Detection mechanisms of terahertz radiation in a short gate In$_{0.3}$Ga$_{0.7}$As/In$_{0.53}$Al$_{0.47}$As field effect transistor

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Abstract. The detection properties of some short-channel field-effect transistors (FETs) have been analyzed using the steady state output characteristics of these devices. The calculated dependences of voltage–power sensitivity on applied voltage are compared with the corresponding curves obtained from high-frequency measurements. It is shown that the nonmonotonic dependence of the FET photosensitivity on gate voltage that is observed in the frequency range of 400–750 GHz is not related to resonant excitation of 2D plasmons in the gated plasma but is due to the change in the distribution of stationary fields in the structure and, as a result, to the change in the efficiency of nonresonant nonlinearity procedures in the transistor’s electron sub-system with an increase in the gate–channel voltage. This conclusion is confirmed by the analysis of the frequency dependences of photoresponse in the range under consideration, which do not exhibit resonant behavior at the frequencies corresponding to the peaks that are measured at a fixed frequency and for different gate voltages.

1. Introduction

Along with the development of the conventional technique for amplifying and transforming electromagnetic signals, some new concepts in this field are actively debated. One of them is based on application of resonant phenomena related to excitation of 2D plasmons in the gated electronic plasma of short channel transistors for detecting and generating terahertz electromagnetic signals [1]. In this context, many current studies are devoted to the search for peculiarities in the emission and detection characteristics of features of short-channel transistors, which would indicate resonant excitation of 2D plasmons in the transistor’s transport channel.

At a low rectified signal, the detection caused by plasmon excitation (if this effect is present in the system under consideration) occurs against the background of other various nonresonant nonlinearity mechanisms such as concentration and carrier drift velocity nonlinearities. Hence, the expected resonant features in the transistor element characteristics can be reliably revealed only by simultaneous experimental and theoretical study of the volt-watt sensibility (VWS) dependences of a nonlinear element on both the external voltage and frequency of incident radiation. The most widespread practice is to study the parametric (most often current and field) dependences of the photoresponse of a short-channel high-electron-mobility transistor (HEMT) to terahertz radiation of a specified frequency.

However, in the absence of a pronounced effect of plasmon generation, explanation of the observed phenomena only within the Dyakonov–Shur instability theory [1,2,3] seems to be not quite correct. To
describe reliably the nature of the experimentally observed nonmonotonic dependences of FET photosensitivity, along with the possible interaction of radiation with excited plasmons, one has to take into account other types of nonlinearities, whose competition with an increase in the external fields applied to a structure can also affect the shape of the curves studied [4]. The most important nonresonant mechanism, along with the nonlinearity of the carrier drift velocity [5], is the concentration nonlinearity [4, 5], which are most pronounced in the FET channel at high transmitted currents, corresponding, in particular, at channel cutoff. When the current flows, the gradient of the potential difference between the gate and channel induced by a source-to-drain bias may cause a coordinate dependence of the 2D transport channel-width, the position of energy levels in the electron spectrum and the equilibrium electron concentration and mobility. Therefore, to get a clearer idea about the mechanisms responsible for the experimental dependences, it is important to consider, along with the widely discussed plasma model [3, 4], the behavior of nonlinear FET response to a high-frequency perturbation on the basis of more conventional (in particular, quasi-static) models, which is facilitated by the choice of the frequency range under study, implying application of a frequency-tunable submillimeter generator based on a backward wave oscillator (BWO) and satisfying the condition \( \omega \tau_p \ll 1 \), where \( \tau_p \) is the electron’s elastic scattering time. The scheme of FET connection in a measuring circuit significantly differs from that for a conventional diode detector. This circumstance may cause peculiarities in the FET VWS that are not specific of diode structures and are related, in particular, to the change in the contribution of different nonlinearity processes to detection with an increase in the longitudinal and transverse field components in the transistor structure. For a short-channel transistor, this fact is extremely important because the longitudinal field component in the channel becomes comparable in magnitude with the transverse component, hindering the use of gradual-channel approximation for estimates.

