Intersubband transitions in band gap engineered parabolic potential wells

M. Hartung, Achim Wixforth, K.L. Campmann, A.C. Gossard

Angaben zur Veröffentlichung / Publication details:

Hartung, M., Achim Wixforth, K.L. Campmann, and A.C. Gossard. 1996. "Intersubband transitions in band gap engineered parabolic potential wells." Superlattices and Microstructures 19 (1): 55–60. https://doi.org/10.1006/spmi.1996.0008.

Intersubband transitions in band gap engineered parabolic potential wells

M. Hartung, A. Wixforth
Sektion Physik der LMU, Geschw. Scholl-Platz 1, D-80539, München, Germany

K. L. Campmann, A. C. Gossard
Materials Dept., UC Santa Barbara CA 93106, USA

Intersubband transitions in spike-inserted wide parabolic quantum wells are investigated. A thin potential barrier within the pure parabola devides the electron system in two well separated but strongly coupled layers, which in turn drastically changes the collective excitations scheme. In contrast to a pure parabolic quantum well where according to the generalised Kohn's Theorem only one fixed resonance is observed, the collective intersubband transitions recover the complex coupling and splitting scheme of the single particle states of a strongly coupled system. We interpret our experimental findings in terms of resonant tunnel processes and discuss them using simple model calculations.

Recently it has been shown that intersubband like transitions in quasi-three-dimensional electron systems based on wide parabolic quantum wells (PQW) serve in some sense as an ideal model system for the collective far infrared excitations of low dimensional structures like quantum wires and dots [1]. The use of sophisticated molecular beam epitaxy growth techniques allow to control the confinement potential very precisely and thus provide the possibility for detailed studies of its influence on the collective excitations of the PQW. Those may then be compared with the results for low dimensional systems were the shape of the confining potential is not exactly known.

Here, we would like to focus on intersubband transitions in coupled electron systems based on PQWs, were the electronic level scheme can be varied over a wide range by means of an external electric field. It turns out, that our system now provides an excellent model system for molecule like states in coupled quantum wires and dots.

Parabolic quantum wells are realised with the $Al_xGa_{1-x}As$ system by appropriately grading the Aluminium content x during growth. As the band gap in this ternary alloy varies nearly linearly with x for not too high Al contents, the grading of the composition directly results in a spatially varying conduction band edge. In particular, this parabolic potential mimics the potential of a homogenous positive background charge n^+ which can be expressed by the growth parameters of the PQW using Poisson's equation:

$$n^+ = \frac{\varepsilon\varepsilon_0}{e^2}\frac{\partial^2 E_C}{\partial z^2} = \frac{8\varepsilon\varepsilon_0\Delta}{e^2 W^2} \tag{1}$$

Here, ε denotes the mean dielectric constant of $Al_xGa_{1-x}As$, Δ is the energy height of the parabola from its bottom to the edges, e the electronic charge, and W the width of the grown PQW. Once this structure is remotely doped, the donors release electrons into the well which in turn will screen the man-made parabolic potential, thus forming a wide and nearly homogeneous electron layer. An undoped layer between the dopants and the well reduces ionized impurity scattering and thus enhances the electron mobility in the well like for conventional heterostructures.

In such a PQW typically three or even more electronic subbands are occupied. The self-consistent subband level scheme is quite complex and strongly affected by the electron density which may be controlled by an external electric field applied on a gate electrode on top of the sample. However, it turns out, that the single particle states do not affect intersubband like transitions in pure PQWs at all. As a consequence, only one single line is observed in far-infrared experiments whose resonance energy is given by the curvature of the bare parabolic potential and by construction is identical to the plasma frequency of a slab of charge density n^+. This fundamental result is theoretically described by the generalised Kohn's Theorem [2].

Here, however, we would like to present our results on the collective spectra of PQW in which a thin potential barrier has been introduced. First, this barrier represents a deviation from pure parabolicity and thus deviations from the validity of Kohn's Theorem are expected. Secondly, if the barrier height and width are properly designed, states on either side may be coupled via a resonant tunnelling process. This is the scenario which we investigate experimentally.

Theoretical as well as experimental investigations [3–7] suggest that the splitting of single particle states in coupled double quantum wells due to resonant tunnelling leads to a splitting of the inter-subband resonance lines whenever transitions between, e.g. one ground state and two resonantly coupled excited states take place. In a recent theoretical work [8] it was shown, that the measured splitting in the collective intersubband spectra reveals the single particle splitting of the coupled symmetric and anti symmetric states Δ_{SAS}, given by twice the tunneling matrix element V_{12} [9]:

$$V_{12} \cong -V\int_{1} \Psi_1 \Psi_2 dz \cong -V\int_{2} \Psi_1{}^* \Psi_2 dz,$$

with V the well depth, Ψ_i the wavefunctions of the uncoupled states and the integrals over the extent of either well.

