Enhanced visibility of graphene: effect of one-dimensional photonic crystal

Kai Chang, J. T. Liu and J. B. Xia
NLSM, Institute of Semiconductors, Chinese Academy of Sciences, P. O. Box 912, Beijing 100083, China
N. Dai
National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China

We investigate theoretically the light reflectance of a graphene layer prepared on the top of one-dimensional Si/SiO$_2$ photonic crystal (1DPC). It is shown that the visibility of the graphene layers is enhanced greatly when 1DPC is added, and the visibility can be tuned by changing the incident angle and light wavelengths. This phenomenon is caused by the absorption of the graphene layer and the enhanced reflectance of the 1DPC.

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Graphene consists of a two-dimensional honeycomb lattice of carbon atoms and has been attracting attention recently due to its remarkable electronic properties and its potential application in nanoelectronics. Graphene exhibits high crystal quality, an exotic Dirac-type spectrum, and ballistic transport on a submicro scale. Graphene samples are usually fabricated by a micromechanical cleavage of graphite. It is difficult to distinguish the single graphene layer from many graphitic pieces, even utilizing the atomic force, scanning-tunneling, and electron microscopes. A recent experiment demonstrated that the graphene visibility depends on both the thickness of the SiO$_2$ layer and the light wavelength. They found that specific thicknesses (300nm and 100nm) are most suitable for its visual detection for the normal light incidence and attribute this phenomenon to the opacity of the graphene layer. Although the relative difference of the reflectance [the contrast C in Ref. (2)] is enhanced significantly, the absolute difference of the light reflectance is still quite low because it is determined by the weak absorption of the graphene layer. In order to enhance the visibility of graphene, i.e., the absolute and relative difference of the light reflectance of the graphene layer, we propose to prepare the graphene layer on the top of Si/SiO$_2$ one-dimensional photonic crystal (1DPC). This 1DPC shows a high dielectric contrast at the Si/SiO$_2$ interface ($\Delta n \approx 2.3$) producing a high reflectance at normal incidence, and can be fabricated by different techniques, e.g., the separation-by-implanted-oxygen technique, sputtering combined with solid-source Si molecular beam epitaxy, and plasma-enhanced chemical vapor deposition.

In this Letter, we investigate theoretically the light reflectance of a graphene layer prepared on the top of Si/SiO$_2$ 1DPC, as shown schematically in Fig. 1(a). We consider an asymmetric 1DPC: $A_0(AB)_l$, where $l$ is an integer denoting the $l$-th layer. All layers are nonmagnetic ($\mu = 1$) and are characterized by their permittivities $\varepsilon_A(\text{SiO}_2$ layer), $\varepsilon_B$(Si layer), and their thicknesses satisfy $\sqrt{\varepsilon_A d_A} = \sqrt{\varepsilon_B d_B} = \lambda/4$ where $\lambda$ is the wavelength required by the observation. The thickness of the top SiO$_2$ layer is $d = \lambda/2\sqrt{\varepsilon_A}$. We find that the difference between the reflectance of the graphene layers with 1DPC can be enhanced greatly, even one order of magnitude larger than that without 1DPC. Furthermore, the visibility of the graphene can be tuned by the incident angle.

We consider a light shedding on the graphene layer prepared on the top of Si/SiO$_2$ 1DPC with a incident angle $\theta$ from air (refractive index, $n_0 = 1$). Based on the Maxwell equations for a monochrome light propagating in the medium, we have

$$\begin{cases}
    k \cdot D = k \cdot \varepsilon_0 E = 0, \\
    k \cdot B = k \cdot \mu_0 H = 0, \\
    k \times E = \omega B = \omega \mu_0 H, \\
    k \times H = -\omega D = -\omega \varepsilon_0 E,
\end{cases}$$ (1)

where $\varepsilon = \varepsilon_r + i\varepsilon_i(\varepsilon_0)$ is the permittivity of the material (vacuum), $\mu(\mu_0)$ the magnetic permeability of material (vacuum), and $\omega$ the angular frequency of the incident light.

