Lithuanian Journal of Physics, Vol. **51**, No. 4, pp. 324–329 (2011)

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

J. Torres [a], L. Varani [a], F. Teppe [b], W. Knap [b], S. Boubanga-Tombet [c], T. Otsuji [c], P. Shiktorov [d], E. Starikov [d], and V. Gružinskis [d]

[a] *Institut d'Électronique du Sud - TeraLab (CNRS UMR 5214), Université Montpellier II, Place Bataillon, 34 095 Montpellier Cedex 5, France*

[b] *Laboratoire Charles-Coulomb - TeraLab (CNRS UMR 5221), Université Montpellier II, Place Bataillon, 34 095 Montpellier Cedex 5, France*

[c] *Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-Ku, Sendai 980-8577, Japan*

[d] *Semiconductor Physics Institute, Center for Physical Sciences and Technology, A. Goštauto 11, LT-01108 Vilnius, Lithuania*

E-mail: jane@pav.pfi.lt

Received 27 August 2011; accepted 1 December 2011

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

PACS: 72.20.Ht, 72.30.+q

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.

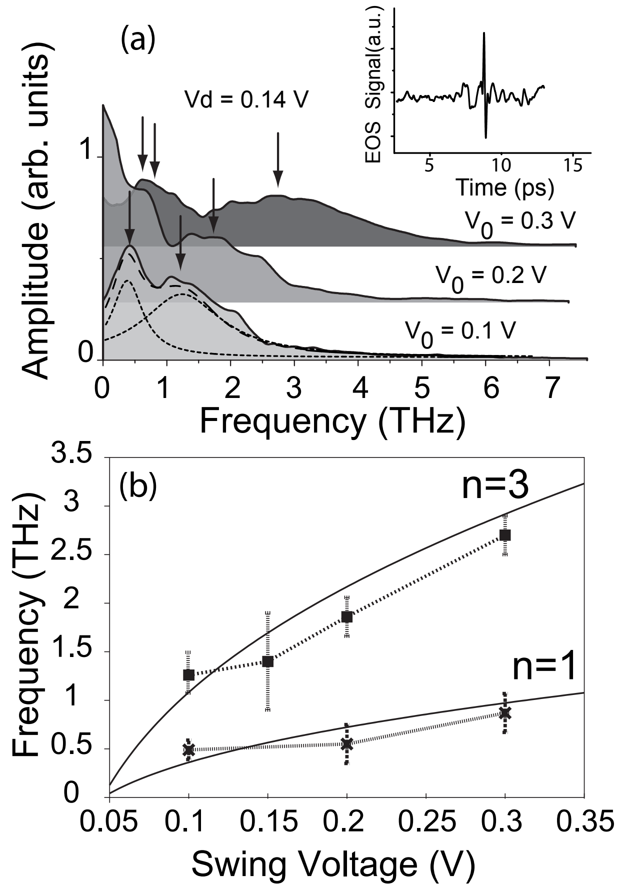

Fig. 1. (a) Measured temporal response of THz field (inset) and corresponding emission spectra obtained at the swing-voltage V_0 varied from 0.1 to 0.3 V. (b) Experimental frequency dependence of the peaks on V_0 (symbols) compared with analytical predictions (solid lines).

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 Fig. 1(b)) in accordance with analytical predictions for 2D plasma mode frequencies which can be excited in the HEMT channel:

$$f_n = \frac{n}{4L_{\text{eff}}}\sqrt{\frac{eV_0}{m_0 m}},\ \ n = 1, 3, 5, ..., \qquad (1)$$

where $L_{\text{eff}} = L_g + 2d$ 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

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]:

$$E_{\mathrm{THz}}(t) \sim \frac{\mathrm{d}}{\mathrm{d}t}\delta j(t), \tag{2}$$

where $E_{\mathrm{THz}}(t)$ 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 $\nu = 5 \cdot 10^{12}$ 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 $V_d = 0.14$ 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 $\mu > 10000$ cm^2/(Vs). ($\nu = 3 \cdot 10^{12}$ 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

