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Selective damping of plasmons in coupled two-dimensional systems by Coulomb drag

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The Coulomb drag is a many-body effect observed in proximized low-dimensional systems. It appears as emergence of voltage in one of them upon passage of bias current in another. The magnitude of drag voltage can be strongly affected by exchange of plasmonic excitations between the layers; however, the reverse effect of Coulomb drag on properties of plasmons has not been studied. Here, we study the plasmon spectra and damping in parallel two-dimensional systems in the presence of Coulomb drag. We find that Coulomb drag leads to selective damping of one of the two fundamental plasma modes of a coupled bilayer (Fig. 1). For identical electron doping of both layers, the drag suppresses the acoustic plasma mode; while for symmetric electron-hole doping of the coupled pair, the drag suppresses the optical plasma mode. The selective damping can be observed both for propagating modes in extended bilayers and for localized plasmons in bilayers confined by source and drain contacts. The discussed effect may provide access to the strength of Coulomb interaction in $2d$ electron systems from various optical and microwave scattering experimnets.

In this paper, we show that Coulomb drag in double-layer resonators leads to the selective damping of plasmon modes in such a way that the damping rate stays finite at long wavelengths $q \to 0$. This contrasts to the viscous damping rate being roughly equal to νq^2, where ν is the kinematic viscosity. In other words, the effect of Coulomb drag damping is "more local" than the effect of viscous damping, though both effects appear already at the level of hydrodynamic equations applicable at relatively long wavelengths. We describe the electron kinetics with account for the Coulomb drag effect using the usual Drude-like theory with the presence of mutual friction between charge carriers in different layers of a two-layer structure [1–3]

$$\begin{aligned}
\frac{\partial \mathbf{v}_t}{\partial t} &= \frac{e\chi_t}{m}\mathbf{E}_t - \frac{\mathbf{v}_t}{\tau_p} - \frac{2n_b}{n_t+n_b}\frac{\mathbf{v}_t-\mathbf{v}_b}{\tau_D};\\
\frac{\partial \mathbf{v}_b}{\partial t} &= \frac{e\chi_b}{m}\mathbf{E}_b - \frac{\mathbf{v}_b}{\tau_p} - \frac{2n_t}{n_t+n_b}\frac{\mathbf{v}_b-\mathbf{v}_t}{\tau_D},
\end{aligned} \tag{1}$$

where indices t, b denote top and bottom layers, $\mathbf{v}_t, \mathbf{v}_b$ are to the drift velocities in the upper and lower layers respectively, n_t and n_b are the carrier densities, $e > 0$ is the elementary charge, $\chi = +1$ for p-doped layer and -1 for n-doped layer, m is the effective mass (assumed the same for both layers), τ_p is the effective momentum relaxation time. The last term of each equation represents the Coulomb drag, τ_D being the characteristic interlayer Coulomb scattering time. It acquires a particularly simple form for equal carrier densities in both layers $n_t = n_b$, and becomes simply $(\mathbf{v}_t - \mathbf{v}_b)/\tau_D$. It equalizes velocities in the different layers exponentially with time. For dissimilar electron densities $n_t \neq n_b$, the drag acceleration is strong for minority carriers and weak for majority ones. The particular form of density prefactors $n_{t/b}/(n_t+n_b)$ is consistent with total momentum conservation in the double layer the upon interlayer Coulomb scattering. Thus, we have shown that long-range Coulomb interactions affect the plasmon modes in multilayer systems by providing an additional damping mechanism. This influence is local and, moreover, is most pronounced at low wave vectors and frequencies comparable with inverse drag time $\omega \lesssim \tau_D^{-1}$. The lowering of quality factor crucially depends on the doping type of the layers and may be totally absent for modes and doping types such that drift velocities of charge carriers in two layers are co-directional. We stress that the predicted effect cannot be predicted from macroscopic electrodynamics calculations, where the current density in 2DES is proportional to its conductivity. Indeed, within such treatment, the layers with identical carrier densities and effective masses are electrodynamically indistinguishable.

