THz Detection by Field Effect Transistors: Antenna and High Magnetic Field Effects

J. Łusakowski[a], M. Sakowicz[a], K. Karpierz[a], W. Knap[b], and M. Grynberg[a]
[a]Instiute of Experimental Physics, University of Warsaw, Warsaw, Poland
[b]Research Institute of Electrical Communication, Tohoku University, Sendai, Japan

***Abstract*—An overview is given on recent experimental results in THz detection with high electron mobility transistors. Polarization studies showed clear antenna (directional) effects in detection. Experiments in quantizing magnetic fields allowed us to clarify the role of gated and ungated parts of the channel in detection.**

I. Introduction And Background

A theoretical model of Dyakonov and Shur [1] triggered an interest in application of field effect transistors (FETs) as detectors and sources of the electromagnetic radiation. One of basic predictions of the model is that the channel of a transistor behaves as a resonator for plasma waves. The fundamental frequency of plasma oscillations falls within the THz range for nanometer lengths of the transistor gate.

The model [1] was developed for a transistor with the gate covering all the source - drain distance (a Si MOSFET-like architecture), but it was used to explain experimental data obtained both on Si MOSFETs and HEMTs. An important difference between these two types of FETs is that in the latter case the gate covers only a small part of the channel. Thus, a HEMT is a system of coupled gated and ungated plasma. Up to now, it is not completely clear how both plasma regions interact one with the other and what is their role in the detection process.

Investigating a variety of HEMTs processed on different III-V heterostructures and quantum wells, we were faced with two fundamental questions: i) what is the mechanism of the coupling of the electromagnetic radiation to the transistor and ii) what is the role of gated and ungated parts of the channel in the detection process.

To answer the first question, we carried out polarization experiments, i.e., we measured a detection signal as a function of direction of the vector of polarization of the radiation. Directional dependencies (antenna effects) were found to be sensitive to the geometry of the transistor chip, transistor electrical polarization and radiation frequency. The second question was addressed by measurements in quantizing magnetic fields which allowed us to observe Shubnikov - de Haas oscillation of the detection signal. An analysis of the oscillations allowed us to show that in the case of HEMTs both the gated and ungated parts of the channel participate in the detection process.

II. Experimental and results

Experiments were performed on GaAs/AlGaAs, GaInAs/AlInAs and GaN/AlGaN HEMTs at room or liquid helium temperature. A transistor was illuminated with the radiation which generated a constant source - drain voltage (the detection signal). The drain was not biased while the gate was polarized with the voltage U_{GS}. The magnetic field, B, if present, was perpendicular to the channel plane. The measurements were carried out as a function of U_{GS} and B.

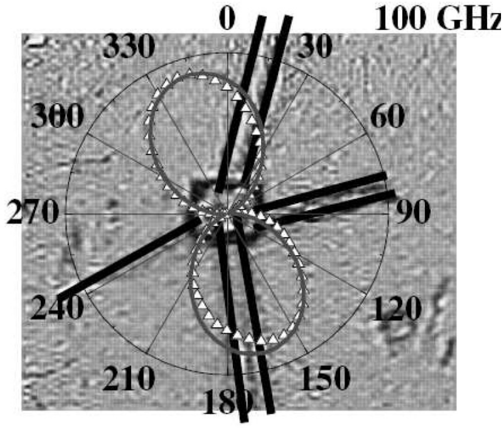

Fig. 1 Fujitsu transistor with bonding wires (thick black lines). Triangles: polar plot of the signal measured at 100 GHz (the angular scale is shown). Grey line: numerical simulations of the transistor response.

Polarization studies were carried out at room temperature on commercial GaAs/AlGaAs (Fujitsu) and GaInAs/AlInAs transistors. In these measurements, a linearly polarized radiation was used and the orientation of the polarization plane was changed within a full polar angle. An example of experimental results is shown in Fig. 1 (triangles). A clear dependence of the detection signal on the direction of polarization of the radiation was observed. Numerical simulations of the transistor response were carried out with a commercially available Quick-Wave 3D simulator. Simulations were based on solving the Maxwell equations by a finite difference time domain method, and allowed us to analyze a spatial distribution of the electromagnetic field within the transistor chip (including the wires bonding the transistor to a support) and in the space around. With appropriately chosen parameters, we could reproduce experimentally observed dependencies (the grey line in Fig. 1). Simulations show that for the frequency of 100 GHz the dominant part of the antenna which couples the transistor to the radiation is composed of bonding wires. This means, in particular, that the orientation of the two-lobe dependence

