Confined acoustic and optical plasmons in double-layered quantum-wire arrays with strong tunneling

A. F. Dethlefsen,* Ch. Heyn, D. Heitmann, and C. Schüller[†]
Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Universität Hamburg, Jungiusstraße 11, 20355 Hamburg, Germany

(Received 29 September 2005; revised manuscript received 28 February 2006; published 16 May 2006)

We investigate electronic excitations in GaAs-$Al_xGa_{1-x}As$ double-layered quantum wire arrays with *strong* tunneling coupling by resonant inelastic light scattering. By applying an external electric field, we can change the one-dimensional (1D) electron density and the symmetry of the double quantum-well (DQW) structure at the same time. We identify confined optical 1D intersubband plasmons (COP) and confined acoustic 1D intersubband plasmons (CAP). Due to the tunneling coupling, the energies of the CAP exhibit a minimum for a symmetric DQW potential, whereas the energies of the COP are dominated by the total carrier density, and are nearly insensitive to the symmetry of the potential.

DOI: 10.1103/PhysRevB.73.193307 PACS number(s): 73.21.Hb, 78.30.Fs

Double-layered two-dimensional electron systems (2DES) with tunneling coupling have attracted considerable interest during the past decade, documented by quite a number of experimental (e.g., Refs. 1–4) and theoretical (e.g., Refs. 5–7) publications. These systems consist of a Coulomb-coupled double quantum well (DQW), separated by a tunneling barrier. By decreasing the width of the barrier, tunneling splits the single-particle levels in each quantum well and forms the well-known symmetric and antisymmetric levels that are delocalized over both wells. This system allows one to study many-body effects in dependence on the interplay between tunneling and Coulomb coupling. The narrower the barrier, the stronger is the tunneling coupling between the two 2DES. Resonant Raman scattering has proved to be a powerful tool to investigate electronic excitations of low-dimensional systems. In particular, the possibility to transfer a finite momentum, q, in the scattering process enables one to study the wave-vector dispersions of the observed electronic excitations. It is well known[8] that the longitudinal collective spectrum of a spatially separated, two-component two-dimensional plasma, coupled by Coulomb interaction, consists of two modes: The acoustic plasmon (AP), where the carriers in both layers oscillate out of phase parallel to the layers, and, the optical plasmon (OP) where both layers oscillate in phase. Recently it was shown theoretically[7] that in the case of tunneling coupling the excitation spectrum is more subtle. For a symmetric DQW potential, the energy of the *intraband* AP is close to zero and becomes finite if the DQW potential is *asymmetric*, whereas the intraband OP is nearly unaffected by the tunneling coupling. The existence of the low-energy intraband AP was subsequently proved by resonant Raman spectroscopy.[4] Now, the interesting question arises how the energies of these modes, which propagate as electron-density waves in the coupled 2DES, are altered if the DQW structure is patterned to quasi-one-dimensional quantum wires. In the direction perpendicular to the wires we should expect a quantization of the intraband OP as well as of the AP modes. In this work we report the experimental observation of such confined modes in quantum wires, which are tunneling coupled in the vertical direction, i.e., the growth direction of the DQW structure.

Up to now there are no measurements on double-layered one-dimensional electronic systems (1DES) with *strong* coupling. Demel *et al.*[9] observed plasmon modes in weakly coupled double-layered 1DES with far-infrared spectroscopy. Theories describing 1DES with weak coupling can be found, e.g., in Refs. 10–13. Until now there have been no theoretical publications concerning strong coupling in double-layered 1DES.

The investigated samples are modulation-doped GaAs-$Al_xGa_{1-x}As$ DQWs. They consist of two 15 nm wide GaAs quantum wells, separated by a 1 nm AlGaAs tunneling barrier. The AlGaAs barriers on both sides of the DQW are modulation doped using Si delta layers. In the top barrier layer, two delta-doping layers were grown, separated by a 28 nm AlGaAs and a 20 nm spacer layer from the upper GaAs well. In the lower barrier, one delta layer was grown, separated by a 41 nm spacer from the lower GaAs well. The asymmetric doping layers compensate the charges at the sample surface and provide an approximately symmetric DQW potential. For further reduction of the dimensionality, we have prepared quantum-wire structures by holographic lithography and deep-reactive-ion etching, i.e., etching all the way through the DQW structure. Figure 1(a) shows a scheme of the prepared sample. It consists of two different lateral areas; a 1DES and a 2DES which allows one the measurement of both systems at one sample by just moving the spot of the exciting laser. Wave-vector transfers can be realized by tilting the sample normal with respect to the directions of incoming and scattered light. In the case of wires, the wave vector q can be transferred, e.g., in y direction, perpendicular to the wires, or in x direction, parallel to the wires. A semitransparent titanium gate covers the sample surface in the wire area as well as in the DQW area.

