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Field effect transistors for terahertz detection – silicon versus III–V material issue

INVITED PAPER

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Resonant frequencies of the two-dimensional plasma in FETs reach the THz range for nanometer transistor channels. Nonlinear properties of the electron plasma are responsible for detection of THz radiation with FETs. Resonant excitation of plasma waves with sub-THz and THz radiation was demonstrated for short gate transistors at cryogenic temperatures. At room temperature, plasma oscillations are usually over-damped, but the FETs can still operate as efficient broadband THz detectors. The paper presents the main theoretical and experimental results on detection with FETs stressing their possible THz imaging applications. We discuss advantages and disadvantages of application of III–V GaAs and GaN HEMTs and silicon MOSFETs.

Keywords: THz detection, imaging, field-effect transistors.

1. Introduction

A field effect transistor (FET) can act as a resonator for plasma waves propagating in the channel. The plasma frequency of this resonator depends on its dimensions and for gate lengths of a micron and sub-micron (nanometer) size can reach the terahertz (THz) range. The interest in the applications of FETs for THz spectroscopy started at the beginning of the 90's with the pioneering theoretical work of Dyakonov and Shur [1] who predicted that a steady current flow in a FET channel can become unstable against generation of the plasma waves. These waves can, in turn, lead to the emission of the electromagnetic radiation at the plasma wave frequency. This work was followed by another one where the same authors have shown that the nonlinear properties of the 2D plasma in the transistor channel can be used to detect THz radiation [2]. THz emission in the nW power range from submicron GaAs and GaN FETs has been observed both at cryogenic as well as at room temperatures [3–5]. THz detection was shown on a variety of FETs, including HEMTs on III–V heterostructures as well as Si-MOSFETs. Results indicate that FETs can be considered as promising devices for THz detection applications. Recently, non-resonant plasma response was shown to be an effective mechanism of room temperature THz detection and imaging.

The mechanism of detection refers to the nonlinear dynamics of the plasma in the transistor channel, which allows rectifying ac currents induced by the incoming radiation. As a result, FET channel responses to the radiation by creating a dc photovoltage between a source and drain. The amplitude of this detection signal is proportional to the radiation intensity.

Depending on the frequency ω of the radiation, one can distinguish two regimes of FET operation, and each of them can be further divided into two sub-regimes depending on the gate length L.

1. The high frequency regime occurs when $\omega\tau > 1$, where τ is the electron momentum relaxation time, related to the conductivity in the channel $\sigma = ne^2\tau/m$. In this case plasma waves which are excited are analogous to the waves in an RLC transmission line and they propagate with the velocity $s = (eU/m)^{1/2}$ [1] and the damping time τ. Thus, their propagation distance is $s\tau$.

1(a). Short gate, L < $s\tau$. Plasma waves, generated at the source, reach the drain side of the channel, get reflected and form a standing wave with enhanced amplitude, so that the channel serves as a resonator for plasma oscillations. The fundamental mode shows the frequency ~s/L, with a numerical coefficient depending on the boundary conditions.

1(b). Long gate, L >> $s\tau$. Plasma waves excited at the source will decay before reaching the drain, so that the ac current will exist only in a small part of the channel adjacent to the source.

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2. Low frequency regime, $\omega\tau << 1$. Now, plasma waves are overdamped. At these low frequencies, the channel can be modelled as an RC line. Its properties further depend on the gate length, the relevant parameter being $\omega\tau_{RC}$, where τ_{RC} is the RC time of the whole transistor. Since the total channel resistance is $L\rho/W$, and the total capacitance is CWL (where W is the gate width and $\rho = 1/\sigma$ is the channel resistivity), one finds $\tau_{RC} = L^2\rho C$.

2(a). Short gate, $L < (\rho C\omega)^{-1/2}$. This means that $\omega\tau_{RC} < 1$, so that the ac current goes through the gate-to-channel capacitance practically uniformly on the whole length of the gate. This is the so-called "resistive mixer" regime [6,7]. For THz frequencies, this regime can apply only for transistors with extremely short gates (smaller than 70 nm at 1 THz in Silicon).

