Detector of modulated terahertz radiation based on HEMT with mechanically floating gate

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***Abstract*—We consider a concept of a resonant detector of modulated terahertz radiation based on a micromachined high-electron-mobility transistor with a microcantilever serving as the mechanically floating gate. The device can exhibit both the plasma (in terahertz range) and mechanical (in megahertz or gigahertz range) resonances.**

The use of a highly conducting microcantilever as a mechanically floating gate in high-electron mobility transistors (HEMTs) provides new functional capabilities for different device applications. The concept of a micromachined HEMT with the cantilever as floating gate was put forward and discussed a long time ago [1]. A floating-gate HEMT device comprising a microcantilever over a two-dimensional electron gas (2DEG) channel was fabricated and characterized [2] (see, also [3]).

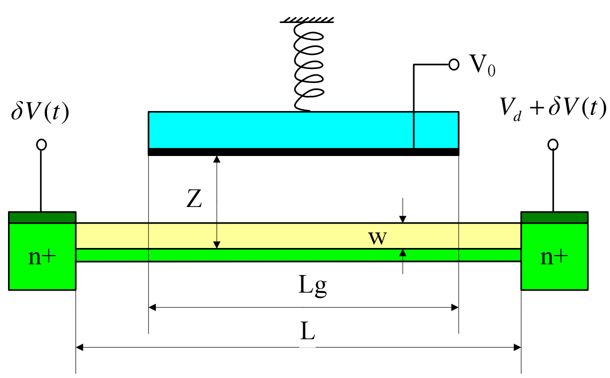

Fig. 1. Schematic view of a micromachined HEMT structure (V_0 is the bias gate voltage and V_d is the bias source-drain voltage).

In this paper, we discuss a resonant detector of modulated terahertz (THz) radiation based on a HEMT with a highly conducting microcantilever playing the role of the HEMT gate [4]. The operation of the device is associated with the excitation of the modulated standing plasma waves in the gated 2DEG channel. The ac electric field of these waves between the 2DEG channel and the microcantilever affects the latter. The modulation of the incoming THz signal and, hence, the modulation of the ac electric field result in the excitation of the microcantilever mechanical oscillations. Relatively low-frequency mechanical oscillations cause the oscillations of the displacement gate current and the source-drain current. These currents can be used as the output signals of the detector. When the carrier and modulation frequency coincide with the plasma and mechanical resonant frequencies, respectively, the output currents and, hence, the detector responsivity may exhibit very sharp and high peaks.

The device structure is shown schematically in Fig. 1. It is assumed that the incoming THz signal is amplitude modulated: $\delta V = \delta V_\omega[1+\alpha\cos(\omega_m t)]\cdot\cos(\omega t)$, where ω_m and ω are the modulation and carrier frequencies and α_m is the modulation depth.

The device model is based on hydrodynamic equations for electron transport along the channel governing the electron average velocity, $u = u(t,x)$, along the 2DEG channel and the electron sheet density, $\Sigma = \Sigma(t,x)$ as well as an equation governing the displacement of the microcantilever:

$$\frac{\partial \Sigma}{\partial t} + \frac{\partial \Sigma u}{\partial x} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \nu u = \frac{e}{m}\frac{\partial \varphi}{\partial x}, \tag{2}$$

$$\frac{\partial^2 Z}{\partial t^2} + \gamma_0\frac{\partial Z}{\partial t} + \Omega_0^2(Z - W) = -\frac{D}{4\pi M}\int_{-L_g/2}^{L_g/2} dx\mathcal{E}^2. \tag{3}$$

Here, $\varphi = \varphi(t,x)$ is the electric potential in the channel, $e = |e|$ and m are the electron charge and effective mass, respectively, and $\nu = e/m\mu$ is the frequency of electron scattering with impurities, where μ is the electron mobility, M is the microcantilever effective mass, K is the stiffness of the effective string (so that the resonant frequency of the microcantilever oscillations associated solely with its mechanical properties is given by $\Omega_0 = \sqrt{K/M}$), γ_0 is the parameter characterizing the damping of mechanical oscillations associated with different mechanisms of the energy loss in the cantilever body and in the clamp, L_g is the microcantilever size in the x-direction (coinciding with the gate length) and D is the microcantilever size in the third direction. The term in the right-hand side of Eq. (3) represents the electric force acting on the microcantilever associated with the bias and ac voltages. In the gradual channel approximation, the electric field $\mathcal{E} = \mathcal{E}(t,x)$ at the microcantilever plane is determined by

$$\mathcal{E} = \frac{(\varphi - V_0)}{(Z - w)} = -4\pi e(\Sigma - \Sigma_d), \tag{4}$$

where V_0 is the bias voltage between the microcantilever and the source contact (gate voltage) and $\Sigma_d = const$ is the donor sheet density.

Using the above equations in the small-signal approximation, we obtained the following equations for the amplitude displacement gate current (between the microcantilever and the 2DEG channel) and for the amplitude of the drain current (at relatively low drain voltages V_d when the HEMT operates in the linear regime) with the frequencies $\omega_m \sim \Omega_m$:

$$\Delta J_g\Big|_{\omega_m\sim\Omega_m} \simeq \frac{16\alpha_m C_0|V_0|}{\pi}\frac{\omega_m\Omega_m^2}{\sqrt{(\omega_m^2-\Omega_m^2)^2+\gamma_0^2\omega_m^2}} \times \frac{\Omega_p^2}{[4(\omega-\Omega_p)^2+\nu^2]}\cdot\left(\frac{\delta V_\omega}{\overline{V_0}}\right)^2 \tag{5}$$

and

$$\Delta J_d\Big|_{\omega_m\sim\Omega_m} \simeq \frac{\alpha_m\mu V_d|V_0|D}{\pi^3 L_g Z_0}\frac{\Omega_m^2}{\sqrt{(\omega_m^2-\Omega_m^2)^2+\gamma_m^2\omega_m^2}} \times \frac{\Omega_p^2}{[4(\omega-\Omega_p)^2+\nu^2]}\cdot\left(\frac{\delta V_\omega}{\overline{V_0}}\right)^2. \tag{6}$$

