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# Self-Excitation of Terahertz Plasma Oscillations in Optically Pumped Graphene

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## 1. Introduction

The gapless energy spectrum of electrons and holes in graphene results in the possibility of the radiative recombination with emission of the long-wavelength photons, in particular the terahertz (THz) photons. Under the optical or injection pumping the interband population inversion of nonequilibrium electrons and holes in graphene is possible [1,2]. Due to this, optically pumped graphene layer supplied with a properly designed resonant cavity or waveguide for electromagnetic waves can emit the stimulated THz radiation [1,3]. Recent experiments [4] confirm the possibility of stimulated THz radiation from optically pumped graphene.

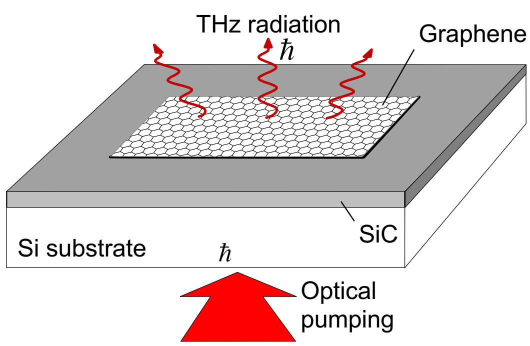


Figure 1: Schematic view of device structure.

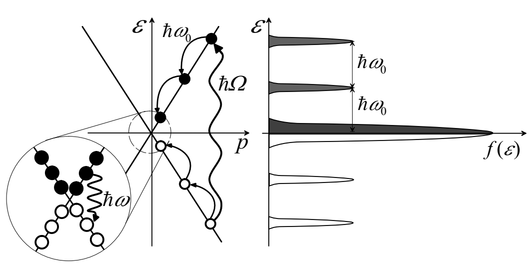


Figure 2: Arrows indicate the transitions associated with pumping as well as with intraband and interband processes. Right panel shows the steady-state energy distributions of photogenerated electrons and holes.

Since the electron-hole system in a graphene layer can exhibit plasma oscillations [5], so that this system can play the role of the plasma resonant cavity [6], the stimulated interband emission of not only photons but also plasmons is possible [1] (see also Ref. [7]). The stimulated generation of plasmons, i.e., the self-excited plasma oscillations lead to the oscillations of the charges in the graphene plane and , hence, to the oscillations of i.e., to the oscillations of the system dipole moment, which, in turn, lead to the emission of THz electromagnetic waves to the outer space. As a result, the plasma resonant cavity can be used instead of the resonator (or waveguide) for the electromagnetic radiation.

In this paper, we calculate the spectra of plasma oscillations in single- and periodic structures with optically pumped graphene and consider the self-excitation of plasma oscillations in such structures in connection with the concept of THz emitter utilizing these oscillations.

## 2. Device structure and operation principle

The device under consideration comprises a graphene rectangular sheet with the lateral sizes $2L$ and $2H$ (plasma cavity) on a thin SiC layer separating graphene from Si- substrate (as schematically shown in Fig. 1) or a periodic array of such cavities. It is assumed that the graphene sheet is excited by optical radiation with the photon energy $\hbar\Omega \geq 2n\hbar\omega_0 = \hbar\Omega_0$, where $\hbar\omega_0 \simeq 0.2$ eV is the optical phonon energy and $n = 1, 2, ....$ In this case, the photoexcited electrons and holes after the emission of the optical phonon cascade are accumulated near the bottom of the conduction band and the top of the valence band, respectively (see Fig. 2). At sufficiently effective electron-electron, electron-hole, and hole-hole collisions, the energy distributions can be characterized by the Fermi function with the Fermi energy $\varepsilon_F$ and the temperature $T$, which are the same for electrons and holes (see also Ref. [2], where the case of strongly nonequilibrium energy distribution was studied). When $\hbar\Omega - \hbar\Omega_0 \leq k_BT$, where $k_B$ is the Boltzmann constant, the temperature $T$ is close to the lattice temperature.

## 2. Spectrum of plasma oscillations

The spectrum of the plasma oscillations, i.e., the values of the complex frequency of plasma oscillations $\omega$ (damped or self-excited) in the device under consideration is determined from the equations governing the electron and hole motion in the graphene sheet coupled with the two-dimensional Poisson equation for the self-consistent ac electric potential $\varphi_\omega(x,z)$ (the axis $x$ is directed in the graphene plane, whereas the axis $z$ is directed perpendicular to this plane) with the pertinent boundary conditions. The latter correspond to the confinement of electrons and holes in the region $-L \leq x < +L$. The sign of the imaginary part Im$\omega$ determines whether the plasma oscillations are damped ( Im$\omega < 0$) or self-excited (Im$\omega > 0$). Taking into account the features of the energy spectrum and energy distributions of electrons and holes, for the real part of the frequency of the $l$-th plasma mode Re$\omega = \omega_l$ ($l = 1,2,3,...$ are the mode indices), we obtain $\omega_l \simeq \xi_l\sqrt{l}\sqrt{\dfrac{\pi\ln[2+2\exp(\varepsilon_F/k_BT)]\,e^2k_BT}{æ\hbar^2L}}$, where $e$ is the electron charge, æ is the dielectric constant, and $\xi_l$ are coefficients on the order of unity, which are found numerically.

