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Nanometer transistors for emission and detection of THz radiation

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Abstract

Experimental results concerning detection and emission of THz electromagnetic radiation in nanometer Field Effect Transistors are reviewed. The experiments were performed on GaAs/GaAlAs and GaInAs/AlInAs High Electron Mobility Transistors and Si Metal Oxide Semiconductor Field Effect Transistors at room and liquid helium temperatures. The results are interpreted within a model of the electron plasma instability in the transistor channel.

Keywords: Electronic devices; Infrared spectroscopy; Nanostructures; THz radiation

1. Introduction

THz sources and detectors attract considerable attention both from the point of view of the basic research as well as technical applications. The aim of this paper is to show that the Field Effect Transistor (FET) is a very promising tool that could serve for this purpose. The paper is organized as follows. In Section 2, we summarize theoretical considerations of Dyakonov and Shur [1] concerning instability of the current flow in the transistor channel and coupling of resulting plasma oscillations with the electromagnetic radiation. Section 3 describes results of detection experiments carried out on GaAs/GaAlAs High Electron Mobility Transistors (HEMTs) and Si Metal Oxide Semiconductor FETs (MOSFETs) at room and liquid helium temperatures. Section 4 summarizes results of emission experiments on GaInAs/AlInAs HEMTs. The results are discussed within the Dyakonov–Shur model [1]. We point out, however, that this model does not take into account some aspects of hot electron phenomena that seem to be important for interpretation of experimental results.

2. Plasma instability in Field Effect Transistors

The model of the electron plasma instability in the FET channel developed in [1] is based on the assumptions that the electron flow in the channel can be described by the Euler equation

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = -\frac{e}{m}\frac{\partial U}{\partial x} \quad (1)$$

supplied with the current continuity equation

$$\frac{\partial \rho}{\partial t} + \operatorname{div}\vec{j} = 0 \quad (2)$$

and a relation between the gate potential and the electron concentration in the channel,

$$n_s = CU/e \quad (3)$$

In these equations, v is the hydrodynamic electron velocity, $\rho = n_s e$ where n_s and e is the electron surface concentration and charge, respectively, j is the current density, C is the gate capacitance per unit area and $U(x)$ is the voltage swing controlling the electron concentration in the channel. These equations lead to

$$\frac{\partial U}{\partial t} + \frac{\partial (Uv)}{\partial x} = 0 \quad (4)$$

which is analogous to the hydrodynamic equation for the shallow

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water. The resulting plasma wave dispersion is $k=\pm\omega/s$, where k is the wave vector, ω is the frequency and $s=(eU_0/m)^{1/2}$ is the plasma wave velocity; U_0 is the voltage swing at the source and m is the electron effective mass. $U_0=U_{GS}-U_{TH}$, where U_{GS} is the applied gate–source voltage and U_{TH} is the threshold voltage. The dependence of s on U_0 means that the plasma wave velocity depends on the electron concentration in the channel and can be tuned by the gate potential. A gradual channel approximation is assumed in the Dyakonov–Shur model which means that the characteristic scale of potential variation along the channel is much greater than the gate–channel separation, d. For asymmetric boundary conditions at the drain and source, a steady flow described by Eq. (4) is unstable against the velocity and voltage fluctuations. The fluctuations are magnified by successive reflections at the drain and source that leads to a coherent spatio-temporal behavior of the electron fluid, i.e., to the plasma oscillations. For a particular choice of the boundary conditions, appropriate in the case of a real FET, the frequency of plasma oscillations in the channel is given by

$$\omega = (2p-1)\frac{\sqrt{eU_0/m}}{8\pi L} \tag{5}$$

where L is the gate length and p is an integer; the fundamental mode, ω_0, corresponds to $p=1$.