Here $C_0 = L_g D/4\pi Z_0$ is the microcantilever capacitance. Equations (5) and (6) lead to the following formulae for the detector responsivities, $R^{(g)}_{\omega_m,\omega}$ and $R^{(d)}_{\omega_m,\omega}$ (determined by the gate and drain currents), as functions of the modulation (ω_m) and carrier (ω) frequencies:

$$R^{(g)}_{\omega_m,\omega} \propto \frac{\alpha_m C_0|V_0|\,\Omega_m^2}{\sqrt{(\omega_m^2-\Omega_m^2)^2+\gamma_m^2\omega_m^2}}\frac{\Omega_p^2}{[4(\omega-\Omega_p)^2+\gamma_p^2]} \tag{7}$$

and

$$R^{(d)}_{\omega_m,\omega} \propto \frac{\alpha_m\mu V_d|V_0|\,\Omega_m^2}{\sqrt{(\omega_m^2-\Omega_m^2)^2+\gamma_m^2\omega_m^2}}\frac{\Omega_p^2}{[4(\omega-\Omega_p)^2+\gamma_p^2]}. \tag{8}$$

Here

$$\Omega_m = \Omega_0\sqrt{1-(V_0/\overline{V_0})^2}, \tag{9}$$

and

$$\Omega_p = \Omega_{0p}\sqrt{1+(V_0/|V_0^{(depl)}|)-(1/2)(V_0/\overline{V_0})^2} \tag{10}$$

are the microcantilever mechanical resonant frequency and the fundamental plasma resonant frequencies, respectively (see [4,5]), γ_m and γ_p are the pertinent damping constants, V_0 is bias gate voltage, $\overline{V_0} = \sqrt{2\pi\Omega_0^2 M Z_0^3/DL_g}$ and $V_0^{(depl)}$ is the gate voltage corresponding to the 2DEG channel depletion, $\Omega_0 = \Omega_m|_{V_0=0}$ and $\Omega_{p0} = \Omega_p|_{V_0=0}$. The parameters characterizing the mechanical and plasma resonance depend, on the device geometrical parameters (see Fig. 1) and the gate voltage.

The frequency dependence of the detector responsivity calculated for a GaAs/AlGaAs device with the following parameters: the electron mobility $\mu = 3\times10^4$ cm^2/Vs (that corresponds to $\gamma_p \simeq 10^{12}$ s^{-1}), $\Omega_{p0}/\gamma_p = 2\pi$, $\Omega_{p0}/2\pi = 1.5$ THz, $\Omega_0/2\pi = 100$ MHz, $\Omega_0/\gamma_0 = 10^3$, $\overline{V_0} = 33$ V, $V_0^{(depl)} = -9$ V, and $V_0 = -3$ V are shown in Fig. 2.

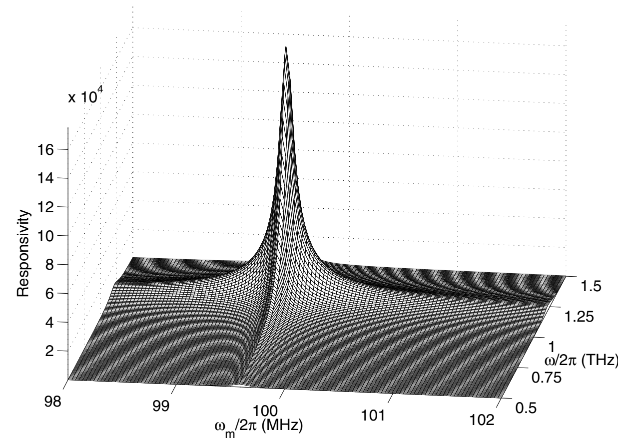

Fig. 2. Responsivity versus modulation and carrier frequencies.

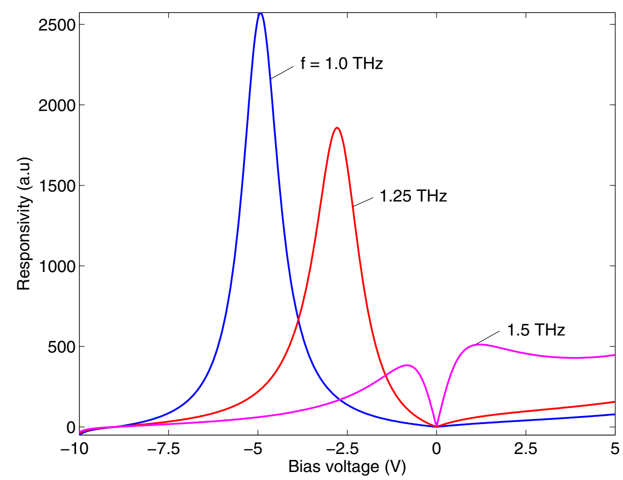

Fig. 3. Responsivity as a function of dc gate voltage for different carrier frequencies.

Figure 3 shows the responsivity as a function of the bias gate voltage for the same device parameters as in Fig. 2.

Very large detector resonant responsivity and its selectivity as well as the voltage control of the resonances can provide significant advantages of the detectors under consideration over the standard detectors.

References

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