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Frequency Dependent Graphene Surface Plasmon Properties on Different Dielectrics

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Abstract*: *Numerical analysis of surface plasmon behaviour is performed on graphene surface supported on different dielectric medium and with varying graphene chemical potential. The dielectric medium of graphene is varied from free standing graphene to rigid SiO_2 wafer substrate to flexible PMMA polymer for diverse graphene plasmonics applications. The dispersion relation, propagation length and penetration depth of graphene surface plasmons are computed and analysed for the different dielectrics. The results show that graphene plasmonic behaviour in the various dielectrics highly depends on its chemical potential, the excitation input frequencies and produces surface plasmons with high field localization and low losses. This study of plasmonic behaviour on flexible dielectric opens up application of graphene plasmonics in the field of flexible optoelectronics.

Keywords*: *Graphene plasmonics, Chemical potential, dielectric medium, flexible dielectric.

I. INTRODUCTION

Surface plasmon polaritons (SPP) on metal-dielectric interface are interesting on account of their high field enhancement and localization [1]. Even though many different applications have been demonstrated [2-5], the high losses and absence of tunability, limits the applications for metal based plasmonics [6].

Graphene 2D material, which is known to possess good electrical, optical and mechanical properties [7-9], has recently, been shown to be a potential candidate for plasmonic applications [10]. The existence of plasmons in graphene in both TM and TE mode of electromagnetic field as well as their tunable nature makes graphene an important material for upcoming plasmonic applications [11], [12]. Since, the generation of surface plasmons is a combined effect of a negative and positive refractive index medium, the dielectric material used will also have a contributing effect [13]. Owing to the flexible nature of graphene [14], the behaviour of graphene plasmons on flexible dielectric substrates was a motivating factor in this study.

In this work, the graphene SPP behaviour is analysed as a function of different graphene doping and dielectric substrate medium such as flexible Poly (methyl methacrylate) (PMMA) polymer and rigid SiO_2 substrate. The dispersion relation, propagation length and penetration depth of graphene surface plasmon on different dielectric medium are numerically computed for varying permittivity of graphene in the THz frequency range.

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II. METHODOLOGY

An infinite single-layer graphene, placed on a different dielectric medium like air, PMMA polymer (n = 1.49) and SiO_2 (n = 2) substrate, is considered for the study of the Graphene surface plasmon polaritons (GSPP). The top medium is assumed to be air in all the three cases. The electronic model of graphene is defined by calculating dynamic conductivity of graphene from Kubo formula in terms of the frequency (ω), chemical potential (μ_c) and relaxation time (τ) [15]. This complex surface conductivity of graphene consists of both intraband and interband conductivities. The bulk conductivity of graphene is obtained as $\sigma_{(\omega,\, \mu c,\, \tau)}/\Delta$ where Δ the thickness of graphene is assumed to be 1 nm. Thus, the permittivity of 2D graphene is obtained as $\varepsilon_{gr}=1+i\sigma_{(\omega,\mu c,\tau)}/\omega\Delta\varepsilon_0$ [16], where ε_0 is free space permittivity.

The dispersion relation of GSPP on different dielectrics is calculated by $k_{sp} \approx i\varepsilon_0(\varepsilon_r+1)\ \omega/\sigma_{(\omega,\ \mu c,\ \tau)}$, where ε_r is the dielectric constant of the medium [17]. SPPs travel along the surface of graphene and decay in both perpendicular and horizontal directions. The propagation length and penetration depth are calculated by $\delta_{spp}=1/2Im[k_{sp}]$ and $\delta_i = \lambda_{spp}/2\pi$, respectively, and where λ_{spp} is SPP wavelength i.e. $2\pi/Re[k_{sp}]$[6].

III. RESULT AND DISCUSSIONS

A material is considered to be a plasmonic material, when the real part of dielectric constant is a negative quantity and the imaginary part of ε_r is very less than the negative real part, in order to accomplish low losses [18]. Figure 1 shows the variation in permittivity computed for freely suspended graphene as a function of THz frequencies with different doping level (μ_c = 0.2 and 0.6 eV). At lower frequencies, the real part of permittivity is < 0 and the imaginary part is lower in magnitude in comparison to the absolute magnitude of the real part of permittivity. This condition allows surface plasmons to propagate on graphene substrate. As the μ_c of graphene is changed from 0.2 to 0.6 eV, the frequency range at which the plasmonic conditions is satisfied is much higher viz. ~ 25 - 250 THz in comparison to the case of lower chemical potential of graphene i.e. ~ 25 - 75 THz.

