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Physica E 8 (2000) 269–274

PHYSICA E

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Depolarization shift in coupled quantum wells with tunable level spectrum

Petra Denk[a, *], Martin Hartung[a], Achim Wixforth[a], K.L. Campmann[b], A.C. Gossard[b]

[a] *Sektion Physik der LMU, Geschw. Scholl-Platz 1, D80539 München, France*
[b] *Department of Materials, UC Santa Barbara, CA 93106, USA*

Received 15 August 1999; received in revised form 21 February 2000; accepted 21 March 2000

Abstract

The degeneracy of electronic subband levels in spike-inserted wide parabolic quantum wells is investigated by far-infrared spectroscopy and magnetotransport measurements. A narrow potential barrier within the parabolic well divides the electron system into two well-separated but strongly coupled layers, leading to a drastical change of the subband system and the collective intersubband excitations. In contrast to a single robust resonance, which, obeying Kohn's Theorem is usually seen in a purely parabolic quantum well, the collective intersubband transitions now recover the complex coupling and splitting of the single-particle states. By applying two different experimental methods being sensitive to either the single-particle spectrum or the collective excitation spectrum, we are able to confirm the theoretical predictions that the size of the observed splitting caused by resonant subband coupling is not altered by collective effects. Rather, the corresponding intersubband resonance lines are shifted to higher energies in a depolarization like manner. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 73.20.Mf; 73.20.Dx; 71.25.Hc; 72.30.+q

Keywords: Collective effects; Subband; Quantum wells; Tunneling

The energetic degeneracy between quantum levels in strongly coupled electronic systems reveals a very profound insight into some basics of quantum mechanics. In atoms, this degeneracy leads to the occurrence of a splitting of these degenerate levels into a series of levels, and hence to the existence of bonding and antibonding states in molecular systems. The same degeneracy is basically responsible for the formation of energy bands in solids. A very interesting problem, however, is the influence of the collective behavior on such splitting as observed usually in far-infrared (FIR) spectroscopic studies. A very versatile system to study such effects is a combination of quantum wells as realized in semiconductor layered structures. Here, both crystal growth techniques as well as the possibility to intentionally alter the electronic spectra by external means like electric fields, etc., offer a variety of possible parameters to investigate the level degeneracy in great detail. Semiconductor quantum wells are for instance realized in $Al_xGa_{1-x}As/GaAs$ heterostructures. Based on the high degree of perfection achieved

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[*] Corresponding author. Present address: L2M, C.N.R.S., 196, Avenue Henri Ravera, 92225 Bagneux Cedex, France.

1386-9477/00/$ - see front matter
PII: S1386-9477(00)00151-X

with molecular beam epitaxy, it is possible to realize a large variety of conduction and valence band profiles in the growth direction of semiconductor heterostructures. In particular, the so-called parabolic quantum wells (PQW) have attracted a lot of attention since they can be used for unique experiments inaccessible to other potential shapes [1]. Once filled with electrons via modulation doping, transport experiments confirm that the screened potential approximates a square well whose single-particle energy levels can be probed. In contrast, spectroscopy of the selfconsistently arranged energy levels of the electron system in a 'filled' PQW is not possible with optical intersubband transmission experiments, as in the case of a bare parabolic potential the equidistant energy levels are probed [2]. Electron–electron interactions turn out to be of no importance. This striking observation was explained by the generalized Kohn's Theorem [3]. This theorem states that the Hamiltonian in this case can be exactly divided into two parts, one containing only center of mass coordinates, the other one containing only relative co-ordinates. Furthermore, it can be shown that the long-wavelength radiation only couples to the center of mass part. As a result, the collective spectrum of a parabolically confined electron system shows only a single, well-defined resonance, it being very much correlated to the plasma frequency of such electronic systems.

However, by inserting a thin potential barrier, we have no longer a purely parabolic potential and the applicability of Kohn's Theorem must be questioned. As a consequence, the single line of the collective intersubband transitions which is observed in transmission spectroscopy may split into several distinct lines [4]. Such a line splitting can be well explained taking into account the level splitting caused by the possible energetic degeneracy as addressed above. It can be investigated by both optical and (magneto) transport experiments. The basic difference between both techniques is that in contrast to the spectroscopic investigations a transport experiment does not probe the center of mass co-ordinates but rather is sensitive to the single-particle spectrum and the density of states in the vicinity of the Fermi level. However, for two degenerated subbands, the subbands split into a symmetric and an antisymmetric state, which are separated by an energy gap Δ_{SAS} ("anticrossing effect"). The interesting question arises, how this level splitting acts on the different experimental approaches. Theoretically, it has been recently predicted that the energetic splitting due to the resonant subband coupling is not altered by collective effects, but that the subband energies are rather shifted to higher energies ("depolarization shift").

