Anisotropic Plasmon Dispersion in a Lateral Quantum-Wire Superlattice

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Plasmon excitations for a lateral superlattice of quantum wires in a modulation-doped GaAs/(AlGa)As multiple-quantum-well system have been investigated by resonant inelastic light scattering. The Raman spectra exhibit a set of resonances with a strongly anisotropic dispersion. For momentum transfer parallel to the wires a significant dispersion is observed; perpendicular to the wires the dispersion is nearly flat. This is an experimental proof that the Coulomb interaction between neighboring wires is weak and the excitations represent confined plasmons of the individual wires. They provide a direct measure of the width of the electron channels.

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The quasi-zero- and quasi-one-dimensional behavior of electrons in semiconductor quantum dots and quantum wires is currently the subject of numerous experimental and theoretical studies. The lateral confinement quantizes the electronic motion in 0D and 1D subbands. The typical energy separation of 1D subbands in experimental GaAs wire samples is 1-2 meV.[1,2] It is usually determined from magnetic depopulation[3] and recently has also been determined by Raman spectroscopy.[4] In far-infrared (FIR) spectroscopy on quantum-wire samples,[5,6] it is found that the response is strongly governed by collective effects which give the observed resonances the character of local confined plasmons in a laterally bounded 2D electron gas (2DEG) in accordance with calculations.[7-9] So far, the experimental results have been interpreted in terms of excitations in an isolated wire, although the experiments are performed, for sensitivity reasons, on arrays of wires. Theory then predicts a Coulomb interaction between neighboring wires which leads to a dispersion with momentum perpendicular to the wire system.[7-10] Furthermore, propagation of plasmons parallel to the wires is expected, with a characteristic dependence of their energy on the momentum parallel to the wires.[8-11]. Neither dispersion is directly accessible in FIR spectroscopy. In inelastic light scattering, however, the dependence of plasmon excitations on size and direction of momentum transferred to the electron gas can be studied by varying the scattering geometry.[12] For the 2DEG, the accessible in-plane momentum range was considerably extended by the new techniques of micro-Raman spectroscopy[13] and grating-coupler-assisted Raman scattering. In the latter case the samples are microstructured by a metal grating[14] and an etched grating structure,[15] respectively, with the unperturbed layered 2D electron gas underneath. In this Letter we report on the first investigation of the plasmon dispersion in lateral quantum-wire superlattices by resonant Raman spectroscopy. We find a strong anisotropy of the plasmon dispersion for different directions of the momentum transfer with respect to the wire direction. We can experimentally demonstrate that for the excitation with momentum perpendicular to the wires the confinement predominates the plasmon energy as compared to the interwire interaction. We can uniquely assign the energetically higher plasmon modes as higher-order standing-wave plasmons in the wire with an increasing number of nodes. We determine for the first time the dispersion of confined plasmons parallel to the wires.

The starting point for the preparation of our quantum-wire sample is modulation-doped GaAs/(AlGa)As multiple-quantum-well structures. Five layers of thin (63 Å) GaAs quantum wells are separated by thick (490 Å) center-doped $Al_{0.35}Ga_{0.65}As$ barriers. The electron density determined from Shubnikov-de Haas oscillations is 7.2×10^{11} cm^{-2}, measured after illumination of the sample. Only the lowest 2D subband is occupied. An etch mask of photoresist stripes with a periodicity $a=8100$ Å was prepared by holographic lithography. The geometrical wire width is $w=4000$ Å. The anisotropic plasma etching process[2] used for the microstructuring gives rectangular profiles with an etch depth of about 6100 Å. A schematic view of the sample is given in Fig. 1. We expect a 1D subband spacing of 1-2 meV and fifteen occupied subbands from a comparison with similar samples prepared in the same way.[2]

The sample was mounted in a He continuous-flow cryostat. The Raman spectra were obtained using a dye laser at about 1.75 eV, in resonance with the transition from the first excited 2D heavy-hole subband to the first