This highlights that the graphene plasmonic behaviour depends strongly on its chemical potential and input excitation frequencies. When graphene is placed on a dielectric medium, the effective transverse permittivity is dependent on the relative permittivity of dielectric medium and the graphene permittivity as given by the relation $\varepsilon_{eff} = \varepsilon_r + i\sigma_{(\omega,\mu c,\tau)}/\omega\Delta\varepsilon_0$ [19].

The interaction of light with graphene surface is important to understand the propagating surface plasmon (SPP) and localized surface plasmon (LSP) on graphene.

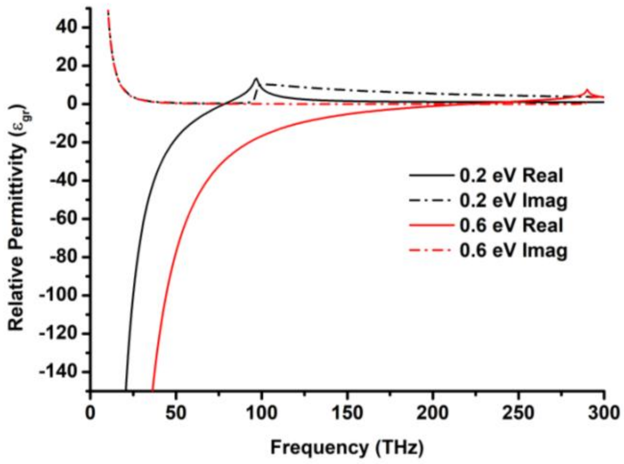

Fig. 1. Plot of variation of real and imaginary part of relative permittivity of graphene as a function input excitation frequencies for μ_c= 0.2 and 0.6 eV.

The dispersion relation of graphene plasmons on different dielectrics is shown in figure 2. In graphene, the region where the wave vector shows a nonlinear relationship with input frequencies corresponds to SPP and at higher frequencies the wave vector shows a saturation, which is related to the localization of surface plasmons.

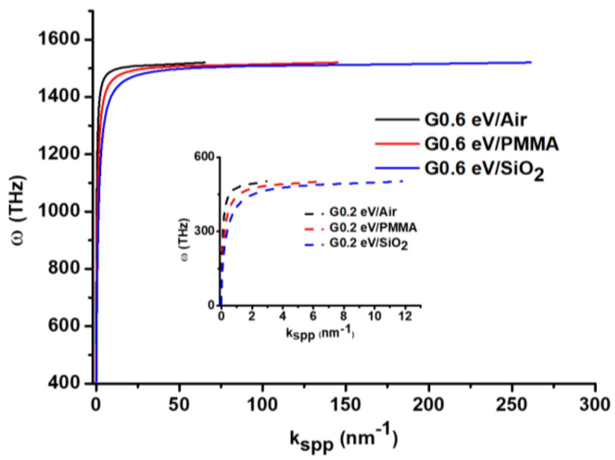

Fig. 2. Dispersion relation of graphene surface plasmons as a function of dielectric medium at μ_c = 0.6 eV. Inset shows the dispersion relation at μ_c = 0.2 eV.

In the nonlinear region, at a particular input excitation frequency, the GSPP wave vector shows an increase for a high refractive index dielectric. Inset in figure 2 shows the dispersion relation at lower chemical potential which points to lower surface plasmon frequencies. In the saturation region, the surface plasmon frequency ω_{SP} slightly reduces as refractive index increases. Hence, the dielectric property of medium and the chemical potential of graphene influences the frequency at which the SPP are generated as well as the confinement of surface plasmon in graphene.

