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Angaben zur Veröffentlichung / Publication details:

Hartung, M., Achim Wixforth, K.L. Campman, and A.C. Gossard. 1996. "The effect of resonant sublevel coupling on intersubband transitions in coupled double quantum wells." *Solid-State Electronics* 40 (1-8): 113–15. https://doi.org/10.1016/0038-1101(95)00228-6.

THE EFFECT OF RESONANT SUBLEVEL COUPLING ON INTERSUBBAND TRANSITIONS IN COUPLED DOUBLE QUANTUM WELLS

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Abstract—The effect of resonant sublevel coupling on intersubband transitions in double quantum wells is investigated using far-infrared spectroscopy. We study widely tuneable parabolic double quantum wells in which potential spikes of different energetic height and thickness provide tunnel barriers for the electron systems on either side of the barrier. The use of gate electrodes enables us to tune both the carrier densities as well as the respective sublevel spacings and allow for a manifold degeneracy scheme like in an artificial molecule where the atomic number of both partners can be intentionally changed. Depending on the actual experimental condition, we observe pronounced level anticrossings into a symmetric and antisymmetric state. This single-particle sublevel coupling manifests itself in a rich spectrum of the observed collective intersubband transitions which occur at the depolarization shifted intersubband energy.

The physics of coupled electron systems confined to length scales comparable to their Fermi wavelength has recently attracted a great deal of interest as they provide an attempt to realize artificial "atoms" and "molecules" with a rich spectrum of internal and collective excitations that can be intentionally tailored by several means. Recent efforts to describe or even realize cellular automata and neural networks using such coupled systems with well defined eigenstates certainly ask for a detailed understanding of the nature of the sublevel coupling and related effects.

Here, the effect of resonant sublevel coupling on intersubband transitions in parabolic double quantum wells has been investigated using far-infrared spectroscopy on widely tuneable double well systems. Our samples consist of wide parabolic GaAs/AlGaAs quantum wells[1] in which AlGaAs potential spikes of different energetic height and thickness provide tunnel barriers for the electron systems on either side. The use of front- and back gate electrodes enables us to tune both the carrier densities as well as the respective sublevel spacings and allow for a manifold degeneracy scheme. Depending on the actual experimental condition, we observe pronounced level anticrossings into a symmetric and antisymmetric state. This single-particle sublevel coupling manifests itself in a rich spectrum of the observed collective intersubband transitions which occur at the depolarization shifted intersubband energy[2].

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 3 monolayer thick $Al_xGa_{1-x}As$ ($x = 0.1, 0.2, 0.3$) 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 25 nm thick Si:GaAs layer located some 1.5 μm below the well including a 300 nm thick low-temperature grown GaAs layer is used as a back gate electrode. A semi-transparent NiCr electrode on top of the structure serves as a front gate. Indium pellets are alloyed at $T = 430°C$ under reducing atmosphere to provide Ohmic contacts to the electron system. Magneto-capacitance measurements at low temperatures ($T = 2$ K) reveal a carrier density of $2.1 \cdot 10^{11}\,cm^{-2}$ per well. A 6 μm period Ag grating coupler on top of the front gate is used to couple the normally incident FIR radiation to the intersubband modes.

Our transmission experiments are performed at low temperatures with the sample mounted in the center of a superconducting solenoid providing magnetic fields up to 15 T. Experimentally, we determine the relative change in transmission $-\Delta T/T = [T(N_S) - T(0)]/T(0)$ which is proportional to the real part of the dynamical conductivity $\tilde{\sigma}_{ZZ}(\omega)$ of the system. $T(0)$ is the transmission of the sample with the well being completely depleted, $T(N_S)$ is the one at finite carrier densities. An Si composite bolometer is used to detect the transmitted radiation.