Intersubband experiments on coupled electron systems based on wide PQW are quite promising for both getting insight into the single particle scheme as well as to investigate the physics of resonant level coupling. The latter is in particular interesting as we are able to widely tune the subband level scheme and occupancy of our coupled system. This way we can investigate the effect of resonant sublevel coupling for a manifold of different states onto the respective collective response.

The samples used in our experiments consist of a 760 Å wide and 75 meV deep PQW with 150 meV high sidewalls. The PQW is capped by 600 Å AlGaAs and 40 Å GaAs. A three monolayer thick AlGaAs tunneling barrier is located in the centre of the PQW. Electrons are provided by symmetrically doping of the AlGaAs barriers. A 250 Å thick Si:GaAs layer located about 1.5 μm bellow the well is used as a back gate electrode. Ohmic contacts are provided by alloyed Indium pellets and a semi-transparent NiCr electrode on the surface serves as a front gate. To couple the normally incident FIR light to the intersubband modes a 6 μm period Ag grating coupler is used. From magnetocapacitance measurements we take that the electron system is devided into two well separated parts and obtain a carrier density of $N_s = 2.1 \times 10^{11}$ cm^{-2} per well.

Our experiments are performed at low temperatures of $T = 2$ K with the sample mounted in the centre of a super conducting solenoid. The 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.

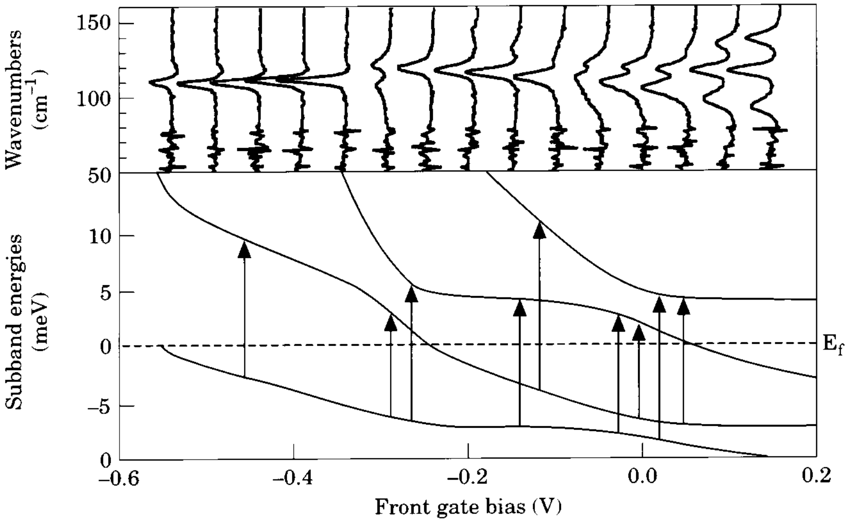

Fig. 1. Absorption spectra at $B=0$ (upper part). With decreasing gate bias (corresponding to the x-axis of the lower part) the double quantum well gets depleted and the level spacing increases as shown in the self consistent subband calculation in the lower part. As a result of resonant tunnelling level anticrossings occur which manifest themselves in the experimentally observed line splittings of the intersubband resonance spectra. Arrows mark the in principle possible intersubband transitions for the certain regimes.

In the upper part of Fig. 1 we show a set of spectra taken at zero magnetic field $B=0$. Parameter is the front gate bias V_g (corresponding to the values given on the lower part of Fig. 1) while the back gate bias is held constant at $V_{bg}=0$. As a function of gate bias we observe a very complicated set of resonances. We interpret the individual lines as intersubband transitions between the more or less coupled subbands of the double quantum well. This interpretation is strongly supported by the results of the self consistently calculated subband energies which are shown in the lower panel of Fig. 1. By changing the carrier density N_s with the gate bias, the corresponding energy levels can be tuned in a very controlled manner. For certain gate voltages we are able to energetically degenerate several single particle levels on either side of the barrier. The respective levels now split into symmetric and anti symmetric like states leading to the well perceptible anticrossings in the E versus V_g diagram. It is worth noting that with increasingly negative gate bias first the level spacings of the surface most side of the well are affected. Only after complete depletion of this portion of the electron system the substrate most part of the well is affected. This can be clearly seen in the lower panel of Fig. 1. Around $V_g=0$ V both the ground states and the first exited states on either side of the barrier are degenerate and strongly coupled. Therefore in principle, as indicated by arrows, four different transitions are possible. Three of them are well featured experimentally while the fourth may just be recognized as a shoulder in the spectra. With decreasing gate bias the surface part of the well becomes more and more depleted and therefore the corresponding subband energies increase; resonant tunnelling vanishes. At about $V_g=-0.3$ V, where only the substrate part of the well remains occupied, its first excited subband becomes degenerated with the (unoccupied) ground state of the other part of the well. Again resonant tunnelling leads to a expected and well resolved splitting in the resonance line.

