Electroluminescent Hyperbolic Cooling of Graphene Field Effect Transistors

Emmanuel Baudin
Christophe Voisin, Bernard Plaçais

Laboratoire de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris

Emmanuel.baudin@phys.ens.fr

Heat management is critical for the performance of most modern electronic devices. It was recently proposed that radiative heat transfer - which is usually negligible in the solid state - could be increased in hyperbolic metamaterials, i.e., materials having a hyperbolic electromagnetic dispersion relation. [1] However, artificial metamaterials can be difficult to fabricate and integrate.

Fortunately, most of Van der Waals materials are natural hyperbolic metamaterials. Indeed, due to their anisotropic layered structure, the in-plane and out-of-plane optical phonon energy splitting results in a hyperbolic dispersion of light in the Resstrahlen bands. As a consequence, in these materials, the strong light-matter coupling can give rise to a 10^2-10^5 increase in the e.m. local density of states, resulting in a dramatic enhancement of the radiative heat transfer. Moreover, the radiative character of heat exchange results in a propagative heat transport via hyperbolic phonon-polariton (HPhP) modes on micrometric scales.

We have studied heat transfer in graphene on hexagonal boron nitride: a natural 2D hyperbolic material. In our devices, graphene is used as a versatile heat source in the near field of a hyperbolic material, and as a sensitive noise thermometer. [2] Using mono-, bi- and trilayer graphene, we demonstrate a strong increase of the electron gas cooling resulting in a large temperature drop when the emission of HPhP sets in. This process shares many analogies with electroluminescence, except that it involves near-field modes. We experimentally evidence that the case of graphene is unique, with cooling powers reaching few milliwatts per micron square [3], i.e., nine orders of magnitude larger than previously reported in the literature.

References

[1] S. Biehs, et al "Hyperbolic metamaterials as an analog of a blackbody in the near field." Phys. Rev. Lett. 109, 104301 (2012)

[2] W. Yang, et al "A Graphene Zener–Klein Transistor Cooled by a Hyperbolic Substrate." Nat. Nanotech. 13, 47 (2018)

[3] E. Baudin, et al "Hyperbolic Phonon Polariton Electroluminescence as an Electronic Cooling Pathway", Adv. Funct. Mat. 1904783 (2019)

Figures

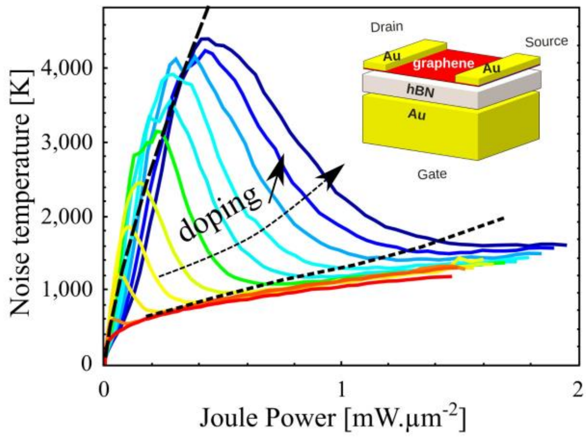

Figure 1: Electron gas temperature function of dissipated Joule power for various dopings. A surprising temperature drop occurs when electron interband tunneling starts.