

Interface phonon polariton coupling to enhance graphene absorption

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Abstract Here we present a graphene photodetector of which the graphene and structural system infrared absorptions are enhanced by interface phonon polariton (IPhP) coupling. IPhPs are supported at the SiC/AlN interface of device structure and used to excite interband transitions of the intrinsic graphene under gated-field tuning. The simulation results show that at normal incidence the absorbance of graphene or system reaches up to 43% or closes to unity in a mid-infrared frequency range. In addition, we found the peak-absorption frequency is mainly decided by the AlN thickness, and it has a red-shift as the thickness decreases. This structure has great application potential in graphene infrared detection technology.

Keywords interface phonon polariton (IPhP), infrared absorption enhancement, graphene photodetector

1 Introduction

Graphene, consisting of one monolayer of carbon atoms arranged in a honeycomb lattice, has important application prospects in materials science, micro-nano processing, energy, biomedicine and drug delivery [1–6]. It is considered to be a revolutionary material in the future with excellent optical, electrical and mechanical properties. Because of the special band structure of graphene, wide spectral absorption can be achieved, but its absorbance is only about 2.3% [7]. The low absorption issue is expected to be overcome for the high responsivity requirement of infrared photodetector.

Optical confinement effects of the surface plasmon polariton (SPP) and surface phonon polariton (SPhP) can be used to significantly enhance the light-matter interaction. As an important area of nanophotonic topic, SPP is

widely used in the fields of enhanced sensing, optical radiation, photodetection, and surface-enhanced spectroscopy [8–14]. First of all, the SPP technology is under consideration for enhancing the graphene infrared absorption. However, SPP is generally excited on the surface of noble metals like Au, Ag, and Cu, etc., and a low quality-factor (Q-factor) is the characteristics when the SPP resonance works at an optical frequency, which limits the further development for SPP applications. It has been found that polar crystals like III-V semiconductors have a high reflectivity in the mid-infrared or far-infrared region. For example, SiC has a reflectance close to 100% in the wavelength range from $\lambda = 10.32$ to $12.61 \mu\text{m}$ [15]. In this spectral region, the polar crystal has a negative dielectric constant, and SPhP modes will be supported at its interface. Derived from optical phonons with long lifetimes, the SPhP mode inherits the characteristics of high Q-factor from phonons. Based on these unique advantages, SPhP becomes an alternative of SPP in the mid-infrared spectrum with a broad prospect.

Similar to SPP, the surface wave frequency must be near the SPhP characteristic frequency to produce significant absorption. The essence of SPhP is the atoms collective oscillation mode which is coupled with the incident electromagnetic wave. As the incident electromagnetic wave interacts with the lattice vibration in the semiconductor, it leads to the transition of the phonon state and the absorption of light. It is impossible to couple the incident light wave into SPhP directly because the propagation wave number of SPhP is far larger than that of free space light. Therefore, it is necessary to meet the wave vector matching condition with the coupling device or by introducing special structures to achieve exciting the SPhP mode. The common excitation approaches are prism coupling, grating coupling, and near-field excitation.

In this paper, we propose an infrared detector based on intrinsic graphene and utilize the optical confinement effect of interface phonon polaritons (IPhPs) to increase the graphene absorbance.

2 Design of the detector

We have designed a structure and explored the graphene and structural system absorption properties by the finite-difference time-domain (FDTD) method. The detector consists of Au gratings on the top of SiC/AlN/graphene/BN stacked structure as shown in Fig. 1. The SiC/AlN is used to support IPhP. The light source is selected as the plane wave which is incident from top to bottom, and periodic boundary conditions are adopted in the x -axis direction and perfect matched layer boundary conditions in the y -axis direction. Using the metal grating on the surface, the light meets the wave vector matching condition, and couples to SiC/AlN to excite IPhP. In consequence, it increases the graphene absorbance.

In this simulation, the surface conductivity of graphene σ_g is derived using the well-known Kubo formula and written as [16–20]

$$\sigma_g = \frac{je^2}{\pi\hbar^2(\omega - j2\Gamma)} \int_0^\infty \xi \left(\frac{\partial f_d(\xi, E_F, T)}{\partial \xi} - \frac{\partial f_d(-\xi, E_F, T)}{\partial \xi} \right) d\xi - \frac{je^2(\omega - j2\Gamma)}{\pi\hbar^2} \int_0^\infty \frac{f_d(-\xi, E_F, T) - f_d(\xi, E_F, T)}{(\omega - j2\Gamma)^2 - 4(\xi/\hbar)^2} d\xi, \quad (1)$$

where

$$f_d(\xi, E_F, T) = \left(e^{(\xi - E_F)/k_B T} + 1 \right)^{-1}. \quad (2)$$

Here, e is the electron charge, k_B is the Boltzmann constant, \hbar is reduced Planck constant, T is Kelvin temperature, E_F is the Fermi level, ω is the angular frequency and Γ is the scattering rate, ξ is the energy of electrons. We take Γ as 16.67 ps^{-1} [21], and assume room temperature $T = 300 \text{ K}$, for all simulations.

