Tunneling-assisted acoustic-plasmon–quasiparticle excitation resonances in coupled quasi-one-dimensional electron gases

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We show that a weak nonresonant tunneling between two quantum wires leads to splitting of the acoustic plasmon mode at finite wave vector. Two gaps open up in the dipersion of the acoustic plasmon mode when its frequency is close to the frequencies of the quasiparticle excitations. In contrast to the Laudau damping of the collective excitations, these gaps are attributed to tunneling-assisted acoustic plasmon–quasiparticle excitation resonances. We predict that such a resonance can be observed in inelastic light scattering spectrum.

The plasmons of coupled low-dimensional electron gas systems provide a valuable platform to study the electronic many-body effects. In coupled double one-dimensional (1D) electron quantum wires, similarly to coupled two-dimensional electron systems,[1] optical and acoustic plasmon modes[2–4] were found. They were interpreted, respectively, as in-phase and out-of-phase oscillations of the electron charge density in the two wires. Theoretical studies[3–10] have been done on the plasmon dispersions, electron-electron correlation, far-infrared absorption, Coulomb drag, and tunneling effects in these systems. Correlation induced instability[8,9] of the collective modes were predicted in coupled low-density quantum wires. Experimentally, far-infrared spectroscopy and Raman scattering were used to detect the collective excitations.[2,11] Very recently, it was shown that a weak resonant tunneling in the coupled two 1D electron gases leads to a plasmon gap in the acoustic mode at zero wave vector.[3]

In this paper, we report a theoretical study of the effects of weak tunneling on the collective excitations in coupled quasi-1D electron gases. Tunneling between quantum wires can modify the collective behavior of the electron systems in several aspects. Interwire charge transfer and intersubband scattering become possible through the tunneling. As a consequence, new plasmon modes and coupling between different modes appear. On the other hand, intersubband interaction leads to intersubband quasiparticle excitations. We expect the tunneling will mainly affect the acoustic plasmon mode because its polarization field is localized in the space between the two wires where the tunneling occurs. Our numerical results of paramount importance show that a weak nonresonant tunneling between the wires produces two gaps in the acoustic plasmon mode at finite wave vector q. These gaps are attributed to the *tunneling-assisted acoustic plasmon–quasiparticle excitation resonances*. It means that, in contrast to the Landau damping of plasmon modes, a resonant scattering occurs between the collective plasmon excitation and the *intersubband quasiparticle excitation* through tunneling. Such a resonance leads to splitting of the acoustic plasmon mode around the quasiparticle excitation region and, consequently, a double-peak structure in the corresponding inelastic light-scattering spectrum.

We consider a two-dimensional system in the xy plane subjected to an additional confinement in the y direction, which forms two quantum wires parallel to each other in the x direction. The confinement potential in the y direction is taken to be of square well type of height V_b and widths W_1 and W_2 representing the first and the second wire, respectively. The potential barrier between the two wires is of width W_b. The subband energies E_n and the wave functions $\phi_n(y)$ are obtained from the numerical solution of the one-dimensional Schrödinger equation in the y direction. We restrict ourselves to the case where $n=1,2$ and define $\omega_0 = E_2 - E_1$ as being the gap between the two subbands. The interpretation of the index n depends on tunneling between the two wires. When there is no tunneling, n is wire index. On the opposite, when the wires are in resonant tunneling condition, n is subband index.

The dispersions of the plasmon modes are obtained by the poles of the density-density correlation function, or equivalently by the zeros of the determinant of the dielectric matrix $\det|\varepsilon(\omega,q)|=0$ within the random-phase approximation (RPA). The RPA has been proved a successful approximation in studying the collective charge excitations of Q1D electron gas by virtue of the vanishing of all vertex corrections to the 1D irreducible polarizability.[3] Figure 1 shows the plasmon dispersions of the coupled GaAs/$Al_{0.3}Ga_{0.7}As$ ($V_b = 228$ meV) quantum wires in (a) resonant tunneling and (b) nonresonant tunneling. The numerical results, with tunneling effects, of the in-phase (optical) ω_+ and out-of-phase (acoustic) ω_- modes are presented by the thin-solid and thick-solid curves, respectively. For a comparison, the in-phase (out-of-phase) plasmon modes without tunneling are plotted in the thin-dashed (thick-dashed) curves. In Fig. 1(a), we observe that, in resonant tunneling, the out-of-phase mode losses its acoustic characteristic at small q replaced by two intersubband modes. In Fig. 1(b), for the two wires out of resonant tunneling, we find that 99.4% of the electrons in the lowest (second) subband are localized in the wide (narrow) quantum wire. In other words, each quantum wire of the 1D electron gas only has a small edge in the other. However, such an edge affects significantly the acoustic plasmon mode. Two gaps open up around the intersubband quasiparticle excitation region.

