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THz Emission Related to Hot Plasmons and Plasma Wave Instability in Field Effect Transistors

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The current flowing in two-dimensional channel of field effect transistors can generate different types of charge density perturbations. They can have a form of uncorrelated hot plasmons or plasma waves. The mechanism of plasma wave generation depends on the parameter ωt and on boundary conditions of the channel. At $\omega t \ll 1$ only hot plasmons can be generated. The THz emission due to radiative decay of hot plasmons has a broad spectrum and can be only poorly controlled by the transistor gate. The tunability of THz emission can be obtained in the case of the Dyakonov–Shur plasma wave instability. In this work we present experimental studies of THz emission in InGaP/InGaAs/GaAs and GaN/AlGaN based field effect transistors. We report on two types of emission onset: (i) a smooth one typical for hot plasmons generation and (ii) threshold-like one characteristic for plasma waves instabilities. The tunability and spectra of emission change depending on the transistor configuration. We discuss the results suggesting several possible mechanisms of plasma wave excitation.

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1. Introduction

Nanometer size two-dimensional (2D) gated structures have been shown as potential sources and detectors of terahertz radiation. The THz emission due to radiative decay of grating coupled hot plasmons in gated 2D structures has been studied by many authors. These studies were performed only at cryogenic temperatures [1, 2]. They were interpreted as due to broad-band non-resonant hot plasmons, thermally excited by hot electrons.

The THz emission due to plasma waves instability in nanosize field effect transistors (FETs) has been studied experimentally [3–5] since the theory of the instability had been developed [6]. Authors have shown that the current-carrying state of a FET with asymmetric source and drain boundary conditions may become unstable against spontaneous generation of plasma waves [6]. The fundamental frequency of excited standing plasma waves can be tuned by the gate bias.

Later it has been shown that the oblique modes of plasma waves also can be generated resulting in the spectrum broadening [7]. In addition, the plasma wave instability in transistor channel can result also in excitation of plasma waves in access regions without gate [8]. Moreover, there has been theoretically demonstrated a new type of instability related to plasma waves propagating along the gate boundary perpendicularly to the current direction. This instability should lead to a broad non-tunable spectrum [7].

In this paper we show experimentally two types of emission onset typical for hot plasmons generation and the plasma wave instability. The frequency tunability and spectra of emission suggest several mechanisms of plasma wave excitation.

2. Devices characteristics and experimental setup

The samples were based on AlGaN/GaN heterostructures grown by metal-organic chemical-vapor deposition method. The electron density was around 1.3×10^{13} cm^{-2}, the mobility of electrons in the two-dimensional electron gas (2DEG) is estimated as ≈ 1500 cm^2/(V s). More details about samples can be found in [5]. The gate layout of high electron mobility transistors (HEMTs) had a T-shape with a gate width of 2×100 μm. The gate length L_g was 250 nm. The threshold voltage extracted at low drain bias was $V_{th} = -4.8$ V. Two types of AlGaN/GaN transistors were tested: standard transistors and transistors with a field plate deposited between gate and drain terminals. Also we studied transistors for which gate length varied from 1 to 16 μm (gated transmission line method (TLM)).

Other investigated samples were fabricated using InGaP/InGaAs/GaAs material systems. The 2D electron gas was formed within a quantum well in the InGaAs channel layer. The doubly interdigitated grating gate was formed with 65 nm thick Ti/Au/Ti by a standard lift-off process: $L_{g_1} = 100$ nm, $L_{g_2} = 1800$ nm, ungated part was 100 nm long and the ratio $L/W = 30/75$. More details can be found in [9].

The emission signal was excited by square source–drain voltage pulses, the source–gate voltage being constant. The measurement of the emission was performed using a 4 K operating silicon bolometer. For measurement of the emission onset the sample was placed directly in front of the bolometer. For the spectral analysis of the radiation a vacuum Fourier transform spectrometer was used.

3. Results and discussion

We observed several types of emission characterized by different emission onset, frequency content and spectrum tunability.

Figure 1 presents the emission onset as a function of drain bias. Curve 1 shows the smooth increase of the integrated emission intensity, which is typical for the emission due to radiative decay of hot plasmons. This type of behavior has been observed in some GaN/AlGaN transistors of both designs and in all InGaP/InGaAs/GaAs structures. For the latter the spectral study has shown that relatively broad emission spectra had maxima around 2.5–3 THz and did not shift with bias voltage [9].