We first study such an anticrossing effect quantitatively as a function of barrier height by magnetotransport experiments. Quantum oscillations in the magnetoresistance (Shubnikov–de Haas oscillations) can be analyzed in terms of level occupancy. From these studies, we can deduce the energetic level structure in the coupled quantum well. Additionally, we experimentally investigate the influence of the well-known depolarization shift on the observation of such level splittings. Here, we are mainly probing the collective effects and their influence especially on the anticrossing effect (Δ_{SAS}). Both experiments are done simultaneously on the same sample by performing FIR and magnetotransport measurements.

After presenting the concept of subband-energy determination by magnetotransport measurements, we will briefly describe the samples investigated followed by some experimental details. This method is then used to extract different Δ_{SAS} for different barrier heights. We proceed by comparing our results with the FIR measurement data obtained on the same samples. Finally, in order to support our experimental findings, we present self-consistent band structure calculations which are in excellent agreement with our experimental data. The single-particle energy levels of the screened potential in a filled PQW are deduced from measuring Shubnikov–de Haas oscillations of the longitudinal magnetoresistivity. These oscillations are Fourier transformed in a straight forward manner to directly obtain the different Landau level occupancies N_i at a given total carrier density and a specific magnetic field. Based on the energy-independent density of state $D = m^*/\pi\hbar^2$ of a two-dimensional electron system, one obtains the difference of the Fermi energy E_{f} corresponding to the respective subband level E_i. The samples described here are grown by molecular beam epitaxy on semi-insulating GaAs substrates. The active layers form a 76 nm wide parabolic quantum well in the center of which a three monolayer thick $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ ($x = 0.1, 0.2, 0.3$ for samples A, B, C, respectively) sheet serves as a tunnel barrier between both parts on either side. The symmetrically doped well is capped by 60 nm AlGaAs and 4 nm GaAs. A semi-transparent NiCr electrode on top of the structure serves as a front gate and alloyed AuGe/Ni/AuGe contacts provide Ohmic contacts to the electron system in the well. Application of a negative bias V_g to the gate leads to a situation, where first the ‘upper’ part of the well becomes slowly depleted and at the same time its energy spectrum is drastically changed. Once this part of the electron system is fully depleted, the electric field can act on the ‘lower’ part of the well. Since the barrier is located in the center of the quantum well, we have flat band conditions for $V_g = 0$ mV. Both FIR and magnetotransport measurements are carried out in the center of a super conducting solenoid at a temperature of about $T = 2$ K. The FIR transmission spectra are collected with a commercial rapid scan Fourier transform spectrometer. An Si composite bolometer is used to detect the transmitted radiation and the relative change of transmission $-\Delta T/T = T(N)_s - T(0)/T(0)$ is examined. From magnetotransport measurements at zero-gate bias, the carrier density of the sample has been determined to $N_s = 4.2 \times 10^{11}$ cm^{-2} per well.

In the transport measurements, we concentrate on the case of two occupied subbands. For different gate voltages, we measure SdH oscillations in the small magnetic field regime between $B = 0$ and 1 T, respectively. For higher magnetic fields magnetic depopulation of the levels leads to a simpler situation where only a few Landau levels become occupied. In that sense, we treat our system like a system with two occupied subbands, as determined by the confining potential in the growth direction. However, in our case the two ‘subbands’ originate from a splitting of a single but degenerate level on either side of the barrier. The resulting subband densities N_i can then be evaluated with high accuracy from a Fourier transformation of the resistance oscillations as a function of the magnetic field and for different gate bias. Here, we gain access to the energetic difference between the position of the Fermi level and the respective subband edges.

