Microscopic view on graphene-based photodetectors

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Abstract

The search for novel structures with new functionalities has brought atomically thin two-dimensional materials into the focus of current research. Graphene as the most prominent respresentative of this class of materials shows a wide range of exceptional optical and electronic properties suggesting technological application in novel optoelectronic devices including photoemitters and photodetectors.

In this work, we have investigated many-particle processes behind the photodetection in graphene. The theoretical approach is based on the density matrix formalism [1] providing microscopic access to optical excitation, Coulomb- and phonon-induced relaxation dynamics, and conversion of light into electrical current in the presence of an electrical field. The aim is to control relaxation pathways allowing us to find optimal experimentally accessible conditions to increase the efficiency of photodetection. Solving the graphene Bloch equations [1] – a coupled system of differential equations for the carrier and phonon occupation as well as for the microscopic polarization, we are able to track the way of electrons towards a quasi-equilibrium distribution under the influence of an electrical field. Figure 1(a) illustrates how an initial Fermi distribution (black dashed line) changes (i) due to the electrical field (red) resulting in a considerable shift in the momentum space and (ii) due to carrier-phonon (c-ph, orange) and carrier-carrier (c-c, purple) scattering counteracting the field-dependent shift and resulting in a spectrally broad quasi-equilibrium distribution close to the Dirac point.

The field-induced shift of the carrier occupation in the momentum space gives rise to the generation of a current. Figure 1(b) illustrates the effect of different many-particle processes on the temporal evolution of the current: The electrical field gives rise to an asymmetric carrier occupation accounting for a significant current (red line). It saturates after approx. 1 ps reflecting the maximum asymmetry in the carrier occupation. Carrier-phonon and carrier-carrier scattering introduce an electrical resistance reducing the current (orange and purple). Interestingly, carrier-carrier scattering accounts for a linear increase of the current due to the extremely efficient impact excitation (IE) generating additional carriers [2]. Switching off Auger channels including IE (dashed purple) demonstrates their crucial impact.

Having understood the elementary microscopic processes behind the generation of photocurrent, we can predict optimal conditions for highly efficient graphene-based photodetecting devices.

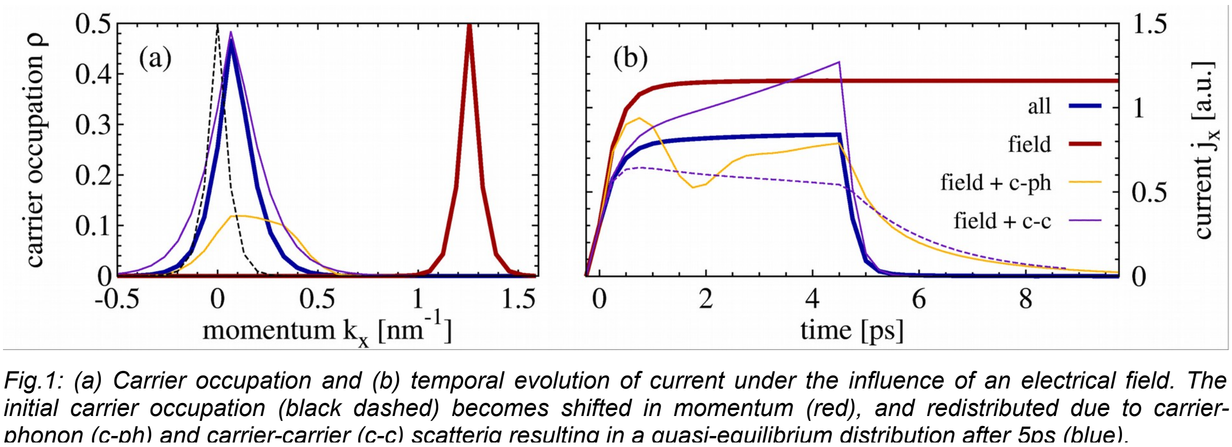

Fig.1: (a) Carrier occupation and (b) temporal evolution of current under the influence of an electrical field. The initial carrier occupation (black dashed) becomes shifted in momentum (red), and redistributed due to carrier-phonon (c-ph) and carrier-carrier (c-c) scatterig resulting in a quasi-equilibrium distribution after 5ps (blue).

References

[1] Ermin Malic, Andreas Knorr, Graphene and Carbon Nanotubes, Wiley-VCH (2013).
[2] F. Kadi, T. Winzer, A. Knorr, E. Malic, Sci. Rep. **5** (2015) 16841; T. Plötzing, T. Winzer, E. Malic et al., Nano Lett. **14** (2014) 5371; T. Winzer, A. Knorr, E. Malic, Nano Lett. **10** (2010) 4839.