Graphene nanoelectromechanical resonators for the detection of modulated terahertz radiation

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Abstract
We propose and analyze a detector of modulated terahertz (THz) radiation based on the graphene field-effect transistor with a mechanically floating gate also made of graphene. The THz component of incoming radiation induces resonant excitation of plasma oscillations in the graphene layers (GLs). The rectified component of the ponderomotive force between the GLs invokes resonant mechanical swinging of the top GL, resulting in drain current oscillations. To estimate the device responsivity, we solve the hydrodynamic equations for the electrons and holes in graphene which govern the plasma-wave response, and the equation describing the graphene membrane oscillations. The combined plasma-mechanical resonance raises the current amplitude by up to four orders of magnitude. The use of graphene for the elastic gate and conductive channel allows the voltage of both resonant frequencies to be tuned within a wide range.

Keywords: graphene, terahertz radiation, nanoelectromechanical systems, plasma waves, field-effect transistors

(Some figures may appear in colour only in the online journal)
schematic view of suspended GL static deflection (bold line) and its swinging \( \delta \text{a}_{\gamma}(x) \) due to the driving GHz force (thin lines), (c) band diagram of the double-GL structure under applied voltage \( V_G \) (filled areas are occupied by electrons).

significantly increase the efficiency of THz detection using transistor-like structures and provide a highly selective (resonant) response [15].

In this paper, we propose a resonant detector of modulated THz radiation which exploits both the unique mechanical and electronic properties of graphene. The necessity for resonant transduction of modulated THz signals may appear in future telecommunication systems, where the THz carrier frequencies are expected to allow for a higher transmission rate.

The structure of the proposed device comprises a graphene FET with a mechanically floating gate also made of graphene (figure 1(a)). The amplitude-modulated signal \( \delta V(t) \) with the modulation frequency \( \omega_{0m} \) is delivered from the THz antenna and applied between the top and bottom layers. The carrier frequency \( \omega \) lies in the THz range, close to the eigenfrequency \( \Omega \) of the plasma oscillations. The modulation frequency \( \omega_{0m} \) is in the GHz range, close to the frequency \( \Omega_{m} \) of the top gate mechanical oscillations.

The carrier frequency excites plasma oscillations, which results in an increase in the electric field strength between the top and bottom GLs. This, in turn, leads to a large ponderomotive force between them. The force spectrum contains the rectified component oscillating at the modulation frequency, which invokes mechanical oscillations of the graphene gate (figure 1(b)). The output signal of the detector is the ac source-drain current varying due to the changing gate-to-channel capacitance. Terahertz demodulators exploiting combined plasmonic mechanical resonance were first proposed in [16–18]. Those devices incorporated a conductive mechanically-floating cantilever [16], nanowire or a nanotube [17] suspended over the channel of a high-electron-mobility transistor. The structures of two aligned nanotubes were also studied [18]. The use of graphene in such a device allows one to attain higher electron mobility, and thus a higher responsivity. The large breaking strain of graphene [5, 7] enables the gate rigidity to be tuned within a wide range, which is hardly possible for metallic cantilevers.

To estimate the plasma-wave response of the device, we apply the hydrodynamic equations for massless electrons and holes in graphene [19]. The mechanical vibrations are modelled using the elasticity theory equations for graphene membranes [20, 21]. We show that the resonant responsivity of modulated radiation detection is proportional to \( Q_mQ_p^2 \), where \( Q_m \) and \( Q_p \) are the quality factors of mechanical and plasma resonators, respectively. We also show that the resonant amplitude of source-drain current oscillations is proportional to the third power of the electron mobility. Thus, the resonant device responsivity appears to be large, reaching \( \sim 3 \text{ A W}^{-1} \) per micron width of the GLs. The gate voltage can effectively tune both the plasma and mechanical resonant frequencies. The optional bottom gate below the whole structure would allow the independent control of those frequencies. The device could also be used as an element of a mixer or a heterodyne detector if two THz frequencies are fed in and the difference is in resonance with the mechanical eigenfrequency. It can also operate as a detector of non-modulated THz radiation, with the responsivity a factor of \( Q_m \) smaller than that in the case of the modulated radiation.