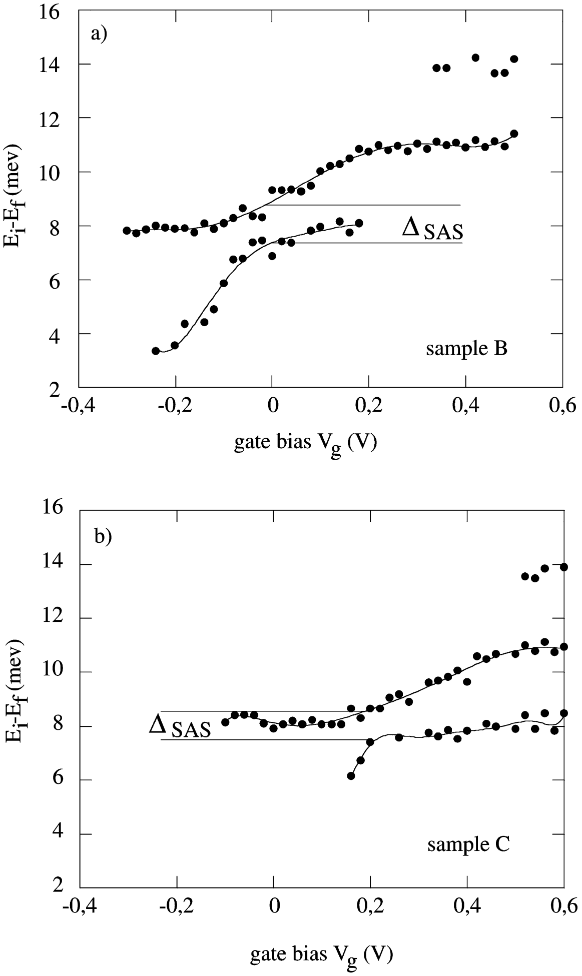

Fig. 1. Energy subband level spacing as a function of gate bias for the coupled well system with a 150 meV high AlGaAs ($x = 0.2$) barrier (a) and with a 225 meV high AlGaAs barrier (b). The splitting $\Delta_{SAS} = 1.4$ meV in (a) is larger than in (b) ($\Delta_{SAS} = 1.0$ meV) as expected from the lower tunnel barrier.

By changing the carrier density N_s with the gate bias, the corresponding energy levels can be tuned in a very controlled manner. By changing the bias, we thus can span a whole range of different sublevel scenarios on either side of the barrier. Eventually, we are also able to degenerate the single-particle levels on either side. The respective levels now split into symmetric and antisymmetric states leading to a well defined anticrossing in the E vs. V_g diagram. This anticrossing behavior is clearly seen in Fig. 1, where the subband energies as a function of gate voltage are shown for sample B and C (barrier heights $E^B_{Barr} = 150$ and 225 meV, respectively). The experimental values are fitted with a fifth degree polynom, from which the splitting Δ_{SAS} due to the resonant subband coupling is determined. For the three different samples, we find $\Delta^A_{SAS} = 1.7$ meV (not shown here), $\Delta^B_{SAS} = 1.4$ meV, and $\Delta^C_{SAS} = 1.04$ meV. The width Δ_{SAS} of

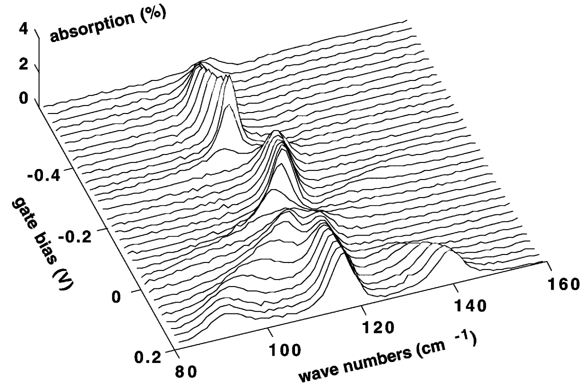

Fig. 2. Absorption spectra for the coupled well system with a 150 meV ($x = 0.2$) high AlGaAs barrier. Parameter is the front gate bias that changes both the level occupancy as well as the subband spacings. Pronounced level anticrossings and splittings are observed as a result of resonant tunneling between both parts of the well.

the single-particle splitting of the coupled symmetric and antisymmetric states Δ_{SAS} directly reflects the tunneling probability, being smaller for larger energetic barrier. It is given by approximately twice the tunneling matrix element [2],

$$V_{12} = -V \int_1 \Psi_1 \Psi_2 = -V \int_2 \Psi_1 \Psi_2, \tag{1}$$

where V denotes the well depth, Ψ_i the wave functions of the uncoupled states and the integrals are taken over the extent of either well.

In order to investigate the effect of collective effects, especially the depolarization shift, it is necessary to perform FIR-measurements and SdH-measurements on the same sample. We therefore prepared samples in van-der-Pauw geometry [5] allowing for the application of both experimental methods at the same time. Moreover, we thus exclude any additional effects which might arise from inhomogeneities between different samples or due to different cooling processes. In Fig. 2 we show the experimental FIR data for sample B. Many different lines with a complicated gate bias dependence are seen which exchange oscillator strength and shift their energetic positions as a function of the applied gate bias. Pronounced level anticrossings and splittings are observed as a result of resonant tunneling between both parts of the well [6]. As has already been addressed in Ref. [6], the different lines observed in the experiment can be perfectly assigned to different transitions between occupied and unoccupied sublevels in our strongly coupled quantum well system. Our aim is now to compare the FIR results with those obtained in magnetotransport experiments as described above.