## 3. Plasma oscillations self-excitation

The signal ac conductivity of graphene $\sigma_\omega$ is determined by the interband and intraband transitions¿ Under the pumping conditions, $\varepsilon_F > 0$ (this implies the population inversion), and the real part of the interband ac conductivity Re$\sigma_\omega^{(inter)}$ is negative in the range $\hbar\omega < 2\varepsilon_F$. The real part of the intraband contribution to the ac conductivity Re$\sigma_\omega^{(intra)}$ is determined by the electron and hole intraband dynamics, their densities, as well as by the scattering on impurities and acoustical phonons and the electron-hole scattering. If the radiative damping of plasma oscillations is insignificant, the self-excitation of the plasma modes with Re $\omega = \omega_m$ occurs when Re$[\sigma_\omega^{(inter)} + \sigma_\omega^{(intra)}]|_{\omega=\omega_l} < 0$ with Re$\sigma_\omega^{(inter)} = \dfrac{e^2}{2\hbar}\tanh\left(\dfrac{\hbar\omega - 2\varepsilon_F}{4kBT}\right)$ and Re$\sigma_\omega^{(intra)} = \dfrac{2e^2k_BT\tau\ln[1+\exp(\varepsilon_F/k_BT)]}{\pi\hbar^2(1+\omega^2\tau^2)}$. Here $\tau$ is the electron and hole momentum relaxation time. We show that the conditions of the plasma oscillations self-excitation are reduced to the following inequalities: $I_\Omega > I_\Omega^{(th)}$ and $\omega^{(-)} < \omega_l < \omega^{(+)}$. Here $I_\Omega^{th} \propto T^{5/3}/\tau^{1/3}\tau_R$ is the threshold value of the optical pumping power, $\omega^{(\pm)} = \omega^{(th)}[1 \pm \sqrt{2/3}\sqrt{(I_\Omega/I_\Omega^{th} - 1)}]$ (this is valid at not too large ratios $I_\Omega/I_\Omega^{th}$), $\omega^{(th)} \simeq 1.9(k_BT\tau/\hbar)^{2/3}/\tau$, and $\tau_R$ is the recombination time. Figure 3 demonstrates the dependences of $\omega_1$, $\omega_3$, $\omega^{(+)}$, and $\omega^{(-)}$ on the pumping intensity, calculated for $2L = 2\mu$m, $T = 77$ K $\hbar\Omega = 0.8$ eV (i.e., $\hbar\Omega \geq 4\hbar\omega_0$), $\tau = 1$ ps, and different values of $\tau_R$. As seen from Fig. 3, the plasma frequencies $\omega_1$ and $\omega_3$ increase with increasing $I_\Omega$. This is due to an increase in the electron and hole densities associated with pumping. One can see also that at the chosen parameters only the fundamental mode ($l = 1$) falls into the frequency range corresponding to its self-excitation (between the dashed curves). In the case of large $L$, a wide spectrum of the plasma modes can self-excite. In the devices with periodic array of relatively small plasma cavities, the spectrum of the self-excited modes can be rather complex.

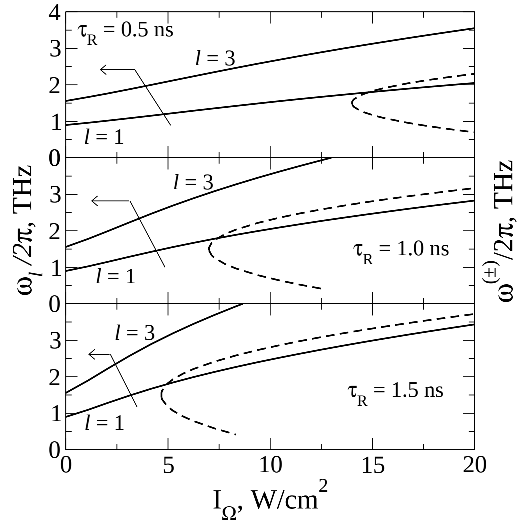


Figure 3: Frequencies of plasma modes $\omega_l$ with $l = 1$ and $l = 3$ and characteristic frequencies $\omega^{(+)}$ (upper branch of dashed curve) and $\omega^{(-)}$ (lower branch) vs pumping intensity $I_\Omega$ for different recombination times $\tau_R$.

## 4. Conclusions

We calculated the spectra of plasma oscillations in optically pumped graphene and found the conditions of their self-excitation. The effect of self-excitation of plasma oscillations under consideration can be used to generate THz radiation. The performance of the device under consideration operating as the THz emitter can be enhanced by the utilization of multi-cavity structures.

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