ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2007, Vol. 71, No. 1, pp. 89–92. © Allerton Press, Inc., 2007.
Original Russian Text © V.V. Popov, G.M. Tsymbalov, T.V. Teperik, D.V. Fateev, M.S. Shur, 2007, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2007, Vol. 71, No. 1, pp. 93–96.

Terahertz Excitation of the Higher-Order Plasmon Modes in Field-Effect Transistor Arrays with Common and Separate Two-Dimensional Electron Channels

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Abstract—Using a rigorous electrodynamic approach, the spectra of the terahertz response of periodically ordered arrays of field-effect transistors with two-dimensional electron channel were calculated. It was shown that the higher-order plasmon resonances can be excited in such structures at frequencies above 10 THz.

DOI: 10.3103/S1062873807010224

It is known that plasma oscillations excited in two-dimensional (2D) electron channels of field-effect heterotransistors (FEHTs) significantly affect the terahertz (THz) response of such devices. This phenomenon can be applied to detection, frequency conversion and generation of THz radiation [1–4]. From the viewpoint of applications, the most attractive modes of plasma oscillations are those excited in the gated region of the electron channel, since the frequency of gated plasma oscillations can be efficiently tuned by changing the gate voltage. However, gated plasmons in FEHTs with single electron channel are weakly coupled to THz radiation [5], since they are strongly screened by the gate electrode. Moreover, the total dipole moment of the gated plasmon mode is vanishingly small due to the acoustic nature of this mode, which also significantly lowers the efficiency of the interaction of gated plasmons with THz radiation. In practical FEHTs, the distance between the gate and 2D electron channel is much smaller than the gate electrode length. In this case, frequencies of gate plasmon modes are well approximated by the simple formula (see [1])

$$\omega = k_n \sqrt{\frac{e(U_g - U_{th})}{m^*}}, \qquad (1)$$

where U_g is the gate voltage, U_{th} is the threshold depletion voltage of the 2D electron channel, e and m^* are the charge and effective mass of electron, respectively. Under symmetric boundary conditions at the gate electrode ends, only gated plasmon modes with wave vectors

$$k_n = (2n-1)\frac{\pi}{w} \quad (n = 1, 2, 3\ldots), \qquad (2)$$

are coupted to THz radiation, where w is the gate electrode length. Estimations by formula (1) for actual FEHT parameters yield frequencies of the fundamental plasmon mode ($n = 1$) on the order of 5 THz at the gate electrode length of 100 nm. A further increase in the plasmon resonance frequency is limited by technological difficulties of ultrashort gate electrode fabrication. The higher-order plasmon modes ($n > 1$) in FEHTs with single electron channel have extremely low excitation efficiency [6] and cannot be used to increase the operating frequency of devices.

In [5], it was noted that the efficiency of the interaction of gated plasmons with THz radiation can be significantly increased due to their interaction with unscreened (intercontact) regions of the 2D electron channel. In this study, the THz absorption spectrum of the grating-gated FEHT with common electron channel (Fig. 1) was calculated. It was shown that the efficiency of plasma resonance excitation in such a structure increases by several orders of magnitude due to excitation of plasma oscillations in unscreened regions of the 2D electron channel. In this case, the higher-order plasmon resonances, with $n \leq 7$, are efficiently excited at frequencies up to 10 THz in FEHTs with narrow-slit grating gate. A THz absorption spectrum of a one-dimensional periodic array of FEHTs with separate 2D electron channels was also calculated. It was shown that the higher-order plasmon resonances in such a structure can be excited at frequencies of 15 THz and above.

Terahertz spectra of plasmon absorption in the structures under study were calculated using a rigorous electrodynamic approach [7] based on the integral equation method. This approach includes the following

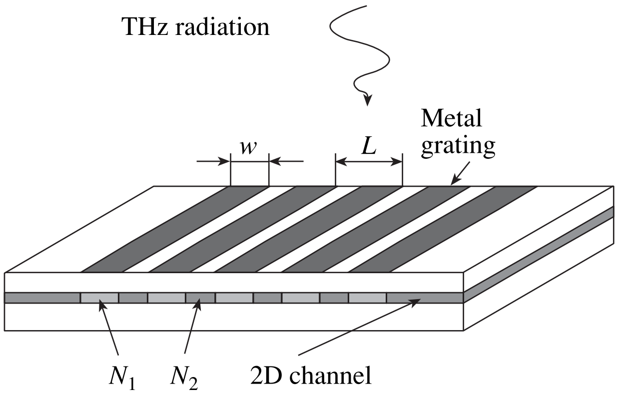

Fig. 1. Schematic image of a field-effect grating-gated transistor.