The dielectric constant of polar crystals is written as

$$\varepsilon_{\parallel, \perp} = \varepsilon_{\infty, \perp} + \frac{\varepsilon_{\infty, \perp}(\omega_{\text{LO}\parallel, \perp}^2 - \omega_{\text{TO}\parallel, \perp}^2)}{\omega_{\text{TO}\parallel, \perp}^2 - \omega^2 - i\omega\Gamma_{\parallel, \perp}}, \quad (3)$$

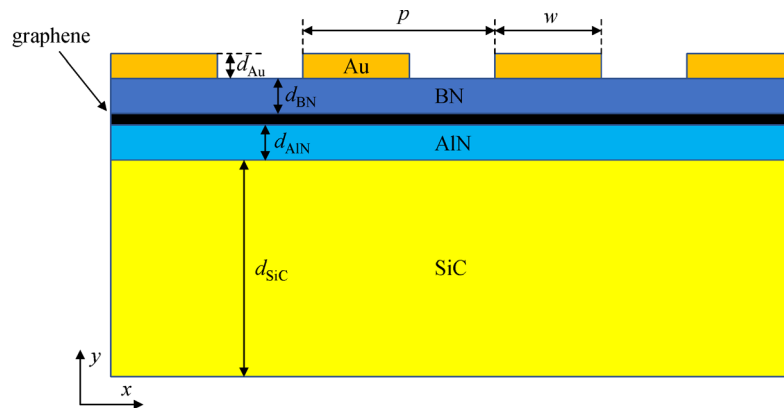


Fig. 1 Schematic of device structure. The thickness of SiC layer, graphene layer and BN layer are $d_{\text{SiC}} = 350 \text{ }\mu\text{m}$, $d_{\text{G}} = 2 \text{ nm}$, $d_{\text{BN}} = 13 \text{ nm}$, respectively. d_{AlN} , which represents the thickness of AlN, is a variable. The Au grating has a period of $p = 10 \text{ }\mu\text{m}$, a width of $w = 5.72 \text{ }\mu\text{m}$, and a thickness of $d_{\text{Au}} = 100 \text{ nm}$

where $\omega_{\text{TO}\parallel, \perp}$ and $\omega_{\text{LO}\parallel, \perp}$ are the transverse and longitudinal optic phonon frequencies, respectively, and $\Gamma_{\parallel, \perp}$ are the phonon damping constants. For SiC, we have $\varepsilon_{\infty, \perp} = 6.4$, $\varepsilon_{\infty, \parallel} = 7.7$, $\omega_{\text{TO}\perp} = 797 \text{ cm}^{-1}$, $\omega_{\text{TO}\parallel} = 782 \text{ cm}^{-1}$, $\omega_{\text{LO}\perp} = 971 \text{ cm}^{-1}$, $\omega_{\text{LO}\parallel} = 965 \text{ cm}^{-1}$, and $\Gamma_{\parallel, \perp} = 2.8 \text{ cm}^{-1}$ [22]. The dielectric constant of SiC is shown in Fig. 2.

3 Results and discussion

With the change of the grating period p , the simulation results are shown in Fig. 3. The absorbance varies significantly with the change of the grating period while the location λ of the absorption peak is unaltered. The grating provides an extra wave vector. It meets the wave vector matching as we set the grating period $p = 10 \text{ }\mu\text{m}$, which leads to the strongest vibration. Meanwhile, the phonon is excited at the interface between SiC and AlN, and the energy of the phonon is coupled into the graphene, which improves the absorption of graphene. Figure 4 is an electric field distribution diagram of a grating period $p = 10 \text{ }\mu\text{m}$ and a light wavelength $\lambda = 10.57 \text{ }\mu\text{m}$. The most filed are distributed in AlN and SiC, which is a feature of phonon [23].

