Room-T detection of THz radiation in van der Waals heterostructures

Marco Polini[1,2]
[1]NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56126, Pisa (Italy)
[2]Istituto Italiano di Tecnologia, Graphene Labs, Via Morego 30, I-16163, Genova (Italy)

***Abstract*—In this talk I will discuss why van der Waals heterostructures comprising graphene and hexagonal boron nitride are an ideal platform to realize resonant detectors of THz radiation operating at room temperature.**

I. INTRODUCTION

A mechanism for detecting Terahertz (THz) radiation in a field-effect transistor (FET) geometry was proposed by Dyakonov and Shur in the '90s [1]. This mechanism relies on the excitation of plasma waves in a FET channel, where electrons behave like a classical fluid described by the laws of *hydrodynamics* [2]. Plasma wave interference generates a dc potential difference between the source and drain of the FET, which is proportional to the intensity of the ac oscillating field, which is fed to source and gate by an antenna. When a plasma wave launched at the source can reach the drain in a time shorter than the momentum relaxation time, the detection of radiation exploits constructive interference in the cavity. In this case one achieves frequency-resolved detection of the incoming radiation or the so-called "resonant regime". Broadband detection occurs when plasma waves are overdamped or when the length of the FET channel is larger than the length over which a plasma wave can travel.

Recently, it has been understood [3] that graphene can pave the way for the realization of robust and cheap THz detectors operating at room temperature and based on the Dyakonov-Shur scheme. Graphene, a two-dimensional (2D) crystal of carbon atoms packed in a honeycomb lattice, has indeed high carrier mobility, even at room temperature, a gapless spectrum, and a frequency-independent absorption, making it an ideal platform for a variety of applications in photonics, optoelectronics, and plasmonics. A detailed theory that highlights the peculiarities of Dyakonov-Shur detection arising from the pseudo-relativistic dispersion of the 2D massless Dirac fermion fluid in graphene has recently appeared in the literature [4].

Vicarelli *et al.* [3] have demonstrated room-temperature THz detectors based on antenna-coupled graphene FETs, which exploit the Dyakonov-Shur mechanism but display also contributions of photo-thermoelectric origin. The plasma waves excited by THz radiation in Ref. [3] are overdamped and the fabricated detectors, although enabling large area, fast imaging of macroscopic samples, do not yet operate in the aforementioned resonant regime. More recently, high-performance bilayer graphene FETs operating as broadband detectors have been also reported [5].

II. RESULTS

In this talk I will try and convince you that graphene sheets encapsulated between thin slabs of hexagonal boron nitride are a very promising platform to achieve resonant Dyakonov-Shur detection of THz radiation at room temperature.

Indeed, these van der Waals stacks host a unique electron system that due to ultra-weak electron-phonon scattering allows micrometer-scale ballistic transport even at room temperature [6,7,8,9] whereas local equilibrium in the system is provided by frequent electron-electron collisions [10]. Under these conditions, electrons in doped samples behave as a highly viscous liquid and exhibit hydrodynamic phenomena similar to classical liquids. In the first part of my talk, I will report on results of combined theoretical and experimental work [11] showing unambiguous evidence for this long-sought transport regime. In particular, graphene exhibits an anomalous (negative) voltage drop near current injection points, which is attributed to the formation of *whirlpools* in the electron flow. Measurements of these nearly local electrical signals enable to extract the value of the kinematic viscosity ν of the two-dimensional massless Dirac fermion liquid in graphene, which is found to be an order of magnitude larger than that of honey, in quantitative agreement with many-body theory [12].

In the second part of my talk, I will discuss plasmon propagation in identical devices. Graphene plasmons [13] were predicted to possess simultaneous ultra-strong field confinement and very low damping, enabling new classes of devices for deep-subwavelength metamaterials, single-photon nonlinearities, extraordinarily strong light–matter interactions and nano-optoelectronic switches. Although all of these great prospects require low damping, thus far strong plasmon damping has been observed, with both impurity scattering and many-body effects in graphene proposed as possible explanations. With the advent of van der Waals heterostructures [6,7,8,9], new methods have been developed to integrate graphene with other atomically flat materials. Near-field microscopy has been recently used [9] to image propagating plasmons in high-quality graphene sheets encapsulated between two films of hexagonal boron nitride. We have determined the dispersion and plasmon damping in real space, finding unprecedentedly low plasmon damping combined with strong field confinement and confirm the high uniformity of this plasmonic medium. The main damping channels are attributed [9,14] to intrinsic thermal phonons in the graphene and dielectric losses in the hexagonal boron nitride.