2(b). Long gate, $L >> (\rho C\omega)^{-1/2}$. Now $\omega\tau_{RC} >> 1$, and the induced ac current will leak to the gate at a small distance l from the source, such that the resistance $R(l)$ of this piece of the channel and the capacitance $C(l)$ of the corresponding part of the transistor satisfy the condition $\omega\tau_{RC}(l) = 1$, where $\tau_{RC}(l) = R(l)C(l) = l^2\rho C$. This condition gives the value of the "leakage length" l on the order of $(\rho C\omega)^{-1/2}$ [which can also be rewritten as $s(\tau/\omega)^{1/2}$]. If $l << L$, then neither ac voltage, nor ac current will exist in the channel at the distances longer than l from the source.

More information on the state of the art of the FETs as emitters and detectors of THz radiation can be found in review papers [8,9]. Here, we concentrate only an overview of a few recent results concerning THz detection. The idea of the present paper is also to compare FETs fabricated on III–V's and silicon as detectors of THz radiation. Obviously, there are big differences, concerning both the architecture and technology, between FETs processed on different materials. Also, the final products are quite different with respect to the electron concentration, mobility, detectivity, signal/noise ratio, possibilities to work at room or cryogenic temperatures, etc. For this reason, to optimize devices for application at specific conditions, a broad spectrum of FETs should be analyzed. The present paper gives an account on such studies to allow the reader grasp the idea of advantages and disadvantages of different kinds of FETs used for THz detection. The paper is organized as follows: Section 2 describes results on THz detection with GaAs and InGaAs HEMTs [10,11]. In Sect. 3, a sub-THz detection by Silicon–CMOS study is presented [12].

2. THz detection by GaAs and InGaAs FETs

Typical results of experiments are shown in Fig. 1(a) [13]. The photovoltaic signal between source and drain is recorded *vs*. the gate voltage or the carrier density in the channel. In Fig. 1(a), the registered signal is presented for two transistors with different threshold voltages. At high carrier densities (open channel), the signal is relatively small and increases when the gate voltage approaches the threshold voltage, V_{th}. This increase follows the $1/(V_g - V_{th})$ functional dependence in agreement with the results presented in Ref. 2. The signal does not diverge, however, when V_g approaches V_{th} but it usually shows the broad maximum. As it can be seen from comparison of the photovoltaic signal Fig. 1(a) and the transfer characteristics Fig. 1(b), positions of these maxima are correlated with the threshold. The shape and the position of the maxima depend also on loading effects [7]. Close to the threshold, the channel resistance tends to the infinity and the transistor behaves like a voltage source with a very high internal resistance. The signal limitation close to the transistor threshold can be also due to the gate leakage current [13]. Detection curves similar to that shown in Fig. 1(a) are related to the so-called broadband nonresonant detection described as the cases 1b, 2a or 2b in the Introduction. The position and shape of the maxima depend also strongly on the temperature because the carrier density (or the threshold voltage), the channel resistance and the gate leakage currents are strongly temperature-dependent. This is illustrated in Fig. 1(c) where results for the same transistor with three different temperatures are shown. The maximum of the detection signal shifts to lower gate voltages with the decrease in temperature. For the lowest temperature one can observe an additional maximum appearing on the $1/(V_g - V_{th})$ shoulder. This maximum is a signature of the resonant detection.

