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Full Length Article

Terahertz plasmon-emitting graphene-channel transistor

A.A. Dubinov[a,*], V.Ya. Aleshkin[a], S.V. Morozov[a], V. Ryzhii[b,c], T. Otsuji[b]

[a] Institute for Physics of Microstructures, Russian Academy of Sciences, 603950, Nizhny Novgorod, Russia
[b] Research Institute of Electrical Communication, Tohoku University, 980-8577, Sendai, Japan
[c] Center for Photonics and Infrared Engineering, Bauman Moscow State Technical University, 105005, Moscow, Russia

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ABSTRACT

In this work we propose and analyze the possibility of creating terahertz plasmon-emitting graphene-channel transistor. It is shown that at electric pumping the damping of the terahertz plasmons can give way to their amplification, when the real part of the dynamic conductivity of graphene becomes negative in the terahertz range of frequencies due to the interband population inversion.

Introduction

Currently compact terahertz (THz) radiation sources are enjoyed very much in demand. Quantum cascade lasers (QCLs) reached the most progress in this area, but there is the terahertz frequency region (5–12 THz) in which the generation of QCLs is impossible due to the strong phonon absorption in A3B5 semiconductors [1].

Graphene has attracted considerable attention due to its massless and gapless energy spectrum. So optical or injection pumping of graphene can enable negative-dynamic conductivity in the terahertz spectral range. This may lead to new types of THz lasers [2,3]. In the graphene structures with p-i-n junctions, the injected electrons and holes have relatively low energies compared with those in optical pumping, so that the effect of carrier cooling can be rather pronounced, providing a significant advantage of the injection pumping in realization of graphene THz lasers. Authors of Ref. 4 implement a forward-biased graphene structure with a lateral p-i-n junction in a distributed-feedback dual-gate graphene-channel field-effect transistor (DFB-DG-GFET) and experimentally observe a single mode emission at 5.2 THz at 100 K.

In this work we have considered the possibility of generating two-dimensional plasmons in a transistor of this kind at room temperature.

Results of calculation

As for the structure GFET [4], it is assumed that graphene will be synthesized by the thermal decomposition of a C-face 4H-SiC substrate. The GFET will be fabricated using a standard photolithography and a gate stack with SiN dielectric layers and gold contacts (see Fig. 1). For calculations, the sizes and materials are the same as Ref. 4. The edges of a graphene layer are connected to the side contacts (Source and Drain contacts). The dc voltage V is applied between the side contacts to provide the forward bias of the p-i-n junction. The p- and n-sections can be created using highly conducting gates over these sections to which the gate voltages $V_p = -V_g < 0$ (G1) and $V_n = V_g > 0$ (G2) are applied.

We analyzed the plasmons propagating along graphene in Z direction. Under electrical excitation, the electron and hole densities exceed substantially their equilibrium values in graphene. Due to this, one can consider the electron and hole systems under consideration as characterized by the quasi-Fermi energies ${\varepsilon_F}^e = -{\varepsilon_F}^h = \varepsilon_F$, respectively, and the effective temperature T, the electron and hole momentum relaxation time τ. Under these conditions, the quasi-Fermi energy ε_F in the i-section (neglecting the leakage and recombination in the lowest approximation) is given by $\varepsilon_F = eV/2$, where e is the electron charge. The net dynamic conductivity of graphene in the lateral direction for frequency ω was calculated in

* Corresponding author.
E-mail address: sanya@ipmras.ru (A.A. Dubinov).

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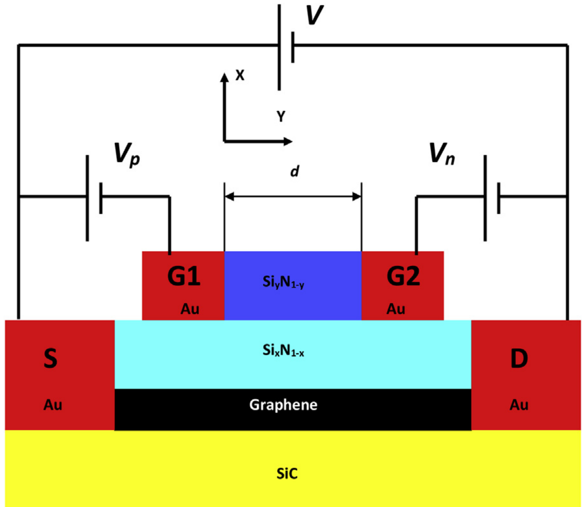

Fig. 1. Scheme of terahertz plasmon-emitting graphene-channel transistor.

