INVESTIGATION OF 2D PLASMA RESONANCES IN HEMTS BY USING ELECTRO-OPTICAL SAMPLING TECHNIQUE

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Possibilities and advantages of the electro-optical sampling (EOS) technique for the investigation of excitation of THz-range 2D plasma waves in FET/HEMT channels are considered both experimentally and theoretically. It is experimentally demonstrated that the EOS technique allows one to identify an excitation of 2D plasma waves in the HEMT channel under a given working point determined by external embedding circuits. Theoretical simulations show that the development of the instability of 2D plasma waves can be easily identified in the framework of the EOS technique.

Keywords: electro-optical sampling, terahertz radiation emission, plasma waves

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1. Introduction

The nanometric high electron mobility transistors (HEMTs) are nowadays considered promising elements for solid-state terahertz (THz) sources, first of all, due to possibility of (i) excitation of THz-range 2D plasma waves whose frequency can be easily tuned by applied gate-to-channel and source-to-drain voltages, and (ii) their instabilities which can be used for THz radiation generation [1]. Therefore, both theoretical and experimental investigation of 2D plasma waves in FETs/HEMTs is of great practical interest and importance.

Up to now, investigations of eigen 2D plasma waves were carried out mainly in the following directions: (i) experimental investigation of the voltage-tunable spectral behaviour of THz radiation emission from FETs/HEMTs (see, e.g. [2, 3] and references therein); (ii) theoretical investigation of spectral behaviour of electronic noise in FET/HEMT channels [2, 4, 5]; and (iii) experimental and theoretical investigation of both THz radiation resonant detection and THz re-emission at the beating frequency of two-laser excitation (see, e.g. [6] and references therein).

All these directions are mainly devoted to investigations of the final results related to an excitation of 2D plasma waves such as emission spectra, detection of 2D plasma waves, their frequency dependence, resonant behaviour, etc. The excitation process itself and further temporal evolution of such 2D plasma waves is beyond the scope of these approaches. In our opinion, this deficiency can be covered by using the electro-optical sampling (EOS)
measurements of THz radiation emission from FETs/HEMTs induced by the femto-second laser pulse [7–9].

An inherent feature of this technique is that, on the one hand, it allows to measure directly time dependence of system response (the so-called waveforms or EOS-signal) to an external optical action. On the other hand, this technique opens a possibility of a direct comparison of experimental and theoretical results with minor additional assumptions related to a measured signal.

The aim of the present work is to demonstrate the possibilities/advantages of the EOS technique for investigation of conditions of the excitation of 2D plasma waves in FET/HEMT channels and identification of conditions favourable for the instability of such waves. The work consists of two parts: experimental part, which shows that the EOS technique allows one to identify an excitation of 2D plasma waves in the HEMT channel under a given working point determined by external embedding circuits, and theoretical part, which shows that if the instability of 2D plasma waves can be developed in a HEMT under investigation this can be easily identified in the framework of the EOS technique.

2. Experiment

Experiments were performed on GaInAs HEMTs from InP technology with a gate-length value \( L_g = 200 \) nm. The threshold voltage \( V_{th} \approx 300 \) meV. The room temperature THz emission measurements were performed using a reflective EOS technique (see [8] for more details). The HEMT was loaded to external source-gate and source-drain circuits which provided constant values of the gate voltage \( V_g \) and the drain current \( j_d \) during the pump and probe optical pulses. In such way, the HEMT pumped by optical pulses remains under the steady-state conditions corresponding to its static current-voltage relation \( j_d(V_d, V_g) \).

Figure 1(a) shows an example of the measured interferogram (inset) and smoothed Fourier transformed spectra for different swing-voltages \( V_0 = V_g - V_{th} \) from 0.1 to 0.3 V at certain drain voltage of \( V_d = 0.14 \) V. The double Lorentzian fit demonstrates that the wide-band emission bump is composed of two peaks. Both peaks shift to higher frequencies with increase of \( V_0 \) (see also

\[
    f_n = \frac{n}{4L_{eff}} \frac{eV_0}{m_e m}, \quad n = 1, 3, 5, \ldots \tag{1}
\]

where \( L_{eff} = L_g + 2d \) is the effective length of the HEMT gated region, \( d \) is the gate-to-channel distance. The coincidence of theoretical and experimental results unambiguously evidences that the EOS technique experimentally observes an optical excitation of the 2D plasma waves.

3. Simulation

The THz electro-optical-sampling (THz-EOS) technique implies that a detected signal (that is the

\[
\begin{align*}
    &\text{amplitude (arb. units)} \\
    &\text{frequency (THz)} \\
    &\text{swing voltage (V)} \\
\end{align*}
\]

Fig. 1. (a) Measured temporal response of THz field (inset) and corresponding emission spectra obtained at the swing-voltage \( V_0 \) varied from 0.1 to 0.3 V. (b) Experimental frequency dependence of the peaks on \( V_0 \) (symbols) compared with analytical predictions (solid lines).
EOS wave form) is proportional to the change rate of the current excitation $\delta j(t)$ induced by the optical pulse action according to equation [7]:

$$E_{\text{THz}}(t) \sim \frac{d}{dt} \delta j(t),$$

(2)

where $E_{\text{THz}}(t)$ is the measured EOS-signal (the EOS-form).

