Photocurrent Measurements of Supercollision Cooling in Graphene P-N Junction Devices

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Abstract:
We measure the hot electron cooling rate in graphene by using the photothermal effect to extract the temperature \( T(t) \) of a dynamically cooling electron gas near the Fermi level. We find the photothermal current \( I \) generated in a graphene \( p-n \) junction is well described by the energy dissipation rate \( \frac{dC}{dt} = -A(T^3 - T_b^3) \), where the heat capacity is \( C = \alpha T \) and \( T_b \) is the base lattice temperature. These results are in disagreement with predictions of electron-phonon emission in a disorder-free graphene system, but in excellent quantitative agreement with recent predictions of a disorder-enhanced supercollision (SC) cooling mechanism. With this new electron cooling mechanism established, we can accurately determine the hot electron temperature in graphene and graphene devices.

Figure 1: Hot electron cooling in graphene. Left; Momentum conservation restricts cooling to low energy (< 4 meV) acoustic phonon emission. Right; The momentum restrictions in supercollision (SC) electron cooling is relaxed by the lattice disorder, enabling faster cooling by emission of higher energy acoustic phonons.

Summary of Research:
With uniform broad spectral coverage, fast response and high carrier mobility, graphene-based \( p-n \) junctions have the potential to be a defining optoelectronic material for next-generation photodetectors, bolometers and plasmonic devices [1]. Graphene is a gapless material, inherently making efficient photocurrent (PC) production challenging. The optimal PC production conditions require that (1) the electron escape time from the \( p-n \) junction is fast, (2) the hot electron cooling rate is slow, and (3) the electrons at the junction are hot relative to device temperature [2]. In this work we measure aspects of all three requirements, and establish a fundamental mechanism for hot electron cooling in graphene and graphene devices.

Graphene hot electron cooling by acoustic phonon emission has been predicted to be very slow, with timescales exceeding > 300 ps [3]. In Figure 1 (left) we illustrate how the energy-momentum relation of the acoustic phonons, restricts phonon emission energies to small energies \(< 4 \text{ meV}\). The slow cascade of acoustic phonons for energy dissipation creates a major cooling bottleneck. Alternatively, Song, et al., predicts that impurities and lattice recoil effectively relax the momentum conservation constraint, resulting in a more rapid energy relaxation; they call this process supercollision (SC) cooling (see Figure 1 (right)) [4]. Compared to the disorder-free acoustic model, the energy dissipated in a SC acoustic emission is many orders of magnitude larger, resulting in enhanced cooling efficiency with rates orders of magnitude faster (~ 1 – 10 ps) [4]. To date, however, this theory has not been tested.

To begin, we fabricated \( p-n \) junctions from large-grain graphene grown by the CVD method and obtained a device carrier mobility of ~ 8000 cm\(^2\)V\(^{-1}\)s\(^{-1}\) [5]. A tuneable back gate (BG) and top gate (TG) couple electrostatically to graphene, and define two \( p-n \) junctions where the PC production is maximal. We optically excite the graphene \( p-n \) junction region with 180 fs pulses produced by two independently-tuneable oscillators plus near-IR optical parametric oscillator (OPO).
The collected PC amplitude is plotted as the laser is raster-scanned over the p-n junction (see Figure 2). We collect the electrical current generated ($\Delta Q_{12}(t_d)$) from the graphene p-n junction as a function of laser-pulse delay time ($t_d$, see Figures 2 and 3). We then combine this time-resolved photocurrent with the photothermal effect to directly calculate the hot electron temperature at the graphene p-n junction.

Figure 3 plots time-resolved PC curves for different base lattice temperatures at constant incident laser photon flux of $1.1 \times 10^{14}$ photons/cm². Upon warming the lattice to room temperature, the amplitude of PC signal shrinks by a factor of ~3, and the kinetic decay exhibits a dramatic shift toward a rapidly decaying exponential function.

To compare with theory, we solve the SC model using our extracted cooling rate. With no adjustable parameters, the SC model accurately predicts in Figure 3 both the (i) amplitudes, and (ii) strongly varying functional decay observed for lattice temperatures ranging from 10 to 295 K. We conclude that the SC electron gas heat loss rate, $H_{sc} = A(T^3 - T_l^3)$ describes electron cooling in graphene over a wide range of electron (10-3000 K) and lattice (10-295 K) temperatures.

At low lattice temperatures, the associated hot electron cooling time in the SC model is given simply by $\tau_o = 1.8$ ns/$T_o$. These cooling times are much faster than those predicted by acoustic phonon emission but are in excellent agreement with disorder-assisted supercollision cooling. This work has broad implications for the use of graphene in terahertz plasmonic devices, photodetectors and bolometers.

References: