wells is fundamentally different to the usual method of luminescence excitation spectroscopy, which is equivalent to selective absorption measurements. In a two-dimensional system the optical absorption, and therefore also the luminescence excitation spectrum consists essentially of a sum of step functions plus additional excitonic contributions. As the energy increases every new subband adds one new step function. In addition, there is substantial enhancement of the absorption by the excitonic interaction making this type of measurement useful to study energy levels in quantum wells. In modulation doped quantum wells the excitonic interaction is screened by the carriers and luminescence excitation spectroscopy has low sensitivity. The Raman process on the other hand is a higher order process - the Raman cross section is proportional to a sum of a series of resonant denominators which are expected to diverge whenever the laser light (ingoing resonance) and/or the Raman scattered light (outgoing resonance) is close to an electronic excitation of the system. In the present work we use both the position of the Raman resonance peaks and the value of the Raman intensity at the resonance peaks to determine (a) the energies of the electron binding energies in the conduction band wells, (b) the conduction band nonparabolicity, and (c) the Fourier components of the hole wavefunction in terms of the electron wavefunctions up to n = 18 in p-type modulation doped AlAs - GaAs - AlGaAs quantum wells.
2. **Experimental.** Our samples have twenty quantum well periods grown by MBE on (100) GaAs substrates. Each period has a 450 Å wide barrier layer, consisting of a 250 Å wide layer of Be doped AlGaAs, followed by a 50 Å AlAs spacer layer, followed by the next Be-doped AlGaAs layer. The measurements are taken with an optical multichannel analyzer (OMA) using a position sensitive detector combined with a SPEX triple monochromator. The samples were mounted on a coldfinger kept at 4K in a cryostat and excited with an Argon ion laser pumped dye laser. We correct the spectra both for the reflection loss and for the response of the detection system.

Typical Raman measurements of such a structure are shown in Figure 1 for a series of dye laser wavelengths. Below about 10 meV we see a several meV broad Raman signal which we attribute to a hole intersubband excitation. We observe a GaAs like LO phonon and an AlAs like LO phonon, which is labelled LO(b) in Figure 1. In Figures 2 and 3 we show the resonance profiles of the GaAs like LO phonon Raman signal for sample A (745 Å well) and sample B (670 Å well). We plot the integral of the LO phonon Raman signal as a function of dye laser photon energy after subtraction of the background and renormalisation for the detector response and the dye laser output. Thus around 150 Raman spectra are analyzed numerically to obtain the results shown in Figures 2 and 3.

3. **Electronic binding energies and nonparabolicity.** We observe that the Raman scattering efficiency depends strongly on the dye laser energy. There are very pronounced sharp peaks for both samples. Similar peaks occur in the resonance profiles of the hole intersubband excitation. The positions of the resonance peaks correspond directly to the electronic binding energies of the subbands in the conduction band well. Indeed the separation of the peaks increases with energy. Thus the peaks n=17 and n=18 are spaced further apart than the peaks n=8 and n=9. The dependence of the spacing on laser energy allows to uniquely identify each resonance peak with the number of the corresponding electronic level. The approximate relationship $E_n = n^2$ also allows to establish a one-to-one correspondence between the resonance peaks of the hole intersubband excitations and those of the LO phonon signals and to identify the scattering mechanism. We find evidence that the Raman mechanism is by the impurity assisted Fröhlich mechanism [4]. In Figure 4 we plot the binding energies determined experimentally from the positions of the Raman resonance peaks as a function of the corresponding wavevector in the conduction band well. This wavevector was determined assuming a square conduction band well. The dashed line shows where the positions would be in the case of a parabolic conduction band. The full line shows the calculated energies using the conduction band dispersion from a $15 \times 15 k \cdot p$ calculation [5, 6]. We find very good agreement between the experimentally determined and the calculated nonparabolicity. This calculation uses the bulk values for the nonparabolicity - thus bulk values are a good approximation to describe the nonparabolicity in a 745 Å wide well.
4. Fourier determination of the hole wavefunction. Figures 2 and 3 show that the Raman efficiency at the resonance energies is strongly modulated by an envelope function. The intensity for Raman scattering by LO phonons is given by

\[ I_n \sim \sum_{k,k',\vec{k}} \left\langle \langle n,k|H_{el}|n,k'\rangle <\langle n,k'|H_{el}|n,k'\rangle \right\rangle ^2 \frac{1}{(E(n,k') - \omega_L + \omega_{LO})(E(n,k') - \omega_L)(E(n,k) - \omega_L)} \]  

Here, the integral \( \langle n,k|H_{el}|n,k'\rangle \) denotes the intraband scattering of an electron by an LO phonon within the 2D space and it can be assumed to be independent of \( n \). Similarly the integral \( \langle n,k|H_{el}|n,k'\rangle \), which denotes the elastic scattering by impurities or imperfections will be assumed to be approximately independent of \( n \). Thus the relative intensity of resonance for different \( n \) can be written as

\[ I \sim \left| \langle \langle n|ln\rangle <nlh|\rangle \right|^2 \]  

where the matrix elements \( \langle h|k|H_{el}|n,k\rangle \) again have been assumed to be independent of \( n \). Thus we find that the envelope function of the Raman resonance profile is proportional to the fourth power of the overlap integral of the hole wavefunction with the corresponding conduction band wavefunction. Thus the heights of the Raman peaks in Figures 2 and 3 measure the Fourier components of the hole wavefunction in terms of the conduction band wavefunctions. Since the wells studied here are very wide, electron wavefunctions up to \( n=18 \) are used for this "Fourier decomposition". In principle, the hole wavefunction could be directly synthesized by summing the Fourier series. There are two obstacles to a direct summation of the Fourier series here: in the part of the spectrum below \( n=6 \) strong luminescence inhibits the measurement of the Raman resonances and secondly the phase of the "Fourier components" is not known. Thus we use additional knowledge about the system and assume the localization of the holes in triangular wells.
at the interfaces and use an Airy function with two fit parameters. The solid line in Figure 2 shows
the best fit we obtained. Thus we determine that the hole wavefunction peaks 65 - 78 Å from the
interface of the well. Less successful fits are shown as the dotted and the dash-dotted curves.

6. Conclusions. We have shown that the Raman efficiency of the LO phonon and the hole
intersubband excitation in wide p-type modulation doped AlAs-GaAs-AlGaAs quantum wells
shows pronounced and sharp peaks as a function of dye laser energy. From the positions of the
resonance peaks we determine the level spacings of the bound electron levels in the conduction
band wells up to \( n = 18 \) in the present cases and the conduction band nonparabolicity
experimentally. The Raman efficiency at the resonance peaks is modulated by an envelope function,
which is proportional to the fourth power of the overlap integral of the hole wavefunction and the
corresponding conduction band wavefunctions. Thus we perform a Fourier type decomposition of
the hole wavefunction in terms of the electron wavefunctions.

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