Electronic Cooling by 2D Acoustic Phonons in Graphene

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We have investigated the energy relaxation of hot electrons in metallic graphene by means of noise thermometry. For this purpose, we have carried out GHz noise measurements at high bias voltage V and liquid helium temperature in various diffusive samples. These include CVD grown samples on Si/SiO_2 substrate as well as graphene deposited on hexagonal boron nitride (hBN). Therein we measure the current noise spectral density S_I as a function of frequency in the range of f=0--0.8GHz, which we are able to convert to electronic temperature T_e. We observe T_e proportional to V and proportional to square root of V at low and high bias, respectively.
The first agrees with the electron-electron relaxation regime where heat conduction to the contacts is given by the Wiedemann-Franz law. The second corresponds to a T_e^4 dependence of the cooling power. It is the signature of a 2D acoustic phonon mechanism and the hallmark of layered conductors. In graphene, the observation of acoustic phonons is difficult due to their weak coupling and the strong effect of optical phonons.
The interpretation above is confirmed by a theoretical analysis of the electron to phonon cooling crossover using the heat equation with a $\Sigma^*T_e^4$ phonon term. By solving the heat equation, assuming perfectly cold phonons, we find the spatial temperature profiles with respect to the incoming Joule power V^2/R and the energy loss towards phonons, $\Sigma^*T_e^4$. Via integration, we then obtain the average electron temperature T_e as a function of applied bias V.
Comparing data and theory, we deduce the coupling constant Σ, [1] which is smaller than theoretical predictions for LA-phonons [2].
For further analysis we will finally discuss our results in terms of Fano factor $F=S_I/2eI$, a dimensionless quantity widely used to discuss electronic noise in mesoscopic physics. Here, I is the drain-source current. In general, the Fano factor will increase from 1/3 to $\sqrt{3}/4$, as a sign of electron-electron interactions, then decrease following a power law with increasing bias due to electron-phonon interactions.
Overall, these measurements give new insight into electronic cooling mechanisms in graphene and can be helpful in the development of graphene based devices, such as graphene electronic sensors.

References

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