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Terahertz Emission and Detection by Plasma Waves in Nanometer Size Field Effect Transistors

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SUMMARY Plasma oscillations in nanometer field effect transistors are used for detection and generation of electromagnetic radiation of THz frequency. Following first observations of resonant detection in 150 nm gate length GaAs HEMT, we describe recent observations of room temperature detection in nanometer Si MOSFETs, resonant detection in GaN/AlGaN HEMTs and improvement of room temperature detection in GaAs HEMTs due to the drain current. Experiments on spectrally resolved THz emission are described that involve room and liquid helium temperature emission from nanometer GaInAs and GaN HEMTs.

key words: *plasma oscillations, field effect transistors, detection and emission of THz radiation*

1. Introduction

Plasma excitations in semiconductor devices are intensively studied and are hoped to be the base of development of semiconductor devices whose performance could fill the so called "THz gap." Emerging plasma electronics is a broad area of technological and scientific research that develops on the border between optics and classical electronics. One of the important directions of research is investigation of semiconductor THz sources and detectors because they are most suitable for integration on a chip. That is why a large effort is devoted to observation of THz plasma oscillations in semiconductors by excitation with femtosecond laser pulses or nonlinear mixing of laser beams with close frequencies. The aim of this paper is to show that Field Effect Transistors (FETs) are also a very promising tool that could serve for coupling of the electromagnetic radiation with plasma oscillations. The interest in using nanometer FETs as detectors and emitters of THz radiation was stimulated by the model of plasma instability developed in [1]. This theory considered the channel of a FET as a resonant cavity for plasma oscillations and predicted that a coupling of the external electromagnetic radiation with plasma instability is possible. An important prediction of the model [1] is that to reach the THz frequencies, the length of transistor gate must be in a nanometer range. In that way, THz plasma electronics is not possible without an advanced nanometer technology.

In the present paper we describe recent experiments on sub micrometer FETs that act as detectors and/or emitters of THz radiation. In Sect. 2 we describe results of detection experiments carried out at low temperature on GaAs/GaAlAs and GaN/AlGaN HEMTs and at room temperature on Si MOSFETs. Section 3 describes basic results on room temperature and liquid helium temperature emission experiments on GaInAs/AlInAs and GaN/AlGaN HEMTs.

2. Detection

According to [1], the mechanism of detection is based on a drain-source asymmetry. One can envisage the channel of a FET as an element that rectifies the oscillatory movement of electrons imposed by the external force resulting from the electric field of the incoming THz electromagnetic wave. In that analogy, the FET acts as a rectifying diode, but at extremely high frequencies. In such a case, a constant drain-source voltage appears as a result of the interaction of the incoming radiation with the electron plasma in the channel (the photovoltaic effect). In the one-dimensional approach to the plasma flow [1], the transistor channel is a resonator for plasma waves, with eigenmodes of vibrations. As in any resonator, the strength of a response depends on the quality factor, $\omega\tau$, which in the case of the FET channel is related to the electron mobility via the momentum relaxation time, τ, and the incoming radiation frequency, ω. That is why, any possibility of increasing the quality factor gives an advantage of improving the detection performance. There are obviously technological improvements that can offer a higher mobility in the channel. However, this is not the only one possibility. As will be shown below, the sensitivity of detection grows when the drain current flows (the photoconductive effect). This is due to the fact that in the case of the drain current flow, the relaxation time that defines the quality factor depends on the effective relaxation time that increases with the current intensity. In the following, we discuss both ways of increasing the quality factor.

Plasma excitations and resonances in semiconductors have been investigated since more than half a century [2]. Measurements of a frequency dependent conductivity of a high mobility 2DEG in GaAs/AlGaAs quantum structures were performed by Burke et al. [3] who determined the real and imaginary part of the conductivity up to 10 GHz and explained their results by plasma resonances. Peralta

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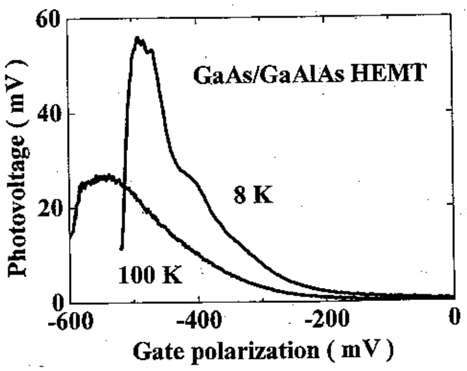

Fig. 1 Source-drain photovoltage (vertical axis) in GaAs/GaAlAs transistor at 100 K and 8 K. The resonance develops at about −380 mV, at low temperatures.