For the TE polarization, the electric field is in the $x$ direction, $E_i = E(y,z)e_x$, and the magnetic field is in the $y$-z plane, $H = H_y(y,z)e_x + H_z(y,z)e_z$, where $e_i(i = x, y, z)$ are the unit vectors in the $x$, $y$, and $z$ directions, respectively. The reflected and transmitted electric fields...
from the 1DPC are, respectively,
\[ E_0(y,z) = [A_0 e^{ik_z z} + B_0 e^{-ik_z z}] e^{-ik_y y} e_x, \]  
(2) \[ E_{N+1}(y,z) = A_{N+1} e^{ik_z z - ik_y y} e_x. \]  
(3)

The electric fields of the monochrome light beam in the l-th layer is given by
\[ E_l(y,z) = [A_l e^{ik_z z} + B_l e^{-ik_z z}] e^{-ik_y y} e_x, \]  
(4) \[ H_l(y,z) = \frac{1}{\omega \mu_0} k_z x E_l, \]  
(5) \[ = \frac{1}{\omega \mu_0} (k_z n_y - k_y n_z) [A_l e^{ik_z z} + B_l e^{-ik_z z}] e^{-ik_y y}, \]  
(6)

where \( k_z = \sqrt{k^2 - k_y^2} \) in the medium. The wavevector \( k = \omega/c \) in a vacuum (c is the speed of light in a vacuum), but is generally complex in a medium. The electric fields of the light in the l-th layer are related to the incident fields by the transfer matrix utilizing the boundary condition \( n \times (H_1 - H_2) = 0, n \times (E_1 - E_2) = 0, \)
\[ \begin{pmatrix} A_l \\ B_l \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} A_0 \\ B_0 \end{pmatrix}, \]  
(7)

The reflectance \( r \) is defined as \( r = \frac{|T_{11}|^2}{|T_{11}|^2 + |T_{12}|^2} \), and \( N \) is the total layer number of the 1DPC \( (N = 10 \) in our calculation). The absolute and relative contrasts describing the difference between the reflectance with and without the graphene layer are defined as
\[ C_a \equiv r(0) - r(n), \]  
(8) \[ C_r \equiv \frac{|r(0) - r(n)|}{r(0)}, \]  
(9)

where \( r(n) \) denotes the reflectance of the sample with \( n \)-layer graphene. The latter \( (C_r) \) is the same as the definition of the contrast \( C \) in Ref. [2]. In order to observe the graphene layer experimentally, both the relative contrast \( C_r \) and the difference in reflectance between the structures with and without the graphene layer, i.e., the absolute contrast \( C_a \), should be large.

The parameters used in our calculation are: the refraction index \( n_g = 2.6 - 1.3 i \), and the permittivity \( \varepsilon_g = n_g^2 = 5.07 - 6.76 i \) for graphene layer, the real and imaginary parts of the permittivity \( \varepsilon_A \) and \( \varepsilon_B \) for Si and SiO2 depending on the wavelength \( \lambda \), the thicknesses of the SiO2 and Si layers are \( d_A = \lambda/4n_A \) \( (n_A = 1.46 \) for SiO2 at \( \lambda = 650 \) nm) and \( d_B = \lambda/4n_B \) \( (n_B = 3.77 \) for Si \( \lambda = 650 \) nm), respectively.

