Quantum-cascade photon gain in tunnel-coupled graphene layers

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The elastic resonant tunneling in graphene-insulator-graphene structures has recently attracted considerable attention of both experimentalists [1] and theorists [2]. The tunneling accompanied by photon emission in such structures is definitely less studied, though this effect can provide the operating principle of room-temperature terahertz (THz) quantum cascade lasers [3]. The possibility of THz optical gain in the waveguides with embedded tunnel-coupled graphene layers (GLs)was demonstrated in [3] for rotationally aligned layers and phenomenological values of electron scattering rate. In this report, we show that the THz gain can still exceed loss due to the Drude and interband photon absorption in slightly misoriented layers for the values of scattering rates limited by the acoustic phonons.

We have evaluated the probability of tunneling with the emission of coherent photon and the respective optical gain using the modified Fermi golden rule, where the electron scattering is taken into account by replacing the single-particle spectral functions by the Lorentz functions. The Lorentzian width is determined by the strength of electron-phonon scattering. For the perfectly aligned layers and in the absence of scattering, the frequency dependence of photon gain is delta-peaked at photon energy $\hbar\omega = \Delta$, where Δ is the energy spacing between Dirac points in GLs. For the rotationally misaligned layers, the gain is still singular at $\hbar\omega = \Delta \pm q_M v_0$, where q_M is the length of the vector connecting the two Dirac points in the adjacent layers. This singularity a square-root one, $g \propto [(q_M v_0)^2 - (\hbar\omega - \Delta)^2]^{-1/2}$; it appears as a result of enhanced tunneling between electron states with the collinear momenta [2].

At finite electron relaxation rate, the gain naturally becomes finite. We have numerically evaluated the photon gain in the dielectric waveguide structure with embedded GLs shown in Fig. 1A for the fundamental TM mode with frequency of 8 THz. The presence of a weak in-plane component of electric field E_{\Box} in the waveguide mode induces Drude and interband absorption in GLs, which competes with

the weak gain proportional to the tunneling probability. However, at least for misalignement angles below 0.5 degrees, the gain exceeds the loss even at room temperature. This justifies the idea of THz lasing using the realistic tunnel-coupled graphene structures.

References

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Figure 1. (A) Schematic view of the THz waveguide with embedded double graphene layer structure as gain medium. The distributions of vertical (left) and lateral (right) electric field are shown with color (B) Room-temperature spectra of photon gain and loss at different misalignement angles. The tunnel dielectric is 2.5 nm WS_2 , bias voltage V=0.2 V.