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Electrical generation of terahertz blackbody radiation from graphene

H. M. DONG,[1] W. XU,[2,3,*] AND F. M. PEETERS,[3,4]

[1]*School of Physical Science and Technology, China University of Mining and Technology, Xuzhou 221116, China*

[2]*Key Laboratory of Materials Physics, Institute of Solid State Physics, Chinese Academy of Sciences, China*

[3]*School of Physics and Astronomy and Yunnan Key Laboratory for Quantum Information, Yunnan University, Kunming 650091, China*

[4]*Department of Physics, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerpen, Belgium*

[*]*wenxu_issp@aliyun.com*

Abstract: Recent experimental work on the application of graphene for novel illumination motivated us to present a theoretical study of the blackbody radiation emission from a freely suspended graphene driven by a dc electric field. Strong terahertz (THz) emission, with intensity up to mW/cm^2, can be generated with increasing electric field strength due to the heating of electrons in graphene. We show that the intensity of the THz emission generated electrically from graphene depends rather sensitively on the lattice temperature in relatively weak electric fields, whereas it is less sensitive to the lattice temperature in relative strong electric fields. Our study highlights the practical application of graphene as intense THz source where the radiation is generated electrically.

1. Introduction

Graphene, a two dimensional Dirac system, exhibits excellent and unique optoelectronic properties which can be utilized for the realization of advanced photoelectric devices. Recently, a series of important developments in the research on the electroluminescence of graphene was achieved experimentally. It was found that due to the hot electrons with high-temperature, light emission can be achieved in electrically-biased graphene on a substrate [1, 2]. This electrically generated light emission from graphene was realized via the heating of electrons in the present of the strong electron-phonon coupling in graphene [3]. On the other hand, light emission have also been observed in graphene pumped by ultrashort laser pulses owing to strong electron-photon and electron-electron interactions [4]. Moreover, it was demonstrated that freely suspended graphene, instead of graphene placed on a substrate, can be used in advanced high field photonic devices [5]. Bright and tunable electroluminescence from blue to red bandwidth was achieved from all-graphene-field effect LED [6]. More interestingly, Kim *et al.* studied bright light emission from a freely suspended graphene, which highlights the realization of commercially viable large-scale, flexible light sources and electroluminescent devices [7]. The bright and uniform incandescent emission based on a freely suspended graphene film has been realized, which was driven by a low turn-on voltage [8]. Recently, stable light emission from thermal radiation of encapsulated graphene is realized by an electric field [9]. These important experimental findings have shed some light on the promise of graphene-based incandescent light sources. Motivated by these recent experimental findings, we conducted a theoretical investigation on THz emission by graphene to predict a new application of graphene based light source in THz field.

2. Theoretical approaches

In this study, we consider a freely suspended graphene device, which is similar to the graphene light source developed experimentally [5, 7]. In such a device, the electrons in graphene are

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accelerated and heated by the source to drain dc electric field with the strength F_x applied to the graphene sheet along the x-direction. We have developed a balance-equation approach on the basis of semi-classical Boltzmann equation (BE) to study the nonlinear electronic transport properties of graphene/substrate systems in the presence of strong electric fields [10], where the electrons interacting with impurities and acoustic- and optic-phonons have been considered. The drift velocity and temperature of electrons in graphene were calculated by solving self-consistently the momentum- and energy-balance equations along with the condition of electron number conservation. The results obtained from this self-consistent balance-equation approach have been applied to reproduce and explain the related experimental findings [11, 12]. In this work, we generalize this approach to investigate a freely suspended graphene device which works at relatively high-temperatures so that electronic couplings with acoustic-, optic-, and flexural-phonons are the main scattering mechanisms [13]. Furthermore, for freely suspended graphene there is no impurity and phonon scattering from the substrate. We focus on suspended graphene film fabricated by chemical-vapour-deposited (CVD) technique with a typical electron density $n_e \sim 10^{12}$ cm^{-2}. Employing our previous theoretical approach [10], the momentum- and energy-balance equations for electrons in graphene are obtained, respectively, as

$$\frac{eF_x}{\hbar} = \frac{16}{n_e}\sum_{\nu,\mathbf{k},\mathbf{q}} q_x f(\mathbf{K}) W(\mathbf{k}, \mathbf{k}+\mathbf{q}), \tag{1}$$

and

$$\frac{eF_x}{\hbar}\sum_{\mathbf{k}} E(\mathbf{k})\frac{\partial f(\mathbf{K})}{\partial k_x} = 4\sum_{\nu,\mathbf{k},\mathbf{q}} \hbar\omega_\nu f(\mathbf{K}) W(\mathbf{k}, \mathbf{k}+\mathbf{q}). \tag{2}$$