This paper is devoted to the analytical model describing the device output current and responsivity. Section 2 deals with the plasma-wave response of the structure. In section 3, the mechanical oscillations of the suspended graphene gate are considered. In section 4, we estimate the output current of the device and its responsivity, and discuss possible generalizations of the considered structures. Section 5 contains the main conclusions.

2. Plasma-wave response

The proposed device consists of two GLs with the top layer suspended over the bottom layer (figure 1(a)). The length and width of the layers are \( L \) and \( W \gg L \), respectively, and the vertical distance between the GLs is \( d \). The constant gate voltage \( V_G \) is applied between left-side contacts to the GLs, and a bias voltage \( V_D \) (drain voltage) is applied across the bottom GL, allowing for dc current flow. The modulated THz signal

\[
\delta V(t) = \delta V_m \cos (\omega t) \left[ 1 + m \cos (\omega_{0m} t) \right]
\]  

(1)

\( m \) is the modulation depth) is delivered from the THz antenna and applied between the top and bottom layers.

Application of the dc gate voltage \( V_G \) leads to the accumulation of electrons and holes in the opposite layers, as shown in figure 1(c). In the absence of a built-in voltage, the Fermi energies \( e_F \) of the electrons and holes are equal in modulus and opposite in sign. The electron and hole two-dimensional sheet densities \( \Sigma \) are related to \( V_G \) via a local capacitance relation

\[
CV_G = e\Sigma,
\]  

(2)

\( C \) is the gate capacitance.
where $C = (C_eC_d/2)/(C_e + C_d/2)$ is the effective specific capacitance corresponding to the series connection of geometric capacitance $C_e$ and quantum capacitances. The geometric capacitance per unit area is $C_e = \varepsilon_0 / d$. The quantum capacitance, defined by $C_q = e^2 \partial^2 \Sigma / \partial \phi^2$ [22], accounts for the dependence of the Fermi energy on the electric field strength between the GLs (figure 1(c)). For large distances between GLs ($d \gtrsim 20 \text{ nm}$ at room temperature) or for high carrier densities, $C_q$ significantly exceeds the geometric capacitance. In such conditions, $C = C_q$, which will be assumed in the following.

Consider the plasma wave response of the transistor structure in figure 1(a) to the application of a small harmonic signal $\delta V e^{-i\omega t}$ between the GLs. The resulting voltage difference between the top and bottom layers, $\delta \phi_+ - \delta \phi_-$, is related to the perturbation of the charge density $e\delta \Sigma$ via

$$C(\delta \phi_+ - \delta \phi_-) = e\delta \Sigma.$$  \hspace{1cm} (3)

Combining the Ohm’s law with the continuity equations for the top and bottom GLs, we can relate the density perturbation $\delta \Sigma$ to the perturbations of top and bottom layer potentials $\delta \phi_\pm$:

$$i\omega e\delta \Sigma = \sigma_+ \delta \phi_+ / \partial x^2,$$  \hspace{1cm} (4)

$$i\omega e\delta \Sigma = -\sigma_- \delta \phi_- / \partial x^2,$$  \hspace{1cm} (5)

where $\sigma_+$ and $\sigma_-$ are the sheet conductivities of top and bottom GLs. The spatial variation of conductivity is weak, which is valid at small drain voltage $V_{DS} < V_{GT}$ (i.e. in the linear mode of FET). Combining (3)–(5), and introducing the propagation constant $\gamma_w^2 = i\omega C (\sigma_1^+ + \sigma_-^1)$, we arrive at the telegraph equation governing the voltage distribution between the GLs:

$$\frac{\partial^2 (\delta \phi_+ - \delta \phi_-)}{\partial x^2} + \gamma_w^2 (\delta \phi_+ - \delta \phi_-) = 0.$$  \hspace{1cm} (6)

The corresponding transmission line circuit is shown in figure 2. Exploiting the Drude-like expression for the graphene conductivity [19]

$$\sigma_\pm = \frac{e^2 \varepsilon_F / (\pi \hbar^2 \nu_\pm)}{1 + i\omega / \nu_\pm},$$  \hspace{1cm} (7)

where $\nu_\pm$ are the carrier collision frequencies in the respective layers, we find the explicit expressions for the equivalent inductance $l = 2\pi \hbar^2 / (e^2 \varepsilon_F)$ and the resistance $r = \pi \hbar^2 / (e^2 \varepsilon_F)$. Alternatively, $\gamma_w$ can be expressed as

$$\gamma_w = \frac{\sqrt{\omega [2\omega + i(\nu_+ + \nu_-)]}}{s},$$  \hspace{1cm} (8)

where $s = [e^2 \varepsilon_F/\pi \hbar^2 C]^1/2$ is the velocity of plasma waves in the gated graphene [14, 19].

