Resonant terahertz detection in InGaAs/AlInAs and AlGaN/GaN – based nanometric transistors.

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We report on resonant terahertz detection by two-dimensional electron plasma located in nanometric InGaAs/AlInAs and A GaN/GaN transistors. Up to now, the biggest part of the research was devoted to GaAs-based devices as the most promising from the point of view of the electron mobility. The resonant detection was observed/reported, however, only in the sub-THz range. According to predictions of the Diakonov-Shur plasma wave detection theory the increase of the detection frequency can be achieved by reducing the length or increase the carrier density in the gated region. We demonstrate that the limit of the 1THz can be overcome by using ultimately short gate InGaAs/AlInAs and/or AlGaN/GaN nanotransistors. In the first one, InGaAs/AlInAs, – 50 nm length – gate was processed. The inherent feature of AlGaN/GaN structures is high electron densities, reaching the values of 10^{13} cm^{-2} which allowed to obtain the detection over 1THz frequencies even for 150nm gate length devices. For the first time the tunability of the resonant signal by the applied gate voltage is demonstrated. The photoresponse is interpreted in the frame of the Diakonov-Shur plasma wave detection theory. We discuss the possible application of detection by nanotransistors in different types of THz spectroscopy research.

Introduction

The terahertz (THz) range of frequencies is often referred to as the "terahertz gap", since it lies in between the frequency ranges of electronic and photonic devices and it is hardly achieved from the both sides. Therefore, the development of the THz emitters and detectors is of the high importance. Dyakonov and Shur, proposed to use the nonlinear properties of plasma excitations in 2D gated electron gas for terahertz detectors, mixers, and THz radiation sources [1,2] The plasma waves in a field-effect transistor (FET) have a linear dispersion law [1], $\omega = sk$, where $s = \sqrt{e(U_{gs} - U_{th})/m}$ is the wave velocity, U_{gs} is the gate-to-source voltage, U_{th} is the threshold voltage, e is the electronic charge and m is the electron effective mass. This plasma wave velocity is typically much larger than the electron drift velocity. A short FET channel of a given length, L, acts as a resonant "cavity" for these waves with the eigen frequencies given by $\omega_N = \omega_0(1+2N)$, where $N = 1,2,3,...$ and the fundamental plasma frequency $\omega_0 = \pi\sqrt{e(U_{gs} - U_{th})/m}/2L$ can be easily tuned by changing the gate voltage, U_{gs}. When $\omega_0\tau \ll 1$, (τ is the momentum relaxation time), the detector response is a smooth function of ω and the gate voltage (broadband detector). When $\omega_0\tau \gg 1$, the FET can operate as a resonant detector. For the submicron gate lengths, the resonant detection frequency $f = \omega_0/2\pi$ can reach the THz range [1].

If the quality factor of the resonant cavity, $\omega_0\tau \gg 1$, the electron flow in the channel may become unstable (at certain boundary conditions) with respect to formation the resonant plasma oscillations. In this paper, we review our recent experimental results for detection of terahertz and subterahertz radiation by submicron heterostructure field effect transistors.

The basic idea of detection can be formulated as follows: An electromagnetic radiation with the frequency ω excites plasma waves in the channel. The nonlinear properties of such waves and asymmetric boundary conditions at source and drain lead to the radiation-induced constant voltage drop along the channel ΔU [1,2], which is the detector response. The experimental exploration of the subject has begun long time ago, starting from the observation of the non- resonant detection in high mobility transistors [3 ,4]. A new boost to the research in this direction was given by a series of publications [5,6,7], observation of the infrared detection in short channel high electron mobility transistors (HEMTs) fabricated from different materials and in Si MOSFETs. The publications reporting non-resonant detection were followed by demonstration of resonant infrared detection in GaAS HEMTs [8,9] and gated double quantum well heterostructures [10,11]. In all devices, the 2D plasmon was tuned to the frequency of subterahertz radiation by varying the gate bias.

Recently, we observed the resonant detection using THz sources in the range from 0.7 to 3.1 THz [12]. The experiment was performed on InGaAs/AlInAs and AlGaN/GaN HEMT with a 50 nm, 150 nm gate lengths respectively, employing the CO_2 pumped FIR gas laser as a source of THz radiation.

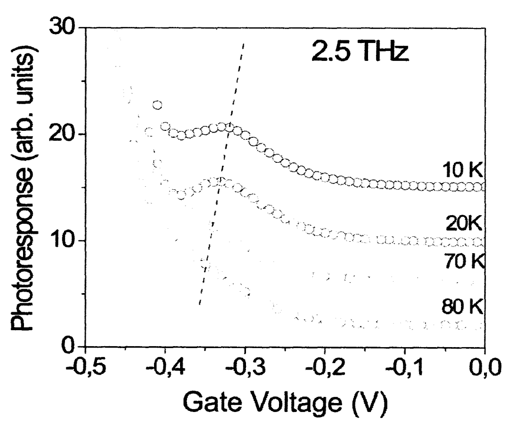

Fig.1: Photoresponse of InGaAs device vs. the gate voltage at different device temperatures at 2.5 THz. For the sake of clarify; curves are shifted in the vertical scale. Dashed lines show the zero levels. (After Ref [12])