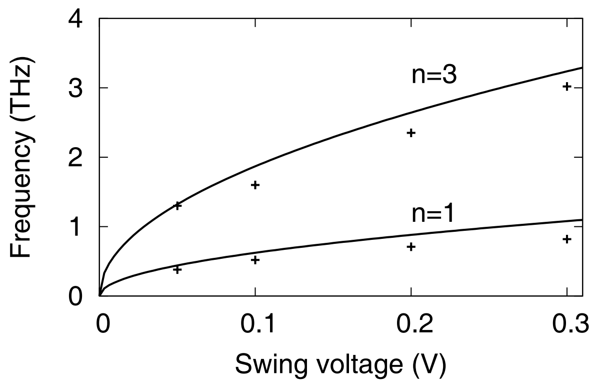

Fig. 3. Frequency of EOS-spectrum peaks as a function of swing-voltage $V_0 = V_g - V_{th}$ calculated for $V_d = 0.14$ V.

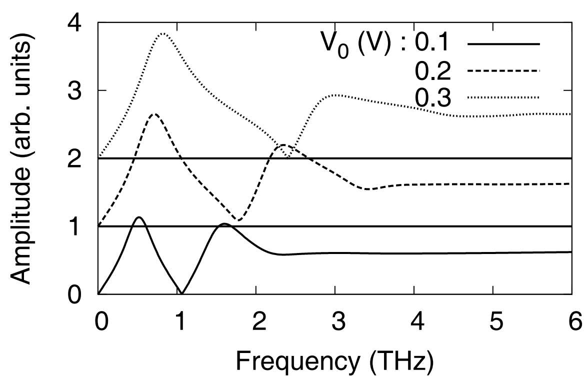

Fig. 2. Emission spectra calculated by HD simulations at $\nu = 5 \cdot 10^{12}$ s^{-1}. $V_{th} \approx -0.3$ V. $V_d = 0.14$ V.

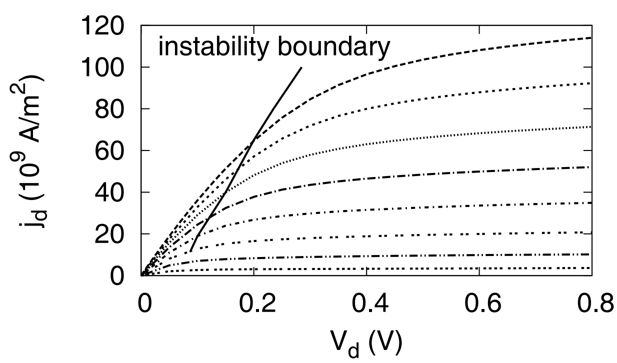

Fig. 4. Static drain current characteristics calculated under constant voltage V_d applied between the source and drain at increasing values of the gate voltage V_g varying from – 0.35 to 0 V with 0.05 V step (from bottom to top). Solid line shows the instability onset under constant drain-current operation.