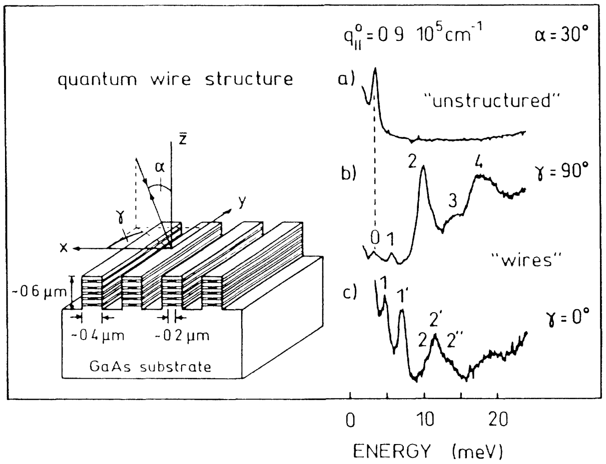

FIG. 1. A schematic view of the quantum-wire structure. Angles α and γ determine the scattering geometry. The right-hand side shows polarized Raman spectra for fixed angle of incidence $\alpha = 30°$ of the reference sample (a) and the wire-structured sample. The laser is tilted parallel (PW geometry, $\gamma = 90°$) and perpendicular (SW geometry, $\gamma = 0°$) to the wires in (b) and (c), respectively.

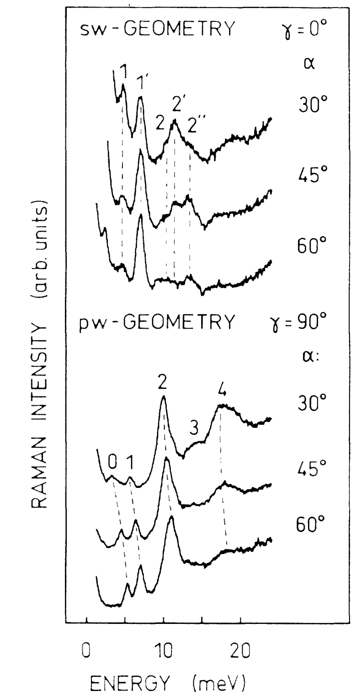

FIG. 2. Raman spectra of the quantum-wire sample for different angles of incidence α obtained in SW and PW geometries ($\gamma = 0°$ and $\gamma = 90°$, respectively). They show the strong anisotropy in the plasmon dispersion with respect to momentum direction relative to the wires.

excited 2D electron subband in the well. At this resonance no strong luminescence background exists. The experiments are performed in backscattering from the sample surface for different angles of incidence α. The in-plane and perpendicular components of the scattering wave vector determined by the scattering geometry are given by $q_{\parallel}^0(\alpha) = (4\pi/\lambda)\sin\alpha$ and $q_{\perp}^0 \approx 4\pi n/\lambda$, respectively. The orientation of the plane of incidence relative to the wires is fixed by the angle γ defined in Fig. 1. Figure 1 shows polarized Raman spectra for $\alpha = 30°$ of an unstructured reference sample and of the wire-structured sample. The reference sample exhibits only one single plasmon peak [Fig. 1(a)]. The plasmon modes for a five-layer 2DEG are given by five branches for each in-plane momentum value, which differ in their perpendicular momentum distribution. We observe the plasmon branch which allows for approximate conservation of the perpendicular momentum in the scattering process.[12] For the structured sample we have to distinguish the plane-wave (PW) geometry [Fig. 1(b)], where the laser is tilted parallel to the wires ($\gamma = 90°$), and the standing-wave (SW) geometry [Fig. 1(c)], where it is tilted perpendicular to the wires ($\gamma = 0°$). Both spectra show a series of peaks which are shifted with respect to the plasmon peak in the unstructured sample as well as with respect to each other.

Figure 2 shows Raman spectra for different angles of incidence obtained in both SW and PW geometries. While the relative intensities of the peaks change, no shift of the position is observed in SW geometry with increasing tilt angle α. On the other hand, the peaks shift to higher energies when α is increased in PW geometry. This shift is stronger for the low-energy excitations.

