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Plasma wave resonant detection of terahertz radiations by nanometric transistors

W. Knap[1], A. El Fatimy[1], J. Torres*[1], F. Teppe[1], M. Orlov[1,2], and V. Gavrilenko[2]

[1]*GES CNRS UMR 5650, Montpellier, France*
E-mail: knap@univ-montp2.fr

[2]*Institute for Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod, Russia*

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We report on resonant terahertz detection by two-dimensional electron plasma located in nanometric InGaAs and 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 reported, however, only in the sub-THz range. According to predictions of the Dyakonov–Shur plasma wave detection theory an 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 1THz limit can be overcome by using ultimately short gate InGaAs and GaN nanotransistors. For the first time the tunability of the resonant signal by the applied gate voltage is demonstrated. We show that the physical mechanism of the detection is related to the plasma waves excited in the transistor channel (Dyakonov–Shur theory). We also show that by increasing of the drain-to-source current leads to a transformation of the broadband detection to a resonant and tuneable one. We can get resonant detection at room temperature. We finally discuss the possible application of detection by nanotransistors in different types of THz spectroscopy research.

PACS: **73.21.–b** Electron states and collective excitations in multilayers, quantum wells, mesoscopic, and nanoscale systems;
73.22.–f Electronic structure of nanoscale materials: clusters, nanoparticles, nanotubes, and nanocrystals;
73.23.Ad Ballistic transport;
73.50.Fq High-field and nonlinear effects.

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1. 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 to achieve from both sides. Therefore, the development of THz emitters and detectors is of high importance. Dyakonov and Shur, have 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 $s = \sqrt{e(V_g - V_{\rm th})/m}$ is the wave velocity, V_g is the gate-to-source voltage, $V_{\rm th}$ is the threshold voltage, e is the electron 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_g, 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 $\omega_0 = \pi\sqrt{e(V_g - V_{\rm th})/m}/2L_g$ can be easily tuned by changing the gate voltage, V_g. 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

* Also with *CEM2, CNRS-Universite Montpellier 2, UMR 5507, Montpellier 34090, France*

resonant detection frequency $f = \omega_0/2\pi$ can reach the THz range [1]. If the quality factor of the resonant cavity, $\omega_0\tau >> 1$, the electron flow in the channel may become unstable (at certain boundary conditions) with respect to formation of 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: electromagnetic radiation with frequency ω excites plasma waves in the channel. The nonlinear properties of such waves and asymmetric boundary conditions at source and drain lead to a radiation-induced constant voltage drop a long the channel ΔU [1,2], which is the detector response. The experimental exploration of this subject began along 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 [5–7], reporting 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.

2. Low temperature

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 50 nm, 150 nm gate lengths respectively, employing the CO_2 pumped FIR gas laser as a source of THz radiation.

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 $-0.4\,V \le V_g \le -0.3\,V$, 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 a momentum relaxation time of 800 fs, we should expect the quality factor at 2.5 THz be $\omega_0\tau \approx 13$. 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 height, $\tau = 1/(\pi\Delta f)$, to be $\tau = 212$ 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

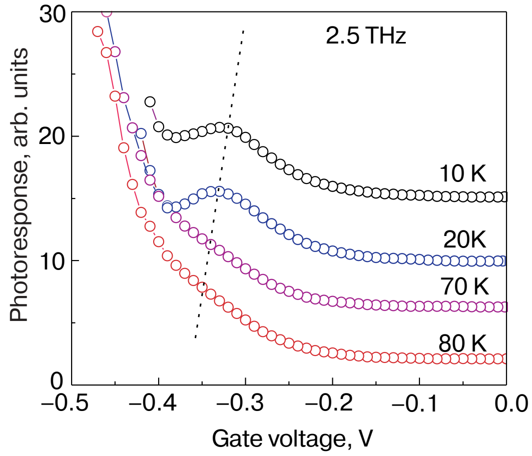

Fig. 1. Photoresponse of InGaAs device versus gate voltage at different device temperatures at 2.5 THz. For the sake of clarity; curves are shifted along the vertical scale.