The boundary conditions for equation (6) imply constant voltage difference $\delta V$ at the left and right contacts:

$$[\delta \phi_+ - \delta \phi_-]_{x = \pm L/2} = \delta V / 2.$$  \hspace{1cm} (9)

Generally, $\delta V$ is different from $\delta V$ due to the contact resistances $r_c$ (units: Ohm·m); $\delta V = \delta V_c = \delta \phi_c$, where $\delta \phi$ is the incoming current density. Solving (6) with boundary conditions (9), we find the voltage difference between GLs

$$\delta \phi_+ - \delta \phi_- = \delta V h_{\omega} \cos (\gamma_w x),$$  \hspace{1cm} (10)

where $h_{\omega}$ is the dimensionless plasma resonant factor

$$h_{\omega} = \left[ \cos \left( \frac{\nu_+}{2\gamma_w} \right) - \frac{i\omega C r_c}{\gamma_w} \sin \left( \frac{\nu_+}{2\gamma_w} \right) \right]^{-1}.$$  \hspace{1cm} (11)

In the limit of weak damping $\nu \ll \omega$, the first resonant frequency $\Omega$ is given by $\Omega = \pi \nu / (\sqrt{2} \gamma_w)$. For a typical value of the plasma wave velocity $s = 5 \times 10^6 \text{ m/s}$ (corresponding to the application of $V_{GT} = 2 \text{ V}$ across the distance $d = 50 \text{ nm}$), it lies in the terahertz range, $\Omega/2\pi = 1.8 \text{ THz}$. In the vicinity of the resonance, the factor $|h_{\omega}|^2$ can be approximated with a Lorentzian function,

$$|h_{\omega}|^2 \approx \frac{0.81 \Omega_{\nu}^2}{1 + 4 Q_{\nu}^2 (\omega / \Omega - 1)^2},$$  \hspace{1cm} (12)

where we have introduced the quality factor of the plasma oscillations

$$Q_{\nu} = \left[ \frac{\nu_+ + \nu_-}{2\Omega} + \frac{4 C L r_c \Omega}{\pi^2} \right]^{-1}.$$  \hspace{1cm} (13)

The magnitude and width of plasma resonance peaks are governed by the average collision frequency $\nu = (\nu_+ + \nu_-)/2$ and also by the contact resistances. The experimental values of those quantities are discussed in section 4. In figure 3 we plot the frequency dependencies of $|h_{\omega}|^2$ for two realistic values of contact resistance, $r_c = 100 \text{ Ohm·nm}$ (top figure) and $r_c = 500 \text{ Ohm·\mu m}$ (bottom figure). The collision frequency $\nu$ for the resonant curves in figure 3 varies from $10^{12} \text{ s}^{-1}$ to $10^{13} \text{ s}^{-1}$. Despite a rather low Q-factor ($Q_{\nu} = 6$), the resonant detection is still pronounced.

Having obtained the plasma-wave response (10), we find the average ponderomotive force $f(x, t)$ acting between the GLs (the averaging is performed over time $2\pi/\omega \ll \tau \ll 2\pi/\omega_{\nu}^3$):

7 The high-frequency (THz) components of the force do not affect the mechanics of GLs as, generally, the amplitude of forced oscillations is inversely proportional to the frequency squared.
3. Mechanical response

