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Analysis of mid-infrared graphene surface plasmons

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ABSTRACT

The graphene plasmonic properties in the air–graphene–SiC (A–G–SiC) structure have been investigated in the mid-infrared region. The influences of the substrate on the dispersion properties and modal fields have been explored. The results show that in the low-wavelength region ($< 10.3\ \mu m$), due to the SiC substrate behaving like "dielectrics", the plasmonic properties of the A–G–SiC structures are closely related to the graphene layer, supporting transverse magnetic (TM) modes with good confinement. But in the long-wavelength region, the SiC substrate manifests "metallic" property, and the plasmonic properties of the A–G–SiC structure mainly depend on the SiC substrate, leading to the effective index and loss decreasing drastically. For the transverse magnetic (transverse electric) modes, as the dielectric constant of the substrate increases, the loss increases (decreases), the modes decay much quickly (slowly) into the air. The results are very helpful to design novel graphene-based waveguides devices, such as modulators, detectors and filters.

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1. Introduction

Surface plasmons (SPs) offer the promise to control electromagnetic waves at subwavelength scales [1]. Generating and controlling SPs are essential for its applications in the fields of microscopy, data storage and metamaterials [2–4]. However, the traditional metal or heavily doped semiconductor SPs devices are limited by the enormous loss and saturated plasma resonance frequency [5–8]. Exploring a new kind of SPs system is very important to the development of plasmonic devices. With its unique electrical and optical properties [9–12], graphene manifests prospective applications in a wide frequency region [13–15], which can serve as a good platform for plasmonics [15–18]. Graphene surface plasmons (GSPs) aid the nano-electronics and nano-optics successfully and display favorable properties of low loss, extreme confinement, and high tunability [19–21]. For instance, the plasmonic properties of GSPs can be conveniently tuned by means of chemical doping, electric field, magnetic field, or gate bias voltage [22]. Additionally, when the inter-band optical transition dominates, the imaginary part of the graphene conductivity ($\sigma_{g,i}$) is negative, graphene may also support transverse electric (TE) modes [23,24]. Therefore, GSPs provide a new way to develop plasmonic devices and arouse many researchers' interests. But because the wave vector mismatch between the GSPs and free space photos is large and the excitation and detection of the GSPs

are very inefficient, it is a little difficult to realize propagating GSPs. Recently, by means of scattering-type scanning near-field optical microscope, the propagating GSPs have been first experimentally demonstrated [25,26], which paves the way for advanced hybrid plasmonic circuits. For instance, Fei et al. [26] showed that in the air–graphene–SiO_2 structures the graphene transverse magnetic (TM) modes manifested good confinement, and the amplitude and plasmons wavelength could be varied using the gate voltage.

In most practical applications, the graphene layer is supported by dielectric substrates, e.g. SiO_2, Si, Al_2O_3, or HfO_2 [14,27]. With increasing popularity in microelectronics, silicon carbide (SiC) is also an important kind of substrate to fabricate large-scale and high-quality homogeneous graphene layer [28], which is very important and helpful to the development of graphene-based plasmonic devices [29]. Additionally, the dielectric constant of SiC strongly depends on wavelength in the mid-infrared spectral range, which provides us with a convenient way of tuning the plasmon wavelength by slightly changing the excitation wavelength. For instance, Chen et al. [25] experimentally investigated the graphene TM modes on the SiC substrate in the mid-infrared spectral range. It should also be noted that the $Re(\varepsilon_{SiC})$ can be negative between the transverse optical (TO) and longitudinal optical (LO) phonon frequencies, which results from the strong coupling of light and the lattice vibrations (phonons) in the polar crystals, instead of the collective oscillations of conduction electrons in metal. Consequently, the loss of the surface phonon polaritions (SPhPs) is smaller than that for SPs [30].

The plasmonic properties of the GSPs are also closely related to the dielectric properties of the substrate, especially for the

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monolayer graphene [31]. It is very important to understand the interaction between graphene and dielectric substrate, which is a key issue for the development of graphene-based electronic devices. Compared with other dielectric substrates (SiO$_2$ and Si), the dielectric constant of SiC changes rapidly in the mid-infrared spectral range, displaying "metallic" or "dielectric" properties with the change of wavelength. Thus, the air–graphene–SiC (A–G–SiC) structure provides us with a good choice to investigate the influences of the change of the dielectric constant of substrates on the plasmonic properties. But regretfully, there has been little study in this aspect. Therefore, the dispersion properties and mode distribution of the graphene TM and TE modes in the A–G–SiC multilayer structures have been explored, which have also been compared and discussed with those of the SiO$_2$ and Si substrates.

2. Theoretical model and method

Fig. 1 shows the sketch of the air–graphene–dielectrics multilayer structure. The graphene layer is sandwiched between air and substrate layer, which can be regarded as a thin surface layer characterized by surface conductivity σ_g. The complex graphene conductivity is related to the radiation frequency ω, temperature T, scattering rate Γ and chemical potential (Fermi level, E_f). Compared with metal and heavily doped semiconductors, graphene can show "metal" or "dielectrics" nature with the change of gate voltage.