The examples of the resonant detection (the case 1a described above), are shown in Fig. 1(c), and Fig. 2. In the majority of experiments, the incoming radiation is a monochromatic beam and the source-drain voltage is recorded versus

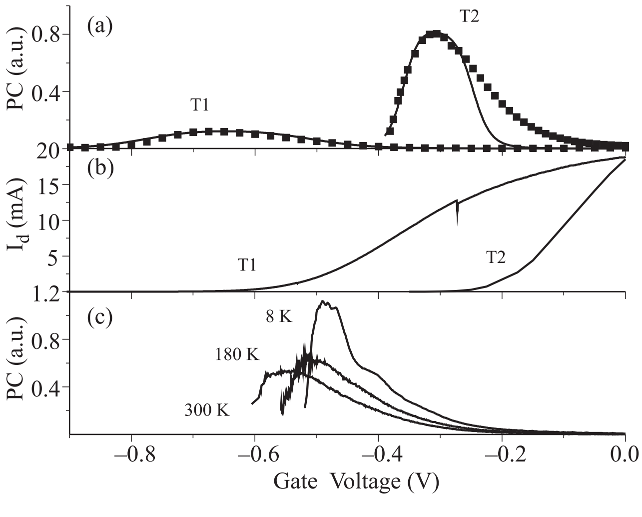

Fig. 1. (a) Experimental photoresponse for GaAs/AlGaAs FETs, (b) drain current vs gate voltage V_g for two transistors T1 and T2. Curves marked T1 correspond to the transistor with the threshold voltage $V_{th} = -0.55$ V measured at 300 K and at the frequency 200 GHz. Curves marked T2 correspond to another transistor with threshold voltage $V_{th} = -0.22$ V measured at 210 K and at 100 GHz, and (c) photoresponse of the transistor with the gate length $L = 0.15$ μm as a function of the gate voltage at the radiation frequency of 600 GHz, the threshold changes with temperature. The result at 8 K shows the appearance of a resonant structure.

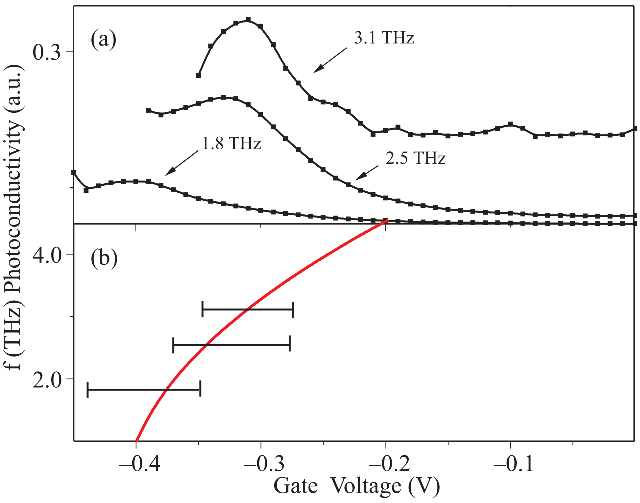

Fig. 2. (a) Resonant response of high mobility InGaAs/InAlAs transistors to 1.8 THz, 2.5 THz, and 3.1 THz registered at 10 K and (b) position of the maxima versus the gate voltage. Solid line follows theoretical calculations after Ref. 18.

the gate voltage. The gate voltage controls the carrier density in the channel and therefore allows the resonant plasma frequency to be tuned. A resonant enhancement of the registered voltage is observed once the resonant plasma frequency coincides with the frequency of the incoming THz radiation. The resonance appears in the lowest temperatures because the carrier mobility increases and $\omega\tau > 1$ condition can be reached.

First detection experiments showing a resonant detection, were performed using submicron GaAs/AlGaAs HEMTs [14–17]. Subsequently, high mobility InGaAs/ InAlAs transistors were studied [18].

Figure 2(a) shows an example of a plasma related resonant detection at 1.8 THz, 2.5 THz, and 3.1 THz registered at 10 K for these transistors.

One can see a feature of the resonant detection that corresponds to the case 1a. In Fig. 2(b), the position of the resonant maxima is shown. As the excitation frequency increases from 1.8 THz to 3.1 THz, the plasma resonance moves to higher swing voltages in an approximate agreement with theoretical predictions (solid line). However, the resonance is much broader than theoretically expected.

An important plasma resonance broadening appears to be one of the main unresolved problems of the resonant THz detection with FETs. The most convenient way to discuss the broadening is to consider the quality factor Q. From the experimental point of view, Q is an important quantity because it describes the ratio of the resonant line position (in frequency or voltage) with respect to the line width. Theoretically, the quality factor can be written as $Q = \omega\tau$. The inverse of τ corresponds to the plasma resonance linewidth in units of frequency.