In Fig. 1(b), the self-consistently calculated conduction band profile of an unpatterned, asymmetric DQW is shown in the z direction. The ground state is split into two levels, which become strictly symmetric and antisymmetric if the DQW would be symmetric. By applying an electrical field between the alloyed contacts of the 2DES and the gate, the electron density and the symmetry of the double-layered systems in the z direction can be controlled at the same time.

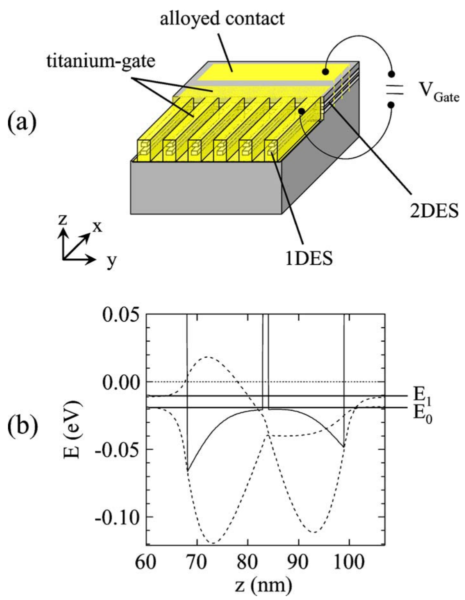

FIG. 1. (Color online) (a) Schematic picture of the investigated sample. (b) Conduction band profile (solid line) of an asymmetric DQW with the two lowest tunneling-split single-particle levels. The corresponding wave functions are indicated as dashed lines. E_0 denotes the energy of the symmetric and E_1 of the antisymmetric level. The Fermy energy (dotted line) is set to 0 eV.

Due to the asymmetry of the DQW in Fig. 1(b), the wave function of the lower level is located dominantly in the left and the wave function of the upper level in the right well.

The electron density of the 2DES can be varied between 5 and 9×10^{11} cm^{-2}. In the high density range, the two lowest tunneling-split subbands of the double-layered potential are occupied. By decreasing the density the occupation changes, which can be deduced from the energy variation of the 2D intersubband plasmon, which originates from intersubband transitions. The measurements of the 2D system are not shown here for brevity.

The period and geometrical wire width of the investigated sample are 700 and 250 nm, respectively. Due to lateral depletion, the *electronic* wire width is smaller. Comparing our wave-vector dependent measurements of confined OP modes (not shown here) with the hydrodynamical model of Eliasson *et al.*,[14] we deduce the effective electronic wire width a. For an applied gate voltage of −400 mV (+700 mV) we get $a=130$ nm ($a=150$ nm) and the one-dimensional density $N_{1D}=2.8\times10^6$ cm^{-1} ($N_{1D}=5.8\times10^6$ cm^{-1}) with $N_{1D}\simeq aN_{2D}$.

The Raman experiments were performed at $T=4.2$ K in a He exchange gas cryostat. For resonant excitation, a Ti:sapphire laser was used, which was tuned conveniently above the energy gap E_0 of the DQW system. The signals were analyzed in a triple Raman spectrometer equipped with a liquid-nitrogen-cooled charge-coupled device camera.

