Resonant and voltage-tunable terahertz detection in InGaAs/InP nanometer transistors

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(Received 22 May 2006; accepted 15 August 2006; published online 29 September 2006)

The authors report on detection of terahertz radiation by high electron mobility nanometer InGaAs/AlInAs transistors. The photovoltaic type of response was observed at the 1.8–3.1 THz frequency range, which is far above the cutoff frequency of the transistors. The experiments were performed in the temperature range from 10 to 80 K. The resonant response was observed and was found to be tunable by the gate voltage. The resonances were interpreted as plasma wave excitations in the gated two-dimensional electron gas. The minimum noise equivalent power was estimated, showing possible application of these transistors in sensing of terahertz radiation. © 2006 American Institute of Physics. [DOI: 10.1063/1.2358816]

The observation/prediction of nonlinearities related to excitation of the plasma waves in a two-dimensional electron gas (2DEG) in nanometer gate length high electron mobility transistors (HEMTs) has opened a new route to create compact solid state high frequency devices. Since the frequency of plasma waves in such transistors lies in terahertz range, they promise a new solution in the design and fabrication of compact terahertz receivers and emitters. In principle, these transistors can be used as both emitters and detectors, and the emission/detection frequency can be tuned by the gate voltage. Until recently, most of the research was devoted to GaAs-based devices. For example, resonant detection in GaAs/AlGaAs-based 150 nm gate length commercial HEMT devices was discovered in subterahertz range, around 0.6 THz.

The frequency of the first harmonic of plasma oscillation in gated two-dimensional electron gas can be estimated using the formula

\[ f = \frac{1}{4L} \sqrt{\frac{e(V_g - V_{th})}{m^*}}, \]

where \( L \) is the gate length, \( V_g \) labels the gate-to-source voltage, \( V_{th} \) designates the threshold voltage, and \( m^* \) is the electron effective mass.

According to Eq. (1), it may be possible to achieve \( f > 1 \) THz by decreasing the gate length and/or by using a semiconductor with a smaller effective mass.

In this letter, we show that InGaAs-based nanostructures can be a good option to reach terahertz frequencies in resonant plasma wave detection. More specifically, we demonstrate the resonant plasma detection above 1 THz range by InGaAs/AlInAs nanometer transistors. This was achieved due to smaller electron effective mass (0.042, \( m \) is electron mass) in InGaAs/AlInAs in comparison to GaAs (0.067) and the availability of facilities enabling the production of very short (50 nm) gate length for this system.

The design and the geometry of our devices are given in Fig. 1. A pseudomorphic InGaAs/InAlAs heterostructure was grown by molecular beam epitaxy on 2 in. InP substrate. All the layers were lattice matched to the InP substrate, except the InGaAs channel. To obtain low electron effective mass, the indium content was fixed at 70%. The structure consists of a 0.3 µm thick In0.52Al0.48As buffer layer, a pseudomorphic 15 nm In0.55Ga0.45As channel, a 5 nm In0.53Al0.47As spacer layer, a silicon delta doping with 5 \( \times 10^{12} \) cm\(^{-2} \) level, a 12 nm In0.52Al0.48As Schottky barrier layer, and finally, the 10 nm silicon doped (6 \( \times 10^{18} \) cm\(^{-3} \)) In0.53Ga0.47As cap layer. The conventional HEMT processing was carried out, via mesa isolation, AuGe Ohmic contact deposition, and T-shaped Schottky gate definition by electron beam lithography.

![FIG. 1. Design of the InGaAs/InAlAs high electron mobility transistors with a T-shaped gate.](image-url)

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beam lithography. Before the Ti/Pt/Au gate metallization, a self-aligned recess etch was performed by a selective etching solution. The gate length and width are 50 nm and 50 μm, respectively. The length of the recessed extensions at both sides of the gate (parts of the device which are not covered by the heavily doped cap layer) is 100 nm. The distance between the source and drain amounts to 1.3 μm, and the 2DEG concentration is found to be about $3 \times 10^{12}$ cm$^{-2}$ at 4.2 K.

The samples were mounted on a quartz plate to avoid any parasitic interferences and reflections. They were then placed in a closed-cycle helium cryostat behind a terahertz radiation transparent polyethylene window. The response to the terahertz radiation was measured as a dc voltage on the open drain as a function of gate voltage. The source was grounded. The terahertz radiation was delivered from CO$_2$ pumped molecular terahertz laser. We used frequencies in the range from 1.8 to 3.1 THz. The incident radiation of 5–10 mW (depending on the emission line) was focused into spot of about 1.5 mm diameter, which is much larger than the gate length and width of the device. No special coupling antennas were used and the radiation was coupled to the device through the contacts pads.

The results of the response $\Delta V$ in the InGaAs/InAlAs transistor exposed to the radiation of 2.5 THz frequency as function of the gate voltage measured at various temperatures are shown in Fig. 2. Above 100 K only nonresonant detection is observed as a broadband peak around 0.47 V. With the decrease of temperature, below 80 K, the additional peak appears as a shoulder on the temperature-independent background of the nonresonant detection. We attribute this behavior to the resonant detection of terahertz radiation by plasma waves.

To support this assumption, we have measured the response at different excitation frequencies of 1.8, 2.5, and 3.1 THz at 10 K.

The experimental results are displayed in Fig. 3(a). For comparison, we have plotted the estimate of the plasma frequency as a function of gate voltage obtained using Eq. (1), shown as a continuous line in Fig. 3(a). One can see that with the increase of excitation frequency from 1.8 to 3.1 THz the plasmon resonance moves with the gate voltage, in rough agreement with Eq. (1).

It is worth noting that the resonance half width of the peak for $f = 2.5$ THz in Fig. 3 is found to be about 60 mV.
frequencies. While varying the temperature in the range from 10 to 80 K and the excitation frequency within 1.8–3.1 THz, we have shown that the resonant detection is due to excitation of resonant plasmon modes. The responsivity of these detectors amounts to about 1 V/W and their NEP is in the range of 10^{-9} W/Hz^{0.5}.

The authors would like to acknowledge help and many helpful discussions with M. Dyakonov and M. Shur and are sincerely grateful to Yahya Meziani, Edmundas Širmulis, and Zigmas Martunas for the kind assistance during the experiments. The work of Montpellier group and collaboration with Vilnius group were supported by CNRS-GDR-E project “Semiconductor sources and detectors of THz frequencies,” and EU project PRAMA via the program “Centres of Excellence,” region of Languedoc Rousillon, and French Ministry of Research and New Technologies through the ACI Grant No. NR0091. The authors also acknowledge the financial support provided by the Russian Fund of Basic Research (Grant No. 05-02-1772) and Civilian Research and Development Foundation (CRDF 2681). The research conducted at Vilnius was performed under the topic “Study of semiconductor nanostructures for terahertz technologies” (No. 144.2). The work at RPI was supported by the NSF under the IGERT (Grant No. 0333314) and by the STTR contract by ARO (subcontract from SET, Inc.).

8The criterion separating the resonant detection/emission nature from the nonresonant one is the so-called quality factor, namely, \(\omega r\), where \(\omega = 2\pi f\) is the excitation frequency and \(r\) denotes the electron momentum relaxation time. If the condition \(\omega r < 1\) is fulfilled, the plasma oscillations are overdamped; consequently, the response is nonresonant, exhibiting smooth function of frequency and the gate voltage. In opposite case, when the quality factor becomes much larger than 1, a spectrally narrow plasmon resonance peak should be clearly resolved—see Refs. 2 and 3.