For this purpose, we compare the observed FIR resonance positions as a function of gate voltage to the results of a self-consistent Hartree calculation. This is depicted in Fig. 3(a), where we show the calculated energy levels in our structure vs. the gate bias. The position of the Fermi level is set to zero in the figure. Some possible transitions from occupied states to unoccupied states are marked by arrows and labeled by the capital letters A–E. The inset of Fig. 3(b) schematically shows the respective conduction band diagram of the double well, including some relevant energy levels. From this figure it becomes evident that the observable lines will exhibit a quite complex behavior as a function of gate bias. This complexity, on the other hand, makes it quite easy to identify the lines in the experiment. Fig. 3(b) shows the experimental resonance positions (dots) together with the possible transition energies as extracted from the differences of the respective single-particle energy levels in Fig. 3(a). To achieve such a remarkable agreement between the calculation and the experiment, the two sets of data had to be shifted against each other by a bias independent energy $\Delta(E) = 3.2$ meV. We attribute this fact to a shift of the observed resonances with respect to the single-particle transition energies caused by many-body effects, e.g., the depolarization shift. This assumption is further confirmed by comparing our findings to the result of the transport measurements as shown in Fig. 4. Here, we plot both the transport data (from Fig. 1a) and the FIR resonance positions (from Fig. 3b) of the same sample vs. a common gate bias axis. Following our above reasoning it is easy to identify the same level splitting for both experiments. Although the general complex line structure in both cases is very well reproduced, we find that the position of the center of the gaps on the voltage axis in both cases is not identical, as indicated by the vertical dased lines in the figure. This is the central point of our present experiments. Although we extract the same Δ_{SAS} splitting in both cases ($\Delta_{\mathrm{SAS}}^{\mathrm{Transport}} = 1.4$ meV, $\Delta_{\mathrm{SAS}}^{\mathrm{FIR}} = 1.5$ meV), the center of the gap (which has been roughly estimated by the crossing point of two simple guide-to-the

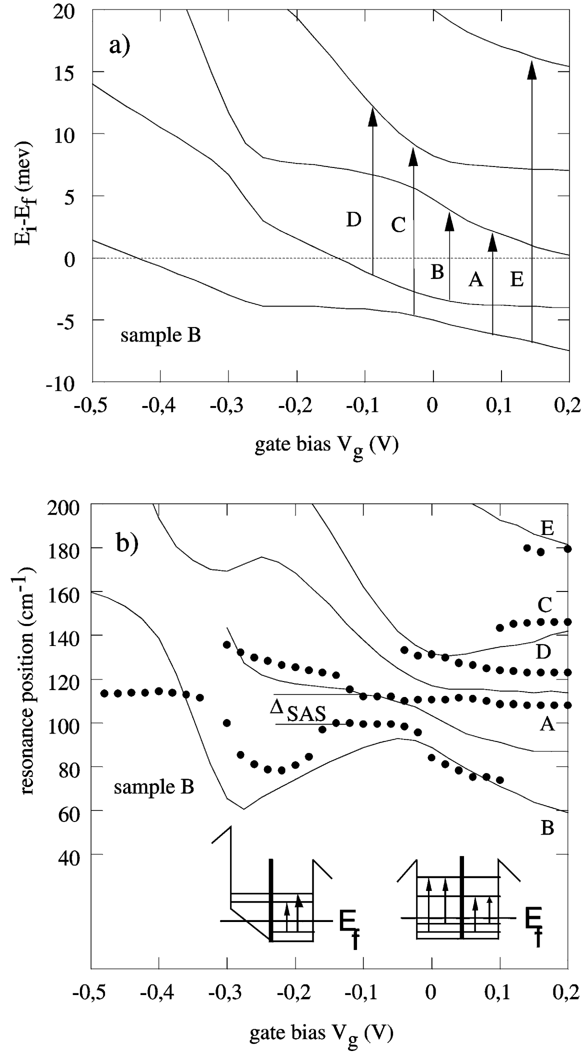

Fig. 3. (a) Result of a self-consistent subband calculation for the sample with the 150 meV high barrier. Arrows indicate possible transitions. (b) Experimental resonance positions (dots) together with the calculated transition energies of Fig. 2. The latter have been shifted upward in energy by $\Delta(E) = 3.2$ meV, simulating the effect of the depolarization shift.