Figure 2 shows a series of measured Raman spectra of electronic excitations in a double quantum-wire sample with 250 nm geometrical wire width. The left (right) figure shows spectra in polarized (depolarized) configuration, i.e., the polarization of the incoming and scattered light are parallel (perpendicular) to each other. The external electric field is varied from 950 mV down to −200 mV in steps of 50 mV. In the experiments presented here, a wave vector $q=0.81\times10^5$ cm^{-1} was transferred perpendicular to the wire direction (y direction) to effectively induce electron motion in the direction of the lateral confinement. The energy of the incoming laser light was 1606 meV. It clearly can be seen that there are two different types of excitations. On the one hand, there are excitations that are shifting to lower energies with decreasing gate voltage (labeled COP); on the other hand there are excitations that are shifting first to lower and then to higher energies when the gate voltage is decreased (labeled CAP). We infer that the CAP are confined acoustic, and the COP are confined optical plasmons of the tunneling-coupled quantum wires (see discussion further below). Macroscopically, for our experimental geometry, the carriers are oscillating in both layers perpendicular to the wire direction. In the case of COP in phase in both layers, and out of phase in the case of CAP. Measurements on the wire sample, which were performed in plane wave geometry, i.e., transferring the wave vector parallel to the wires (x direction) support this interpretation: We observe modes, which can be identified as acoustic intrasubband plasmons and optical intrasubband plasmons by their wave-vector dispersions, which are linear in q and proportional to $\sqrt{q}$, respectively. The identification of the COP is also confirmed by comparing wave-vector-dependent measurements with the hydrodynamical model of Eliasson *et al.*[14], which are not shown here for brevity. Furthermore we did investigations of the 2D wafer. We observe 2D-intrasubband plasmons, which can also be clearly distinguished from 2D-intersubband plasmons, i.e., transitions across the tunneling gap, by their different linewidths. The former are smaller (~1 meV) than the latter (~4 meV) and comparable with the observed 1D confined excitations.

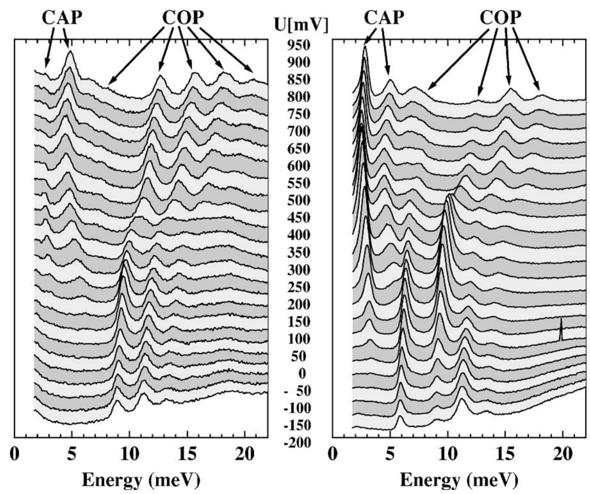

FIG. 2. Polarized (left) and depolarized (right) spectra of electronic excitations in a tunneling-coupled GaAs-AlGaAs quantum-wire array. The spectra are shifted against each other for clarity.

At the moment it is not clear, why the observed excitations in Fig. 1 do not show distinct polarization selection rules, as, e.g., reported for single-layered quantum wires.[15] There, charge density excitations should only be observable in polarized configuration if the wave vector was transferred

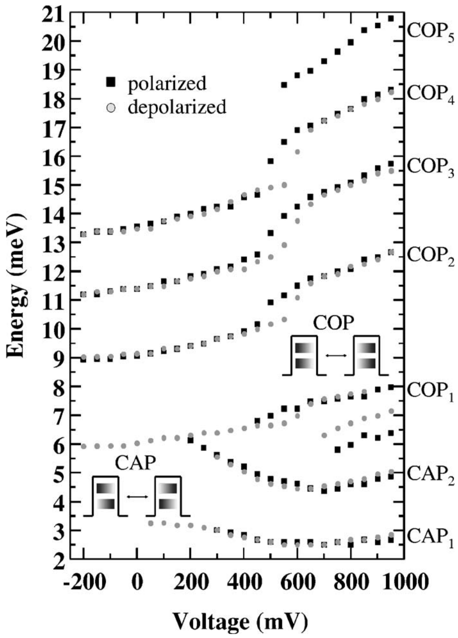

FIG. 3. Measured peak positions of the confined optical ($COP_{\Delta j}$) and acoustic ($CAP_{\Delta j}$) intersuband plasmons in a double-layered 1DES vs gate voltage. The insets show a scheme of the macroscopic density distribution for the first localized optical (upper) and acoustic (lower) intersubband plasmons.