The deflection, \( u(x, t) \), of the suspended GL is found from the solution of the elasticity equations for graphene. According to the theory developed in [21], the bending energy of graphene is much less than its stretching energy. Thus, the time-dependent deformation of the GL is governed by the wave equation of the membrane oscillations. Presenting the deflection \( u(x, t) \) of the top GL as \( u_0(x) + \delta u(x, t) \), where \( \delta u(x, t) \) oscillates with the modulation frequency, \( \delta u(x, t) = \delta u_m(x) \text{e}^{-i\omega_m t} \), we write this equation as

\[
\rho \omega_m^2 (\omega_m - \nu_m) \delta u_m + T \frac{d^2 \delta u_m}{dx^2} = -\frac{CV_m^2}{d^2} \delta u_m - \frac{m C\delta V_m^2}{d} |\delta u_m|^2 \cos (\gamma_\omega x)^2. \tag{15}
\]

Here, \( \rho = 7 \times 10^{-7} \text{ kg m}^{-2} \) is the mass density of graphene, the frequency \( \nu_m \) phenomenologically accounts for mechanical damping, and \( T \) is the elastic force density. The latter is proportional to the tensile strain \( \delta_0 \) of the graphene layer:

\[
T = Eh\delta_0, \tag{16}
\]

where \( E = 340 \text{ N m}^{-1} \) is the two-dimensional elastic stiffness.

The first term on the right hand side of equation (15) is known to pull the resonant frequencies to lower values [7, 23]. We denote the corresponding frequency shift as \( \omega_{sh} = (V_G d/C \rho)^{1/2} \) (for \( V_G = 2 \text{ V} \) and \( d = 50 \text{ nm} \) \( \omega_{sh}/2\pi = 100 \text{ MHz} \)). Introducing the modified mechanical frequency \( \omega_m = \omega_m \text{ (} \omega_m - \nu_m \text{) + } \omega_{sh} \) and the velocity of transverse sound \( c_s = \sqrt{T/\rho} \), we present equation (15) in a concise form:

\[
\frac{\omega_m^2}{\rho d^2} \delta u_m + \frac{C\delta V_m^2}{4d} \delta u_m = -\frac{m C\delta V_m^2}{\rho d \delta_m^2} |\delta u_m|^2 \cos (\gamma_\omega x)^2. \tag{17}
\]

The solution of equation (17) with zero boundary conditions (clamped edges) is straightforward; moreover, for the estimate of change in the gate-to-channel capacitance we need to know only the deflection averaged over the x-coordinate \( \langle \delta u_m(x) \rangle \). The latter can be presented as

\[
\langle \delta u_m(x) \rangle = \frac{m C\delta V_m^2}{4\rho d \delta_m^2} |\delta u_m|^2 |H_{u_m}\rangle. \tag{18}
\]

Here we have introduced the mechanical resonant factor \( |H_{u_m}| \). In the limit of weakly damped plasma oscillations, \( \nu \ll \Omega \), it is given by the following expression

\[
H_{u_m} = \tan \frac{\gamma_m L}{\gamma_m L} \left[ \frac{\cos \gamma_w L}{1 - (\gamma_w / \gamma_m L)^2} + 1 \right] - \left[ \frac{\sin (\gamma_w L) / (\gamma_w L)}{1 - (\gamma_w / \gamma_m L)^2} + 1 \right], \tag{19}
\]

where \( \gamma_m = \delta_m / (2c_s) \), \( \gamma_w \) is the real part of \( \gamma_m \), and its imaginary part is assumed to be small.

The dependence of the mechanical resonant factor \( H_{u_m} \) provides a complicated pattern of resonances and anti-resonances appearing due to the spatial distribution of the driving force (see figure 4). The principal resonant dependence is given by the term \( \tan (\gamma_m L) \). In the vicinity of the first mechanical resonant frequency \( \Omega_m = \pi c_s / L \) and plasma resonance, \( |H_{u_m}| \) is described by the Lorentzian function

![Graph showing plasma response function](image-url)
versus modulation
(23)
(24),
resulting from the varying gate-to-channel capaci-
tance. Provided that the FET operates in the linear mode (the constant drain voltage \(V_D\) is smaller than the gate voltage \(V_G\)), the detector current is the rectified (zero-frequency) component of ponderomotive force detector for non-modulated THz radiation. In this case, the detector current density is proportional to \(Q_m^2\):

\[
\delta J(\Omega_m) \approx m \frac{\mu CV_G V_D}{L} \frac{C_\text{D} V^2}{\rho \Omega_m^2 d^2} Q_m^2 Q_m.
\]  
(23)

In figure 5, we plot the dependence of combined plasma-mechanical resonant factor \([h_{\text{m}2}^0 | H_{\text{m}m} |] \) on carrier and modulation frequencies. The following parameters are used: \(v = 10^{12} \text{s}^{-1} \), \(v_m = 10^9 \text{s}^{-1} \) \((Q_m = 7 \times 10^3)\), \(L = 1 \mu m \) (log scale).