The dynamical dielectric function is given by $\varepsilon_{nn',mm'}(\omega,q) = \delta_{nm}\delta_{n'm'} - V_{nn',mm'}(q)\Pi_{nn'}(q,\omega)$, where δ_{nm} is the Kronecker δ function, $V_{nn',mm'}(q)$ the bare electron-electron Coulomb interaction potential, and $\Pi_{nn'}(\omega,q)$ the 1D polarizability.[3,12] Within the RPA, $\Pi_{nn'}(\omega,q)$ is taken as the non-interacting irreducible polar-

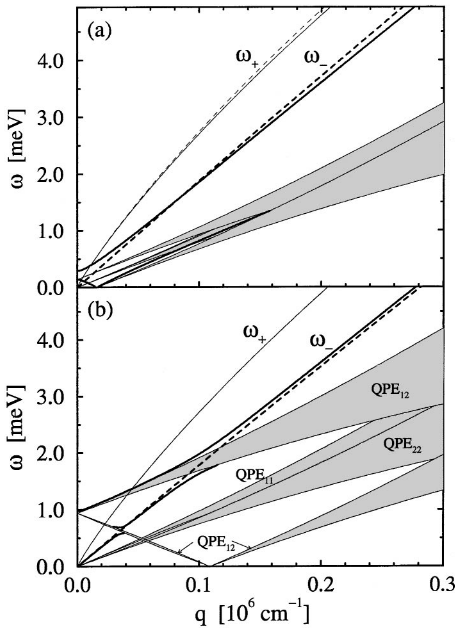

FIG. 1. Plasmon dispersions in two coupled GaAs/$Al_{0.3}Ga_{0.7}As$ ($V_b = 228$ meV) quantum wires separated by a barrier of width $W_b = 70$ Å of (a) $W_1 = W_2 = 150$ Å and (b) $W_1 = 150$ Å and $W_2 = 145$ Å. The total electron density $N_e = 10^6$ cm^{-1}. The solid (dash) curves present the plasmon dispersions with (without) tunneling. The thin and thick curves indicate the in-phase (ω_+) and out-of-phase (ω_-) plasmon modes, respectively. The shadow area presents the quasiparticle excitation regions $QPE_{nn'}$.

izability function for a clean system free from any impurity scattering. In the presence of impurity scattering, we use Mermin's formula[13] including the effect of level broadening through a phenomenological damping constant γ. The electron-electron interaction potential $V_{nn',mm'}(q)$ describes two-particle scattering events.[12,14] There are different scattering processes in the coupled quantum wires: (i) Intrawire (intrasubband) interactions $V_{11,11}(q) = V_A$, $V_{22,22}(q) = V_B$, and $V_{11,22}(q) = V_{22,11}(q) = V_C$ representing the scattering in which the electrons keep in their original wires (subbands); (ii) Interwire (intersubband) interactions $V_{12,12}(q) = V_{21,21}(q) = V_{12,21}(q) = V_{21,12}(q) = V_D$ representing the scattering in which both electrons change their wire (subband) indices; and (iii) Intra-interwire (subband) interactions $V_{11,12}(q) = V_{11,21}(q) = V_{12,11}(q) = V_{21,11}(q) = V_J$ and $V_{22,12}(q) = V_{22,21}(q) = V_{12,22}(q) = V_{21,22}(q) = V_H$ indicating the scattering in which only one of the electrons suffers the interwire (intersubband) transition. Notice that, when there is no tunneling, $V_D = V_H = V_J = 0$. Clearly, they are responsible for tunneling effects on the collective excitations.

When the tunneling is considered, the plasmon dispersions of two coupled quantum wires are determined by the equation,

$$F_1F_2 - [(1-V_A\Pi_{11})V_H^2\Pi_{22} + (1-V_B\Pi_{22})V_J^2\Pi_{11} - 2V_CV_JV_H\Pi_{11}\Pi_{22}](\Pi_{12}+\Pi_{21}) = 0, \tag{1}$$

where $F_1 = (1-V_A\Pi_{11})(1-V_B\Pi_{22}) - V_C^2\Pi_{11}\Pi_{22}$ and $F_2 = 1 - V_D(\Pi_{12}+\Pi_{21})$. This equation consists of two terms: F_1F_2 and the rest. We know that tunneling introduces the Coulomb scattering potential V_D, V_J, and V_H. However, for two symmetric quantum wires in resonant tunneling, V_J and V_H vanish and, consequently, the second term in Eq. (1) is zero. So, the plasmon modes are determined by equations $F_1 = 0$ and $F_2 = 0$. The latter carries the information of tunneling effects resulting in two out-of-phase (intersubband) modes as shown in Fig. 1(a). To reveal the relative importance of the different plasmon modes, we performed a numerical calculation of the oscillator strength defined by $\pi\{|\partial(\det|\varepsilon|)/\partial\omega|_{\omega=\omega_\pm}\}^{-1}$. It was found that the higher frequency out-of-phase plasmon mode is of finite oscillator strength at $q = 0$. But the lower one has a very small oscillator strength and is unimportant.[14]

When the two wires are out of resonant tunneling, the out-of-phase plasmon mode changes dramatically at small q as shown in Fig. 1(b). It restores the acoustic behavior at $q \to 0$ but develops two gaps at finite q. The splitting of the acoustic plasmon mode occurs when its frequency is close to the frequencies of the *intersubband* quasiparticle excitations QPE_{12}. In this case, the small overlap between the wave functions of the two subbands leads to V_A, V_B, and $V_C \gg V_D$, V_J and V_H. It means that the F_1 in Eq. (1) is now responsible for the main features of both the optical and acoustic plasmon modes. A numerical test indicates that the roots of the equation $F_1 = 0$ can almost recover the optical and acoustic plasmon dispersions of which tunneling is not considered. Whereas, the part F_2 relating to possible intersubband plasmon becomes less important. We also notice that V_D does not appear in the coupling term in Eq. (1). So, the potentials V_J and V_H are responsible for the splitting of the acoustic plasmon mode. These interactions represent the electron-electron scattering during which only one of them experiences intersubband transition. When the momentum and energy transfer between the two electrons occur in the region QPE_{12}, only this electron creates an intersubband electron-hole pair. From this point of view, the momentum and energy conservation in the scattering leads to such a transition getting rid of the Landau damping. In other words, the intra-intersubband scattering V_J and V_H produce a resonance between the collective excitation and the quasiparticle excitation. From another point of view, the scattering V_J and V_H result in a net charge transfer between the wires. Thus, they produce a local electric field between the two wires and disturb the polarization field of the acoustic plasmon mode. The energy gaps in the acoustic plasmon mode are dependent

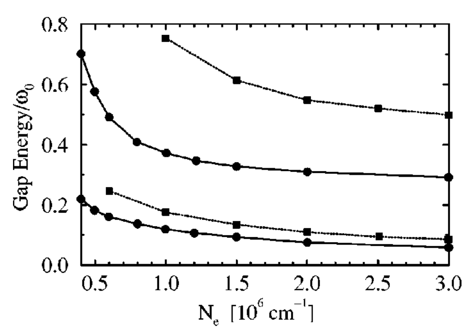

FIG. 2. The normalized gap energies as a function of the total electron density in the coupled GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wires of (a) $W_1 = 150$ Å, $W_2 = 145$ Å, and $W_b = 70$ Å (solid circles with $\omega_0 = 0.94$ meV); and (b) $W_1 = 150$ Å, $W_2 = 140$ Å, and $W_b = 50$ Å (solid squares with $\omega_0 = 2.01$ meV).