In Fig. 3 the dependence of the measured peak energies (represented by open symbols) on the geometrical scattering wave vector $q_{\parallel}^0$ is shown for the two geometries. In PW geometry the spectrum of plasmon modes and their dispersion exhibits all the features predicted by Eliasson *et al.*[8] several years ago for plasmons in a spatially periodic single-layer 2DEG. The lowest "acoustical" plasmon mode is, in principle, the first experimental demonstration of a 1D plasmon, which is characterized by logarithmic terms in the dispersion for very small values of $q_y w_e$,[8,11] where q_y is the momentum parallel to the wires and w_e is the width of the electron channels. The higher "optical" modes start at a finite energy for vanishing momentum parallel to the wires and show for increasing momentum a dispersion which is largest for the lowest mode and gets rather weak for the highest. Eliasson *et al.*[8] further found that the plasmon modes in a lateral superlattice of wires with a period-to-channel-width ratio of 5 broaden only in very narrow bands with a width of a few percent. This is confirmed by the almost flat dispersion we obtained in SW geometry for vanishing momentum parallel to the wires. Therefore we have experimental proof that Coulomb coupling between neighboring wires is very weak and we are allowed to discuss the observed plasmon modes in terms of excitations in an isolated wire. For a quantitative description the model of confined plasmons is used, which allows us

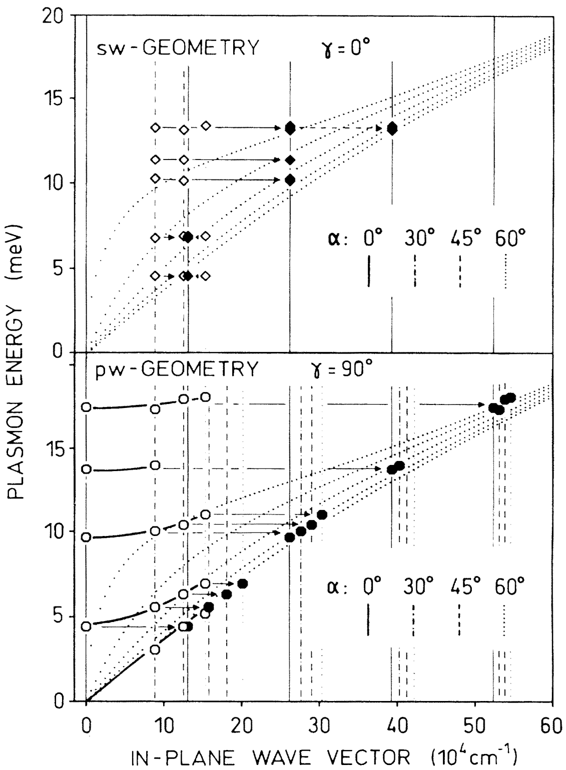

FIG. 3. Dependence of the observed plasmon excitations, represented by open symbols, on their momentum perpendicular ($\gamma=0°$) and parallel ($\gamma=90°$) to the wires. For PW geometry the open circles are connected by solid lines as guides to the eye to stress the characteristic dispersion of the plasmon modes. The observed resonances are assigned to confined plasmons (solid symbols) of a five-layer 2DEG: The dotted lines represent the 2D plasmon dispersion calculated for an electron density of 5.1×10^{11} cm^{-2}. The vertical lines mark the allowed quantized in-plane momenta. The arrows indicate the shift of the resonances from the in-plane momentum determined by the scattering geometry to quantized momenta where their energy coincides with the energy of a calculated plasmon branch.

to incorporate easily the layered structure of our wires neglected in the discussion so far.

We keep the plasmon dispersion of a layered 2DEG and impose standing-wave conditions for the plasmon in a direction perpendicular to the wires. Then the in-plane component of the plasmon perpendicular to the wires is restricted to integer multiples of π/w_e. The component parallel to the wires remains unrestricted. The plasmon peaks in Figs. 1 and 2 are labeled by the quantization index m. The scattering wave-vector component perpendicular to the electron-gas plane is smeared out inside the wire structure. Therefore we can excite simultaneously confined plasmons which originate from different 2D plasmon branches and may have different quantized momenta. Different branches of the layered 2DEG plasmon dispersion are distinguished by primes.