Fig. 1(b) depicts the photonic band gap of 1DPC without the graphene layer for different incident angles \( \theta \). The photonic band gap of SiO2(SiO2/Si)\( _{10} \) 1DPC increases as the incident angle \( \theta \) increases. The decrease of the reflectance in the band gap at very large incident angle is caused by the absorption in the Si layers. Fig. 2 shows the contour plots of the relative and absolute contrast \( C_r \) and \( C_a \) of single graphene layer (SGL) with and without 1DPC as a function of the light wavelength \( \lambda \) and the incident angle \( \theta \). In this figure we find that that the difference between the reflectances with and without the 1DPC exhibits a maximum at specific light wavelengths and large incident angles \( \theta \). This light wavelength is in the band gap of the 1DPC, i.e., the high reflection region [see Fig. 1(b)]. The maxima of the contrasts \( C_r \) and \( C_a \) come both from the absorption or opacity of the graphene layer and the maximum reflection of the eigenmode of the 1DPC, i.e., \( \lambda = 650 \) nm at normal incidence. This figure demonstrates that the reflection of the light is enhanced greatly compared to that without the 1DPC, consequently leading to a large difference in the absolute contrast \( C_a \) between the two samples, i.e., \( C_a \) with the 1DPC is one order magnitude (actually 20 times) larger than that without the 1DPC [see Fig. 2 (c) and (d)].
This enhancement should be helpful for the observation of the graphene. In addition, the contrasts also increase significantly with increasing the incident angle at a specific wavelength, and the maxima of the contrast shift to the shorter wavelengths such as $\lambda = 525\text{nm}$ at larger incident angles. This is due to the enhancement of the absorption of the graphene layer and the increase of the optical path length at larger incident angles $\theta$. The light wavelength corresponding to the maxima of the contrasts can be tuned by changing the layer thicknesses of the 1DPC and the incident angle $\theta$. This also provides us a new way to observe the graphene in the light frequency region.

In order to understand the big difference of the absolute contrast $C_a$ between the samples with and without the 1DPC (see Fig. 2(b) and 2(d)), we calculated the reflectance of the different structures, i.e., the SiO$_2$ layer prepared on Si substrate with and without SGL, and the SiO$_2$ layer prepared on the 1DPC with and without SGL. In Fig. 3(a) we find that the reflectances of the 1DPC with and without SGL are both enhanced greatly compared to that without the 1DPC (see the inset of Fig. 3(a)) since the light wavelength locates at the band gap of the 1DPC. If the absorption of the SGL is neglected, i.e., $Im(\varepsilon) = 0$ (see the green lines in Fig. 3(a)), the reflectance of the 1DPC with SGL is almost same as that of the 1DPC without the SGL, i.e., the very small absolute contrast $C_a$. Fig. 3(a) demonstrates clearly that the absorption of SGL and the enhanced reflection of light by the 1DPC are both important for the large absolute contrast $C_a$ (see Fig. 2(b)). The light reflectance of the system is determined not only by the 1DPC, but also the absorption of the graphene layer. At the large incident angle case (see Fig. 3(b)), the absolute contrast $C_a = r(0) - r(n)$ can be enhanced significantly compared with that at the normal incidence nearby the valley ($\lambda = 510\text{nm}$) of the reflectance of the 1DPC which is caused by the absorption of the Si and SiO$_2$ layers in the 1DPC, but becomes negligible small at other light wavelengths.

Considering the multi-layer graphene prepared on the top of the 1DPC, we plot the absolute and relative contrasts as a function of the wavelength and the incident angle (see Fig. 4). The multi-layer graphene is modeled by the corresponding number of planes separated by $d_1 = 0.34\text{nm}$ (the thickness of the single graphene layer). From this figure one can see that the contrasts $C_r$ and $C_a$ exhibit significant differences among the graphene layers with different thicknesses and the maximum as a function of the light wavelength and the incident angle. The difference increases as the number of the graphene layers increases. This feature makes it possible to distinguish the number of the graphene layers.

In summary, we demonstrate theoretically that the visibility of the graphene layers prepared on the top of SiO$_2$(SiO$_2$/Si)$^{10}$ 1DPC can be enhanced greatly, especially at the large incident angles and specific wavelengths in the photonic band gap. The large differences in the reflectance make it possible for the graphene layers of different thicknesses to be more easily observed and distinguished experimentally.

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