Figure 1 presents the results of the photoresponse measured in InGaAs/AlInAs-based devices. At the device temperature below 100 K, the shoulder becomes pronounced in the lower gate voltage side, in between -0.4 ÷ -0.3 V, in addition to the temperature-independent non-resonant detection peak near the transistor threshold voltage. It further evolves to the clearly resolved temperature-sensitive spike nicely visible below 40 K. We attribute these peaks to the resonance detection of THz frequencies by plasma waves. Since the electron mobility at 60 K is about 36 000 $cm^2/V \cdot s$, which corresponds to the momentum relaxation time of 800 fs, we should expect the quality factor at 2.5 THz be of $\omega_0\tau \approx 13$. However, one can note, that even at 10 K, when the plasma resonance is visible around 0.33 V, it still remains very broad, about 60 mV, or about 1.5 THz in frequency domain. The corresponding relaxation time determined from the resonance half width at half as height, $\tau = 1/(\pi\Delta f)$, to be τ =212 fs, and the quality factor $\omega_0\tau \approx 3$. This additional resonance peak broadening shows that additional mechanisms of the plasma waves damping must be involved. These mechanisms might include the effect of ballistic transport [13],, viscosity of the electron fluid due to the electron-electron collisions [1] and a possible effect of oblique plasma modes [14]. Figure 2 shows the photoresponse at difference excitation frequencies at 10 K. One can see, that with the increase of excitation frequency from 1.8 THz to 3.1 THz, the plasmon resonance moves to higher gate voltages in a decent agreement with the calculated fundamental plasma frequency as a function of the gate voltage.

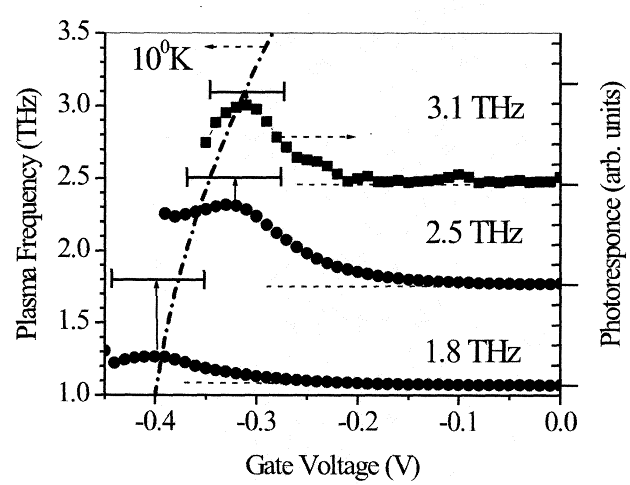

Fig. 2. Photoresponse in InGaAs/AlInAs-based device vs. the gate voltage at three different frequencies of excitation

(1.8 THz, 2.5 THz and 3.1 THz) at 10 K. (right axis). Curves are shifted in the vertical scale. Dashed lines indicate zero photoresponse at corresponding frequency. Arrows indicate resonance positions. Calculated plasmon frequency as a function of the gate voltage for V_{th} = -0.41 V (threshold voltage) is shown by the dash-doted line (left axis). The error bars corresponds to the linewidth of the experimental resonance peaks. (After Ref [12].)

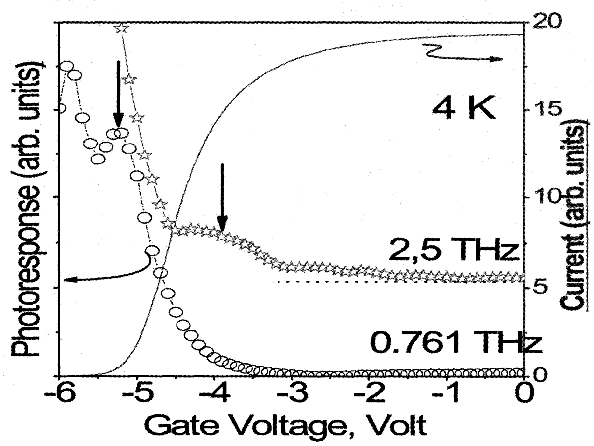

Fig. 3. Photoresponse in AlGaN/GaN-based device vs. the gate voltage at two different frequencies of excitation (0.761THz and 2.5 THz) at 4 K. (left axis). Curves are shifted in the vertical scale. Dashed lines indicate zero photoresponse at corresponding frequency. Arrows indicate resonance positions. Drain current vs. the gate voltage at 4 K (right axis). V_{th} = -5.2 V (threshold voltage).

Figure 3 shows the photoresponse at difference excitation frequencies at 4 K. One can see, that with the increase of excitation frequency from 0.761 THz to 2.5 THz, the plasmon resonance moves to higher gate voltages. In a agreement with the calculated fundamental plasma frequency as a function of the gate voltage.

The responsivity of the device was estimated to be of the order of 1V/W. Such a low value is due to a weak coupling of the THz radiation to the channel plasma, and to small area of the device, capturing only a tiny fraction of the incoming THz beam. According to the recent theoretical calculation [15] the coupling could be dramatically increased by using large area multi-finger design or employing THz antennas. Operating temperature, required for the resonant detection, could be increased then driving transistor into the saturation mode [16] and ideally the temperature can reach 300 K.

To conclude, both resonant and non-resonant detection of sub-THz and THz radiation exploiting plasma waves have been observed in transistors of different materials including InGaAs/AlInAs and AlGaN/GaN.

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