4. Results and discussion: output current, responsivity, and tuning

Now we can estimate the amplitude of source-drain density \(\delta J(\omega_m)\) resulting from the varying gate-to-channel capacitance. Provided that the FET operates in the linear mode (the constant drain voltage \(V_D\) is smaller than the gate voltage \(V_G\)), \(\delta J(\omega_m)\) is given by

\[
\delta J(\omega_m) = \mu CV_G \delta u_m(x) \frac{V_D}{d} L,
\]  
(21)

where \(\mu\) is the carrier mobility in the bottom GL. Using the obtained frequency dependence of the top GL deflection (18), we ultimately find

\[
\delta J(\omega_m = 0) \approx 0.22 m \frac{\mu CV_G V_D}{L} \frac{C_\text{D} V^2}{\rho \Omega_m^2 d^2} |h_{\text{m}2}| |H_{\text{m}m}|.
\]  
(22)

The quantity \(\mu CV_G V_D/L\) is the steady-state charge accumulated on a single GL per unit width \(W\), divided by the electron drift time from the source to the drain. Under the conditions of the combined plasma and mechanical resonance \((\omega = \Omega, \omega_m = \Omega_m)\), the detector current density is proportional to \(Q_m^2\):

\[
\delta J(\omega_m = 0) \approx 0.2 m \frac{\mu CV_G V_D}{L} \frac{C_\text{D} V^2}{\rho \Omega_m^2 d^2} Q_m^2.
\]  
(24)

Figure 4. Mechanical response function \(|H_{\omega_m2}|\) versus modulation frequency \(\omega_m\). Structure length \(L = 1 \mu m\), tensile strain of top GL is \(\delta_e = 0.01\), quality factor \(Q_m = 10^3\). Inset: response functions in the vicinity of resonance for \(Q\)-factors ranging from \(10^2\) to \(10^3\).

Figure 5. Dependence of combined plasma-mechanical response function \([h_{\text{m}2}^0 | H_{\text{m}m} |] \) on carrier and modulation frequencies. The following parameters are used: \(v = 10^{12} \text{s}^{-1} \), \(v_m = 10^9 \text{s}^{-1} \) \((Q_m = 7 \times 10^3)\), \(L = 1 \mu m \) (log scale).
\( V_G = 2 \ V, \ V_D = 1 \ V, \ Q_p = 6, \ Q_m = 10^3, \ m = 1 \). Relating \( \delta P \) to \( \delta V^2 \) via

\[
\delta P = \frac{2Gc\varepsilon_0}{\pi} \delta V^2
\]

de (25)

where \( G \) is the antenna gain (for dipole antenna \( G = 1.5 \)), we obtain the responsivity of 3 A W\(^{-1}\) per micron width \( W \) for the detection of the modulated radiation, and 2.5 mA W\(^{-1}\) per micron width \( W \) for the detection of non-modulated radiation. The responsivity might be greatly enhanced by increasing \( V_D \) due to a large nonlinearity in the FET saturation regime.