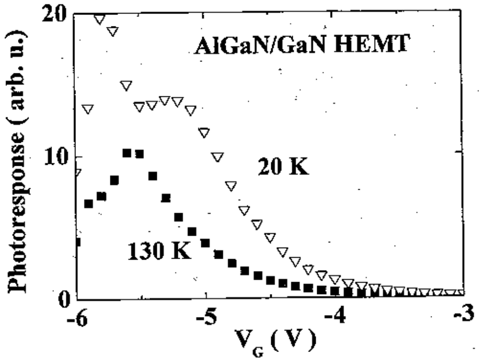

Fig. 2 Detection of 761 GHz radiation by GaN/AlGaAlN HEMT at 130 K (lower curve) and 20 K (upper curve), as a function of the gate voltage. The resonant structure appears at low temperatures for V_G about −5 V.

et al. [4] demonstrated a voltage tuneable photoconductivity response of a double quantum well heterostructure that showed plasma resonances excited by radiation in the range between 120 GHz and 4.8 THz. Lü et al. [5] where the first to observe detection of THz radiation in sub micrometer HEMT by measuring the photoresponse of the transistor as a function of the gate-source bias. Clear evidence of a resonant detection of THz radiation by plasma oscillation was shown by Otsuji et al. in InGaP/InGaAs/GaAs HEMT with the gate length of 150 nm [6]. In that experiment, the transistor was exposed to a photomixed laser beam that contained a THz difference component that could be tuned between about 1 THz and 8 THz. Two resonances in the photoresponse were observed at 1.9 THz and 5.8 THz. The frequencies of these resonances corresponded to predictions of the Dyakonov-Shur model.

THz detection in GaAs/AlGaAs and GaN/AlGaN transistors was first demonstrated by Knap et al. [7], [8] in a wide range of temperature between 8 K and 300 K. In these experiments, a sub THz radiation between 100 GHz and 600 GHz was used and the experimental results were interpreted within a model based on the original Dyakonov-Shur approach. A resonant plasma peak [9] appears as a small structure on a nonresonant background when the temperature is low enough (Fig. 1). To verify that this structure is related to plasma excitations, the concentration of the electrons in the channel was changed by subsequent illuminations with the halogen light. This caused a shift of the threshold voltage and a corresponding shift of the position of the resonance.

A similar resonant detection experiment was carried out on GaN/GaAlN HEMT, exposed to 761 GHz radiation generated by a molecular laser (Fig. 2). The gate length was 150 nm and the photovoltaic signal was measured as a function of temperature between 20 K and 130 K. As in the case of the GaAs/AlGaAs HEMT, a resonant structure appears at low temperatures and is superimposed on broadband non resonant signal.

A nonresonant detection signal was also observed at room temperature on nanometric Si MOSFETs with the gate length down to 30 nm exposed to 119 GHz radiation [10]. In that experiment, the quality factor was smaller than 1. The shape of the detected signal was explained by the theory developed in [8]. Although the observed MOSFET response was nonresonant, the theoretical model predicts a resonant detection at room temperature for higher values of the quality factor. This shows a possibility of a room temperature resonant detection by Si MOSFETs of a high electron mobility.

Passing from the non resonant to the resonant detection can be achieved by technological improvements of the mobility, that increases the electron scattering time and makes the quality factor higher. Another way is to carry out detection on a higher harmonics of the fundamental frequency, i.e., by increasing ω. It was shown recently, that a large increase of an effective scattering time can be achieved by increasing the drain current. The first demonstration of an increase of the FET detection signal with the drain current was presented in [11]. Recently, Teppe et al. gave a more detailed analysis of this phenomenon [12] showing that the current leads to an increase of the amplitude of the detection resonance and shrinkage of the resonance line.

3. Emission

The first observation of THz emission from a transistor structure was due to Tsui, Gornik and Logan [13]. The excitation of emission was due to the drain-source current. The spectral dependence of the emission was analysed with a tunable GaAs detector which performance is based upon tuning the energy of intra shallow donor transitions in the magnetic field. Deng et al. [14] observed an emission at 75 GHz from a GaN HEMT with the gate length of 1.5 μm and the drain-source separation of 5 μm. In this case, the spectrum of the emission was analyzed with a Fabry-Perrot interferometer. An important difference in the above experiments is that totally different structures were used. In the case of [13], the authors used a large transistor with a semi-transparent gate, on which a grid of metallic lines was deposited. The role of such was to couple the plasma resonances to the external radiation. On the other hand, a stan-

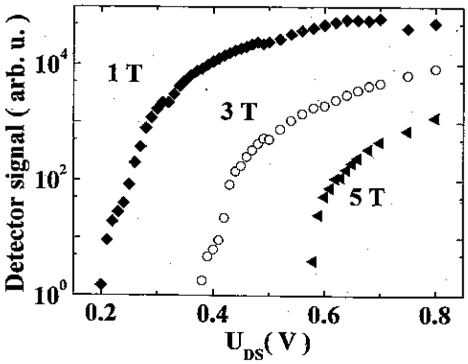

Fig. 3 The threshold behavior of the integrated emission signal for the transistor magnetic field of 1 T, 3 T and 5 T.