This instability of the current flow in the transistor channel was a new aspect of the plasma physics predicted by the theory developed in [1]. Originally, the theory was formulated for a ballistic transistor but the same type of behavior was later proven in the presence of scattering and electron fluid viscosity [2]. The dispersion relation of the plasma waves obtained in [1] coincided with the result of a standard approach for a two-dimensional gated plasma [3] in the case of the long wavelength limit, i.e., for $kd\ll 1$; ε_1 and ε_2 are the frequency dependent dielectric functions of the channel and the barrier material, respectively.

$$\omega^2 = \frac{n_s e^2}{\varepsilon_0 m} q[\varepsilon_1 + \varepsilon_2 \coth(qd)]^{-1} \tag{6}$$

As it was mentioned above, in the case of the zero drain current, the voltage swing that controls the electron concentration in the channel is equal to $U_{GS}-U_{TH}$. In general, this relation should be corrected by taking into account the access resistance and the drain current saturation effects, as it will be shown below.

From the application point of view, the important fact is a possibility of coupling the plasma oscillations in a FET to the external electromagnetic radiation. According to [1], the coupling is due to the dipole composed of an oscillating electron density in the channel and corresponding oscillations of the image charge. The coupling enables detection and emission of the electromagnetic radiation by a FET. The detection requires only application of the gate polarization because its mechanism is based on the source–drain asymmetry only and rectification of the signal originating from the incoming radiation. In such a case, a constant drain–source voltage appears as a result of interaction of the incoming radiation with the electron plasma in the channel (photovoltaic effect). However, as it will be shown below, sensitivity of detection grows when the drain current flows (photoconductive effect). On the other hand, the experiments show that the emission occurs only when the drain current approaches the saturation.

Another quantity important for observation of plasma resonances is the quality factor, $\omega\tau$, where ω is the radiation frequency and τ is the momentum relaxation time. In the following, we will discuss possibility of increasing the quality factor by technological improvements and increasing the drain current.

3. Detection

Observation of plasmon resonances in 2DEG started with the work of Allen, Tsui and Logan [4] who showed resonances in transmission through a gated MOS structure. Burke et al. [5] performed measurements of frequency-dependent electron conductivity in a high mobility 2DEG in GaAs/AlGaAs quantum structures, determining the real and imaginary part of the conductivity up to 10 GHz. They found that both parts show an oscillatory character as a function of frequency and explained this behavior by plasma resonances. The main argument for this interpretation was that the experimentally determined wave velocity was proportional to the square root of the 2DEG concentration, as predicted by the plasmon theory (see Eq. (6)). Peralta et al. [6] demonstrated a voltage tunable 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. In that experiment, the sample was a 2 mm×2 mm mesa on which a grid gate was deposited in the form of metal bars with 4-μm or 8-μm period, the bars covering half of the period. A theoretical description of the plasma resonances in this system was presented in [7] while its application as a millimeter wave mixer was given in [8].

The first implementation of a submicrometer FET as a detector of THz radiation was reported by Lü et al. [9] who exposed a commercial 0.18-μm-long HEMT to 2.5 THz radiation and measured the photoresponse as a function of the gate–source bias. A clear evidence of a resonant detection of THz radiation by plasma oscillations in a transistor was given by Otsuji et al. in InGaP/InGaAs/GaAs HEMT with the gate length of 150 nm [10]. In that case, the transistor was exposed to a photomixed laser beam that contained THz difference component. The frequency of this component was tuned between about 1 THz and 8 THz and two maxima in the photoresponse, observed at 1.9 THz and 5.8 THz, were interpreted as the first and third harmonics of the plasma resonance described by the Dyakonov–Shur model ($p=1$ and 2 in Eq. (5)). The importance of the experiment described in [10] relies in a direct presentation of a frequency spectrum of plasma excitations in a nanometer FET.

Detection in GaAs/AlGaAs and GaN/AlGaN transistors was investigated by Knap et al. [11,12] in a wide range of temperatures between 8 K and 300 K. Radiation between 100 GHz and 600 GHz was used and the experimental results were interpreted within a model that was a modification of the original Dyakonov–Shur approach: a proportionality of the