Original research article

Determination of the number of graphene layers on one-dimensional photonic crystal by using polarization-dependent absorption effect

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In this paper, we study polarization-dependent optical absorption of a graphene on the top of one-dimensional photonic crystal (1DPC), which offer a method to accurately count the number of graphene layers. The 1DPC is composed of 10 pairs of (SiO_2/TiO_2), and the two kinds of material is transparent, which is different from the commonly substrate with significant contrast to graphene. The absorption difference fitting formula is given by the 0–10 graphene layer. It may be applicable to other two-dimensional materials optically counting layers.

1. Introduction

Graphene as a one-atom thick and two-dimensional semiconductor has attracted significant attention in recent years due to the richness of its optical, thermal, mechanical and electronic properties [1–3]. The material also has a great potential application in optoelectronic devices such as transparent electrodes, transistors, biosensing and photovoltaic cells [3–6]. With the development of graphene, the research of graphene is not limited to single-layer graphene (SLG), and the study of bilayer or multilayer graphene is also increasing. Even the number of graphene layers will affect its dynamic, thermotics, optical, electrical property and so on. Han et al. [7] studied the relaxation property of graphene sheet by using molecular dynamics simulation and found that the waviness at the edges of multilayer graphene sheets is a little less than that of the single layer. Ghosh et al. [8,9] measured the thermal conductivities of single and multilayer graphene by using a noncontact technique based on micro-Raman spectroscopy and found that the thermal conductivity decreases with the increase of the number of graphene layers. The optical absorption of the graphene monolayer is about 2.3% in visible range, and the number of layers of graphene will affects the transparency and optical properties of the film [10,11]. For lithium ion battery, the electronic structure of graphene have significantly change with the number of layers, which will affect the conductivity of graphene and the performance of lithium ion battery [12]. Ding et al. [13] have demonstrated that polarization-dependent optical absorption is highly related with the thickness of graphene.

To date, the methods of measuring the number of graphene layers are mainly optical microscope [14], atomic force microscope [15], transmission electron microscopy [16], Raman spectroscopy [17,18], quasi-Brewster angle [19] and so on. These methods count the thickness of graphene layers to a certain extent, but which also have limitations. Recently, Wang [20] reported that a method to accurately count the number of carbon atomic layers based on polarization-dependent optical absorption effect of graphene under total internal reflection (TIR). The absorption difference of transverse electric (TE) and transverse magnetic (TM)

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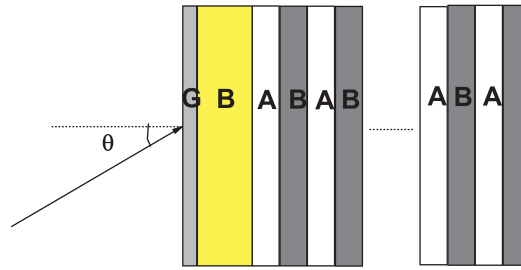 E-mail address: wangyu1901@m.scnu.edu.cn (Y. Wang).

Fig. 1. Schematic of the graphene layer prepared at front of a 1DPC with a spacer layer.

polarized light has large dependence on the number of graphene layer. In this letter, we theoretically investigate the polarization-dependent optical absorption of graphene layer prepared on top of a SiO_2/TiO_2 1DPC with a spacer layer. For this structure, the absorption difference (ΔA) of graphene has large dependence on the number of graphene layers. We theoretically investigate the optical absorption of graphene in visible range, and obtain the analytical equation for the relation between ΔA and the number of graphene layers.

2. Model and method

In this paper, we adopted a structure of graphene layer/spacer layer/1DPC, as shown in Fig. 1. The 1DPC is composed of N periodic of (A/B). The thickness of the graphene $d_g = M * 0.34$ nm, where 0.34 nm is the thickness of the monolayer graphene and M is the number of graphene layers. The thickness of the A and B layers are $\lambda_0/4\sqrt{\varepsilon_{A0}}$ and $\lambda_0/4\sqrt{\varepsilon_{B0}}$ respective, where λ_0 is the center wavelength of the input light beams and $\varepsilon_{A0}(\varepsilon_{B0})$ is the permittivity of the $A(B)$ layer at λ_0. The spacer layer is materials B, the thickness of the spacer layer is $\lambda_0/2\sqrt{\varepsilon_{B0}}$.

For the model shown in Fig. 1 in this letter, using the transfer matrix method (TMM) [21,22], we can obtain the transfer matrix of a 1DPC containing l layers in the form:

$$M_l = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \prod_{j=1}^{l} \begin{bmatrix} \cos\delta_j & -\iota\sin\delta_j/\eta_j \\ -\iota\eta_j\sin\delta_j & \cos\delta_j \end{bmatrix},$$

(1)

where $\delta_j = 2\pi n_j d_j \cos\theta_j/\lambda$, θ_j is the angle of incidence, n_j is the refractive index, and d_j is the thickness of the jth layer, λ is the wavelength of incident light. For the TE mode, $\eta_j = n_j\cos\theta_j$; for the TM mode, $\eta_j = \cos\theta_j/n_j$. The reflectance and transmittance are given as:

$$r = \frac{(M_{11} + M_{12}\eta_0)\eta_0 - (M_{21} + M_{22}\eta_0)}{(M_{11} + M_{12}\eta_0)\eta_0 + (M_{21} + M_{22}\eta_0)}$$
$$t = \frac{2\eta_0}{(M_{11} + M_{12}\eta_0)\eta_0 + (M_{21} + M_{22}\eta_0)}.$$

(2)

Then, the reflectance $R = |r|^2$ and transmittance $T = |t|^2$ can be obtained, respectively. Thus, one can use Poynting vectors to calculate the absorption in graphene layer as [11]

$$A_o = \frac{(S_0^+ - S_0^-) - (S_S^+ - S_S^-)}{S_0^+},$$

(3)

where S_0^+ and S_0^- (S_S^+ and S_S^-) are the incident and reflected Poyinting vectors in the air (in the spacer layer), respectively. The reflectance $R_0(R_S)$ and transmittance T_0 (T_S) of the entire structure (the 1DPC) can be obtained, respectively, by

$$R_0 = \frac{S_0^-}{S_0^+}, \qquad T_0 = \frac{S_{sub}^+}{S_0^+}, \qquad R_S = \frac{S_S^-}{S_S^+}, \qquad T_S = \frac{S_{sub}^+}{S_S^+},$$

(4)

where the transmitted Poynting vector of the entire structure is S_{sub}^+. Then, from (3) and (4) we can obtain expression of the absorptivity that contains only reflectance and transmittance

$$A_0 = 1 - R_0 - \frac{T_0}{T_S}(1 - R_S).$$

(5)

3. Numerical results and discussions

In order to reduce the experimental cost and substrate is transparent, we choose two cheap materials and select dielectric A and B to be silicon dioxide and titanium dioxide, respectively. The structure parameters of this text are set as follow: the center wavelength $\lambda_0 = 550$ nm, the refraction index of graphene layer in the visible range $n_g = 3.0 + iC_1\lambda/3$, $C_1 = 5.446\,\mu m^{-1}$ [23], the permittivity of SiO_2 $\varepsilon_A = 1.4923 + c_1\lambda^2/(\lambda^2 - c_2^2) - c_3\lambda^2$, where $c_1 = 0.61497$, $c_2 = 0.115\,\mu m$, and $c_3 = 0.01059\,\mu m^{-2}$ [24], the permittivity of