Absorption of graphene is written as [24]

$$A_G = \frac{2\pi}{\lambda_0 |E_0|^2 S} \varepsilon_G'' \iiint_V |E_G|^2 dV. \quad (4)$$

Equation (4) indicates that the absorbance of graphene is proportional to imaginary part of dielectric constant.

Then, we explore the influence on graphene absorption with different AlN thickness. The metal grating is chose as $p = 10 \text{ }\mu\text{m}$, $d_{\text{Au}} = 100 \text{ nm}$, and $w = 5.72 \text{ }\mu\text{m}$. The thickness of AlN changes to $d_{\text{AlN}} = 100, 80, 60, 40, 20 \text{ nm}$, while the other parameters keep unchanged. As shown in Fig. 5, the absorbance of system reaches close to 100% at $\lambda = 10.57 \text{ }\mu\text{m}$. In Fig. 6, the peak absorbance of graphene for the different AlN thickness are 28.3%, 30.8%, 34.0%, 37.5%, and 43.6%, respectively. As the thickness of AlN

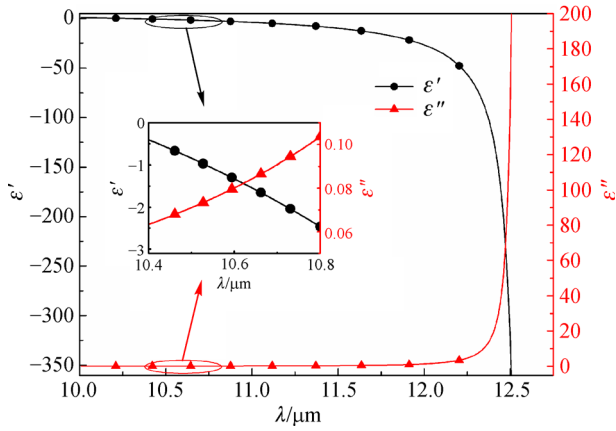


Fig. 2 Dielectric constant of SiC in the x direction, i.e., perpendicular to the lattice C -axis (the parallel-directional values are not plotted here). The real part (in black dot) of dielectric constant is negative while the imaginary part (in red triangle) is positive

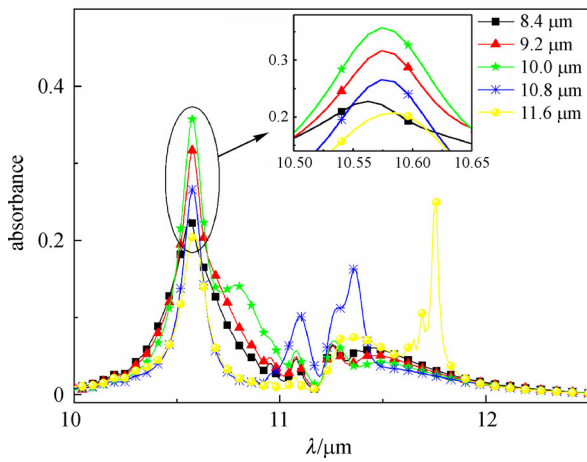


Fig. 3 Effect of different grating period p on the absorbance of graphene. The main absorption peak is located at $\lambda = 10.57 \mu\text{m}$. The inset shows that the peak location remains unchanged at $\lambda = 10.57 \mu\text{m}$

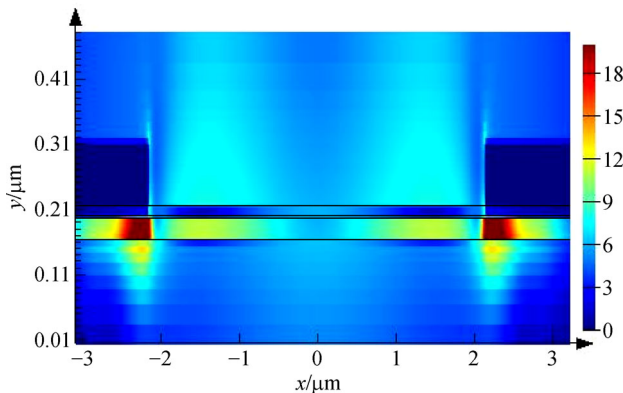


Fig. 4 Electric field distribution at $\lambda = 10.57 \mu\text{m}$. The fields are mainly confined within AIN and SiC