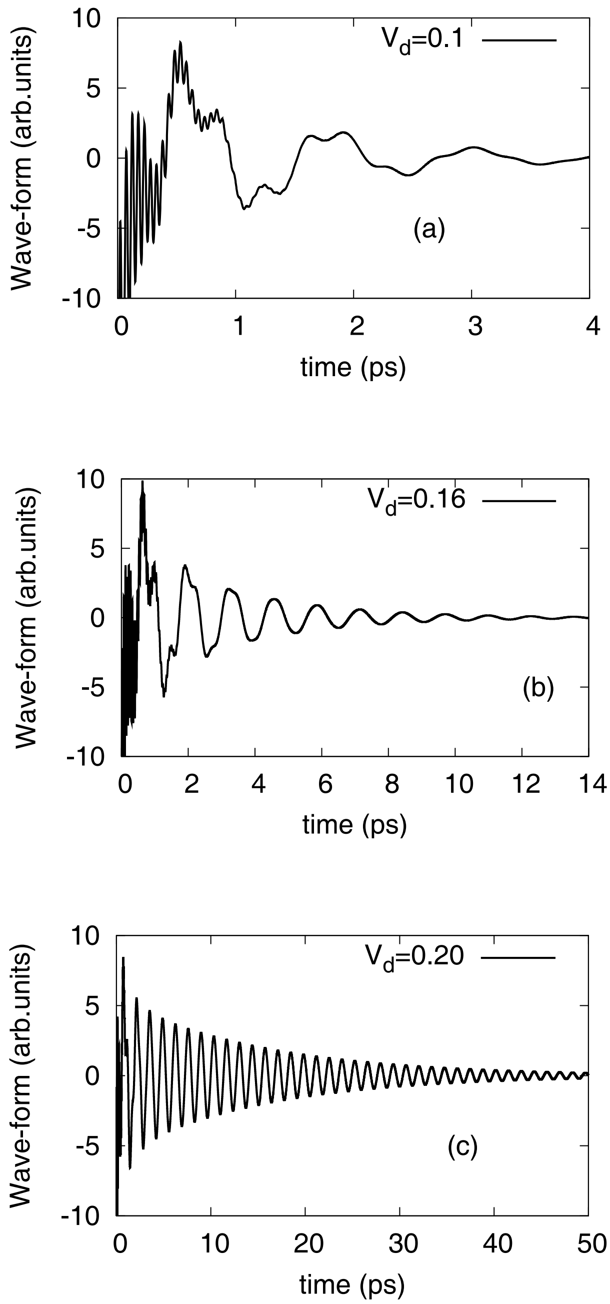

Fig. 5. EOS-signal calculated at $V_g = 0$ V and increasing values of V_d.

self-oscillations of 2D plasma waves. A typical behaviour of the wave-forms in going to the threshold 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

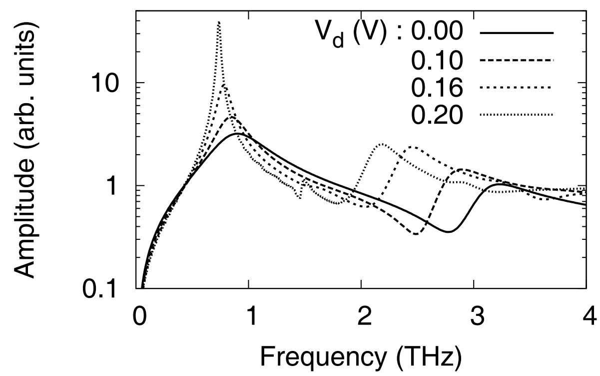

Fig. 6. Spectrum of EOS-signal calculated from data of Fig. 5.

behaviour of the EOS-signal unambiguously evidences 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 relaxation 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 determined by scattering mechanisms. Thus, its rapid increase unambiguously evidences that the system is approaching the instability threshold.

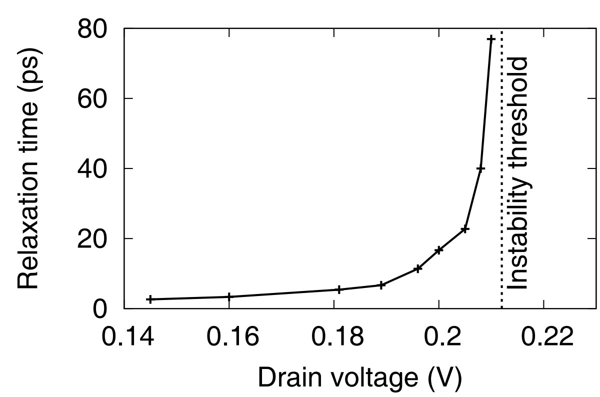

Fig. 7. Effective plasma mode relaxation time dependence on the drain voltage approaching instability.

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.

Acknowledgments

This work was partially supported by grant No. MIP-87/2010 of the Lithuanian Science Council.

References

[1] M. Dyakonov and M. Shur, Shallow water analogy for a ballistic field effect transistor: new mechanism of plasma wave generation by dc current, Phys. Rev. Lett. **71**(15), 2465–2468 (1993).