Here, $\mathbf{k} = (k_x, k_y)$ is the electron wavevector, $E(\mathbf{k}) = \hbar v_F|\mathbf{k}|$ with v_F being the Fermi velocity in graphene, $W(\mathbf{k}, \mathbf{k}') = (2\pi/\hbar)|U_\nu(q)|^2\delta_{\mathbf{k}+\mathbf{q},\mathbf{k}'}\delta[E(\mathbf{k}) - E(\mathbf{k}') + \hbar\omega_\nu]$ is the electronic transition rate for an electron from a state $|\mathbf{k}>$ to a state $|\mathbf{k}'>$, ω_ν is the phonon frequency, $f(\mathbf{K})$ is the drifted Fermi energy distribution function with μ being the Fermi energy (or chemical potential) and T_e the electron temperature in the present of the electric field, $\mathbf{q} = (q_x, q_y)$ is the phonon vector, and $\mathbf{K} = (k_x - k_F v_x/v_F, k_y)$ with v_x the drift velocity and k_F the Fermi wavevector for electrons. Moreover, the summation ν is for different phonon scattering mechanisms and $|U_\nu(q)|^2$ is the square of the matrix element for electronic interaction with the ν^{th} phonon, where $|U_{ap}(q)|^2 = (\hbar E_0^2 q/4\rho v_s)(1+\cos\theta)$, $|U_{op}(q)|^2 = g^2\hbar^2 v_F^2$ and $|U_{fp}(q)|^2 = D_0^2\cos^2(\theta/2)$ are respectively for electronic coupling with acoustic-, optic- and flexural-phonons and θ is the scattering angle [10, 13]. In this study we do not take the usual quasi-elastic scattering approximation for electron interacting with acoustic-phonons via deformation potential coupling and with flexural-phonons. We take $\hbar\omega_{op} = 196$ meV for optic-phonons and $\omega_{ac} = v_s q$ for acoustic- and $\omega_{fp} = \alpha q^2$ for flexural-phonons [13] with v_s being the sound velocity and $\alpha = 4.6\times10^{-7} m^2/s$ in graphene. Thus, we are able to evaluate the electron drift velocity v_x and the electron temperature T_e in freely suspended graphene as a function of electric field strength F_x through solving self-consistently Eqs. (1) and (2). In the presence of a driving dc electric field, thermal excitation of the carriers can occur in graphene [7, 9]. The corresponding density is evaluated roughly as $n_t = (\pi/6)(k_B T_e/\hbar v_F)^2$ [7]. Because the thermal excitation of the carrier density n_t is of the order of 10^{10} cm^{-2} even for electron temperature of $T_e \sim 1000$ K, we have that $n_e >> n_t$ for $T_e < 1000$ K. Therefore, the effect of thermal excitation of carriers via interband transition is relatively weak when T_e is less than 1000 K in CVD grown graphene film. The corresponding effects such as hole conduction, electron-hole recombination, Auger process, etc. can be neglected in the present calculation [14] when T_e is below 1000 K.

The dynamical or optical conductivity $\sigma(\omega, T_e)$ for electrons in graphene at a finite temperature and nonzero chemical potential can be calculated via [15]

$$\sigma(\omega, T_e) = \frac{e^2}{8\hbar}\left[\tanh\left(\frac{\hbar\omega + 2\mu}{4k_B T_e}\right) + \tanh\left(\frac{\hbar\omega - 2\mu}{4k_B T_e}\right)\right] + \frac{iD}{\pi(\omega + i\Gamma)}. \tag{3}$$

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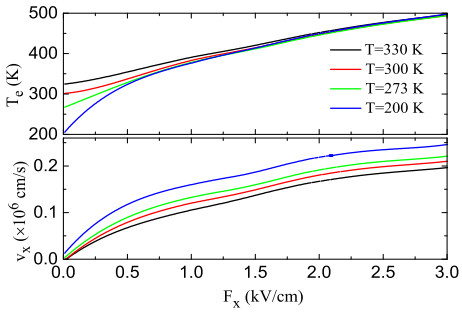

Fig. 1. The electron temperature T_e (upper panel) and the electron drift velocity v_x (lower panel) as a function of electric field strength F_x for different lattice temperatures T as indicated.