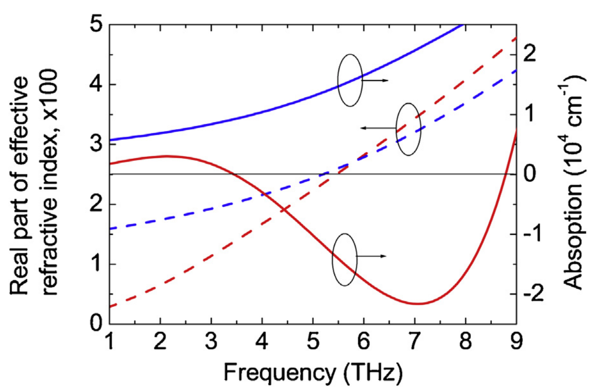

Fig. 2. Frequency dependence of the real part of effective refractive index and absorption for plasmons under (blue curves) and beyond (red curves) contacts.

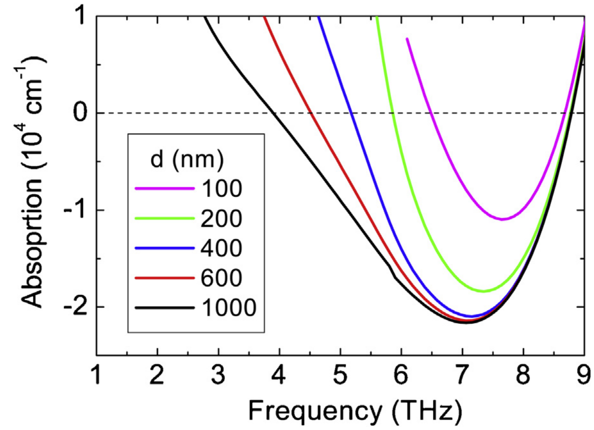

Fig. 4. Frequency dependence of the absorption for plasmons with different *d*.

the approximation of Ref. 5:

$$\sigma = \left(\frac{e^2}{4\hbar}\right)\frac{8k_BT\tau}{\pi\hbar(1-i\omega\tau)}\ln\left[1+\exp\left(\frac{\varepsilon_F}{k_BT}\right)\right]+$$

$$\left(\frac{e^2}{4\hbar}\right)\left[\tanh\left(\frac{\hbar\omega-2\varepsilon_F}{4k_BT}\right)-\frac{4\hbar\omega}{i\pi}\int_0^\infty\frac{G(\varepsilon,\varepsilon_F)-G\left(\hbar\omega/2,\varepsilon_F\right)}{(\hbar\omega)^2-4\varepsilon^2}d\varepsilon\right] \qquad (1)$$

where $G(\varepsilon,\varepsilon_F)=\frac{\sinh(\varepsilon/k_BT)}{\cosh(\varepsilon_F/k_BT)+\cosh(\varepsilon/k_BT)}$, e is the electron charge, $\hbar$ is the reduced Planck constant, k_B is the Boltzmann constant.

For calculation of the effective refractive index and absorption (Fig. 2) of plasmons under/beyond gold gate contacts we used the transfer matrix method [6]. We assumed that the plasmon will be localized only between the gate contacts and, therefore, did not take into account the side contacts in the calculations. This assumption was further confirmed. We used next parameters: ε_F =20 meV, T =300 K, τ =1 ps. From the Fig. 2 you can see that gain (negative absorption) is possible in THz frequency range (from 3.5–8.5 THz) for plasmon beyond gold contacts. Figure 2 shows that real part of the effective refractive index is very high (30–500). So due to the relatively small plasmon group velocity, the absolute value of their gain can be large (~ 20,000 cm^{-1}) that the same in modes of dielec-