2. Analysis of the transistor’s nonlinear response on the basis of output characteristics

To reveal the general regularities and understand better the observed dependences, we analyze the VWS of some short-channel transistors on the basis of their output characteristics. The calculations are performed using the output characteristics of a short-channel In\(_{0.7}\)Ga\(_{0.3}\)As/In\(_{0.47}\)Al\(_{0.53}\)As FET, which was previously considered in [3, 4]. For the most promising In\(_{0.7}\)Ga\(_{0.3}\)As/In\(_{0.47}\)Al\(_{0.53}\)As HEMTs, the conductivity \( \sigma \) is approximately \( 3.5 \times 10^4 \text{ S m}^{-1} \). As a result, at \( n_i \geq 5 \times 10^{11} \text{ cm}^{-2} \), we have \( \mu_e = \sigma / e n \lesssim 0.65 \text{ m}^2 \text{V}^{-1} \text{s}^{-1} \), which corresponds to the characteristic room-temperature values of electron mobility in the system under study. Accordingly, for \( \tau_p = m_e \mu_e / e \) at \( m_e \approx 0.03 m_0 \), we obtain \( \tau_p \lesssim 10^{-13} \text{s} \). These relaxation times \( \tau_p \) at frequencies \( f \approx 0.65 \text{ THz} \) yield \( \omega \tau_p \lesssim 0.4 \) at \( T = 293 \text{K} \). The values \( \omega \tau_p \ll 1 \) measured at room temperature justify the quasi-static approximation, which is used below to analyze the observed regularities in the effect of transistor detection of submillimeter (\( f < 1\text{THz} \)) radiation.

To estimate the experimental VWS values of the In\(_{0.7}\)Ga\(_{0.3}\)As/In\(_{0.53}\)Al\(_{0.47}\)As transistor, we will use the output characteristics of the transistors which were discussed previously in [3, 4]. In figure 1a, the experimental dependences \( \Delta U(I_B) \), found in high-frequency experiment (see, for example, [4]), are compared with the theoretical curves derived from analysis of the output characteristics (figure 1a) of transistor. Comparison of the theoretical and experimental dependences in figure 1a indicates along with the prepared above estimations on the possibility using a quasi-static approximation. The increase in VWS with an increase in channel current, experimentally observed at frequencies up to 1 THz, is most likely related to the nonresonant mechanisms responsible for the nonlinear shape of output characteristics of the transistor; this circumstance was noted, in particular, in [4, 5], where more specified models were analyzed.

In view of the search for peculiarities in the characteristics of a high-frequency transistor, related to resonant excitation of 2D plasmons in the electron subsystem, the subject of the most animated
discussion is the dependences of the high-frequency photoresponse of a nonlinear element on the gate voltage $U_G$ [2, 3, 5], specifying the electron concentration and, correspondingly, the resonant plasmon frequency $\omega_0$ in the transistor channel.

![Figure 1. Nonlinear response of an InGaAs/InAlAs transistor: (a) the experimental [4] (1–3) and calculated (4–6) dependences of VWS on the current $I_D$ at $U_G = (1, 4) -0.2$, (2, 5) –0.1, and (3, 6) 0 V and (b) the experimental [4] (1, 2) and calculated (3, 4) dependences of VWS on $U_G$; $U_D = (1, 3) 0.2$ and (2, 4) 0.4 V.](image)

However, a variation in the gate voltage not only changes the carrier concentration in the electron channel but leads also to a change in the field distribution along and across the transistor structure. Correspondingly, along with the concentration along the channel length, the contributions of different nonresonant nonlinearities to the total nonlinearity of the system change as well. In view of the aforesaid, the dependence $\Delta U(U_G)$ may be nonmonotonic far from the resonant frequency $\omega_0$. To estimate the possibility of such a situation, we calculated the dependences of nonlinear high-frequency transistor response on voltage $U_G$ in the quasi-static approximation, using the transistor’s output characteristics. The dependences derived from the output characteristics $\Delta U(U_G)$ (figure 1b) are compared with the corresponding experimental dependences at high frequencies (400–700 GHz) [3, 4]. It follows from figure 1b that the dependence of the response of the system to a high-frequency perturbation, found in the quasi-static approximation based on the analysis of the transistor’s transfer characteristics, on the gate voltage, has a maximum.

