Hot carriers in graphene

Preface

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Guest Editors

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Hot carrier effects are key issues in the operation of electronics and optoelectronic devices. They can also be regarded as an insightful probe of interactions in condensed matter. In this context they have been extensively investigated both in metals [1] and semiconductors [2]. Depending on the excitation energy, electron or hole relaxation mainly involves non-radiative electron–electron and electron-phonon collisions. Electron–electron interactions dominate at high energy and amount to redistribute the electrical or optical power within the electron gas and build up a hot carrier population. Electron-phonon intervenes on a longer time scale to equilibrate the electron and phonon bath temperatures and to cool the hot carriers. Both processes are highly sensitive to the nature of electronic excitations due to dispersion relation and dimensionality effects which constrain the available phase space for interactions.

The advent of graphene, a decade ago, has shed a new light in this field, offering genuine 2D materials where both electrons and phonons are ultimately confined at the atomic scale. Furthermore, the nature of the carriers is new: in monolayer graphene one deals with massless Dirac fermions characterized by a linear dispersion with a large Fermi velocity, whereas multilayer graphene supports low-mass carriers but still with a gapless spectrum. Furthermore graphene is ambipolar and widely tunable with an electron-hole symmetry inherited from the crystal structure. Dirac Fermion physics is served in graphene by robust material parameters providing large energy scales suitable for physical characterization and valuable for applications. Put together, these symmetry and material properties have promoted graphene as a remarkable platform for hot carrier physics, attracting large interest from both optics and transport communities.

Transport tools are appropriate to investigate, with enhanced energy resolution, the gradual building-up of a hot carrier population from a degenerate ground state. Probes are e.g. the conductance, the magneto-conductance or the current noise. At the other end of the energy spectrum, electrical heating can eventually be used to push the carrier temperature high enough to radiate light in the optical spectrum. It was soon realized that in graphene [3, 4] and carbon nanotubes [5–7], the electronic temperature can rise very high due to the combined effects of low dimensionality and weak acoustic phonon scattering. A broad temperature window is thus accessible to investigate the various phonon cooling mechanisms at work in graphene [8]; in particular the exotic regime of so-called 'supercollisions' could be predicted and observed in graphene [9–11]. The situation is different for electron–electron collisions which preserve the total electron gas momentum and therefore leave the electrical current unchanged. Transport alone is not a direct probe of these interactions and there is need for complementary optoelectronic characterizations.

Hot carrier effects are also at the heart of the opto-electronic properties of graphene with the particularity that photo-carriers are generally excited at high

energies, well above the Fermi level. The subsequent relaxation, which drives the working efficiency of opto-electronic devices, is here the realm of electron–electron interactions with efficient Auger scattering and carrier multiplication [12, 13] and of the electron-optical phonon interaction. In this respect, optical investigations of hot carriers in graphene are very complementary to transport studies that deal with lower energy excitations. As a consequence of the efficiency of the relaxation channels for higher excited states, the typical time-scales are usually sub-picosecond and are best investigated with ultra-fast time-resolved optical techniques, such as pump-probe spectroscopy [14] or angle-resolved photo-electron spectroscopy [15, 16].

On the applicative side, the hot carrier distribution subsequent to photo-excitation may be exploited in view of photo-detection [17–19] or energy harvesting in several schemes [20]. In all cases, the key is to get the most of the large electronic temperature increase (as a consequence of the extremely low thermal capacity of the 2D-electron gas) before the relaxation to the acoustical phonons takes over. This transient off-equilibrium distribution gives rise to several physical signatures such as photo-thermoelectric voltage [21, 30], black-body radiation [22] or even electronic population inversion [23] that can be measured either in the time-domain or in a steady-state regime.

Most of the relaxation processes involved here (either electron–electron or electron-phonon) are strongly constrained by specific conservation laws as a consequence of the linear electronic dispersion in graphene. In this respect, a general trend is to expend these studies to the case of bi-layer or few-layer graphene where the lift-off of some of these constrains may considerably modify the hot carrier effects. Here again, the possibility to effectively tune the Fermi level by gating the sample is extremely valuable to explore the energy (and thus density of states) dependence of the processes. These studies pave the way to original schemes for electrical modulation of the optical properties through the gate modulation of the relaxation bottlenecks.

In this special issue, we present a collection of papers that cover some exciting advances in the field of hot carriers in graphene, including a theoretical survey of electron cooling in graphene [24], the investigation hot carrier relaxation by magneto-transport [25], THz detection at low flux [26], population inversion and optical gain [27], the theory of Zener tunneling in graphene at high field [28], high energy electron relaxation studied by time-resolved photo-emission [29], hot carrier and photo-detection [30, 31].

Acknowledgments

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