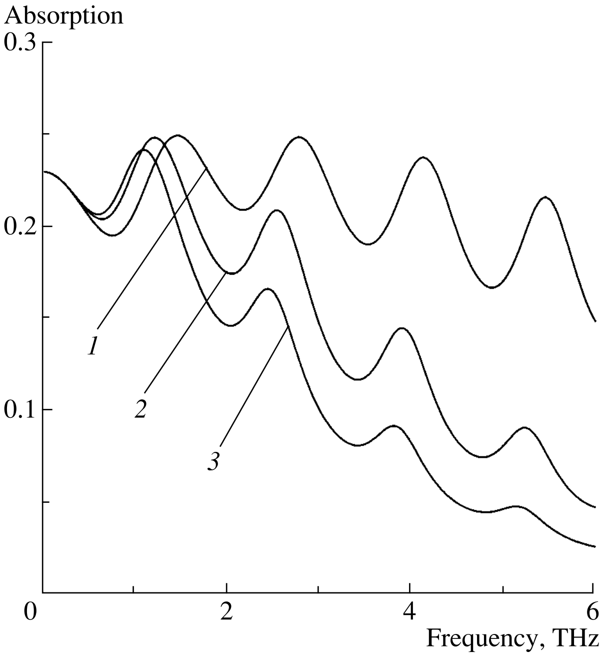

Fig. 2. Absorption spectra of a grating-gated FEHT with a common electron channel, based on the AlGaN/GaN structure with a grating-gate electrode strip width of 1 μm for three various widths of grating slits: (*1*) 0.1, (*2*) 0.3, and (*3*) 0.5 μm. The electron relaxation time $\tau = 2.27 \times 10^{-13}$ s corresponding to room temperature was used in the calculations.

main stages: (i) Maxwell's equation is written in the Fourier representation, (ii) the amplitudes of the Fourier harmonics of the surface density of electric current in the both 2D electron channel and the grating gate planes are expressed in terms of the corresponding amplitudes of the Fourier harmonics of the lateral electric field in these planes, (iii) using Ohm's law, integral equations for the lateral electric field on metal contacts and in various regions (screened and unscreened) of the 2D electron channel are formed, (iv) the obtained set of integral equations is numerically solved using the Galerkin method by projecting the integral equations onto the orthogonal basis of Legendre polynomials in a corresponding interval. The terahertz response of the 2D electron channel is described by local surface conductivity in the Drude model as

$$\sigma(\omega) = \frac{e^2 N_{1,2}\tau}{m^*(1 - i\omega\tau)},$$

where τ is the characteristic time of electronic relaxation and N_1 and N_2 are the equilibrium electron densities in the screened and unscreened regions of the 2D electron channel. The equilibrium electron density under gate electrode strips was calculated in the parallel-plate capacitor model $N_1 = \varepsilon\varepsilon_0(U_g - U_{th})/ed$, where ε is the barrier-layer permittivity, ε_0 is the permittivity of free space, d is the barrier-layer thickness (the distance from the 2D electron channel to the gate). Characteristic parameters of FEHTs based on the AlGaN/GaN structure were used in calculations: $\varepsilon = 9$, $U_{th} = -3$ V, and $d = 8$ nm. The surface conductivity of the metal strips of the gate electrode was set equal to 2.5 Ω^{-1} (gold). The calculated results show that plasmon absorption spectra of FEHTs remain almost unchanged in the typical range of direct current variation in the transistor channel (neglecting the effect of transistor channel shortening with the bias current). Below we present the results of numerical calculation in the absence of direct current in the transistor channel. We note that a change in the transistor channel length with the bias current can be easily taken into account by a corresponding variation of the channel length w in formula (1).

The calculated THz absorption spectra of the FEHT based on the AlGaN/GaN structure with common electron channel and grating gate with a micrometer period (see Fig. 2) show a series of plasmon resonances. At narrow slits of the grating gate, the higher-order plasmon resonances are excited at high THz frequencies up to the 7th resonance at a frequency near 10 THz (not shown in Fig. 2). The radiative linewidth of the higher-order plasmon resonances in FEHTs with narrow-slit gate becomes comparable to the dissipative linewidth of the resonance, which makes excitation of the higher-order plasmon resonances highly efficient. The maximum absorbance of 0.25 at the plasmon resonance frequency is achieved when radiative and dissipative widths of the resonance are equal [7]. We note that the plasmon resonance frequencies are multiples of $2\pi/L$ (L is the grating period) at narrow slits of the grating gate, in contrast to the dependence given by formulas (1) and (2) for a single transistor channel; therefore, resonances shift upward in frequency as L decreases. The calculated results show that all plasmon resonances become more than two orders of magnitude weaker when the electron density in unscreened channel regions becomes zero. This demonstrates the fundamental role of unscreened (intercontact) regions of the 2D electron channel in plasmon resonance excitation. Unscreened regions of the common 2D electron channel play the role of electric vibrators efficiently exciting gated plasmons.