Complex conductivity is an important parameter to describe the electronic and optical properties of graphene. The real part of graphene conductivity can be acquired by using the Kubo formula [32]

$$\Re\sigma(\Omega) = \frac{e^2 N_f}{4\pi^2 \Omega} \int_{-\infty}^{+\infty} d\omega \left[[f_0(\omega) - f_0(\omega')] \times \Re \left\{ \begin{array}{c} \frac{2B}{\Delta^2 - (\omega + i\Gamma)^2}[\Xi_1(-B) - \Xi_2(-B)] + \\ [\Xi_1(-B) - \Xi_2(+B) - \Xi_2(-B) - \Xi_2(+B)] \\ \times \psi\left(\frac{\Delta^2 - (\omega + i\Gamma)^2}{2B}\right) + (\omega \Leftrightarrow \omega', \Gamma \Leftrightarrow \Gamma') \end{array} \right\} \right] \tag{1}$$

where

$$\Xi_1(\pm B) = \frac{(\omega + i\Gamma)(\omega' + i\Gamma') - \Delta^2}{[(\omega - \omega') + i(\Gamma - \Gamma')][(\omega + \omega') + i(\Gamma + \Gamma')] \pm 2B} \tag{2}$$
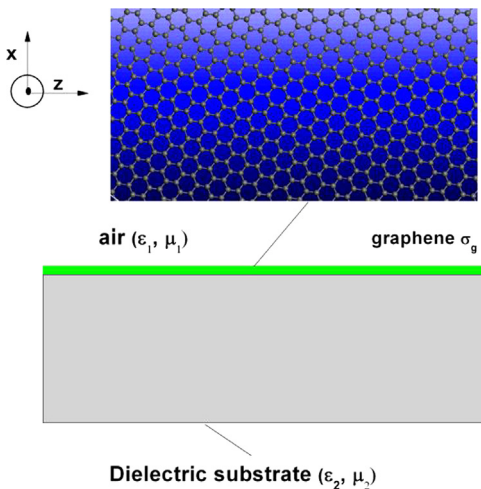

Fig. 1. The sketch of the A–G–D structure. The graphene layer with the conductivity of σ_g is sandwiched between air and dielectric substrate. The substrate layer can be SiO$_2$, Si and SiC layers.

$$\Xi_2(\pm B) = \frac{(\omega + i\Gamma)(\omega' - i\Gamma') - \Delta^2}{[(\omega - \omega') + i(\Gamma + \Gamma')][(\omega + \omega') + i(\Gamma - \Gamma')] \pm 2B} \tag{3}$$

in which $f_0(\omega)$ is the Fermi distribution function, ψ is the digamma function, Γ and Γ' are the phenomenological scattering rates, $\omega' = \omega + \Omega$, N_f is the number of spin components, and Ω is the frequency. The imaginary part of the complex conductivity can be calculated by using the Kramers–Kronig relation

$$\Im\sigma(\omega) = \frac{2\omega}{\pi} \int_0^\infty \frac{\Re\sigma(\omega')}{\omega'^2 - \omega^2} d\omega' \tag{4}$$

when $\sigma_{g,i} > 0$ (Re($\varepsilon_{g,eq}$) < 0), the graphene layer can support TM modes, the relative field components can be written as [33]

$$H_y = \begin{cases} H_2 e^{\gamma_2 x} & x < 0 \\ H_1 e^{-\gamma_1 x} & x \geq 0 \end{cases}, \tag{5}$$

and $E_x = (i/\varepsilon_i\omega\varepsilon_0)(\partial H_y/\partial z)$, where $\gamma_i = k_0\sqrt{\beta^2 - \varepsilon_i\mu_i}$, β is the propagation constant along the z direction. The dispersion relation for graphene-supported TM modes can be written as

$$\varepsilon_1/\gamma_1 + \varepsilon_2/\gamma_2 + j\sigma_g/\omega\varepsilon_0 = 0. \tag{6}$$

On condition that $\beta \cdot k_0 \gg \omega/c_0$, the above equation can be roughly equal [5]

$$\beta \approx \varepsilon_0 \frac{\varepsilon_1 + \varepsilon_2}{2} \frac{2i\omega}{\sigma_g} \tag{7}$$

when $\sigma_{g,i} < 0$ (Re($\varepsilon_{g,eq}$) > 0), the graphene layer can support TE modes, the relative field components can be written as

$$E_y = \begin{cases} E_2 e^{\gamma_2 x} & x < 0 \\ E_1 e^{-\gamma_1 x} & x \geq 0 \end{cases}, \tag{8}$$

and $H_x = (i/\mu_i\omega\mu_0)(\partial E_y/\partial z)$. The dispersion relation for graphene-supported TM modes can be written as

$$\gamma_1/\mu_1 + \gamma_2/\mu_2 - j\sigma_g\omega\mu_0 = 0. \tag{9}$$

In the mid-infrared spectral range, the dielectric constant of 6H–SiC includes phonon polaritons and plasmon polaritons can be written as [34]

$$\varepsilon_{SiC} = \varepsilon_\infty \left(\frac{\omega_{LO}^2 - \omega^2 - i\omega\gamma_{SiC}}{\omega_{TO}^2 - \omega^2 - i\omega\gamma_{SiC}} \right) \tag{10}$$

where ω is the angular frequency, ε_∞ is the infinite frequency dielectric response, γ_{SiC} is the damping factor, and ω_{TO} and ω_{LO} are the TO and LO phonon frequencies, respectively. The spectral range between ω_{TO} and ω_{LO} is generally called the phonon-polariton gap, which extends roughly from 10.3 to 12.6 μm for SiC. Inside the polariton gap, the real part of ε_{SiC} is negative, which can support the surface phonon polaritons. The wave vectors of the SPhPs can be written as [35]

$$k_{SPhP}(\omega) = k_0 \sqrt{\frac{\varepsilon_{SiC}(\omega)\varepsilon_d}{\varepsilon_{SiC}(\omega) + \varepsilon_d}} \tag{11}$$

3. Results

Fig. 2(a) shows the dielectric constant of 6H–SiC versus wavelength in the mid-infrared spectral range. When the wavelength is