Here, $D = (v_F e^2/\hbar)\sqrt{\pi|n_e|}$ is the Drude weight, Γ is the electronic scattering rate [16], the chemical potential μ can be determined by the condition of electron number conservation, ω is the radiation frequency, and $\tanh(x)$ is the hyperbolic tangent function. The expression of $\sigma(\omega, T_e)$ indicates that light absorption can only be achieved when the photon energy is larger than twice the chemical potential and the thermal energy ($k_B T_e$), as a consequence of the quasi-linear energy spectrum for electrons in graphene. Thus, the corresponding optical properties of graphene depend strongly on the chemical potential and electron temperature T_e owing to the state-blocking effect. The universal optical conductivity of graphene can be obtained in the high frequency regime. With $\sigma(\omega, T_e)$, we can calculate the spectral function of an electronic system via [17]

$$A(\omega, T_e) = \frac{4\mathrm{Re}[y]}{|1 + \sqrt{\kappa_s} + y|^2}, \quad y = \frac{4\pi}{c}\sigma(\omega, T_e), \tag{4}$$

with c being the light speed in vacuum and κ_s the dielectric constant of the substrate. In this work, we take $\kappa_s = 1$ for freely suspended graphene in vacuum. Moreover, the spectral density of blackbody radiation per unit area from hot electrons with temperature T_e is given by Planck's law [18]

$$I(\omega, T_e) = \int_0^{2\pi} \frac{\hbar\omega^3 A(\omega, T_e)\cos\theta}{4\pi^3 c^2[\exp(\hbar\omega/k_B T_e) - 1]} d\Omega, \tag{5}$$

where $d\Omega = 2\pi \sin\theta d\theta$ is the solid angle element. In the present study, we consider a configuration of normal propagation of the light wave, i.e., by taking $\theta = 0$ into consideration. Thus, the spectrum function of the light emission from an electronic system is obtained as

$$I_0(\omega, T_e) = \frac{\hbar\omega^3 A(\omega, T_e)}{4\pi^3 c^2[\exp(\hbar\omega/k_B T_e) - 1]}, \tag{6}$$

which shows that the light emission spectrum of hot electrons is determined by the distribution of blackbody radiation and the spectral function $A(\omega, T_e)$. From I_0, the intensity of the light emission per unit area from the hot electrons in a freely suspended graphene is then given by

$$I_e = \int_0^{\infty} I_0(\omega, T_e) d\omega. \tag{7}$$

3. Results and discussions

In Figure 1 we show the electron temperature T_e and the electron drift velocity v_x as a function of the electric field strength F_x at different lattice temperatures T in freely suspended graphene. We find that the hot electron effect is pronounced even at relatively weak electric fields. This

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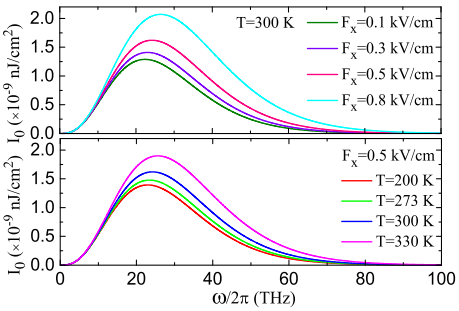

Fig. 2. The spectrum of light emission I_0 for different electric field strengths F_x (upper panel) and for different lattice temperatures T (lower panel).

is a result of the absence of impurity and phonon scattering from the substrate. The electrons in freely suspended graphene are dramatically heated by the driving electric field so that the electron temperature T_e increases almost linearly with electric field strength F_x in relatively high fields and high lattice temperature. Meanwhile, the electron drift velocity v_x increases from linearly to nonlinearly with driving electric field F_x. We find that the electron drift velocity v_x decreases with increasing lattice temperature T in freely suspended graphene, which indicates that the resistivity R increases as the temperature T increases. This finding differs from previous theoretical results by Vasko and Ryzhii [19]. They found that the increase in lattice temperature can suppress the resistance in intrinsic graphene on SiO_2 substrate. The physical reason for this difference is that the carrier scattering mechanisms are significantly different in the two graphene systems. More importantly, the electron temperature can directly be obtained based on present theoretical approach, which is vital for understanding and studying the electroluminescence from graphene. The results obtained from present self-consistent calculations can reproduce qualitatively the experimental results [5, 7].