The observation and in-depth understanding of hydrodynamic flow and ultra-low plasmon damping in encapsulated graphene sheets [15] are the key to the development of Dyakonov-Shur resonant detectors of THz radiation.

REFERENCES

[1]. M.I. Dyakonov and M.S. Shur, Detection, mixing, and frequency multiplication of Terahertz radiation by two-dimensional electronic fluid, *IEEE Trans. Electron Devices*, vol. 43 1640, 1996.

[2]. L.D. Landau and E.M. Lifshitz, *Course of Theoretical Physics: Fluid Mechanics* (Pergamon, New York, 1987).
[3]. L. Vicarelli, M.S. Vitiello, D. Coquillat, A. Lombardo, A.C. Ferrari, W. Knap, M. Polini, V. Pellegrini, and A. Tredicucci, Graphene field-effect transistors as room-temperature terahertz detectors, *Nature Mater.*, vol. 11, 865, 2012.
[4]. A. Tomadin and M. Polini, Theory of the plasma-wave photoresponse of a gated graphene sheet, *Phys. Rev. B*, vol. 88, 205426, 2013.
[5]. D. Spirito, D. Coquillat, S.L. De Bonis, A. Lombardo, M. Bruna, A.C. Ferrari, V. Pellegrini, A. Tredicucci, W. Knap, and M.S. Vitiello, High performance bilayer-graphene terahertz detectors, *Appl. Phys. Lett.*, vol. 104, 06111, 2014.
[6]A.S. Mayorov *et al.*, Micrometer-scale ballistic transport in encapsulated graphene at room temperature, *Nano Lett.*, vol. 11, 2396, 2011.
[7]L. Wang *et al.*, One-dimensional electrical contact to a two-dimensional material, *Science*, vol. 342, 614, 2013.
[8]T. Taychatanapat *et al.*, Electrically tunable transverse magnetic focusing in graphene, *Nature Phys.*, vol. 9, 225, 2013.
[9]A. Woessner *et al.*, Highly confined low-loss plasmons in graphene–boron nitride heterostructures, *Nature Mater.*, vol. 14, 421, 2015.
[10] M. Polini and G. Vignale, *The quasiparticle lifetime in a doped graphene sheet*. In *No-nonsense physicist: an overview of Gabriele Giuliani's work and life* (eds. M. Polini, G. Vignale, V. Pellegrini, and J.K. Jain) (Edizioni della Normale, Pisa, 2015). Also available as arXiv:1404.5728.
[11] D. Bandurin *et al.*, Negative local resistance due to viscous electron backflow in graphene, to appear on arXiv soon.
[12] A. Principi, G. Vignale, M. Carrega, and M. Polini, Bulk and shear viscosities of the 2D electron liquid in a doped graphene sheet, *arXiv:1506.06030*.
[13] A.N. Grigorenko, M. Polini, and K.S. Novoselov, Graphene Plasmonics, *Nature Photon.*, vol. 6, 749, 2012.
[14] A. Principi, M. Carrega, M.B. Lundeberg, A. Woessner, F.H.L. Koppens, G. Vignale, and M. Polini, Plasmon losses due to electron-phonon scattering: the case of graphene encapsulated in hexagonal boron nitride, *Phys. Rev. B*, vol. 90, 165408, 2014.
[15] This work was done in collaboration with Iacopo Torre (NEST, Scuola Normale Superiore, Pisa, Italy), Andrea Tomadin (NEST, Istituto Nanoscienze-CNR, Pisa, Italy), Alessandro Principi (Radboud University Neijmegen, The Netherlands), Matteo Carrega (SPIN-CNR, Genova, Italy), Giovanni Vignale (University of Missouri-Columbia, USA), Achim Woessner (ICFO, Spain), Mark B. Lundeberg (ICFO, Spain), Frank H.L. Koppens (ICFO, Spain), Pablo Alonso-González (NanoGune, Spain), Rainer Hillenbrand (NanoGune, Spain), Yuanda Gao (Columbia University, USA), James Hone (Columbia University, USA), Denis Bandurin (The University of Manchester, UK), Roshan K. Kumar (The University of Manchester, UK), Moshe B. Shalom (The University of Manchester, UK), Leonid A. Ponomarenko (Lancaster University, UK), and Andre K. Geim (The University of Manchester, UK). Marco Polini's work on graphene plasmonics is kindly supported by the EC under the Graphene Flagship program (contract no. CNECT-ICT-604391) and by MIUR through the program "Progetti Premiali 2012" - Project "ABNANOTECH". Marco Polini wishes to thank the PE3 Panel Members of the ERC-2015-CoG call for NOT sponsoring his work on hydrodynamic flow in ultra-clean graphene sheets.