For $Q = \omega\tau << 1$, the plasma oscillations are overdamped, consequently, the response is expected to show a non resonant, monotonic behaviour. In the opposite case, when the quality factor becomes much larger than 1, narrow plasma resonance peaks are expected. The main motivation behind changing the transistor material system from GaAs/GaAlAs, as used in the first experiments [13,17], to InGaAs/InP [18] and using higher excitation frequencies (up to 3 THz instead of 0.6 THz) was to improve the quality factor.

A longer carrier scattering time (or a higher mobility) combined with the use of higher excitation frequencies was expected to result in an increase in the quality factor by at least an order of magnitude, leading to sharp plasma resonances. However, experimentally observed plasma resonances remain broad. Even at 3 THz excitation, the quality factor Q is never higher than 2–3. One of the most important experimental and theoretical challenges is to understand and to minimize the broadening of the plasma resonance peak.

Two main hypotheses on the origin of an additional broadening are currently under consideration:

- existence of oblique plasma modes [19,20],
- additional damping due to the leakage of gated plasmons to ungated parts of the transistor channel [21].

The first hypothesis is related to the fact that in realistic devices the gate width is much greater than the gate length. Thus, the transistor channel serves as a waveguide rather than a resonator for plasma waves. In such a case, plasma waves can propagate not only in the source-drain direction but also in oblique directions. The spectrum of plasma waves in this case is continuous, with a low frequency cut-off at the resonant plasma frequencies. The second hypothesis, considers a leakage of gated plasmons to ungated parts of the channel [21] It is related to the observation that normally the gate covers only a small part of the source-drain distance. Therefore, the plasma under the gate cannot be treated independently of the plasma in ungated parts. An interaction between the two plasma regions can lead not only to a modification of the resonant frequency [19,21], but also to line broadening. To decrease the role of oblique modes, one has to change the geometry of the channel. One can, for example, replace a wide single channel with a series of many narrow channels [19].

At room temperature, FETs can operate as efficient broadband detectors of sub-THz radiation. Recently, Lisauskas *et al.* have reported the possibility of sub-THz (0.6 THz) imaging with GaAs FET [6]. However, up to now there exists only very few results on imaging with FETs at the frequencies above 1 THz. This is because in condition of a broadband detection (a typical case at room temperatures), the photovoltaic signal decreases strongly with the increase in the radiation frequency either because of a reduction in the coupling efficiency or because of the water vapour absorption. El Fatimy *et al.* [22] have reported images obtained in a transmission mode at a frequency higher than 1 THz using a GaAs FET irradiated by a broadband pulsed radiation and driven by a drain current up to 40 mA. Here (Fig. 3), we present two-dimensional images obtained with CO_2 pumped far infrared laser (providing a CW radiation of 1.6 THz) and a GaAs FET operating at room temperature [10].

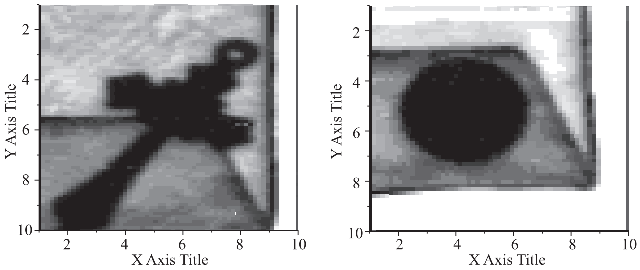

Fig. 3. 1.6 THz images ($I_{ds} = 0$) of the metallic cross (in the left) and of medicament tablet (in the right) in the transmission mode at room temperature. The two objects are placed into a postal envelope [10].

The particularity of this work consist in:

- imaging with single frequency above 1 THz to improve the resolution;
- studying the effect of the drain-to-source current on the contrast of the image.

