Towards electrical control of graphene nonlinearity

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Abstract

This conference contribution explores the potential of graphene as a platform for THz nonlinear photonic applications. By applying DC electric fields or currents to break inversion symmetry, we aim to induce an effective second-order nonlinearity in graphene, enabling applications such as difference frequency generation and heterodyne detection. This study investigates the general feasibility and the achievable magnitude of electric-field induced nonlinearities in graphene.

Results

Because of its exceptionally high THz nonlinearity, graphene is currently discussed as a technological platform for a variety of THz nonlinear photonic applications ranging from saturable absorbers to THz frequency multipliers [1, 2]. Recently, it has been shown that (i) the nonlinearity of graphene can be controlled over two orders of magnitude by applying moderate gate voltages in the sub-Volt regime [3] and (ii) that a specifically designed grating-graphene meta-material enables further increase in the THz nonlinearity via field enhancement [4]. In these previous works, the focus was on studying nonlinearities of odd -orders, since monolayer graphene is a centrosymmetric material, where even-order susceptibilities cancel out. Next step is to investigate if an effective second order nonlinearity ($\chi(2)$) can be efficiently generated by applying appropriate in-plane DC electric fields or currents (V or I, see fig. 1 (b), thus breaking the inversion symmetry, such as what has recently been demonstrated and observed in GaAs [5]. We will quantify the achievable magnitude of electric-field induced second-order THz nonlinearity in graphene in order to elucidate its potential for nonlinear photonic applications relying on even-order susceptibilities, such as difference frequency generation. The derived results will directly allow us to evaluate the potential of graphene devices of this type as e.g. efficient mixers in heterodyne spectroscopy applications. Figures 1 (a) and (c) illustrate the introduced PCB design and grating-graphene assembly. Data from recently performed experiments with a newly developed table-top high-field THz emission spectroscopy set-up as well as from a beamtime at the high-field THz user facility TELBE [6] are presented.

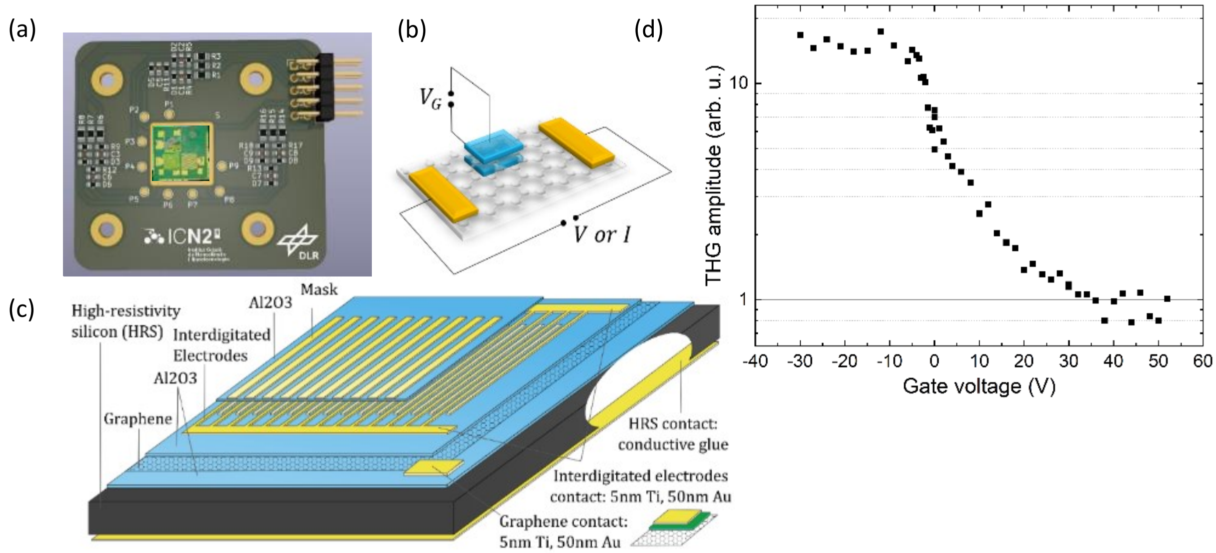

Figure 1: (a) Sample implemented in a printed circuit board (PCB) (b) Schematic of the gating V_G and in-plane electric field or current. (c) Architecture of the sample: Electrical contacts to graphene and the interdigitated electrodes are made with 5nm Ti and 50nm Au. Substrate, graphene, interdigitated electrodes and the mask layer are separated by a 150nm thin Al_2O_3-oxide layer. The back-gating functionality is provided by contacting of the silicon substrate to the PCB board. (d) Graphene's third harmonic amplitude response (measured by the integrated THG peak) to back gate tuning, demonstrating a significant change across a range of over one order of magnitude.

References

[1] H. A. Hafez, S. Kovalev, J.-C. Deinert, Z. Mics, B. Green, N. Awari, M. Chen, S. Germanskiy, U. Lehnert, J. Teichert, Z. Wang, K.-J. Tielrooij, Z. Liu, Z. Chen, A. Narita, K. Müllen, M. Bonn, M. Gensch, D. Turchinovich, “Extremely efficient terahertz high-harmonic generation in graphene by hot Dirac fermions”, Nature, 561 (7724):507-511 (2018).

[2] H. A. Hafez, S. Kovalev, K.-J. Tielrooij, M. Bonn, M. Gensch, D. Turchinovich, “Terahertz Nonlinear Optics of Graphene: From Saturable Absorption to High-Harmonics Generation”, Adv. Opt. Mat. 8, 1900771 (2020).

[3] Sergey Kovalev et al., “Electrical tunability of terahertz nonlinearity in graphene”.Sci. Adv. 7, eabf9809 (2021).

[4] J.-C. Deinert, D. A. Iranzo, R. Pérez, X. Jia, H. A. Hafez, I. Ilyakov, N. Awari, M. Chen, M. Bawatna, A. N. Ponomaryov, S. Germanskiy, M. Bonn, F. H.L. Koppens, D. Turchinovich, M. Gensch, S. Kovalev, and K.-J. Tielrooij, “Grating-Graphene Metamaterial as a Platform for Terahertz Nonlinear Photonics” ACS Nano 2021 15 (1), 1145-1154 ACS Nano 15, 1145 (2021).

[5] K. Lee, J. Park, B. J. Kang, W. T. Kim, H.-D. Kim, S. Baek, K. J. Ahn, B. Min, F. Rotermund, “Electrically Controllable Terahertz Second-Harmonic Generation in GaAs”, Adv. Opt. Mat. 8, 2000359 (2020).

[6] B. Green, S. Kovalev, V. Asgekar, *et al.* “High-Field High-Repetition-Rate Sources for the Coherent THz Control of Matter” Sci Rep 6, 22256 (2016)