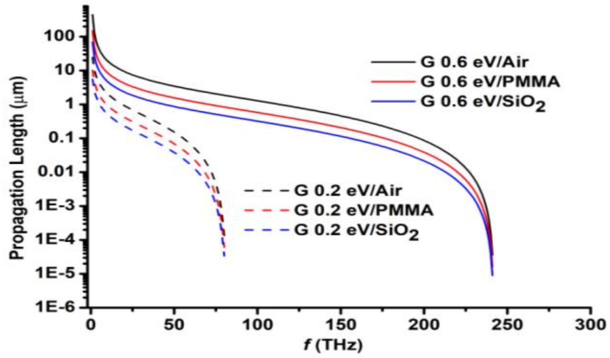

Fig. 3. Plot showing variation of graphene plasmon propagation length as a function of input frequencies for different dielectric mediums and chemical potentials (0.2 eV - dashed line; 0.6 eV - solid line).

It is important to study how the graphene surface plasmon decay in the longitudinal direction, parallel to the graphene surface. Hence, the propagation length of graphene surface plasmons was computed as a function of the input excitation frequencies. Figure 3 shows the propagation length of graphene surface plasmon on different dielectric medium with different graphene chemical potential. It is clear that the presence of dielectric medium and a change in chemical potential can greatly control the propagation length. As the chemical potential increases, the propagation length on graphene dielectric interface also increases. With increase in refractive index of the dielectric medium, the propagation length decreases. At higher input excitation frequencies, as SPPs become LSPs, the propagation length decreases.

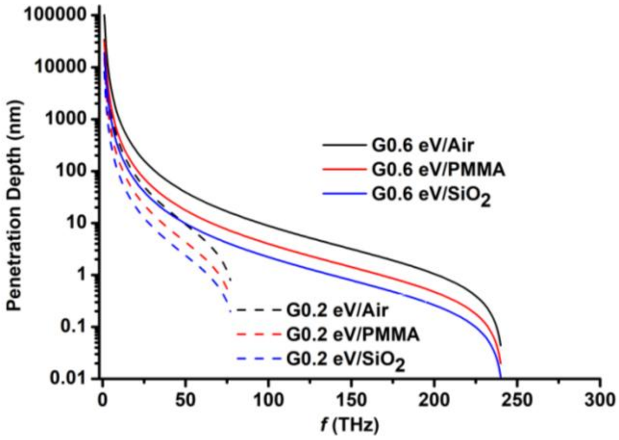

Fig. 4. Plot showing the effect of variation of dielectric mediums and chemical potentials (0.2 eV - dashed line; 0.6 eV - solid line) on graphene plasmon penetration depth as a function of input frequencies.

Penetration depth of surface plasmon implies the distance at which the excited plasmons' electric field losses perpendicular to the graphene dielectric interface reduce to 1/e of the electric field intensity at the excitation point.

Accordingly, figure 4 shows a decrease in the penetration depth of graphene surface plasmons as a function of increase in input excitation frequency. With higher chemical potential, the penetration depth also increases.

The penetration depth decreases as the dielectric constant of medium increases, indicating the surface plasmons show better confinement and lower losses.

IV. CONCLUSION

In this work, the behaviour of graphene surface plasmons has been analysed for different dielectric mediums and varying graphene chemical potentials. At higher chemical potential, the graphene surface plasmons are generated over a wider range of input excitation frequency when compared to the case of lower graphene chemical potential. The dispersion relation shows that at particular lower frequencies, the propagating surface plasmon wave vector shows an increase for a high refractive index dielectric. Both dielectric constant of medium as well as the chemical potential affect the surface plasmon frequency, with ω_{sp} being lower for lower chemical potential and higher dielectric medium.

The distance over which the graphene surface plasmon decay in the longitudinal direction viz. the propagation length of GSPP, increases with increasing chemical potential and decreases with increase in the refractive index of dielectric medium. In contrast, the decay of GSPPs in a direction perpendicular to the graphene dielectric interface viz. penetration depth shows a decrease with increase in input excitation frequency, chemical potential and dielectric constant of the medium. This results in better confinement and lower losses for GSPPs. These results show that surface plasmon enhancement with high field localization obtained for graphene on PMMA polymer is comparable to SiO_2 substrate, which makes graphene is a good candidate for flexible optoelectronics applications.

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