Plasmonic vs. electronic mechanism of the QED Kapitza Conductance for nanotube materials

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Recently the interface (Kapitza[1]) thermal conductance in nanocarbon materials has been explored experimentally[2,3] and theoretically[4-6]. It was understood that the near-field (aka QED) component of Kapitza conductance across the interface between a nanotube (NT) forest[4], or an individual NT[5,6] or graphene monolayer[7] and surface of quartz[4-7] or other substrate materials[8] is very significant.

Thermal conductance across the interface can be found as the ratio of the power of the heat flux, $\dot{Q}$, and the temperature difference, $\Delta T=T_c-T_s$, between the nanocarbon material and the substrate. The total thermal conductance is proportional to the interface area: L^d where d is the dimension of the interface area of a nanocarbon material. General expression for the specific thermal conductivity for graphene or NT, normalized to the contact area, has been obtained earlier:

$$\kappa = \frac{\dot{Q}}{L^d\,\Delta T} = \frac{f\,e^2}{\hbar}\left(\frac{\omega}{V_F}\right)^{d+1} D\left(\frac{z\,\omega}{V_F}\right)\,\Theta\left(\frac{\hbar\omega}{k_B\Delta T}\right)F\left(\frac{\mu}{\hbar\omega}\right)$$

where e, k_B and $\hbar$ are the elementary charge, Boltzmann and Planck constants, f is the oscillator strength for the surface EM mode of the substrate and ω is its frequency (if more than one surface mode contribute significantly to QED Kapitza conductance, a summation should be performed over the modes), $V_F \approx 8\,10^7$ cm/s is the Fermi velocity in nanocarbon material, μ is the chemical potential (relevant for graphene case, $d=2$, only), $\Theta(..)$ is the equilibrium thermal black-body distribution function. The functions $D(..)$ and $F(..)$ are calculated as Fermi integrals and give the dependencies of the QED Kapitza conductance on the distance between the nanocarbon and surface and on the chemical potential (graphene only).

This universal expression allows us to predict the magnitude of the QED component of Kapitza conductance for nanocarbon materials of different morphology and interacting with the surface modes of different substrates. However it was derived within the single-electron inelastic scattering theory and as such did not explicitly include the collective phenomena. Recently it was augmented by numerical analysis of the QED Kapitza conductance of the NT vertical forest[8] where a similar dependence of the conductance on the characteristic frequency of the surface modes was found for the series of materials (Fig. 1), including metals. In this Ref.[8] the NT plasmonic (collective) mode contribution was found to make the most important contribution to the QED heat.

Here we present analytical theory for the QED Kapitza conductance due to inelastic scattering of the plasmons by the surface EM modes. This plasmonic mechanism is compared to the single-electron scattering for the same substrate. The QED Kapitza conductance is very efficient for both mechanisms which allows one to propose nanocarbon thermal materials for thermal interconnect applications and thermal management solutions for all-carbon nanoelectronics[9,10].

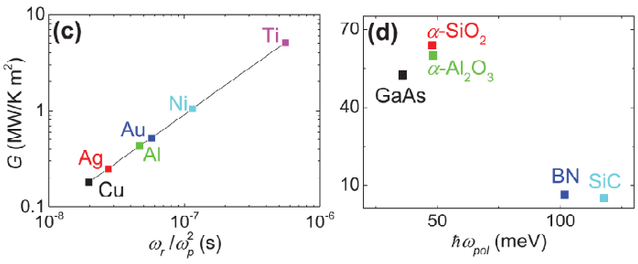

Figure 1. The plasmonic component of the QED Kapitza conductance between (15,0) NT vertical forest and different substrates at T=300K [8]. ω_r, ω_p, and ω_{pol} are electron relaxation, plasma and polariton frequencies in corresponding materials.

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