For a more quantitative consideration we have plotted in Fig. 2 the experimentally obtained resonance positions together with the self consistently calculated subband spacings. A surprisingly good agreement between both is found, when the calculated transition energies are shifted upward in energy by 26 cm^{-1} or 3.2 meV, respectively. In particular, the nearly perfect correspondence of the gate voltages (i.e. carrier densities) at which level anti crossings—manifested by a line splitting—

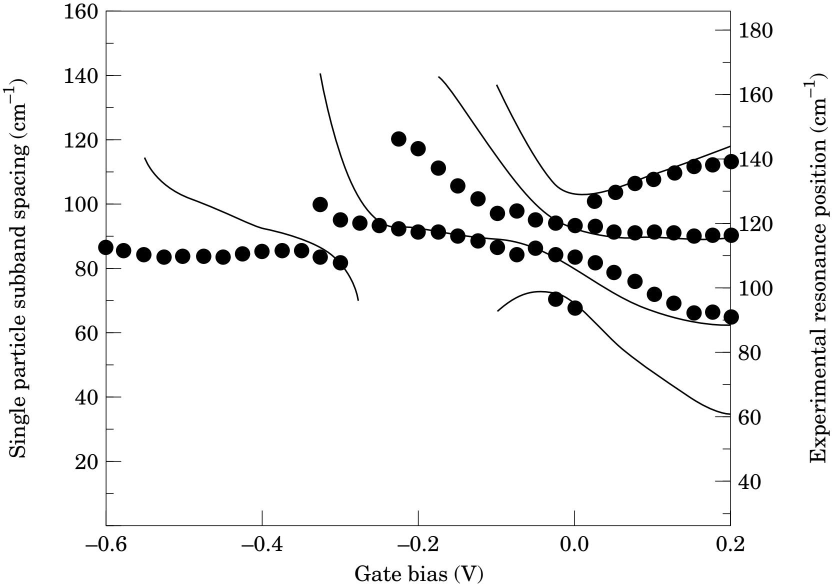

Fig. 2. The experimentally obtained spectrum of intersubband resonances (●) is well described by the self consistently calculated single particle level spacings (——) if the latter are shifted upward in energy at a factor of 3.2 meV.

occur, as well as the absolute value of the splittings themselves is remarkable. The latter is in very good agreement with a recent theoretical investigation [8]. There it was shown that the splitting of the single particle states, known as Δ_{SAS} splitting is completely reflected by the splitting of the collective and depolarization shifted intersubband resonances. The fact that we have to shift the single particle transition energies to slightly higher values may is caused by many body effects, like the depolarization shift. However, this shift should depend on the actual carrier density which is in contrast to our findings. This point certainly needs a more sophisticated theoretical investigation which also should consider the behavior of the oscillator strength of the individual transitions.

In the last section we would like to focus on a direct measurement of the Δ_{SAS} splitting. To allow a transition between the symmetric and anti symmetric ground states of the coupled system the Fermi level has to be adjusted in a way that it falls in between both levels. In our actual sample we are not able to achieve this just by changing the gate biases, as this simultaneously changes the level spacings. Instead, we apply a strong magnetic field perpendicular to the surface. Each subband i now condenses into a Landau ladder E_i^l, whereas the relative energy spacings of, e.g. the lowest Landau levels of all subbands remain unchanged as compared to $B=0$. For an only weakly non-parabolic system as GaAs this implies that Landau levels E_i^l on both sides of the well are resonantly coupled whenever the respective subband levels E_i are coupled at $B=0$. Therefore it is possible to magnetically depopulate all Landau levels of the anti symmetric ground state. As a matter of fact, we observe this transition experimentally with increasing magnetic field when the filling factor ν of the whole system becomes $\nu \leq 2$. Of the well resolved three resonances for $V_g > 0$ at $B=0$ only two remain, which corresponds to the intersubband transitions from the only occupied symmetric ground state to the split excited states. In addition, for certain gate voltages a new resonance occurs at about 55 cm^{-1}. We interpret this resonance as the direct transition between the symmetric and anti symmetric ground states of the coupled double quantum well. Of course this resonance as an collective excitation is depolarization shifted. If we again assume the manybody contribution to the resonance