The responsivity crucially depends on the quality factor \( Q_p \) of the plasma oscillations. The latter is governed by contact resistances and collision frequencies in the GLs. Recently, the contact resistances of the order of 500 Ohm-\( \mu \)m were reported for graphene/nickel contacts [24], while special treatment procedures can reduce this value down to 100–200 Ohm-\( \mu \)m [25, 26]. The collision frequency in suspended GL \( \nu_c \) is quite small, being limited by acoustic phonon scattering [9]. Provided \( \nu_c \gg k_B T \), it can be estimated as \( \nu = \nu_0 (\nu_0/k_B T) \) [27], where \( \nu_0 \approx 3.5 \times 10^{11} \) s\(^{-1}\). This corresponds to the experimentally measured mobility \( \mu = 10^5 \) cm\(^2\) V\(^{-1}\) s\(^{-1}\) at near-room temperature [9]. The electron mobility in graphene on the substrate is definitely lower as it is limited by the defect scattering. However, room-temperature mobilities exceeding \( 10^6 \) cm\(^2\) V\(^{-1}\) s\(^{-1}\) were reported for graphene on hexagonal boron nitride substrates [28, 29]; these are lower than the average collision frequency in suspended graphene by only one order. Thus, the average collision frequency \( \nu = 10^{12} \) s\(^{-1}\) seems audible. The relaxation time exceeding 1 ps in graphene on substrate is also confirmed by the optical measurements [30, 31].

Both plasma and mechanical resonant frequencies \( \Omega \) and \( \Omega_m \) can be tuned by applying the constant top gate voltage \( V_G \) since it controls the electron and hole densities in the GLs and their Fermi energies \( \varepsilon_F \). The plasma wave velocity is \( s = [e^2 \varepsilon_0 / (\pi\hbar^2 C)]^{1/2} \). Thus, the plasma resonant frequency is a slowly increasing function of the gate voltage, \( \Omega \propto V_G^{1/4} \). The dependence of the mechanical resonant frequency on \( V_G \) is more complicated [8, 23]. On the one hand, the application of the gate voltage increases \( \omega_m \) and pulls the resonant frequency to lower values. On the other hand, at low voltages another factor is more important. The tensile strain of GL \( \varepsilon_t \) includes the built-in strain \( \delta_{oo} \) and voltage-induced strain \( 1/2[\partial u_{\Omega}(x)/\partial x]^2 \), which is a growing function of \( V_G \). Without going into mathematical details too deeply, we note that the addition of a back gate below the entire structure makes the independent tuning of mechanical and plasma resonances plausible. In this case, \( \Omega_m \) will still depend only on the top gate voltage, \( V_G \), while the plasma wave velocity will be a function of both top and bottom gate voltages.

Finally, we note that the incoming THz signal can be delivered to the device in different ways. The excitation scheme of figure 1(a) supposes that the contacts to the bottom layer are connected to one side of the THz antenna, and the top layer contacts are connected to another. Log-periodic antennae have proved efficient for the signal delivery to the plasma resonant circuits [32]. For matching reasons, the radiative resistance of the antenna should be close to the real part of the detector impedance. The latter is

\[
Z = \frac{\delta V}{\delta W} = \frac{1}{W} \left[ 2r_c + i \frac{\omega_m}{\omega C} \cot (\nu_m L / 2) \right].
\]

de (26)

For detector width \( W = 2L \) and plasma resonant frequency \( \Omega = 1.5 \) THz, \( \Re Z = 150 \) Ohm. Alternatively, terahertz radiation can be coupled directly to the graphene sheet if the latter is placed in the immediate vicinity of the antenna metal contacts. In this case the contact resistance does not affect the quality of the plasma resonator.

The proposed device might also find applications as an extremely sensitive mass, gas [33] or biosensor [34]. Its advantage in mass sensing compared to NEMs is that it has a much larger area of graphene gate compared to a nanowire or a nanotube. The sensing responsivity is also greatly enhanced in THz plasmonic devices [34] because of a high plasma-wave sensitivity to changes in the electric field distribution caused by the sensed medium.

5. Conclusions

We have proposed and substantiated the operation of a resonant detector of THz radiation modulated by GHz signals. The device uses a graphene field-effect transistor with a mechanically floating graphene gate. The THz component of incoming radiation invokes plasma resonance in the graphene layers, thus leading to a high ponderomotive force. The component of the ponderomotive force oscillating with the modulation frequency excites the mechanical vibrations of the graphene gate. This leads to a change in the source-drain current. The resonant responsivity is proportional to \( Q_p Q_m \). For the structures that are 0.5...1 \( \mu \)m long, the values \( Q_p = 10 \) and \( Q_m = 10^3 \) look feasible. The frequencies of both the plasma and mechanical oscillations can be tuned by a constant gate voltage.

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