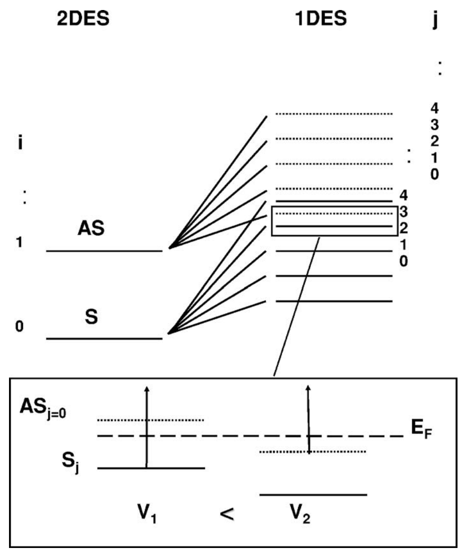

FIG. 4. Scheme of one-particle energy levels of double-layered 1D and 2D systems. The band dispersion of the levels is neglected. S and AS denote symmetric and antisymmetric levels, respectively. *i* means the 2D-subband and *j* the 1D-subband quantum number. E_F in the lower box is the Fermi energy. V_1 and V_2 are applied gate voltages with $V_1 < V_2$.

perpendicular to the wire direction. We think that in our case both resonant scattering and near-field effects within the wire array play an important role and need to be further investigated theoretically. We note that on the 2D wafer we observe no intrasubband spin-density excitations in depolarized geometry in the investigated gate voltage and laser energy ranges.

In Fig. 3, the measured excitation energies versus gate voltage are depicted. Black squares represent excitations, which are detected in polarized gray circles in depolarized configuration. The indices give the change, Δj, in the one-dimensional subband quantum number, j, for the transitions, which contribute predominantly to the observed excitations. The insets show a simple scheme of the macroscopic density distributions for the first localized optical (COP_1, upper scheme) and acoustic (CAP_1, lower scheme) intersubband plasmons in a double-layered quantum wire. The arrows indicate the two extreme situations, between which the system oscillates macroscopically. Calculations of density distributions in weakly coupled, double-layered 1DES had been performed by Steinebach *et al.*[16]

The striking feature observed here is the different behavior of optical modes in comparison to the acoustic modes. We will first concentrate on the characteristics of the excitation energies for both excitation types. Those can be explained in a simple macroscopic picture as follows: In the case of $COP_{\Delta j}$, the carriers in both 1D layers oscillate in phase perpendicular to the wire direction. The spatial separation of the electrons in both layers is essentially given by the tunneling barrier with a width of 1 nm. The higher the charge density of the wires, the larger is the Coulomb interaction. Therefore, the energies of the $COP_{\Delta j}$ increase with increasing charge density, i.e., with increasing gate voltage. The excitation energies are dominated by the total carrier density and are nearly insensitive to the variation of the double-well potential from symmetric to asymmetric and vice versa. The energies of the $CAP_{\Delta j}$ are lower in comparison to the optical excitations for the whole voltage range. In the extreme situations, sketched in the inset of Fig. 3, due to the out-of-phase oscillation, one part of the carrier density is located in one well on one side of the wire, while the other is located in the other well just on the opposite side of the wire. Therefore, generally, the Coulomb interaction is weaker for the acoustic modes than for the optical modes and, hence, the excitation energies are smaller. This effect approaches a maximum when the DQW potential is symmetric. Then, the effective charge displacement is just zero, since half of the density is moving to one side while the other half is moving in the opposite direction. In this case, we expect a minimum in the excitation energy, since the effect of the Coulomb interaction is minimal. This is observed experimentally in the excitation energies of the acoustic modes in Fig. 3. In this simple picture, however, one cannot explain why the minima for the CAP_1 and CAP_2 do not occur at exactly the same voltage.