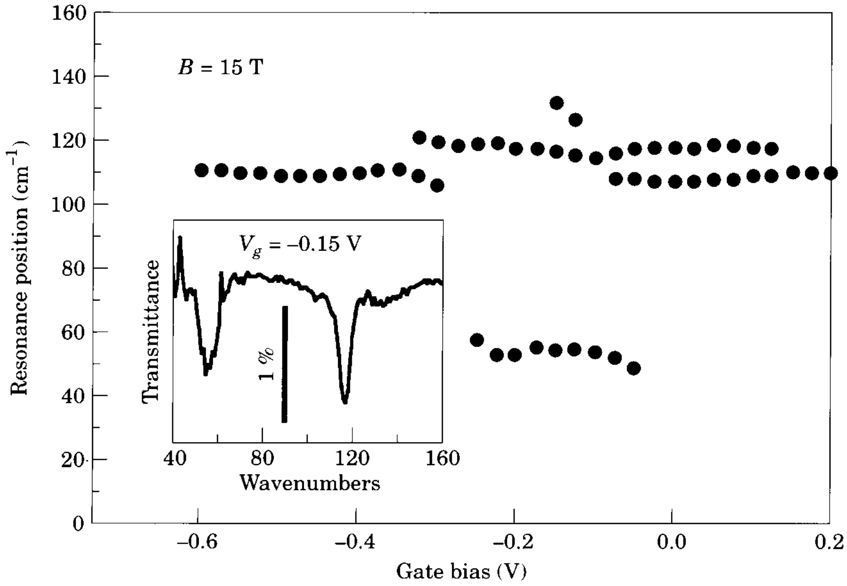

Fig. 3. By means of a strong magnetic field the anti symmetric ground state gets magnetically depopulated. Therefore at positive gate voltages only two resonances remain, whereas for $V_g < -0.25$ V the situation is the same as at $B = 0$. For slightly negative gate voltages a new resonance occurs (see inset) at about 55 cm^{-1} which is supposed to be the direct transition between the Δ_{SAS} splitted ground states.

energy to be roughly 3 meV as before, we may extract an Δ_{SAS} splitting in the order of 3.5 meV. Although this attempt is quite simple the value is in good agreement with the one obtained from our self consistent calculation for the relevant gate voltages.

In conclusion, we obtain well pronounced line splittings in the collective excitation spectra of our parabolic double quantum well. Self consistent calculations of the density dependent subband spectra show that the splittings reveal the resonant coupling scheme of the single particle states. The size of the level splittings obtained experimentally are in good agreement with our calculations in the single particle picture. Using a magnetic field to magnetically depopulate the anti symmetric ground state we adjust the Fermi level in between the Δ_{SAS}-split subbands and thus allow for direct transitions between these states.

Acknowledgements—We gratefully acknowledge fruitful discussions with A. Lorke and J. P. Kotthaus. This work has been financially supported in part by the Deutsche Forschungsgemeinschaft, in part by the Air Force Office of Scientific Research under grant AFOSR-91-0214, by the NSF Science and Technology Center for Quantized Electronic Structures (QUEST) DMR-91-20007, by the NSF DMR-90-02291, and the ONR N000-14-92-J1452. The Munich/Santa Barbara Co-operation has been supported by a joint NSF/European grant (EC-US 015:9826).

References

[1] A. Wixforth, M. Kaloudis, C. Rocke, K. Ensslin, M. Sundaram, J. H. English and A. C. Gossard, Semiconductor Science and Technology **9,** 215 (1994).
[2] L. Brey, N. F. Johnson and B. I. Halperin, Phys. Rev. B **40,** 10 647 (1989).
[3] N. Voldjdani, B. Vinter, V. Berger, E. Böckenhof and E. Costard, Appl. Phys. Lett. **59,** 555 (1991).
[4] W. P. Shen and M. L. Rustgi, J. Appl. Phys. **74,** 4006 (1993).

[5] E. Dupont, D. Delacourt and M. Papuchon, Appl. Phys. Lett. **63,** 2514 (1993).
[6] J. Faist, F. Capasso, A. L. Hutchinson, L. Pfeiffer and K. N. West, Phys. Rev. Lett., **71,** 3573 (1994).
[7] Yu. N. Soldatenko and F. T. Vasko, J. Appl. Phys. **77,** 4024 (1995).
[8] K. Leo, J. Shah, J. P. Gordon, T. C. Damen, D. A. B. Miller, C. W. Tu and J. E. Cunningham, Phys. Rev. B **42,** 7065 (1990).
[9] M. Zaluzny, Appl. Phys. Lett. **65,** 1817 (1994).