# Ultrafast and efficient photo-induced electron heating in graphene

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Graphene has many characteristics that make it a highly suitable material for optoelectronic applications, such as photodetection and light harvesting: a tunable carrier density, extremely broadband light absorption and an ultrafast photoresponse, amongst others. Here we assess the ability of graphene to perform high-speed and efficient photon-to-current conversion through photo-induced carrier heating and subsequent current generation through the photo-thermoelectric effect, driven by the hot carriers [1].

First, we discuss the ultrafast (sub-picosecond) energy relaxation process of primary photoexcited e-h pairs in intrinsically doped monolayer graphene [2], as this ultimately defines the carrier heating efficiency. We experimentally quantify the branching ratio between the two competing energy relaxation pathways – optical phonon emission vs. intraband carrier-carrier interaction. The latter process leads to carrier heating as photoexcited carriers transfer their energy to intrinsic carriers in the Fermi sea, which develop into a broader (hotter) distribution. Our ultrafast optical pump – terahertz probe measurements show that carrier-carrier interaction dominates the ultrafast energy relaxation process, when specific requirements concerning the fluence and the Fermi energy are met [3].

We furthermore study basic graphene-based photo-thermoelectric devices that give a photoresponse driven by hot carriers, where we are interested in two key questions: How fast can we create a photoresponse? And how efficient is carrier heating? Using scanning photocurrent microscopy we observe a hot-carrier photocurrent, when we shine light on the interface between monolayer and bilayer graphene [4] or the interface between graphene of different Fermi energies [1]. Employing an advanced ultrafast time-resolved photocurrent setup with an unprecedented time resolution of ~35 fs, we find that the photo-thermoelectric photovoltage in graphene is created with a time scale <50 fs, corresponding to THz speeds [5]. This ultrafast time scale suggests highly efficiency carrier heating through intraband carrier-carrier scattering.

To quantify the efficiency of carrier heating, we measure the energy-resolved photocurrent between 500 and 1500 nm. We observe that when we keep the absorbed power constant, while decreasing the number of incident photons (by decreasing the wavelength of the incident light), the photocurrent signal stays constant. This indicates that the additional energy of each absorbed photon is efficiently transferred to electron heat. Therefore we conclude that due to carrier-carrier scattering dominated ultrafast energy relaxation cascade, the photo-thermoelectric response of graphene devices is ultrafast and carrier heating is highly efficient.

These results show that graphene is a promising material for ultrafast, efficient, broadband extraction of light energy into photocurrent, enabling a new class of photo-thermoelectric applications.

## References

[1] N.M. Gabor et al. Science 334 (2011) 648
[2] K.J. Tielrooij et al. Nature Phys. 9 (2013) 248
[3] K.J. Tielrooij et al. Submitted (2014)
[4] X. Xu et al. Nano Lett. 10 (2010), 562
[5] K.J. Tielrooij et al. In preparation (2014)