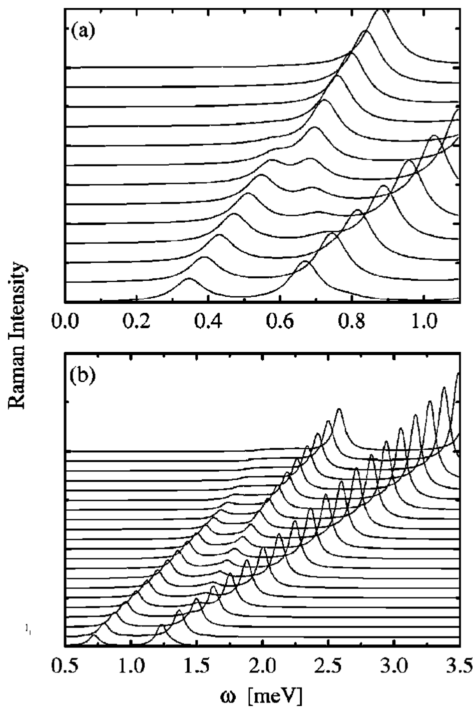

FIG. 3. Raman scattering spectra in the coupled quantum wires with $W_1=150$ Å, $W_2=145$ Å, and $W_b=70$ Å at different q: (a) from 2 to 5×10^4 cm^{-1} with equivalent difference $\Delta q=0.25\times10^4$ cm^{-1}, and (b) from 0.4 to 1.4×10^5 cm^{-1} with $\Delta q=0.05\times10^5$ cm^{-1}. $N_e=10^6$ cm^{-1} and $\gamma=0.05$ meV. The intensity in (a) is enlarged 4 times as compared to (b). The different curves are offset for clarity.

on the electron density and tunneling strength. We can define the gap as the frequency difference between the lower and upper branch of the split mode at the q where the unperturbed acoustic plasmon frequency is in the center of the quasiparticle excitation region. In Fig. 2, we show the electron density dependence of the two gaps normalized by ω_0 in different structures. The energies of the two gaps decrease with increasing the total electron density. One also sees that, for smaller barrier width, the plasmon gaps become larger.

The plasmon modes in the coupled quantum wires can be observed in the Raman spectroscopy. The intensity of the Raman scattering is proportional to the imaginary part of the screened density-density correlation function with a weight reflecting the coupling between the light and different plasmon modes.[14,15] Figure 3 shows the calculated Raman spectra due to the plasmon scattering of the corresponding modes in Fig. 1(b) around (a) the lower and (b) the higher energy gap. In the calculation, we took the damping constant $\gamma=0.05$ meV corresponding to a sample with electron mobility in order of 5×10^5 cm^2/Vs. We see a strong Raman scattering peak at high frequencies due to the optical plasmons.

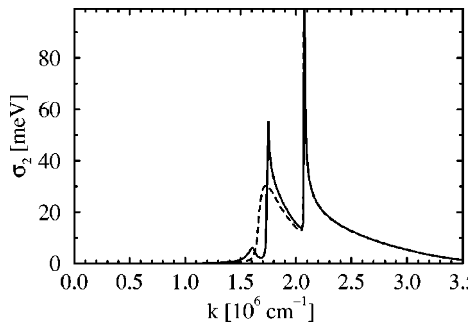

FIG. 4. Inelastic Coulomb scattering rate $\sigma_n(k)$ in the narrower one ($n=2$) of the coupled quantum wires corresponding to Fig. 1(b). The solid and dashed curves present the results with and without tunneling, respectively.

Besides, there are two split peaks due to the acoustic plasmons. With increasing q, the spectral weight transfers from the lower to the higher frequency one.

Finally, we show the effects of the weak nonresonant tunneling on the inelastic Coulomb scattering rate $\sigma_n(k)$ of an injected electron in the wire n with momentum k. The inelastic Coulomb scattering rate was obtained by the imaginary part of the electron self-energy within the GW approximation.[14,16] In Fig. 4, we plot $\sigma_n(k)$ of an electron in the narrower quantum wire ($n=2$) of the coupled wire system corresponding to Fig. 1(b). When the tunneling is not included, the lower and higher scattering peaks are resulted from the emission of the acoustic and optical plasmons, respectively. The weak tunneling influences its k-dependent behavior and leads to a splitting of the lower scattering peak in $\sigma_2(k)$, corresponding to the splitting of the acoustic plasmon mode.

In summary, we have studied the effects of weak tunneling on the collective excitations in two coupled quantum wires. We show that a weak nonresonant tunneling between the wires leads to the splitting of the acoustic plasmon mode. Two gaps open up in the dispersion of the acoustic plasmon mode. In contrast to the Landau-damping mechanism of the collective excitations, our result gives an evidence that the resonant coupling between the collective excitations and the quasiparticle excitations occurs in coupled quantum wires through tunneling. Furthermore, we predict that such a resonance can be observed in the inelastic light-scattering spectrum. Besides the optical plasmon scattering, a double peak structure appears around the quasiparticle excitation regime due to the split acoustic plasmon modes. The splitting of the acoustic plasmon mode also influences other electronic properties of the system, for instance, the Coulomb inelastic-scattering rate.

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