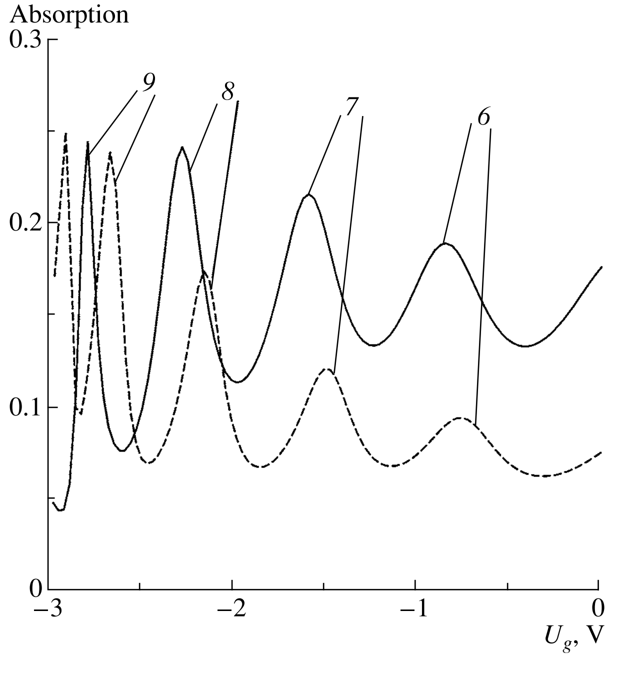

Fig. 3. The same as in Fig. 2 at a frequency of 6.86 THz as a function of the gate voltage for two various widths of grating gate electrode slits: 0.1 μm (solid line) and 0.2 μm (dashed line). Numerals indicate the resonances of corresponding plasmon modes.

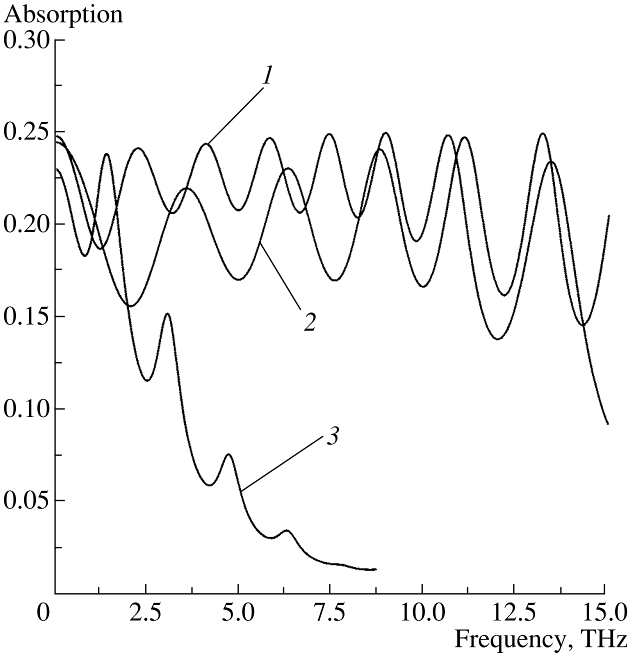

Fig. 4. Absorption spectra of a one-dimensional periodic array of FEHTs with separate electron channels, based on the AlGaN/GaN structure with an array period of 1.2 μm for two various gate electrode widths: (*1*) 0.8 μm and (*2*) 0.5 μm. The electron relaxation time $\tau = 2.27 \times 10^{-13}$ corresponding to room temperature was used in the calculations. For comparison, the calculated plasmon absorption spectrum of a FEHT with a common electron channel with the same grating gate period and a strip width of 0.8 μm is also shown (curve *3*).

Figure 3 shows the THz absorption spectrum of the FEHT with narrow-slit gate as a function of the gate voltage. A remarkable result is that the excitation intensity for the higher-order plasmon resonances, up to the 9th resonance inclusive, significantly increases at more negative (close to the threshold) gate voltages.

This phenomenon results from the fact that the radiative activity of the higher-order plasmon modes increases with lateral modulation of the electron density in the transistor channel [7]. We also note that plasma resonances excited at more negative U_g are narrower. This fact can be easily explained by differentiating formula (1),

$$\Delta U_g = \frac{2}{(2n-1)}\frac{w}{\pi}\sqrt{\frac{m^*(U_g - U_{th})}{e}}(\Delta\omega_n),$$

where $\Delta\omega_n$ is the width of the nth plasma resonance in the frequency domain. It is clear that $\Delta\omega_n$ tends to zero at a specified value of ΔU_g, when the gate voltage approaches the threshold value.

Figure 4 shows the plasmon absorption spectrum of a one-dimensional periodic array of field-effect transistors with separate 2D electron channels (electron channel regions with concentration N_2 in Fig. 1 are replaced by lateral metal contacts). One can see that the higher-order plasmon resonances up to a frequency of 15 THz are efficiently excited in such a structure. In this case, there is no need for narrow lateral spacings, which reduces the technological requirements for fabrication of the structure in comparison to the previously considered structure with a common channel and grating gate. This positive effect occurs because the electron liquid in lateral metal contacts is much more “rigid” in comparison with 2D electron gas in the transistor channel. Therefore, side metal contacts are more efficient electric vibrators, exciting gated plasmon modes, in comparison to unscreened regions in the grating-gated FEHT with common 2D electron channel.

Thus, it was shown that the higher-order plasmon resonances are efficiently excited by external THz radiation in periodically ordered arrays of FEHTs with 2D electron channels. This presents an opportunity to significantly increase the operating frequency of plasmon devices based on FEHTs up to 15 THz and higher.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, project no. 06-02-16155, and the program “Quantum Nanostructures” of the Russian Academy of Sciences.

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