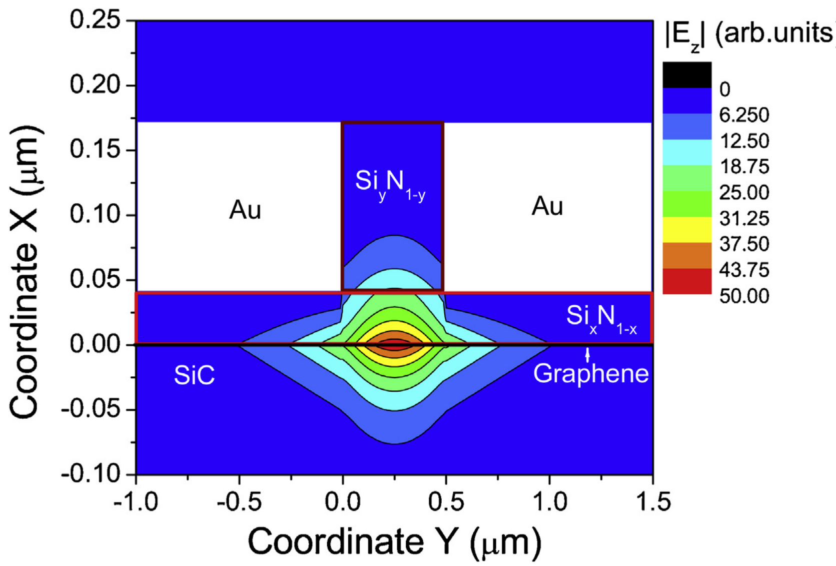

Fig. 3. Spatial distribution of Z - component of the plasmon electric field under consideration for d = 500 nm. The wave frequency is $\omega/2\pi$ =5.3 THz.

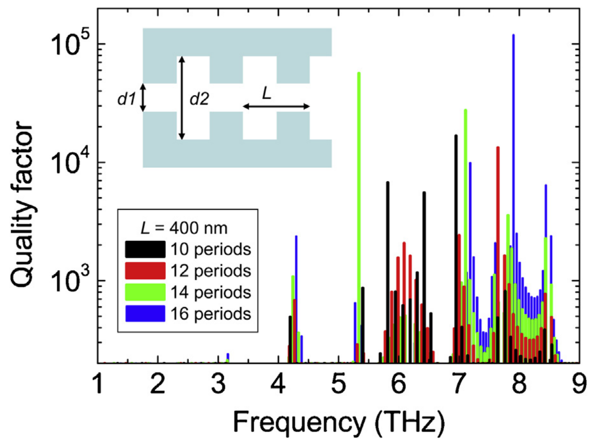

Fig. 5. Frequency dependence of the Quality factor for different quantity of periods. $d1 = 200$ nm, $d2 = 500$ nm. The inset shows the scheme of DFB type waveguide structure.

tric waveguides ($\sim 60\,\mathrm{cm}^{-1}$) [6]. Due to the same there is strong localization of electric field around graphene.

For calculation of the electric field distribution (Fig. 3) and absorption (Fig. 4) of plasmons with different *d* (size between gold contacts) we used the transfer matrix [6] and the effective refractive index method [7]. Figure 4 shows that the gain region decreases as the distance between contacts *d* decreases. For *d* larger 400 nm gain saturation is observed at the frequency range of 6–8.5 THz.

To make single-mode lasing, one needs to implement a pertinent high-Q (Quality factor) laser cavity structure in which the gain medium of the graphene under carrier injection pumping is accommodated. Such a laser cavity can be realized by using the gate electrodes as a DFB type waveguide structure [4] (See the inset in Fig. 5). The Quality factor of DFB type structure with periodic ($L = 400$ nm) modulation of the *d* ($d1 = 200$ and $d2 = 500$ nm, correspondently) was calculated using the transfer matrix method for some periods (Fig. 5). From Fig. 5 you can see, that even for a small number of periods, frequencies with a huge Quality factor are observed. The reason for this is big difference between effective refractive indices of plasmon with different *d*. We note that the necessary dimensions of the periodic plasmon structure are substantially smaller in comparison with the periodic slot mode structure [4] due to the large value of the plasmon effective refractive index.

Conclusions

We theoretically examined the terahertz plasmon-emitting graphene-channel transistor and conducted that due to the relatively small plasmon group velocity (high effective refractive index), the absolute value of their gain can be large that the same in modes of dielectric waveguides. So a small number of periods in DFB structure will allow observed single-mode lasing.

Authors' statements

Authors confirm that there are no known conflicts of interest, other than directly indicated in the manuscript.

Authors confirm that if the study described in the manuscript of the work involved animals or humans as subjects, then these studies were performed according to applicable standards as directly described in the manuscript.

Authors confirm that, if the study described in the manuscript of the work involved animals or humans as subjects, then written informed consent was obtained from all human participants involved in the study as directly described in the manuscript.

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