Graphene doping inhomogeneities: plasmonic taper applications

G. Rosolen,[1] B. Maes,[1]

[1] Micro- and Nanophotonic Materials Group, Faculty of Science, University of Mons, 20, place du Parc, B-7000 Mons, Belgium

Combining plasmonics and graphene is a new promising application for optoelectronic circuits since graphene supports low-loss plasmons and is tunable via doping. Therefore, a study of these graphene plasmons with various doping profiles is proposed. We show that the reflection at abrupt doping interfaces is a simple function of the doping difference. Improved transmission is obtained with a tapered interface and an optimal size for the transition zone is found. Finally, localized inhomogeneities are considered. A Fabry-Perot cavity leading to an absorption above 60% is described and a 6nm length cavity achieving 100% absorption is proposed. These results may lead to novel optical switches or nano-sensors.

Introduction

Surface plasmons [1], the collective oscillations of electrons at the surface of a metal, couple with the electromagnetic field at the sub-wavelength scale. Combining plasmonics with graphene promises many technological applications since graphene supports low-loss plasmons and is tunable via doping [2, 3]. However graphene sheet samples are not always uniformly doped: grain boundaries are known for locally distorting the graphene doping [4, 5] and plasmons are then reflected depending on the doping profile.
In order to get a complete understanding of these graphene plasmons (GPs) under various doping conditions, we numerically investigate their transmission and reflection along multiple doping profiles. We demonstrate a simple doping difference dependence in the GP reflection at abrupt interfaces and we subsequently improve the transmission with a tapered doping interface. Finally, a cavity design is proposed and a critical 100% absorption is reached with an extremely small cavity only 6nm long.

Materials and method

In this work the two-dimensional simulations are performed with COMSOL Multiphysics, a commercial finite element based software package. Graphene is modelled as a thin layer of 0.3nm thickness and its optical parameters are defined via the relative permittivity (the tilde symbol depicting a complex number): $\widetilde{\varepsilon}(\omega, E_F) = 1 + i\widetilde{\sigma}(\omega, E_F)/(\varepsilon_0 \omega t)$, where t is the thickness of the graphene sheet, E_F the Fermi energy, ω the angular frequency and $\widetilde{\sigma}(\omega, E_F)$ the optical surface conductivity computed by the Kubo-Greenwood formula [6]. The scattering lifetime of electrons in graphene is fixed to $\tau_g = 1$ps. Note that the GPs are so confined that interactions with this ground plane are negligible, we thus suppose free-standing graphene in the simulations [3]. The plasmonic mode is excited along the sheet of graphene and propagates towards the doping profile i.e. the index change. We propose first an abrupt change of doping (Figure 1a), then we improve transmission with

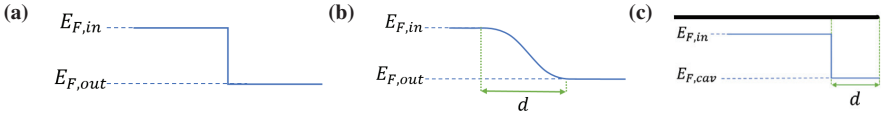

Figure 1: Doping configurations: (a) abrupt interface (b) tapered interface (c) a doping defect at the edge of a semi-infinite graphene sheet. The doping profile is represented beneath.

a tapered variation (Figure 1b) and finally we show a semi-infinite graphene sheet with a slight doping at its end to reach total absorption (Figure 1c).

Abrupt interface

Suppose a GP excited along a $E_{F,\mathrm{in}}$ doped graphene sheet that encounters an abrupt change of doping $E_{F,\mathrm{out}}$ i.e. a refractive index variation: the GP is reflected depending on the strength of the doping change. Simulated results are plotted by points in Figure 2a at $\lambda = 6\mu$m varying the incoming doping (legend) and the outgoing doping (abscissa).
First, one can check that same doping ($E_{F,\mathrm{in}} = E_{F,\mathrm{out}}$) gives zero reflection since there is no index change. Then bigger changes in the doping, implying greater changes in the refractive index, lead to larger reflections. It is coherent with a Fresnel approach that we develop below.
Since a propagating GP is defined by an effective refractive index $\widetilde{n}_{\mathrm{eff}}$, one can approximate it by a plane wave propagating in an effective medium with index $\widetilde{n}_{\mathrm{eff}}$. With the conductivity of graphene $\widetilde{\sigma}(\omega, E_F)$, the effective index of free-standing graphene is simply given by [2]

$$\widetilde{n}_{\mathrm{eff}} = \frac{1}{k_0}\sqrt{\frac{-4\omega^2\varepsilon_0^2}{\widetilde{\sigma}(\omega,E_F)^2} + k_0^2} \tag{1}$$

where k_0 is the wave number in vacuum. Taking in account this indexes in the Fresnel coefficient one finds [7]

$$T_{\mathrm{in,out}} = \left|\frac{2\widetilde{n}_{\mathrm{in}}}{\widetilde{n}_{\mathrm{in}} + \widetilde{n}_{\mathrm{out}}}\right|^2 \frac{n_{\mathrm{out}}}{n_{\mathrm{in}}} \tag{2}$$

$$R_{\mathrm{in,out}} = \left|\frac{\widetilde{n}_{\mathrm{in}} - \widetilde{n}_{\mathrm{out}}}{\widetilde{n}_{\mathrm{in}} + \widetilde{n}_{\mathrm{out}}}\right|^2 \tag{3}$$

