Tunneling Assisted Acoustic Plasmon-Quasiparticle Excitation Resonances in Coupled Q1D Electron Gases

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We show that a weak non-resonant tunneling between two quantum wires leads to splitting of the acoustic plasmon mode at finite wavevector. Two gaps open up in the dispersion of the acoustic plasmon mode when its frequency is close to the frequencies of the quasiparticle excitations. In contrast to the Landau 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, optical and acoustic plasmon modes 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 have been done on the plasmon dispersions, electron-electron correlation, far-infrared absorption, Coulomb drag, and tunneling effects in these systems. Correlation induced instability 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. 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 wavevector.

In this Letter, 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 non-resonant tunneling between the wires produces two gaps in the acoustic plasmon mode at finite wavevector $q$. 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 $V_0$ 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 $\det \left[ \varepsilon(\omega, q) \right] = 0$ 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. Fig. 1 shows the plasmon dispersions of the coupled GaAs/Al$_{0.33}$Ga$_{0.7}$As ($V_0 = 228$ meV) quantum wires in (a) resonant tunneling and (b) non-resonant tunneling. The numerical results, with tunneling effects, of the in-phase (optical) $\omega_+$ and out-of-phase (acoustic) $\omega_-$ 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

$$\varepsilon_{nn',mm'}(\omega, q) = \delta_{nm} \delta_{n'n'} - V_{nn',mm'}(q) \Pi_{nn'}(q, \omega),$$

where $\delta_{nm}$ is the Kronecker $\delta$ 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 polarizability function for a clean system free from any impurity scattering. In the presence of impurity scattering, we use Mermin’s formula [14] including the effect of level broadening through a phenomenological damping constant $\gamma$. The electron-electron interaction potential $V_{nn',mm'}(q)$ describes two-particle scattering events. [3,12] There are different scattering processes in the coupled quantum wires: (i) Intrawire (intersubband) 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) Intewire (intersubband) interactions $V_{12,12}(q) = V_{21,21}(q) = V_{22,21}(q) = V_{21,12}(q) = V_D$ representing the scattering in which both electrons change their wire (subband) indices; and (iii) Intrawire (subband) interactions $V_{11,12}(q) = V_{21,21}(q) = V_{12,11}(q) = V_{21,11}(q) = V_J$ and $V_{22,22}(q) = V_{22,21}(q) = V_{12,22}(q) = V_H$ 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,

$$F_1 F_2 = [(1 - V_A \Pi_{11}) V_D^2 \Pi_{22} + (1 - V_B \Pi_{22}) V_J^2 \Pi_{11} -$$

$$2V_C V_J V_H \Pi_{11} \Pi_{22} (\Pi_{12} + \Pi_{21})] = 0,$$  \(1\)

where $F_1 = (1 - V_A \Pi_{11}) (1 - V_B \Pi_{22}) - V_J^2 \Pi_{11} \Pi_{22}$ and $F_2 = 1 - V_D (\Pi_{12} + \Pi_{21})$. This equation consists of two terms: $F_1 F_2$ 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 $
abla (|\det (\varepsilon) / \omega |_{\omega = \omega_p})^{-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. [4]

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 wavefunctions 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 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 $\omega_0$ 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. Fig. 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 $\gamma = 0.05 \text{ meV}$ corresponding to a sample with electron mobility in order of $5 \times 10^5 \text{ cm}^2/\text{Vs}$. We see a strong Raman scattering peak at high frequencies due to the optical plasmons. 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 non-resonant 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. 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 non-resonant tunneling between the wires leads to the splitting of the optical 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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[1] D. S. Kainth, D. Richards, H. P. Hughes, M. Y. Simmons, and D. A. Ritchie, Phys. Rev. B. 57, R2065 (1998); S. Das Sarma and E. H. Hwang, Phys. Rev. Lett. 81, 4216 (1998); and references therein.

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