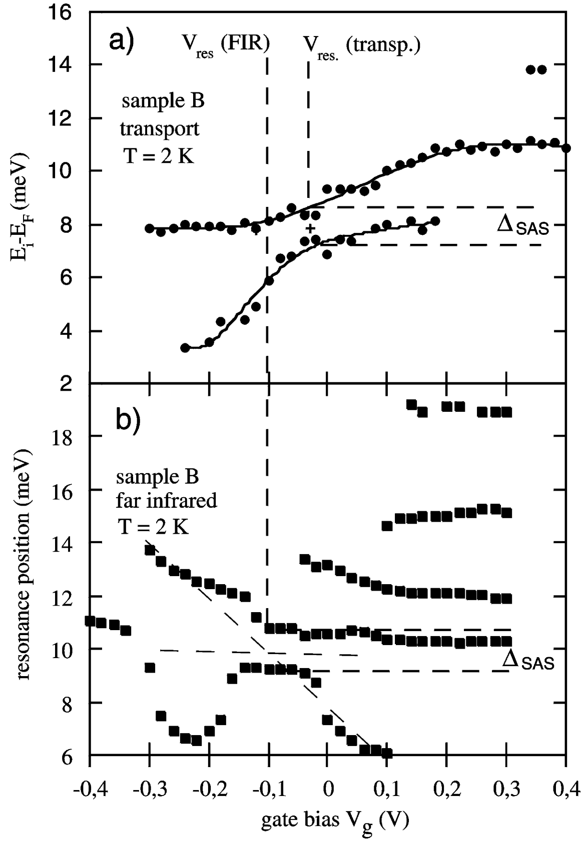

Fig. 4. Subband level spacing (upper) and resonance position (lower) as a function of gate voltage for the coupled well system with a 150 meV ($x = 0.2$) high AlGaAs barrier. The size of the splitting Δ_{SAS} remains unchanged, whereas the position is shifted by $V_g = 80$ mV in the transport measurements due to the depolarization shift.

eye lines as indicated in the lower panel of the figure) between both sublevels is shifted towards larger positive gate bias by $V_g = +80$ mV. A very simple approach to explain this experimental finding has been recently given by Zaluzny [7], who calculated the effect of collective effects on the observability of level splittings in a simple model system. Based on a single-particle level calculation for a square potential well, the effect of a depolarization shift on the observed FIR resonances could be shown to result in an energetic upward shift of the respective level crossings, leading to a shift of the apparent gap towards higher gate bias. Hence, the main result of his calculations agrees very well with our findings. To account for the observed finite depolarization shift, one has to account for a composite effective energy level including the depolarization shift which is simply added to the single-particle spectrum.

Zaluzny states that the collective intersubband-like transitions of a strongly coupled electron system completely mirror the single-particle tunneling scheme apart from being depolarization shifted. In particular, the observed level anticrossing reflecting the tunneling matrix elements of the respective eigenstates remain unchanged by many-particle effects. This is directly probed by measuring the same Δ_{SAS} in transport (one electron spectrum) and in the FIR-measurements (collective excitation spectrum). Although our coupled electron system is more complicated than the one used in Ref. [7], the overall agreement is quite perfect. From our data we can directly deduce the influence of collective effects on the FIR spectrum of a coupled quantum well system. A somewhat surprising experimental finding, however, is the fact that the observed depolarization shift seems to be completely independent of the gate bias or the shape of the self-consistent Hartree potential, respectively. Such behavior would be ideally expected only for the case of a perfectly parabolic external potential, where Kohn's theorem applies. This, however, is definitely not the case for our samples, as has been directly proved by the existence of the complicated absorption spectrum. As in many other cases that have been investigated before, however, this surprising fact can be taken as another indication of the rigidity of this remarkable theorem connected to the collective excitation spectrum of parabolically confined electron systems.

In summary, we have investigated the effect of resonant sublevel coupling in strongly coupled double quantum wells. Both the single-particle spectra as well as collective excitation spectra have been probed simultaneously by magnetotransport and FIR measurements. We find that the size of the level splitting between the two degenerate sublevels is directly proportional to the tunneling matrix element of the respective sublevel states, which have been tuned by tunnel barriers of different heights. In particular, we find that the collective response of strongly coupled electron systems completely mirrors the single-particle tunneling scheme apart from being depolarization shifted by a fixed energy. Our experimental findings are in perfect agreement with recent theoretical predictions.

Acknowledgements

We acknowledge very useful discussions with J.P. Kotthaus, and M. Zaluzny. This work has been generously sponsored by the Deutsche Forschungsgemeinschaft.

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