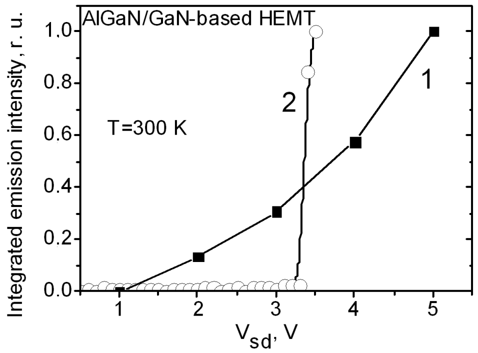

Fig. 1. Integrated emission intensity as a function of the source–drain bias. Both samples (1 and 2) were covered with field plate and had identical technological parameters.

We also observed the THz emission related to plasma waves instability in the GaN/AlGaN transistors. The main feature of the emission due to the plasma wave instability is the threshold-like emission onset as it is shown in Fig. 1, curve 2. This type of the emission onset has been observed in transistors with the field plate as well as without it. However, only in a transistor with the field plate we have found that the radiation frequency is controlled by the gate as it is described by the theory [6]. Plasma wave instability can result in the excitation of standing waves in different locations in the 2D channel: in the region under the gate, or in the access regions, or else at the boundaries of the two regions [6–8]. However, we would like to note that we did not observe any emission in the ungated 2D structures.

The emission from the gated part of the transistor is characterized by its frequency tunability. As it has been shown in Ref. [6], the fundamental frequency of plasma waves propagating along the channel can be tuned by the gate voltage and is given by: $f = \frac{1}{4}\frac{s}{L_{\text{eff}}}\left(1 - \frac{v^2}{s^2}\right)$, where $s = (eU_0/m)^{1/2}$ is the plasma wave velocity, e is the electron charge, v is the electron drift velocity, m is the effective electron mass, L_{eff} is the effective gate of the channel, and U_0 is the gate-to-channel voltage swing.

Figure 2 shows the dependence of emission frequency on the gate bias for the field plate covered GaN/AlGaN transistor with the threshold-like emission onset. One can see that emission frequency is controlled by the gate bias in agreement with the theory (open points). The emission spectrum width determined by the momentum relaxation time is also in a good agreement with theoretical estimations.

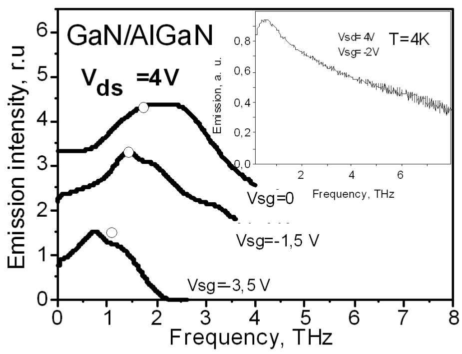

Fig. 2. Emission spectra for GaN/AlGaN transistor (sample 2) at several gate bias. Inset: the example of broad spectrum for a transistor showing the threshold-like emission onset.

However, the transistor whose gate was covered by the field plate has only shown this type of instability [5]. For standard transistors without field plate as well as for gated TLM structures even when we observed the threshold-like onset of the emission, the spectra were broad and the gate bias did not control their frequency [8]. The example of spectrum for this type of emission is shown in the inset of Fig. 2.

The broadband emission can be due to an excitation of other modes of plasma waves in the channel. As it has been shown in Ref. [7] the plasma wave instability in transistor channel can result also in excitation of oblique modes. The excitation of these modes should result in broad emission spectra uncontrolled or weakly controlled by the gate bias.

As it has been recently demonstrated theoretically, another type of instability can exist in gated 2D structures, where W is much bigger than L (typical for transistors) [7]. It has a form of plasma wave turbulence — a localized mode propagating along the gate boundaries in the direction perpendicular to the drain current.

The frequency range of described above types of broad-band emission is limited by minimal and maximal frequencies. The minimal frequency, $f_{\min}$, is defined by the condition $\omega\tau > 1$. The spectrum width is limited by the $f_{\max} \sim s/(2\pi d)$, where d is the gate-to-channel separation [7]. For our GaN/AlGaN transistors the estimation gives $f_{\min} \approx 1$ THz and $f_{\max} \approx 10$ THz. Estimated values of $f_{\min}$ and $f_{\max}$ are in a reasonable agreement with our experimental results.

4. Conclusions

We observed THz emission from nanosize FETs. The onset, tunability and spectra of radiation suggest different mechanisms of emission: (i) radiative decay of non-resonant hot plasmons (ii) and plasma waves instability due to the current flowing through the channel. The plasma wave instability can result in the excitation of different plasma wave modes depending on the boundary conditions on the source and drain sides of the gate. In particular, the field plate deposited over the gate resulted in tunable THz emission.

Acknowledgments

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