The spectrum of light emission from hot electrons in graphene I_0 in the present of different electric field strengths F_x and at different lattice temperatures T is shown in Figure 2. We note that the spectrum of blackbody-like radiation can be observed from electrically driven graphene. The intensity of the light emission increases with increasing electric field strength because T_e increases with F_x. Similarly, stronger light emission can be observed for a higher lattice temperature because T_e increases with T (see upper panel of Figure 1). A blue-shift of the light emission spectrum can be observed with increasing electric field and/or lattice temperature. The physical reason behind this effect is that the number of high energy (frequency) electrons increases with increasing driving electric field and/or lattice temperature. We notice that the shape of the THz emission spectrum obtained theoretically from this study is in line with the corresponding experimental results [7]. More interestingly, we found that the light emission spectra are in the THz bandwidth when the driving electric fields result in $T_e < 1000$ K. This finding implies that intense THz emission can be generated electrically via blackbody radiation from graphene. Electrically tunable visible light emission has been observed experimentally from hot electrons with very high electron temperatures (1500 K-2500 K) in encapsulated graphene. Moreover, it was found that the hot phonon effect can play an important role in affecting blackbody radiation from graphene when electron temperature is above 1500 K [9, 20]. Because the present study is focused on THz blackbody radiation from graphene with $T_e < 1000$ K, the hot phonon effect can be neglected in the calculations.

Figure 3 shows the intensity of light emission I_e from hot electrons in graphene as a function of electric field strength F_x for different lattice temperatures. THz emission can be strongly generated sith higher intensity for lager dc electric field and/or at a higher lattice temperature and/or at a higher lattice temperature. The dependence of the intensity of the light emission generated

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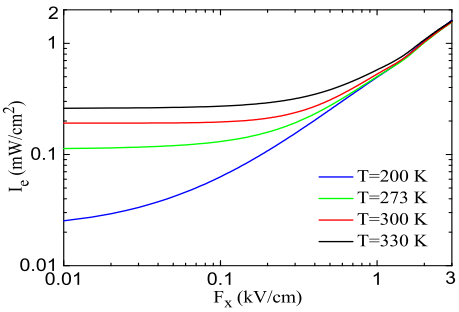

Fig. 3. The intensity of light emission from graphene I_e as a function of electric field strength F_x for different lattice temperatures T.

electrically from graphene upon driving electric field was observed experimentally [6–8]. The theoretical results obtained here indicate that strong THz emission, with an intensity up to mW/cm^2, can be generated electrically in freely suspended graphene at room temperature. This is due to the fact that the electron temperature T_e significantly increases with driving electric field as shown in Figure 1. Electrons can gain energy from the driving electric field and lose it via emission of phonons and photons. The optic-phonon energy in graphene is relatively high ($\hbar\omega_{op} \sim 196$ meV or 2275 K) and therefore the electron-phonon interaction in low-energy regime is dominated by = coupling with acoustic- and flexural-phonons. Because electronic coupling with acoustic- and flexural-phonons is a low-energy scattering mechanism, the electronic energy relaxation via these phonon couplings in graphene is less efficient. As a result, the effect of heating of electrons in graphene becomes strong. Once electrons are highly heated, strong blackbody radiation occurs. Therefore, in the presence of relatively strong dc electric fields (e.g. $F_x < 1$ kV/cm), the emission of THz radiation can become a principle channel for electronic energy relaxation. These theoretical findings and analysis can be used to understand and explain the important experimental results [2,7,8]. In Figure 3, the intensity of light emission I_e depends strongly on the lattice temperature T in relatively weak electric fields, whereas the lattice temperature dependence of the light emission intensity is inconspicuous in relatively strong electric fields because the difference in electron temperature for different lattice temperatures becomes smaller in strong electric fields as shown in Figure 1. Finally, we estimated the efficiency of the proposed device as THz source with dissipated Joule power $I_j = en_e v_x F_x$. It was found that the efficiency of the proposed THz emission decreases with increasing the electric field intensity. The efficiency in the suspended graphene is about 0.19% for a typical electric field intensity $F_x = 0.1$ kV/cm and $n_e = 1 \times 10^{12}$ cm^{-2} at room temperature. At present, the efficiency of the small practical THz and infrared sources from thermal radiations are all far less than 1% [21]. Thus, the proposed graphene mode provides a feasible choice for generating THz.

4. Conclusions

In this study, we have developed a theoretical approach to study THz blackbody radiation from freely suspended graphene driven electrically. It was found that strong THz emission can be generated via the hot electron effect due to electron coupling with phonons in graphene in the presence of relatively intense driving electric fields. The obtained theoretical results are in agreement with recent experimental findings.

At present, practical THz light sources are mainly generated electrically via, e.g., free-electron lasers and quantum cascade lasers and optically via, e.g., ultrafast laser pulses. The THz light emission generated electrically via blackbody radiation from graphene can provide cheap, compact and broadband THz sources. We hope that the results obtained and discussed in this

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work can help us to gain an in-depth understanding of graphene based electroluminescent devices and to provide a new tunable THz emission.

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