Graphene opto-electronics and plasmonics for infrared frequencies

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Abstract— Here, we present novel aspects of infrared photocurrent and plasmonics in graphene, with a focus on understanding the physical mechanisms of plasmon damping and infrared photovoltage creation [Badioli et al. 2014]. Both far-field and near-field microscopy as well as near-field and far-field photocurrent mapping are used to study the nanoscale interactions between infrared light, hot carriers and plasmon excitations. We report record-high optical field confinement while maintaing relatively high plasmon quality factors (>30) [Woessner et al. 2014].

I. INTRODUCTION

Graphene photonics [Bonaccorso et al., 2010], optoelectronics [Koppens et al. 2014, Ferrari et al., 2015] and nanophotonics [Koppens et al., 2011, Grigorenko et al., 2012] are fast growing fields with increasing attention for the mid- infrared (MIR) regime. This spectral region is interesting both from fundamental and technological points of view. For example, MIR covers the characteristic vibrational frequency range of many relevant molecules, as well as most of the thermal radiation emitted from warm objects. Therefore, the MIR range is crucial for spectroscopy and biosensing, and for thermal imaging in applications ranging from medical diagnostics to damage-assessment, and defence. Graphene is in particular a promising material for detecting MIR light because it provides additional features with respect to current technologies, such as broadband absorption for infrared and visible light, in-situ tunable doping, monolithic integration with silicon (CMOS) electronics, room temperature operation, and integration with flexible and transparent substrates.

In addition, graphene MIR physics is enriched by the fact that the energy scale of the photons is comparable to the Fermi energy, the energy of quasi-particle excitations such as plasmons [Koppens et al., 2011, Grigorenko et al., 2012], and the energy of intrinsic and substrate phonons. Pioneering works have already demonstrated bolometric [Freitag et al., 2013] or photoconductive [Yao et al., 2014] MIR detection, and a photo-thermoelectric photoresponse of graphene p-n junctions to 10.6 μm light has been studied [Herring et al., 2014], showing higher responsivity for the appropriate choice of substrate. In nano-patterned graphene, the bolometric photoresponse has been observed to be enhanced by the plasmon-phonon polariton supported by the substrate [Freitag et al., 2014]. Furthermore, photocurrents arising from photo-galvanic and photon drag effects under oblique incidence on large-area epitaxially grown graphene have been reported [Jiang et al., 2011].

Here, we study the physical mechanisms of plasmon damping and infrared photovoltage creation in graphene. We report record-high optical field confinement while maintaing relatively high plasmon quality factors (>30). In addition, we find a novel type of photovoltage generation mediated by substrate phonons and hot carriers in graphene.

II. RESULTS

Graphene plasmonics

Graphene plasmonics provides an excellent new platform for strong optical field confinement with relatively low damping. This enables new device classes for deep subwavelength metamaterials, single-photon nonlinearities, extraordinarily strong light-matter interactions and nano-optoelectronic switches.

The main problem thus far was that strong damping was observed [Fei et al., 2012, Chen et al. 2012]. Different reasons for the unexpected strong damping, such as many-body effects

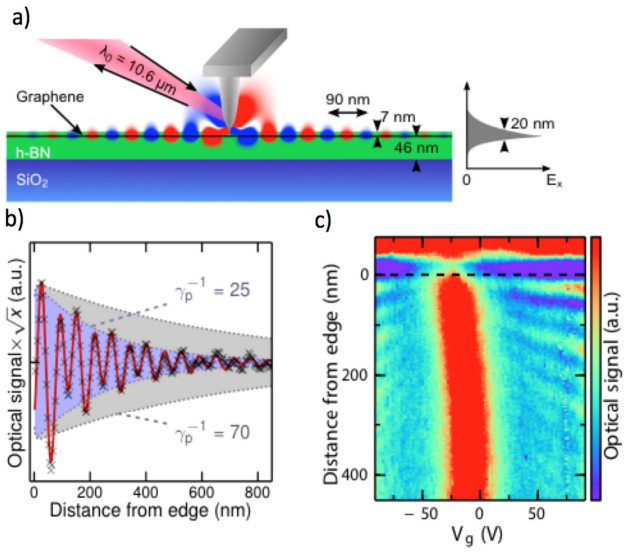

Figure 1 a) Illustration of the plasmon excitation and detection by light scattering of a metallized AFM tip (s-SNOM). b) Plasmon interference fringes near a graphene edge. c) Voltage tuning of the plasmon velocity

in graphene and impurity scattering, were proposed as possible explanations. This strong observed damping hindered the further development of graphene plasmonic devices.

