Plasmons in tunnel-coupled graphene layers: backward waves with gain

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The discovery of van der Waals heterostructures comprised of graphene and monolayers of boron nitride (BN) and metal chalcogenides gave a second breath to graphene plasmonics. Infrared surface plasmons (SPs) in graphene encapsulated in BN demonstrate deep subwavelength confinement along with the elevated propagation distance to wavelength ratio [1]. In this report, we demonstrate that SPs in tunnel-coupled graphene layers possess also a number of unusual properties absent in the coupled layers of massive electrons [2].

The dispersion $\omega(q)$ and damping of acoustic SP mode is sensitive to the high-frequency non-local interlayer tunnel conductivity $G_{q\omega}$. Our calculation based on the density matrix formalism shows that $G_{q\omega}$ possesses singularities at $q^2v_0^2=(\hbar\omega-\Delta)^2$, where Δ is the energy spacing between the Dirac points in the neighboring layers. These singularities emerging in both real and imaginary parts of $G_{q\omega}$ can be interpreted as an enhanced tunneling between electron states with collinear momenta. Under application of bias voltage V between layers, $\mathrm{Re}\,G_{q\omega}$ is negative at frequencies $\omega<eV/\hbar$ due to the dominance of the tunneling transitions accompanied by the SP emission over those accompanied by absorption.

The character of acoustic SP dispersion and damping is illustrated in Fig. 1, where the plasmon spectral function is shown. The dispersion tends to 'evade' the regions of singular negative conductivity $q^2v_0^2\approx(\hbar\omega-\Delta)^2$, nevertheless, it is quite close to these singularities. As a result, the plasmons can get amplified instead of being damped, which is due to the large probability of electron tunnel transitions accompanied by the plasmon emission. At the same time, there emerges a part of SP spectrum with negative group velocity (backward wave) in the vicinity of the tunnel conductivity singularities.

The excitation of SPs upon resonant tunneling followed by their conversion into free-space modes might be responsible for the terahertz emission observed from the graphene-BN junctions [3]. With optimal selection of the barrier layer, not only the spontaneous plasmon emission, but also the coherent SP amplification can be achieved, which opens the possibility to create graphene-based spasers.

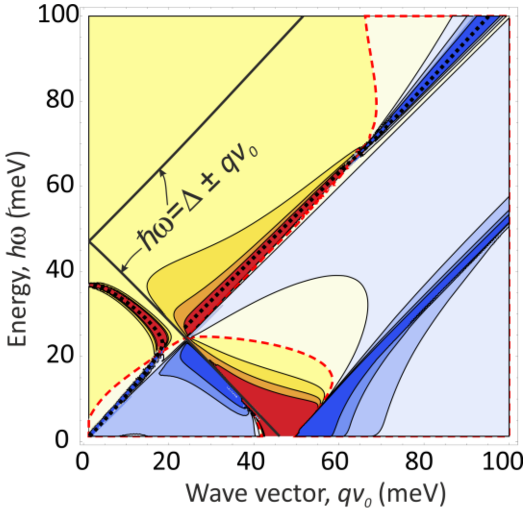

Figure 1. Spectral function of acoustic plasmons $\mathrm{Im}\,\varepsilon_{\mathrm{ac}}^{-1}(q,\omega)$ in the tunnel coupled graphene layers. Sharp peaks are the plasmon peaks. Black dashed line shows the plasmon dispersion in the absence of damping and gain. Red dashed line separates the regions of the net negative conductivity (warm colors) and net positive conductivity (cold colors). The dielectric is 3 nm WS$_2$, temperature T=77 K, $V=0.2$ V

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