To simulate electron transport in HEMTs we used a simplified hydrodynamic (HD) approach coupled with the pseudo-2D Poisson equation [10]. The parameters of the InGaAs HEMT structure were taken similar to those used above and in recent experiments [8].

In essence, the obtained theoretical results agree reasonably well with tendencies demonstrated by EOS measurements. This is illustrated by Fig. 2 which shows the frequency dependence of the THz emission spectra calculated by HD simulations at the velocity relaxation rate $\nu = 5 \cdot 10^{12} \text{ s}^{-1}$ corresponding to the entirely stable situation. Figure 3 summarises the dependence of the frequency positions of EOS-spectrum peaks corresponding to the first and third harmonics on the swing-voltage, $V_0 = V_g - V_{th}$, calculated for $V_d = 0.14 \text{ V}$ by HD approach (crosses) and by Eq. (1) (solid lines).

A reasonably good agreement between the experiment and our theoretical simulation of an EOS-signal allows us to extend a scope of possible situations which can be considered in the EOS technique frameworks. Below we shall consider the EOS-response behaviour under conditions when the development of the Dyakonov–Shur instability [1] of 2D plasma waves can take place. The necessary condition for such an instability development is a rather high mobility of carriers in the channel which can usually be achieved by decreasing the lattice temperature. To fulfil this condition we took the case corresponding to the electron mobility $\mu > 10000 \text{ cm}^2/(\text{Vs})$ ($\nu = 3 \cdot 10^{12} \text{ s}^{-1}$).

Figure 4 presents the steady-state drain current–voltage relation $j_d(V_d)$ where the solid line shows the threshold for the development of instability boundary.

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**Fig. 2.** Emission spectra calculated by HD simulations at $\nu = 5 \cdot 10^{12} \text{ s}^{-1}$, $V_{th} = -0.3 \text{ V}$, $V_d = 0.14 \text{ V}$.

**Fig. 3.** Frequency of EOS-spectrum peaks as a function of swing-voltage $V_0 = V_g - V_{th}$ calculated for $V_d = 0.14 \text{ V}$.

**Fig. 4.** Static drain current characteristics calculated under constant voltage $V_0$ applied between the source and drain at increasing values of the gate voltage $V_g$ varying from $-0.35$ to $0 \text{ V}$ with $0.05 \text{ V}$ step (from bottom to top). Solid line shows the instability onset under constant drain-current operation.
behaviour of the EOS-signal unambiguously evi-
dences that the system approaches the threshold of 
self-oscillations originated from the development 
of instability. Beyond the instability threshold, the 
standard version of the EOS technique becomes 
invalid since the system under test cannot be in a 
static state without external action.

This tendency is illustrated by Fig. 7, which 
presents a voltage dependence of an effective re-
 laxation time of an excited 2D plasma wave when 
the system approaches the instability threshold. 
It is natural that such dependence has nothing in 
common with the internal relaxation time deter-
 mined by scattering mechanisms. Thus, its rapid 
increase unambiguously evidences that the system 
is approaching the instability threshold.

Fig. 5. EOS-signal calculated at $V_{g} = 0$ V and increasing 
values of $V_{d}$.

self-oscillations of 2D plasma waves. A typical 
behaviour of the wave-forms in going to the thresh-
old of self-oscillations is illustrated by Fig. 5. One 
can see that the duration of a transient response 
to a laser excitation starts sharply to increase in 
time. In the spectral representation of an EOS-
signal (see Fig. 6) this, in turn, is accompanied 
by the formation of a sharp resonant peak at the 
frequency of excitation of the fundamental mode 
of 2D plasma waves. Such a temporal and spectral

Fig. 6. Spectrum of EOS-signal calculated from data of 
Fig. 5.

Fig. 7. Effective plasma mode relaxation time 
dependence on the drain voltage approaching instability.
4. Conclusions

The above-presented experimental and theoretical results of EOS technique based measurements and simulations of the electrical response of photo-excited free carriers in FET/HEMT channels evidence that such direction of investigations is rather informative for the analysis of conditions corresponding to the excitation of 2D plasma waves. The realisation of the EOS technique proposed in this article allows to investigate directly a small-signal response in FET/HEMT channels since photo-excitation is performed with respect to the stationary steady state which is already formed in the transistor channel by some external embedding circuits. As it was demonstrated above, these features inherent in the EOS technique allow to carry out a response study directly approaching the threshold conditions for the development of 2D plasma wave instabilities. The system proximity to the threshold of the development of 2D plasma wave instability can be easily identified by a sharp increase of the EOS-signal relaxation time or and the narrowing of the resonant peaks of 2D plasma wave excitations in, respectively, temporal and spectral representations.

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References

Santrauka

Eksperimentiškai ir teoriniškai išnagrinėtos elektro-optinės atrankos (EOA) metodo galimybės ir privalumai tiriant dvimatęs plazmos bangų sužadinimą lauko tranzistorių arba didelio elektronų judrio tranzistorių (FET/HEMT) kanaluose. Eksperimentiškai parodyta, kad EOA metodas leidžia identifikuoti dvimatęs plazmos bangas HEMT kanale, kai jo darbo taškas yra sąlygotas išorinių grandinių. Teoriniai modeliavimai rodo, kad taikant EOA metodą galima lengvai nustatyti dvimatęs plazmos bangų nestabilumus.