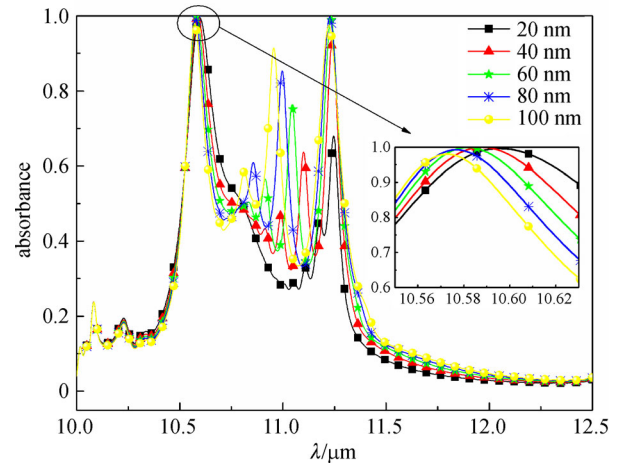


Fig. 5 Absorbance of the structural system with different AIN thicknesses d_{AIN} . The inset shows the absorption peak has a red shift as the d_{AIN} decreases

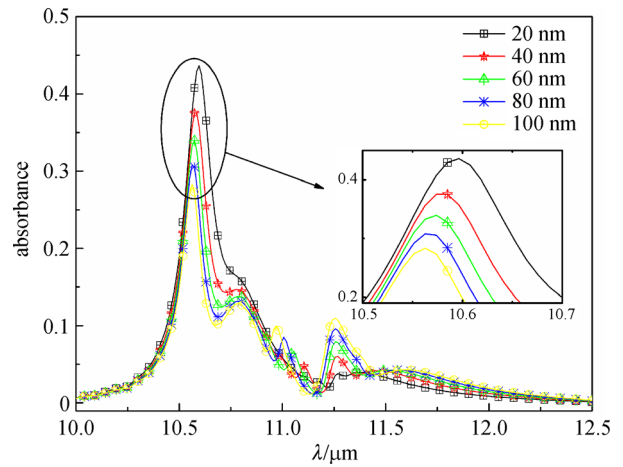


Fig. 6 Graphene absorbance with different AIN thicknesses d_{AIN} . The inset shows that the absorption peaks locate at $\lambda = 10.562, 10.568, 10.574, 10.580, \text{ and } 10.596 \mu\text{m}$ are red-shifted with the decrease of AIN thickness

decreases, the absorbance of graphene increases. It is due to that as the thickness of AIN increases, the path of IPHP in AIN increases, which means more energy loss, and the energy that eventually couples into the graphene decreases. While the AIN becomes thinner, the propagation path of IPHP getting shorter, and the energy consumed by the AIN decreases; in consequence, the energy coupled into the graphene increases, resulting in an increase of the graphene absorption. In addition, we found that as the thickness of AIN decreases, the absorption peak shifts toward the long wavelength direction. This is due to that for multilayer dielectric film, the characteristic frequency of IPHP is not only related to the materials, but also to the thickness of each dielectric layer [25]. As the thickness of AIN decreases, it has an impact on the characteristic frequency

of the interface phonon, which causes the resonance absorption peak red-shifted.

4 Conclusion

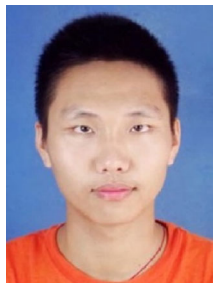
In summary, we presented the design of graphene photodetector based on IPhPs in mid-infrared region. With the extra wave vector provided by the grating, the light is coupled into the SiC/AlN interface to excite the IPhPs. Then, the optical confinement effects of IPhPs increase the graphene absorbance. As for the main absorption peak ($\lambda = 10.57 \mu\text{m}$), the grating period (p) has no impact on the location, while the graphene absorbance is affected seriously. We found that the absorbance and absorption peak position of graphene change with the thickness of AlN (d_{AlN}), the graphene absorbance reaches 43.6% at the wavelength of $\lambda = 10.57 \mu\text{m}$, meanwhile the system absorbance reaches 100%. Both graphene and the system's absorption peak have a red shift as the d_{AlN} decreases. The remarkable enhancement in graphene absorption suggests that the IPhP structure is potentially helpful for designing high-performance graphene photodetectors.

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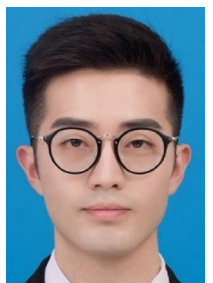
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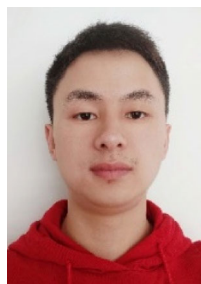
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