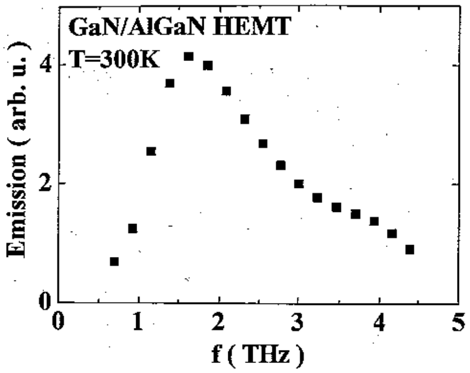

Fig. 4 Emission spectrum at room temperature from GaN/AlGaN HEMT with the gate length of 150 nm.

dard HEMT structure was used in the case of [14].

Our emission experiments concentrate on InGaAs/AlInAs and GaN/GaAlN HEMTs and are carried out at 4.2 K and 300 K. The first THz emission from a InGaAs/AlInAs transistor was observed by Knap et al. [15]. The transistors used were lattice matched GaInAs/AlInAs HEMTs on InP substrate grown by molecular beam epitaxy. The transistor channel was a 20 nm Ga$_{0.47}$ In$_{0.53}$As quantum well surrounded by Al$_{0.48}$In$_{0.52}$As barriers and the gate was 60 nm long. Other experimental and technological details can be found in [15], [16]. The measurements were carried out with a magnetic field tunable InSb detector that allowed to obtain a spectrum of the emitted signal. The observed spectra are broad with a sharper maximum at around 1 THz and a broad structure at about 6 THz. The low frequency peak was interpreted as resulting from the Dyakonov-Shur instability of the plasma in the transistor channel (see [15] for details).

According to the Dyakonov-Shur model, the plasma instability should show a threshold behavior, i.e., the intensity of the emitted signal should grow rapidly when a certain parameter increases over a threshold value. In our experiments the threshold behavior was investigated with the InSb detector placed in zero magnetic field. In such a case, the detector acts as a broadband detector and gives a response integrated over a wide frequency range. The results of such measurements are shown in Fig. 3.

In this investigation, the transistor was additionally put in a magnetic field [17] and the emission signal was measured as a function of the drain-source voltage. As was shown in [17], the shift of the threshold voltage with the magnetic field can be explained by the geometrical magnetoresistance of the ungated part of the channel [18]. Low temperature emission was also observed from GaN/GaAlN HEMTs. This transistors showed an emission signal that was similar to that of GaInAs/AlInAs emission.

Emission form HEMTs was also observed at room temperature. For such measurements we used GaInAs/AlInAs and GaN/AlGaN transistors. The threshold behaviour was measured with a Si bolometer cooled to 4.2 K and the spectra of the emission were analysed with a Fourier transform spectrometer working in the step scan mode. In both cases the emission signal is characterized by a strong increase once the drain-source voltage increases certain threshold voltage. An example of room temperature emission signal from GaN/AlGaN HEMT is shown in Fig. 4. Essentially, the emission spectra of low and high temperature have a very similar form with a broad maximum around 1–2 THz.

Let us notice that in all cases investigated, the emission appears in the bias conditions close to the saturation of the drain current. Then, the transistor is in a state characterized by very strong electric fields, and hot electron phenomena make an important contribution to the device performance. This indicates that the hot electron phenomena like electron transfer to the L valleys or tunnelling through the barrier can have an important impact on the mechanism of the emission. This point of view may be supported by observation of a striking similarity of emission performance of GaN/AlGaN and InGaAs/AlInAs transistors in both room and liquid helium temperatures. This similarity may come form the fact that for a hot electron phenomena, the temperature of the lattice is relatively of no importance.

Up to now, the emission experiments were explained based on the Dyakonov-Shur model of plasma instability. This model was, however, developed with an assumption of a linear response of the electron fluid to the external electric fields. In view of the recent experimental observations, we indicate, that this model should be generalized to include hot electron effects to properly describe the observed emission. Another possible modification is related to the fact that the model of plasma instability [1] was developed for a one dimensional case, where the lateral dimension of the transistor was not important. The transistor channel is, however, a wave guide rather than a resonator that gives a possibility of propagation of oblique modes, with a component of the wave vector perpendicular to the current flow. The spectrum of such modes is continuous which could explain why experimentally observed emission spectrum is a broad one. Additionally, the processes underlying plasma oscillations in FETs are nonlinear that leads to mixing of modes and to a broadening of the spectrum down to frequencies much lower than the THz range.

4. Conclusions

This paper reviews basic facts concerning experimental investigation of detection and emission of THz radiation by nanometer field effect transistors. The detection can be achieved both at room and cryogenic temperatures and its character (resonant or non resonant) depends on the quality factor of the transistor resonating cavity. The emission was observed at room and liquid helium temperatures showing a similarity of the results obtained in these two cases. This suggests that hot electron phenomena are essential for the emission to appear.

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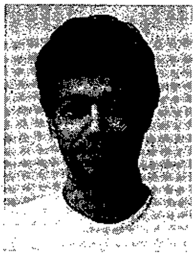

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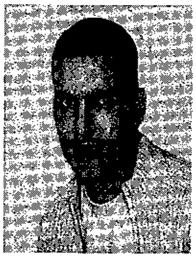

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