Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp226-227

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Terahertz Laser on Optically Pumped Graphene: Concept and its Substantiation

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1. Introduction

Under optical excitation, the interband population inversion in graphene can be achieved [1,2]. Due to the gapless energy spectrum of graphene, such a population inversion can lead to the stimulated emission of long-wavelength photons, in particular, the photons in the terahertz (THz) range of frequencies. The results of recent experiments [3] confirm this. A THz laser based on optically pumped graphene with metal waveguide was considered and evaluated recently [4]. In this paper, we propose the concept of a THz laser based on an optically pumped graphene structure with a Fabri-Perrot type resonator and substantiate this concept.

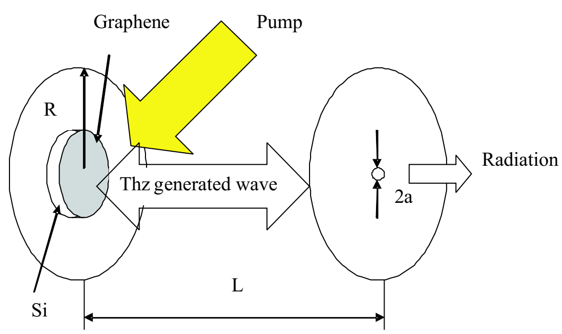

Figure 1: Schematic view of graphene THz laser with optical pumping.

2. Device structure

The active section of the laser proposed consists of a pure Si layer of thickness t followed by a graphene-SiC-Si-SiC-graphene structure (with thin SiC layers) of the net thickness d. Thus, the laser active section comprises two separated graphene layers. The first Si layer is adjacent to a metal mirror (made of ,say, Al, Au, or Ag). Another mirror with a hole of diameter $2a$ is placed at the distance L from the first one, so that a Fabri-Perrot resonator is formed. The laser structure under consideration is shown in Fig. 1. The graphene layers are excited by optical radiation with the photon

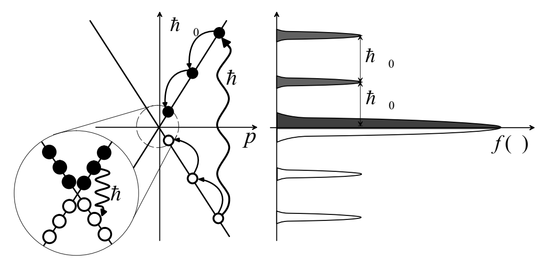

Figure 2: Transitions associated with the optical pumping due to absorption of photons with energy $\hbar\Omega$, emission of THz radiation with photon energy $\hbar\omega$, intraband relaxation due to emission of optical phonons with energy $\hbar\omega_0$ (wavy and smooth arrows, respectively), and the distribution functions of electrons and holes (both thermal and photogenerated).

energy $\hbar\Omega$. It is assumed that $\hbar\Omega$ somewhat exceeds the value $2n\hbar\omega_0 = \hbar\Omega_0$, where $\hbar\omega_0 \simeq 0.2$ eV is the optical phonon energy and $n = 1, 2, ...$ In this case, the photogeneration of electrons and holes followed by the emission of an optical phonon cascade, results in substantial electron and hole populations of the conduction band bottom and the valence band top, respectively [1] (see Fig. 2).

3. THz absorption coefficient

The absorption coefficient of THz photons with the energy $\hbar\omega$ in an optically pumped graphene layer is expressed via the real part of the dynamic conductivity σ_ω as follows: $\alpha_\omega = \dfrac{4\pi}{c}\mathrm{Re}\sigma_\omega$, where c is the speed of light. The dynamic ac conductivity σ_ω comprises both the interband and intraband contributions, so that $\mathrm{Re}\sigma_\omega = \mathrm{Re}\sigma_\omega^{(inter)} + \mathrm{Re}\sigma_\omega^{(intra)}$. If the electron and hole energy distributions near the band edges are characterized by the Fermi distribution functions with the quasi-Fermi energy ε_F and the effective temperature T, one obtains $\mathrm{Re}\sigma_\omega^{(inter)} = \dfrac{e^2}{2\hbar}\tanh\left(\dfrac{\hbar\omega - 2\varepsilon_F}{4kBT}\right)$ and

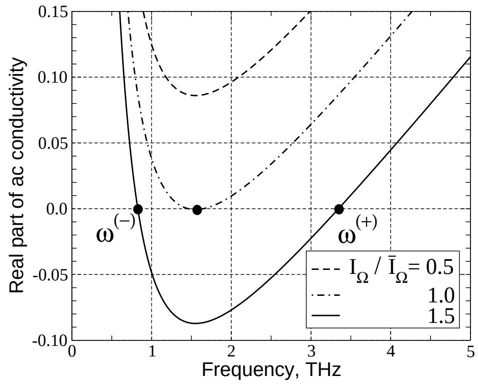

Figure 3: Example of $\mathrm{Re}\sigma_\omega$ (normalized) vs $\omega/2\pi$ dependences at different ratios of pumping intensity I_Ω and its characteristic value $\overline{I_\Omega}$.