where n_{in} and n_{out} are the real parts of $\widetilde{n}_{\mathrm{in}}$ and $\widetilde{n}_{\mathrm{out}}$, respectively. Results are plotted with lines in Figure 2a, closely following the simulated points except for high doping changes due to the limit of the plane wave propagation approximation.
We now rewrite Eq. 3 in function of the doping change. When $\hbar\omega \ll E_F \ll k_B T$ [6] (at $\lambda = 6\mu$m for example, $E_F \gg 0.3$eV), k_0^2 can be neglected in Eq. 1 and the graphene conductivity reduces to a Drude-like form linear to the doping level E_F [2]. In this approximation one finds the simplified reflection:

$$R \approx \left(\frac{E_{F,\mathrm{out}} - E_{F,\mathrm{in}}}{E_{F,\mathrm{out}} + E_{F,\mathrm{in}}}\right)^2 \tag{4}$$

which does not depend on the wavelength. The approximation is plotted in Figure 2a (grey line). It diverges for small doping as expected from the approximation validities.

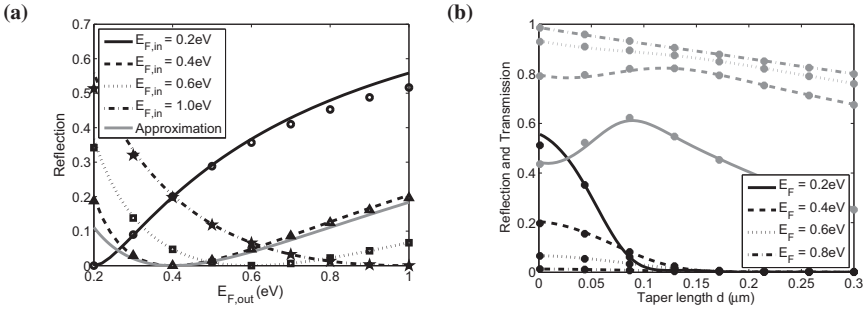

Figure 2: (a) Plot of the reflection of GPs at an abrupt interface of two different dopings. GPs propagate from $E_{F,\text{in}}$ to $E_{F,\text{out}}$. Points are simulated results and lines are computed with the Fresnel coefficient. The grey line stands for the approximate relation (Equation 4). (b) Plot of the reflection (black lines) and transmission (grey lines) of GPs with a smooth cosine-shaped transition of doping. GP propagates from 1eV to a range of smaller doping going from 0.2eV to 0.8eV. Points are simulated reflection and lines are from theoretical considerations.

Tapered interface

The previous section shows that abrupt changes in the doping level give a large reflection and a subsequently poor transmission. In order to improve it, we propose here a cosine shaped transition from incoming doping $E_{F,\text{in}}$ to outgoing doping $E_{F,\text{out}}$ (Figure 1b). The simulated points are represented in Figure 2b by points in function of the transition zone size d: grey stands for transmission and black for reflection. Here, $E_{F,\text{in}} = 1$eV and $E_{F,\text{out}}$ varies in the legend. The lines are computed from Fresnel coefficients discretizing the doping transition in a number of layers of different doping (implemented with the software module CAMFR). The model fits very well with the COMSOL simulation results, except for large doping changes, as observed in the previous section.
The main observation is the fall of the reflection down to nearly zero after a transition size of $d > 100$nm. Transmission, on the other hand, does not always increase since GPs are lossy and an optimum transition zone is found for $E_{F,\text{out}} = 0.2$eV. The best transmission is then obtained with a trade-off between a small transition zone leading to high reflection values and a large transition zone where GPs are absorbed while propagating.

Abrupt cavity

In this last section, we propose an ultra-thin perfect absorber. We design a highly doped ($E_{F,\text{in}} = 1$eV) semi-infinite graphene sheet and we slightly dope ($E_{F,\text{cav}} = 0.25$eV) a small zone d at its end as depicted in Figure 1c. We then vary the vacuum wavelength of the excitation from $\lambda = 3$ to 6μm and we compute the reflection of the GP. The results are plotted in Figure 3.
Figure 3 shows that a critical coupling of total absorption is reached for a particular wavelength $\lambda \approx 4\mu$m. It is explained by a Fresnel approach (destructive interference in reflection) considering that the plasmon is totally reflected at the end of a ribbon with a phase shift of $\varphi = -0.8\pi$ [8, 9]. Its curve is plotted in grey line and the small differences arise from the evanescent fields involved due to the small size of the cavity, which are not taken into account in the Fresnel model.

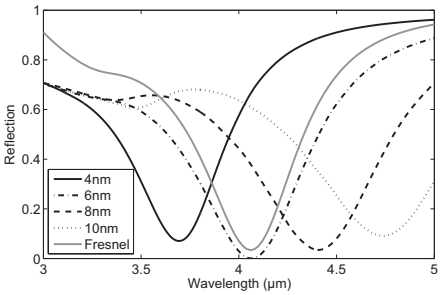

Figure 3: Plot of the reflection of GPs with a change of doping from $E_{F,\text{in}} = 1\text{eV}$ to $E_{F,\text{cav}} = 0.25\text{eV}$ at the end of a semi-infinite graphene sheet with length d indicated in the legend. Critical coupling is reached when the size of the smaller doping zone is 6nm. The grey curve stands for the Fresnel computed reflection.

Conclusion

This paper showed a brief overlook on the behaviour of graphene plasmons under various doping profiles. Abrupt changes demonstrated high reflection easily described by a function of the doping change, in contrast transmission was improved with a tapered transition. The taper size should be chosen by considering a trade-off between large reflection and high losses. Finally, we designed a 6nm long cavity supporting 100% absorption that may lead to novel nano-sensors and optical switches.

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