[2] J. Lusakowski, W. Knap, N. Dyakonova, L. Varani, J. Mateos, T. Gonzalez, Y. Roelens, S. Bollaert, A. Cappy, and K. Karpierz, Voltage tuneable terahertz emission from a ballistic nanometer InGaAs/InAlAs transistor, J. Appl. Phys. **97**, 064307 (2005).

[3] A. El Fatimy, N. Dyakonova, Y. Meziani, T. Otsuji, W. Knap, S. Vandenbrouk, K. Madjour, D. Théron, C. Gaquiere, M.A. Poisson, S. Delage, P. Prystawko, and C. Skierbiszewski, AlGaN/GaN high electron mobility transistors as a voltage tunable room temperature terahertz sources, J. Appl. Phys. **107**, 024504 (2010).

[4] J.-F. Millithaler, L. Reggiani, J. Pousset, L. Varani, C. Palermo, W. Knap, J. Mateos, T. González, S. Perez, and D. Pardo, A Monte Carlo investigation of plasmonic noise in nanometric n-$In_{0.53}Ga_{0.47}As$ channels, J. Stat. Mech. Theor. Exp. **01**, P01040 (2009).

[5] P. Shiktorov, E. Starikov, V. Gružinskis, L. Varani, G. Sabatini, H. Marinchio, and L. Reggiani, Problems of noise modeling in the presence of total current branching in high electron mobility transistor and field-effect transistor channels, J. Stat. Mech. Theor. Exp. **01**, P01047 (2009).

[6] P. Nouvel, H. Marinchio, J. Torres, C. Palermo, D. Gasquet, L. Chusseau, L. Varani, P. Shiktorov, E. Starikov, and V. Gružinskis, Terahertz spectroscopy of plasma waves in high electron mobility transistors, J. Appl. Phys. **106**, 013717 (2009).

[7] C. Kubler, R. Huber, and A. Leistenstorfer, Ultrabroadband terahertz pulses: generation and field-resolved detection, Semicond. Sci. Technol. **20**, S128–S133 (2005).

[8] S. Boubanga-Tombet, F. Teppe, J. Torres, A.El. Moutaouakil, D. Coquillat, N. Dyakonova, C. Consejo, P. Arcade, P. Nouvel, H. Marinchio, T. Laurent, C. Palermo, A. Penarier, T. Otsiji, L. Varani, and W. Knap, Room temperature coherent and voltage tunable terahertz emission from nanometer-sized field effect transistor, Appl. Phys. Lett. **97**, 262108 (2010).

[9] M. Abe, S. Madhavi, Y. Shimada, Y. Otsuka, K. Hirakawa, and K. Tomizawa, Transient carrier velocities in bulk GaAs: Quantitative comparison between terahertz data and ensemble Monte Carlo calculations, Appl. Phys. Lett. **81**(4), 679–681 (2002).

[10] S. Asmontas, P. Shiktorov, E. Starikov, V. Gružinskis, L. Varani, G. Sabatini, H. Marinchio, J. Torres, Plasma waves induced by the optical beating in HEMT channels as an expected source of TeraHertz radiation generation, AIP Conf. Proc. **1199**, 211–212 (2010).

DVIMATĖS PLAZMOS REZONANSŲ DIDELIO ELEKTRONŲ JUDRIO TRANZISTORIUOSE TYRIMAS, TAIKANT ELEKTROOPTINĖS ATRANKOS METODĄ

J. Torres [a], L. Varani [a], F. Teppe [b], W. Knap [b], S. Boubanga-Tombet [c], T. Otsuji [c], P. Shiktorov [d], E. Starikov [d], V. Gružinskis [d]

[a] *Monpelje II universiteto Pietinis elektronikos institutas, Monpelje, Prancūzija*

[b] *Monpelje II universiteto Šarlio Kulono laboratorija, Monpelje, Prancūzija*

[c] *Tohoku universitetas, Sendai, Japonija*

[d] *Fizinių ir technologijos mokslų centro Puslaidininkių fizikos institutas, Vilnius, Lietuva*

Santrauka

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