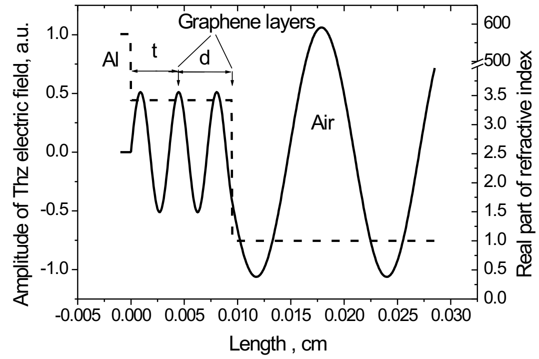

Figure 4: Spatial distribution of the THz electric field (solid line) and the real part of refractive index (dashed line) in the Fabri-Perrot resonator.

$\mathrm{Re}\sigma_\omega^{(intra)} = \dfrac{2e^2 k_B T\tau \ln[1+\exp(\varepsilon_F/k_BT)]}{\pi\hbar^2(1+\omega^2\tau^2)}$. Here e is the electron charge, k_B is the Boltzmann constant, and τ is the electron and hole momentum relaxation time. The case $\varepsilon_F = 0$ corresponds to the equilibrium, while the case $\varepsilon_F > 0$ corresponds to the interband population inversion. As follows from eq. (3) in the latter case, $\mathrm{Re}\sigma_\omega^{(inter)} < 0$ for $\hbar\omega < 2\varepsilon_F$.

Since the electron and hole densities increase with increasing optical pumping intensity I_Ω, the quasi-Fermi energy ε_F also increases. This implies that at sufficiently strong pumping, $\mathrm{Re}\sigma_\omega$ can become negative in a certain range of frequencies. Due to a strong contribution of the intraband transitions (i.e., a strong Drude absorption) in the range of low frequencies, the frequency range where $\mathrm{Re}\sigma_\omega < 0$ is sandwiched between some characteristic frequencies $\omega^{(-)}$ and $\omega^{(+)}$ with $\omega^{(+)}-\omega^{(-)}$ increasing when I_Ω increases (see Fig. 3).

Equations for $\mathrm{Re}\sigma_\omega^{(inter)}$ and $\mathrm{Re}\sigma_\omega^{(intra)}$ were obtained for the Fermi distributions of electrons and holes near the edge of the bands. If the electron-electron, electron-hole, and hole-hole interactions do not provide an effective "fermisation" of the electron and hole energy distributions in a narrow energy range near $\varepsilon = 0$, the equations in question should be modified taking into account the deviation of the distributions from the Fermi distribution [2]. However, this can be essential only in not so interesting range of fairly small ω, in which the achievement of the negative absorption coefficient is suppressed by the Drude mechanism.

4. Condition of lasing

Using the above equations, we showed that at sufficiently strong optical pumping the real part of the net dynamic conductivity $\mathrm{Re}\sigma_\omega < 0$ and, hence, the THz absorption coefficient $\alpha_\omega < 0$ in the THz range. The threshold value of the pumping intensity strongly depends on the nonradiative recombination time τ_R. However, even at most "pessimistic" (i.e., rather small) values of τ_R, the threshold intensity can be easily overcome using the standard lasers. As a result, we obtained that the amplification of THz wave with the frequency $\omega/2\pi = 2.46$ THz (wavelength $\lambda = 122$ μm) associated with a single pass of two graphene layers is $-2\alpha_\omega = 0.04$. For the calculations we assumed that the thicknesses of pure Si layers $t = d = 50$ μm, the length of Fabri-Perrot resonator $L = 1$ cm, the radius of the mirrors $R = 0.5$ cm, and the radius of the hole $a = 0.05$ cm. The THz field distribution in the Fabri-Perrot resonator calculated using the Maxwell equations for these parameters is shown in Fig. 4. The coefficient of losses in the pure Si layers was estimated as $\alpha_\omega^{(Si)} = 0.007$ [5]. Our calculations using the data from Ref. [5] resulted in the following value of the reflection coefficient of the mirrors: $r_\omega^{(M)} = 0.994$. As found, the diffraction losses are characterized by $\alpha_\omega^{(D)} \simeq 0.001$, whereas the calculations of the losses associated with the output radiation through the hole in the mirror yield $\alpha_\omega^{(H)} \simeq 0.005$. As a results, for the net losses in the Fabri-Perrot resonator one obtains $\alpha_\omega^{(F-P)} = \alpha_\omega^{(Si)} + [1 - r_\omega^{(M)}] + \alpha_\omega^{(D)} + \alpha_\omega^{(H)} \simeq 0.019$. Comparing the above values of α_ω and $\alpha_\omega^{(F-P)}$, one can see that $2\alpha_\omega + \alpha_\omega^{(F-P)} \simeq -0.021$, i.e., the condition of lasing in the THz laser under consideration can be well satisfied.

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