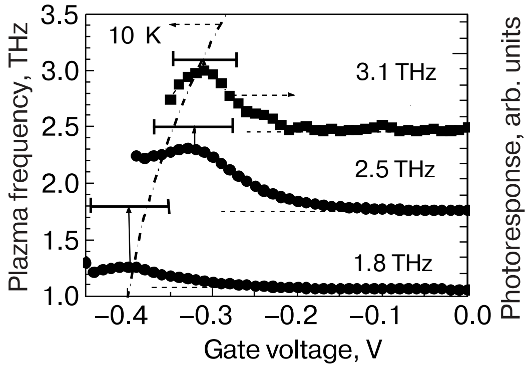

Fig. 2. Photoresponse in InGaAs/AlInAs-based device versus the gate voltage at three different frequencies of excitation (1.8 THz, 2.5 THz and 3.1 THz) at 10 K (right axis). Curves are shifted along the vertical scale. Dashed lines indicate zero photoresponse at corresponding frequency. Arrows indicate 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.)

fundamental plasma frequency as a function of the gate voltage.

Figure 3 shows the photoresponse in AlGaN/GaN-based device at different 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 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, captures 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. The operating temperature, required for the resonant detection, could be increased, driving transistor into the saturation mode [16] and ideally the temperature can reach 300 K.

3. Room temperature

Recently, Teppe and co-workers have demonstrated room-temperature, resonant detection of sub-terahertz radiation by 250 nm gate length GaAs/AlGaAs transistor [17]. They have shown that the detection regime, initially nonresonant, becomes resonant even at 300 K by increasing the drain current and driving the transistor into the current saturation region.

We have shown experimentally [18] that the resonant detection of sub-THz radiations can be continuously tuned by the applied gate voltage even at room temperature.

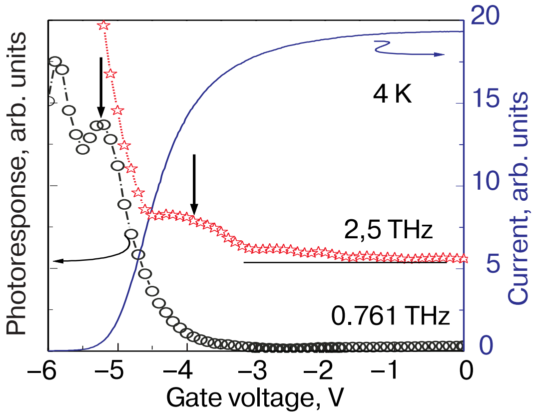

Fig. 3. Photoresponse in AlGaN/GaN-based device versus the gate voltage at two different frequencies of excitation (0.761 THz and 2.5 THz) at 4 K (left axis). Curves are shifted in the vertical scale. Solid lines indicate zero photoresponse at corresponding frequency. Arrows indicate resonance positions.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

The experiments were performed on two 50 nm gate length AlGaAs/InGaAs HEMTs called sample 1 and sample 2. The active layers consisted of a 200 nm $In_{0.52}Al_{0.48}As$ buffer, a 15 nm $In_{0.7}Ga_{0.3}As$ channel, a 5-nm-thick undoped $In_{0.52}Al_{0.48}As$ spacer, a silicon planar doping layer of $5{\cdot}10^{12}/cm^2$, a 12-nm-thick $In_{0.52}Al_{0.48}As$ barrier layer, and finally, a 10-nm-silicon-doped $In_{0.53}Ga_{0.47}As$ cap layer. The cap layer length is 500 nm and drain-source separation is 1.4 μm. The threshold voltages, extracted from transfer characteristics were −0.6 V and −0.4 V, respectively. The photo-response measurements were performed with a backward wave oscillator (BWO) source which gives powerful and tuneable sub-terahertz radiations from 450 GHz up to 700 GHz. The radiation beam was not focused and the diameter of the spot was approximately five centimetres at the position of the sample, i.e. much larger than the gate length of the device. The maximum output power was around 20 mW for each lines of the BWO.