978-1-4244-2120-6/08/$25.00 ©IEEE.

shown in Fig. 1 is defined by the actual configuration of bonding wires rather than by a symmetry axis of the transistor chip. Simulations show, however, that at frequencies higher than about 120 GHz, the dominant role of the antenna is played by the contact pads. With a GaInAs/AlInAs HEMT and 285 GHz radiation we verified that the orientation of the two-lobe dependence coincides with the symmetry axis of the transistor, defined by the configuration of the contact pads. Our polarization experiments prove that the radiation couples to the whole transistor chip rather than to the transistor channel directly. Similar conclusions were found by Veksler *et al.* [2] in spatially resolved THz detection experiments. More details on polarization measurements can be found in [3].

High magnetic field experiments were carried out on GaAs/AlGaAs and GaN/AlGaN transistors cooled to liquid helium temperatures. The detection signal was measured as a function of the magnetic field at a constant gate voltage. Application of a modulation of the gate voltage allowed us to measure also a derivative of the detection signal with respect to the gate voltage (Fig. 2). We found that both the detection signal and its derivative oscillated as a function of the magnetic field, and the periodicity of the oscillations was the same as that of Shubnikov - de Haas magnetoresistance oscillations. A Fourier analysis of the oscillations was carried out. It was found that two components (i.e., two free electron concentrations) were found in oscillations of the detection signal: one of them changed linearly with the gate voltage, and the other one was constant. We attribute these two concentrations to the gated and ungated parts of the channel, respectively. Only one component, linearly dependent on U_{GS} was found in oscillations of the derivative of the signal. This is because the modulation of the gate voltage influences the gated part of the channel only. Results similar to that shown in Fig. 2 were also obtained on GaAs/AlGaAs transistors.

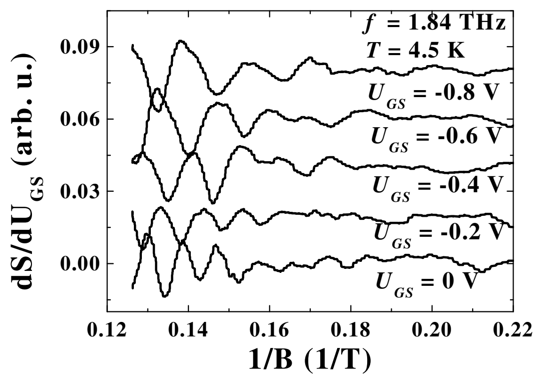

Fig. 2 Shubnikov - de Haas oscillations of the derivative of the detection signal of a GAN/AlGaN transistor, as a function of the inverse magnetic field at 1.84 THz. Each curve is labeled with a corresponding gate voltage.

A theory of THz detection with HEMTs in quantizing magnetic fields has not been formulated so far. To explain the oscillations observed, we note that the original theory of detection proposed in [4] gives the amplitude of the detection signal as a function of a dimensionless parameter $\omega\tau$, where ω is the incident radiation frequency and τ is a relaxation time. It is evident that the detection signal in the magnetic field must depend also on $\omega\tau$. Shubnikov - de Haas oscillations of the signal, or its derivative, just reflect a modulation of τ with the magnetic filed.

Measurements in the magnetic field clearly show that both parts of the channel are active in the detection process. They indicate that a generalization of the model [1] is necessary to analyze detection in HEMTs with coupled gated and ungated plasma. More details on detection in magnetic fields can be found in [5].

In conclusion, results reported in this communication answer some questions concerning detection of the electromagnetic radiation with HEMTs and define directions of improvements of the transistor architecture necessary to get a better control over this process. Even if the understanding of detection process has not been completed yet, HEMTs are successfully used for detection experiments.

ACKNOWLEDGEMENTS

This work was supported by Polish 3T11B04528 and 162/THz/2006/02 and European Union MTKD-CT-2005-029671 grants. It was also supported by the CNRS and GDR-E project *Semiconductor sources and detectors of THz frequencies.* WK acknowledges a support of the Japanese JSPS society.

REFERENCES

[1] M. Dyakonov and M. S. Shur, Phys. Rev. Lett. **71**, 2465 (1993).
[2] M. Sakowicz *et al.*, J. Appl. Phys., in press.
[3] D. M. Veksler et al., ISDRS 2007, College Park, MD, USA.
[4] M. Dyakonov and M. S. Shur, IEEE Trans. Electron. Dev. **43**, 380 (1996).
[5] M. Sakowicz *et al.*, Appl. Phys. Lett. **92**, 203509 (2008).

978-1-4244-2120-6/08/$25.00 ©IEEE.