3. Frequency characteristics of an InGaAs/InAlAs transistor detector

Reliable information about the occurrence of the resonant plasma process in a system can be obtained only from analysis of the frequency dependences of the rectified signal at specified contact voltages. In particular, the plasma resonance suggested in [3, 5] could be confirmed by coincidence of the positions of resonant peaks in the dependences $\Delta U(U_G)$ and $\Delta U(\omega)$, all other factors being equal. A more convenient technique was used in [3], where radiation sources were high-frequency tunable BWO-based generators. The study of the rectified signal dependence with the radiation frequency is made possible with that experimental configuration.

Figure 2 shows the dependences of the photoresponse of an $\text{In}_{0.7}\text{Ga}_{0.3}\text{As/In}_{0.52}\text{Al}_{0.48}\text{As}$ transistor on the radiation frequency for drain voltages $U_D = 0.1, 0.2$, and 0.3 V at a fixed gate voltage $U_G = 0$ V. The solid line is the approximation of experimental points by the dependence of a second-order polynomial. Hereinafter, the power $W$ detected by the transistor is normalized to the power $W_0$ of the generator based on the BWO-74, measured at the same radiation frequencies using an M3-22A thermistor power meter. The corresponding emission spectrum of the generator near some fixed
frequencies is shown in the inset in figure 2. The envelope of the frequency dependence of the generator signal is characterized by a wide band with close values of maximum emitted power at selected frequencies in the range of 580–650 GHz.

![Figure 2](image)

**Figure 2.** Dependences of the photoresponse of an In$_{0.7}$Ga$_{0.3}$As/In$_{0.52}$Al$_{0.48}$As transistor on the generator frequency $f$ at the drain voltages $U_D = (1) 0.1$ V, (2) 0.2 V, and (3) 0.3 V and gate voltage $U_G = 0$ V. The curves of photosensitivity $W$ are normalized to the BWO power $W_0$, whose amplitude–frequency characteristic is shown in the inset.

The frequency dependences of a detected signal at different gate voltages are shown in figure 2. It follows from them that the transistor photosensitivity decreases with an increase in frequency in the range of 450–600 GHz, such a decrease is typical of nonlinear elements operating in the quasi-static mode (Schottky diodes, detectors based on heating photoconductivity). Above 600 GHz (figure 2), the photosensitivity of the transistor detector increases with an increase in the radiation frequency. The dependence of the Schottky diode’s VVS is known to decrease with an increase in frequency as $1/\omega^2$, and the photosensitivity of detectors based on heating photoconductivity decreases even more rapidly.

Obviously, if plasma model corresponded to the experiment, there would be a resonance at $\omega = \omega_0$ in the frequency dependence of the photocurrent. However, there are no resonant features in the observed dependences (figure 2) in the range from 550 to 700 GHz. The absence of resonant features in the curves in the noted range confirms the conclusion about dominant contribution of nonresonant nonlinearities to the formation of features observed in this frequency range in the field dependences of the photoresponse [3, 4, 6].

The above VVS analysis shows that features observed in the dependence of the high frequency response on $U_G$ [3,4] may be related not only to the plasma resonance, as was suggested in the overwhelming majority of studies on this subject [3,5]. Comparing the rectifying characteristics received from the output characteristics and from high-frequency measurements one can see that observed nonmonotonic dependence of photosensitivity on gate voltage can be also related to change in field distribution and, as a result, to the change in the efficiency of nonresonant nonlinearity expression in the transistor’s electron sub-system with an increase in the gate–channel voltage.

**References**

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