In the case of the $COP_{\Delta j}$, furthermore, discontinuities are clearly observed in both polarization configurations at gate voltages between 450 and 650 mV. It seems that the strengths of these discontinuities increase with increasing excitation energies, and they might be also present for the $CAP_{\Delta j}$ but are not clearly resolvable, since their excitation energies are smaller. To discuss the discontinuities, Fig. 4 shows a scheme of 2D and 1D sublevels in a double-layered system. For simplicity, the horizontal lines should indicate the band edges of the subbands, and the band dispersions are neglected. On the left panel, the situation for a double-layered 2DES is depicted. The lowest sublevel is symmetric (S) followed by an antisymmetric (AS) sublevel, and so on. Due to the further reduction of the dimensionality of the electronic system in the case of the 1DES (right panel), each 2D sublevel splits into 1D sublevels (numbered by j). The box on the bottom of Fig. 4 shows a blowup of a special situation: At some gate voltage, the second 2D level starts to be filled with electrons. If in this situation the DQW potential is asymmetric, this would mean that the carrier density will be redistributed in the z direction [cf. wave functions in Fig. 1(b)]. This would, in turn, more or less abruptly change the self-consistent potential. We suggest that this charge redistribution is responsible for the observed discontinuities of the excitation energies, observed dominantly for the $\mathrm{COP}_{\Delta j}$ in Fig. 3. The total carrier density in the sample is certainly also influenced by the amount of photoexcited carriers due to the absorption of laser photons. Obviously, in quantum wires, the amount of absorption can depend on the relative orientation of the polarization of the photons with respect to the wire direction. Therefore, it seems reasonable that the absorption, and hence the total carrier density, might be slightly different for polarized and depolarized scattering geometries. We believe that this could be the reason why the discontinuities appear at slightly different gate voltages for depolarized and polarized geometries in Fig. 3.

In conclusion, we have observed confined optical and acoustic intersubband plasmons in double-layered quantum wires in the regime of strong tunneling coupling. By applying an external electric field, which influences, on the one hand, the 1D electron density and, on the other hand, the symmetry of the DQW structure, we could differentiate between the two excitation types by the variation of their energies with gate voltage.

We acknowledge valuable discussions with Can-Ming Hu. This work was supported by the Bundesministerium für Bildung und Forschung, and the Deutsche Forschungsgemeinschaft via SFB 508, and a Heisenberg Grant No. (SCHU1171/2).

*Present address: Institut für Festkörperphysik, Universität Hannover, 30167 Hannover, Germany.

†Present address: Institut für Experimentelle und Angewandte Physik, Universität Regensburg, 93040 Regensburg, Germany.

[1] R. Decca, A. Pinczuk, S. Das Sarma, B. S. Dennis, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **72**, 1506 (1994).

[2] V. Pellegrini, A. Pinczuk, B. S. Dennis, A. S. Plaut, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **78**, 310 (1997).

[3] S. Holland, C.-M. Hu, Ch. Heyn, and D. Heitmann, Phys. Rev. B **66**, 073305 (2002).

[4] M.-T. Bootsmann, C.-M. Hu, Ch. Heyn, D. Heitmann, and C. Schüller, Phys. Rev. B **67**, 121309(R) (2003).

[5] P. G. Bolcatto and C. R. Proetto, Phys. Rev. Lett. **85**, 1734 (2000).

[6] C.-M. Hu and D. Heitmann, Appl. Phys. Lett. **77**, 1475 (2000).

[7] C.-M. Hu, C. Schüller, and D. Heitmann, Phys. Rev. B **64**, 073303 (2001).

[8] S. Das Sarma and A. Madhukar, Phys. Rev. B **23**, 805 (1981).

[9] T. Demel, D. Heitmann, P. Grambow, and K. Ploog, Phys. Rev. B **38**, 12732 (1988).

[10] V. Shikin, T. Demel, and D. Heitmann, Phys. Rev. B **46**, 3971 (1992).

[11] Q. P. Li and S. Das Sarma, Phys. Rev. B **43**, 11768 (1991).

[12] C. Steinebach, D. Heitmann, and V. Gudmundsson, Phys. Rev. B **58**, 13944 (1998).

[13] F. Stern, Phys. Rev. Lett. **18**, 546 (1967).

[14] G. Eliasson, J.-W. Wu, P. Hawrylak, and J. J. Quinn, Solid State Commun. **60**, 41 (1986).

[15] C. Dahl, B. Jusserand, and B. Etienne, Phys. Rev. B **51**, 17211 (1995).

[16] C. Steinebach, D. Heitmann, and V. Gudmundsson, Phys. Rev. B **56**, 6742 (1997).