Using van der Waals heterostructures new methods to integrate graphene with other atomically flat materials have become available. Graphene encapsulated between two films of hexagonal boron nitride (h-BN) is an example of such a heterostructure and shows extremely high room temperature transport mobility of charge carriers, only limited by the scattering with acoustic phonons in the graphene. It was expected that this high mobility also decreases the damping of plasmons in the graphene.

We present results where we image propagating plasmons in real space in such high quality graphene devices encapsulated between boron nitride by exploiting scattering-type scanning near-field optical microscopy (see Figure 1) [Woessner et al., 2014]. The frequency dispersion and particularly plasmon damping in real space is determined and we show that these high quality graphene samples show unprecedented low graphene plasmon damping combined with extremely strong field confinement. We identify the main damping channels to be intrinsic thermal phonons in the graphene as well as dielectric losses in the h-BN [Principe et al, 2014]. The low obtained damping as well as the theoretical understanding of the damping mechanisms are the key for the development of graphene nano-photonic and nano-optoelectronic devices.

The plasmon dispersion, which follows usually the typical $\omega \sim \sqrt{k}$ relation for two-dimensional electron gases, is strongly modified for h-BN encapsulated graphene due to the strong coupling of plasmons to the phonon modes of the h-BN. Interestingly, the hyperbolic character of h-BN gives rise to extraordinary phonon modes, which propagate like sub-diffraction rays with a well-defined propagation angle, depending on the frequency (see Figure 2). These phonon polaritons propagating in a thin hexagonal Boron Nitride (h-BN) slab, reveal some remarkable properties, including ultraslow group velocities and negative phase velocities.

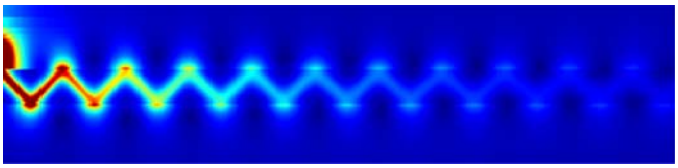

Figure 2: Phonon propagation in a 100-nm slab of h-BN, excited by a dipole (on the left side)

Infrared photodetection

In addition, we address the interactions between plasmons, phonons and hot electrons in graphene. In particular, hot electrons in graphene can generate a photovoltage due to the photothermoelectric effect (Seebeck effect) [Badioli et al. 2014]. We find different mechanisms of photocurrent generation in graphene on a polar substrate under excitation with MIR light. Understanding the role of the photocurrent generation mechanisms paves the way to the possibility of tailoring the magnitude and spatial extent of the graphene photoresponse.

A typical photocurrent spectrum is shown in Figure 3. We observe a clear peak at 1080 cm^{-1}, with a shoulder extending up to 1280 cm^{-1}. We find a correlation between the substrate absorption and the photocurrent spectrum, as they both peak at the TO phonon band. Therefore, we explain the relationship between the MIR light absorption in the SiO_2 and the photocurrent in the following way: after light absorption, heat is generated in the substrate, where it diffuses and equilibrates with the graphene, which generates locally hot carriers. As a consequence of the carrier temperature difference in the source and drain regions, a thermovoltage is generated, governed by the Seebeck coefficient of graphene. The large spatial extent of the photoresponse can thus be related to the temperature distribution in the substrate.

We note that this photo-thermoelectric mechanism is markedly different from the reported photo-thermoelectric response for VIS and NIR light in graphene or interfaces, such as p-n junctions or single-bilayer graphene. In those cases, the graphene carriers are directly excited by the laser and the temperature gradient is generated within or close to the laser spot.

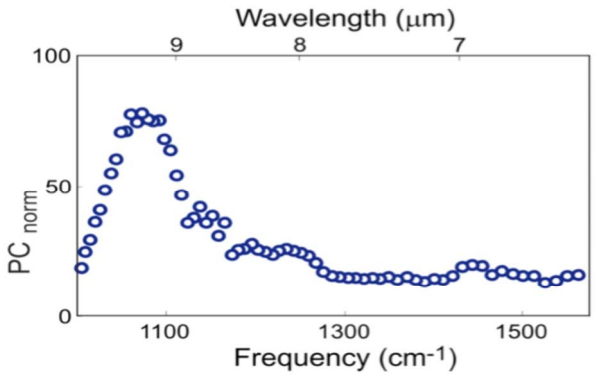

Figure 3: Photocurrent spectrum

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