The assignment is based on the dispersion shown in Fig. 3. The dotted lines are the five plasmon branches calculated for an electron density of 5.1×10^{11} cm^{-2} using the standard random-phase-approximation model.[16] The electron density is determined from a fit to the measured plasmon dispersion of the unstructured sample. The discrepancy of about 2×10^{11} cm^{-2} compared to the density obtained from transport measurements is not fully understood but might be due to a real-space transfer of electrons to states in the (AlGa)As barrier due to the laser illumination. The allowed values of the in-plane momentum for the different angles α are given by

$$q_{\parallel} = m\pi/w_e \quad (m\neq0)$$

in SW geometry and

$$q_{\parallel} = \{(m\pi/w_e)^2 + [q_{\parallel}^0(\alpha)]^2\}^{1/2}$$

in PW geometry. These values are represented as vertical lines. The effective wire width w_e can be determined from the confined-plasmon peak labeled 1 in SW geometry. It is attributed to a confined plasmon with momentum perpendicular to the wire equal to π/w_e, which originates from the lowest plasmon branch of the layered 2DEG. From Fig. 3 we obtain a perpendicular momentum of 1.25×10^5 cm^{-1} which results in an effective wire width of 2500 Å. We use the slightly lower value $w_e \approx 2400$ Å which gives a very good agreement for all observed modes. In Fig. 3 all the measured peak positions (open symbols) with higher energy have been shifted to the quantized momenta where their energy coincides with the energy of a 2D plasmon branch (solid symbols). In PW geometry our assignment shows that we observe those confined plasmons arising from 2D plasmon branches which allow for approximate conservation of the momentum perpendicular to the electron-gas planes. Thus an almost perfect description of the dispersion is obtained in the confined-plasmon model. We do not observe the strong deviations predicted by Eliasson *et al.*,[8] who took into account from the start the lateral boundaries confining the 2DEG. This might be due to the multiple-layer structure of our sample.

In SW geometry we observe for $m=1$ two different branches and for $m=2$ three branches. The peak labeled 2″ in SW geometry also fits the $m=3$ mode, as indicated by the dashed arrow in Fig. 3. The peak identification becomes rather stringent if we follow the peaks while changing, for fixed tilt angle α, the orientation of the plane of incidence relative to the wires from perpendicular ($\gamma=0°$) to parallel ($\gamma=90°$). A continuous shift of the confined plasmons to higher energies is observed as they gain momentum parallel to the wire. At the same time the maximum intensity is gradually transferred from the highest to the lowest branch which is the only one observed in PW geometry. An explanation of this geometry-dependent scattering efficiency would require a detailed calculation of the electromagnetic light fields inside the wire.

The SW-geometry spectrum for $\alpha=60°$ in Fig. 2 shows an additional peak at about 2 meV, which is also present for $\alpha=45°$ although hard to detect due to the high laser stray light. The peak energy is close to the expected 1D subband spacing. Therefore it may be related to a weakly depolarization-shifted intersubband excitation, predicted by Que and Kircenow.[7]

Raman spectroscopy also offers the unique possibility to excite, in cross polarization of incident and scattered light (by spin-density fluctuations), intersubband transitions, which are found in 2D systems close to the one-particle energies.[12] The depolarized Raman spectra of our structured sample deviate substantially from the spectra of the unstructured sample. The single-particle-like spectrum extends up to 8 meV, far above the cutoff energy $\hbar q v_F$ (2 meV) of the 2D intrasubband single-particle excitation of our unstructured sample. In PW geometry it shows a two-step-like structure, which shifts slightly to higher energies with increasing angle α. These observations need further investigation and will be published elsewhere.

In conclusion, using inelastic light scattering we found a strongly anisotropic dispersion of plasmon excitations in a lateral wire superlattice. The nearly flat dispersion perpendicular to the wires indicates that the Coulomb coupling between neighboring wires is weak. This allows a quantitative description of the Raman spectra in terms of standing-wave plasmons perpendicular to the wires whose energies increase if the wave vector is rotated towards the parallel direction.

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