In Fig. 1 we present a set of spectra for the sample with the highest ($x = 0.3$) $Al_xGa_{1-x}As$ barrier. Parameter is the front gate bias $V_{g,f}$ with the back gate bias held constant at $V_{g,b} = 0$ V. A very rich behavior with up to three individual lines, depending on the bias, is observed. We interpret these lines as intersubband-like depolarization shifted transitions between the more or less strongly coupled single

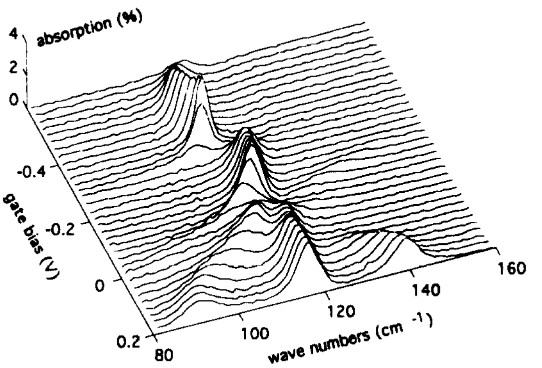

Fig. 1. Absorption spectra for the coupled well system with a 225 meV ($x = 0.3$) high AlGaAs barrier. The parameter is the front gate bias that changes both the level occupancy as well as the subband spacings. Pronounced level anticrossings and splittings are observed as a result of resonant tunnelling between both parts of the well.

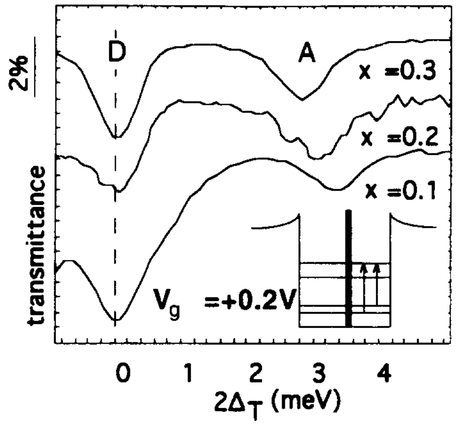

Fig. 3. Comparison of a representative line splitting for the three different samples investigated. Only two transitions are shown, which correspond to the situation as given in the inset. The higher the tunnel barrier, the smaller the line splitting, indicating a smaller tunnel matrix element. The spectra have been offset for clarity such that the low energy lines (D) coincide.

particle states in the structure. Depending on the actual gate bias the occupation of both parts of the well, as well as the corresponding energy level spacings, can be tuned in a very controlled manner. In particular, we are able to energetically degenerate several single particle levels on either side of the barrier, thus allowing for resonant tunneling. This sublevel coupling manifests itself in a pronounced level splitting level into a symmetric and an antisymmetric state which are then separated by an energy Δ_{sas} given basically by twice the tunnel matrix element Δ_T of the appropriate states[3] and a strong influence on the intersubband resonance lineshape and position[4].

In Fig. 2a we plot the self-consistently calculated energy levels of the coupled system as a function of the front gate bias $V_{g.f}$. The Fermi level is kept constant to be $E_f = 0$ in the figure. With increasingly negative bias, the surface-side part of the well becomes more and more depleted and consequently the energy level separations increase. At a positive bias of $V_{g.f} = +0.2$ V three levels are occupied, two at the surface side part of the well, and one at the substrate side. Hence, in principle three intersubband-like transitions are allowed, in agreement with the experiment. More negative bias changes the subband spectra, as depicted in the figure, and different transitions are allowed, as indicated by the vertical arrows.