Concerning sample 1, the photoconductive response versus the gate voltage for different values of applied drain–source voltage V_d from 0.025 V up to 0.55 V at a fixed value of the external frequency of 663 GHz is shown in Fig. 4. One can see that for $V_d = 0.025$ V typical nonresonant signal can be observed. The resonant peak appears at higher V_d, its amplitude increases and its position shifts to higher values of gate voltage with the applied V_d. We want here to point out that the plasma wave resonance appears when the transistor is driven into the current saturation region. This behavior was observed in sample 2 as well.

The photoconductive response of sample 2 versus gate voltage for frequencies (473, 679 GHz), is shown in Fig. 5 while keeping constant the source drain voltage to 0.3 V. One can see that for the lowest one, only typical nonresonant signal can be observed. For higher frequencies, after a typical increase of the nonresonant background signal with applied drain voltage/current, the resonant structure starts to grow.

Results shown in Figs. 4 and 5 show clearly that the resonant detection is obtained either by i) increasing the relaxation rate «τ» or by ii) increasing resonance frequency «ω». Both these effects lead to increasing of the effective quality factor ωτ, which as mentioned before, should be higher than unity to get resonant detection. As discussed in our earlier work [16,17], with increase of the current, the electron drift velocity v increases leads to the increase of an effective relaxation rate given by $1/\tau_{\text{eff}} = 1/\tau - 2v/L_g$; L_g is the gate length. When $1/\tau_{\text{eff}}$ becomes on the order of unity, the detection becomes resonant.

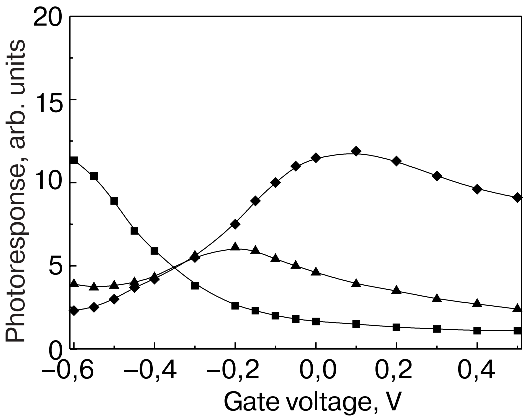

Fig. 4. Photoconductive response versus gate voltage for different values of applied drain–source voltage V_d from 0.025 V up to 0.55 V: 0.025 V (■), 0.3 V (▲), 0.55 V (◆) at a fixed value of the external frequency of 663 GHz. For V_d = 0.025 V typical nonresonant signal is observed. For higher Vd values the resonant peak start to grow and shifts to higher values of gate voltage.

4. Conclusion

In conclusion we have shown experimentally that the resonant detection of terahertz and sub-terahertz radiations can be tuneable with gate voltage at low temperature as well as room temperature in InGaAs and GaN nanometric transistors. The physical mechanism of the detection is related to the plasma waves excited in the transistor channel.

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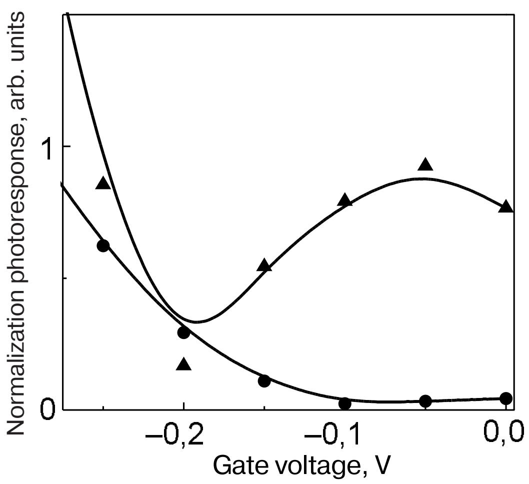

Fig. 5. Photo-induced drain–source voltage as a function of gate bias for different external frequencies, GHz: 679 (▲), 473 (●) at a fixed value of applied drain–source voltage of 0.3 V. At the lowest frequency, the response is nonresonant. The resonance appears for high frequency (679 GHz).

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