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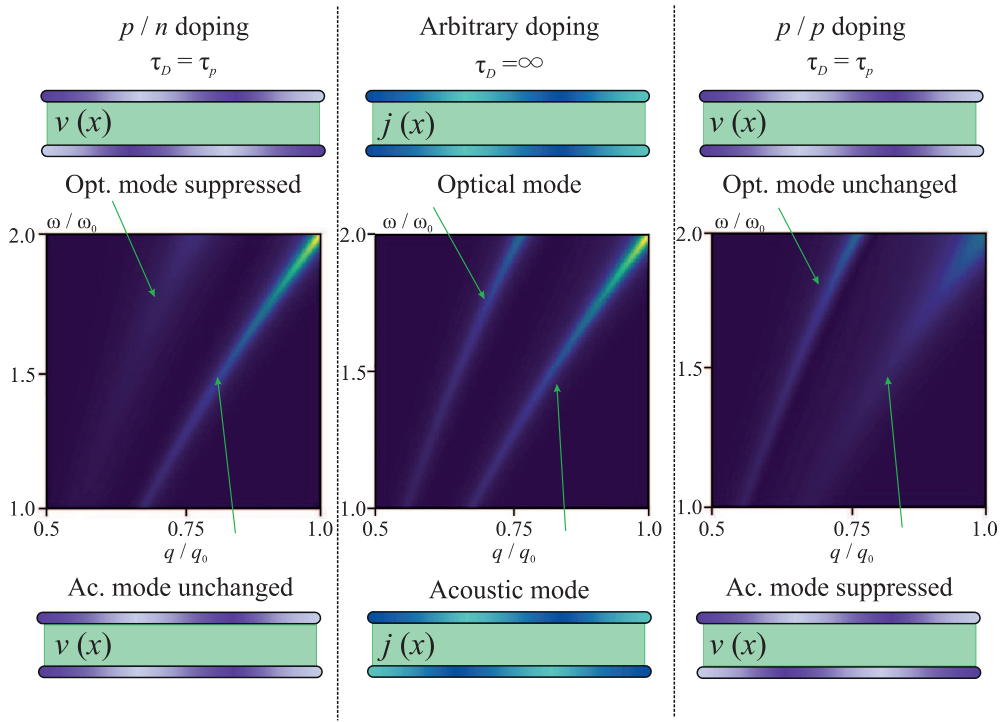

Fig. 1. (Color online) Selective influence of Coulomb drag on plasmon resonances in coupled 2DESs with equal conductivities. Central column: loss function and spatial distributions of current density for acoustic and optical modes in the absence of Coulomb drag. For the definition of the loss function, see Section II of the main text. Crucially, the current density distribution does not depend on the carrier type in neither of the 2DESs. Left column: Schematic spatial distributions of carrier velocity for acoustic and optical modes for p/n layer doping in the presence of Coulomb drag. The width of the acoustic mode is unaffected by the drag as its velocity distribution is symmetric, leading to no drag friction. The optical mode is suppressed due to asymmetric velocity distribution. Right column: the same as in the left column, but for p/p doping of the layers. Switching the carrier type in one of the layers switches the velocity distribution and allows to selectively attenuate either of the modes. Parameters of calculation: $q_0 = 2/d$, $\omega_0 = 7 \cdot 10^{13}$ rad/s, $\tau_p^{-1} = 3.5 \cdot 10^{12}$ s, $d = 2$ nm

The above discussion was based on hydrodynamic equations of motion for charge carriers in the two layers. It is generally accepted that such equations are applicable for wave frequencies ω below the carrier- carrier collision frequency within the layer τ_{ee}^{-1}. Yet, several recent exact solutions of the kinetic equation with model carrier-carrier collision integrals have shown that the applicability of hydrodynamics is much broader, though the coefficients of hydrodynamic equations can be renormalized. In the absence of magnetic fields, hydrodynamic formulation is possible provided $qv_0/|\omega+i/\tau_{ee}| \ll 1$ [4], while in finite magnetic fields the criterion is $qv_0/\omega_c \ll 1$, where ω_c is the cyclotron frequency [5–7].

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