The calculated transitions as a function of the gate bias together with the experimental resonance positions are plotted in Fig. 2b. To obtain a quantitative agreement between experiment and calculation *the calculated transitions have been shifted upwards* in energy by $\Delta E = 3.2$ meV ("depolarization shift"). This procedure is consistent with a recent theoretical calculation[2], where it has been pointed out that the collective intersubband-like transitions of a strongly coupled electron system completely reflect the single particle tunneling scheme apart from being depolarization shifted. In particular, the observed level anticrossings reflecting the tunneling matrix

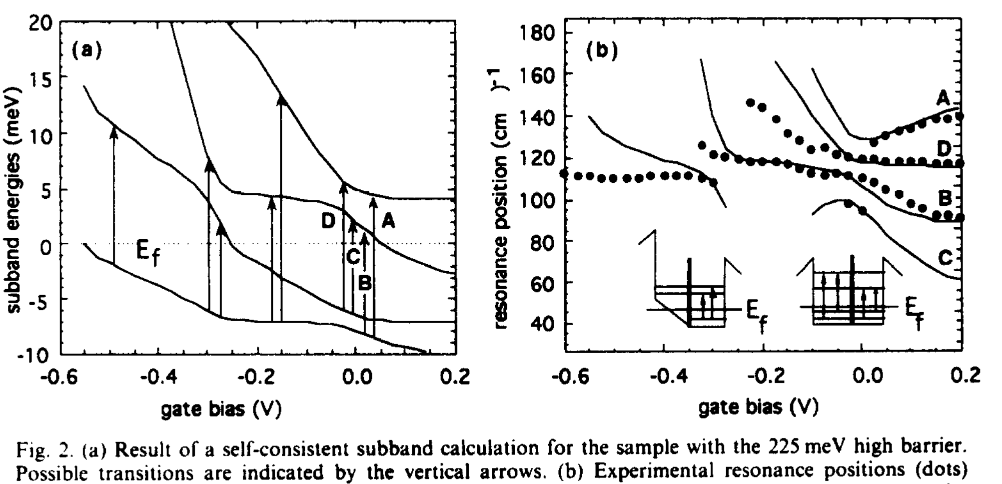

Fig. 2. (a) Result of a self-consistent subband calculation for the sample with the 225 meV high barrier. Possible transitions are indicated by the vertical arrows. (b) Experimental resonance positions (dots) together with the calculated transition energies of (a). The latter have been shifted upwards in energy by $\Delta E = 2.2$ meV, simulating the effect of the depolarization shift.

elements of the respective eigenstates remain unchanged by many-particle effects. To demonstrate this, we compare three spectra taken at $V_{g,f} = +0.2$ V for the three different samples investigated here. This is shown in Fig. 3, where we only show the transitions labeled A and D in Fig. 2a. Those are directly related to a transition from the lowest lying Δ_{sas}-splitting into the first excited state as indicated in the inset. To simplify the figure, all three spectra are shifted such that the lower energy transitions (D) coincide. The observed splitting increases from $2\Delta_T \approx 2.8$ meV up to $2\Delta_T \approx 3.5$ meV as the barrier height is lowered from $x = 0.3$ (225 meV) to $x = 0.1$ (75 meV). Obviously, the size of the observed gaps is in perfect agreement with the ones calculated for single particle coupling, as can be seen from Fig. 2 for the sample with the highest barrier.

In summary, we have investigated the effect of resonant sublevel coupling in strongly coupled double quantum wells on the collective excitation spectra. We find that the level splitting into a symmetric and an antisymmetric state under resonance conditions is directly reflected in the intersubband-like transitions of the system under investigation. The size of the level splitting being directly proportional to the tunneling matrix elements of the respective sublevel states is in very good agreement to the ones calculated in a single particle picture. The collective spectra are then obtained by depolarization-shifting the single particle transitions upwards in energy. Thus the spectroscopy of strongly coupled electron systems reveals profound insight into the physics of resonant tunneling.

Acknowledgements—We gratefully acknowledge fruitful discussions with A. Lorke, C. Gauer, R. Warburton and J. P. Kotthaus. This work has been sponsored in part by the Deutsche Forschungsgemeinschaft and in part by the AFOSR Grant no. F49620-94-1-0158. The collaboration is also supported by the European Community via ESPRIT (EC-US.015:9826).

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