The images (Fig. 3) were recorded in a a transmission mode by a raster scanning the sample in X and Y directions. The main conclusions from these measurements were good resolution, contrast, and acquisition rate obtained with our imaging systems. This experiment demonstrates the capacity of FETs as important candidates for fast video room temperature THz imaging at frequencies above 1 THz.

3. Detection by Si-MOSFETs

We studied sub-THz detection by silicon FETs. In this particular material, because of a low electron mobility plasma waves in the channel are overdamped. As it was shown theoretically [9], in this case the nonresonant detection depends on one parameter only: the characteristic length of the charge distribution decay l_c. When we assume the THz excitation only on the source side, the photoinduced voltage is given by

$$U(x) = \frac{U_a^2}{4U_0}[1 - \exp(-2x/l_c)], \qquad (1)$$

where x is the distance from the source, $U(x)$ is the dc voltage generated by THz rectification, U_a is the amplitude of the ac modulation due to the incident THz radiation on the source side, U_0 is the gate voltage swing, l_c is the length that characterizes the exponential decay of the plasma density perturbation and ac voltage (and current) with distance x from the source. It can be written as $l_c = s(2\tau/\omega)^{1/2}$ with the plasma waves velocity $s = (eU_0/m)^{1/2}$.

In the case of short gate transistors, $L_g << l_c$, the ac current induced by the incident radiation goes through the gate-to-channel capacitance practically uniformly on the whole gate length, and only a part of the photo generated dc voltage builds up. In this case, the total measured voltage is expected to depend on the gate length. On the opposite, in the case of long gate transistors with $L_g >> l_c$, the ac current will leak to the gate before it achieves the drain, and the photoresponse is built up in the distance up to l_c. One expects that the total measured voltage does not depend on the gate length.

We studied fully depleted nMOS transistors fabricated on biaxially strained SOI. The channel width of studied devices was $W_g = 10$ μm. The gate length, L_g was in the range from 50 nm to 10 μm. The channel depletion threshold voltage was near 0.2 V, and the channel resistance decreased linearly with its length. The photoresponse measurements were performed using a back wave oscillator (BWO) at 230 GHz with the output power of a few mW. The electric field of the incoming radiation was polarized in parallel to the source-drain direction. The radiation intensity was mechanically chopped and the open-circuit source drain voltage was measured using a lock-in technique. All measurements were done at room temperature. Figure 4 shows the photoresponse of the FETs with different gate lengths (from 50 nm up to 500 nm). Black points are experimental values of the photoresponse, taken in the range of the gate voltage swing where signal shows a $1/U_0$ shape (broadband-detection theory). The solid curve is a fit of experimental results using Eq. (1) with the fixed critical length $l_c = 100$ nm. One can see that the theoretical estimation is in a relatively good agreement with experimental results.

Hence we have established that for this type of detection (broadband at low frequency regime) one can observe two regions of detection for:

- short gate transistors, the signal increases with the gate length,
- long gates, the signal saturates at a constant maximal value.

Our results show also that to obtain the maximal detection signal, the gate length should be at least 2–3 times the characteristic plasma damping critical length l_c. The results allow predicting the parameters for the THz detectors based on Si-MOSFETs technology. Because of their competitive NEP and their fast modulation frequency, these improved detectors could be used in arrays for real time imaging applications at room temperature (THz camera) [7].

A construction of this first prove-of-principle THz camera based on several Si-MOSFETs shows that the FET--based detector technology is developed well enough to enable construction of more advanced devices. It also indicates that the physical phenomena responsible for the detection process are sufficiently well understood. In spite of the success of the first camera demonstration, many difficulties are still to be overcome before a commercial product could be realized. One of the issues is the construction of a proper antenna that would couple the incoming radiation with the plasma in the transistor channel. The antenna layout depends in a crucial way on the high-frequency parameters of the material used for FET production, which are not always very well known in the THz band. Another point is the design of electronics integrated with the FET (amplifiers, read-out circuits, converters, etc.) which should be integrated with the detectors on a chip.

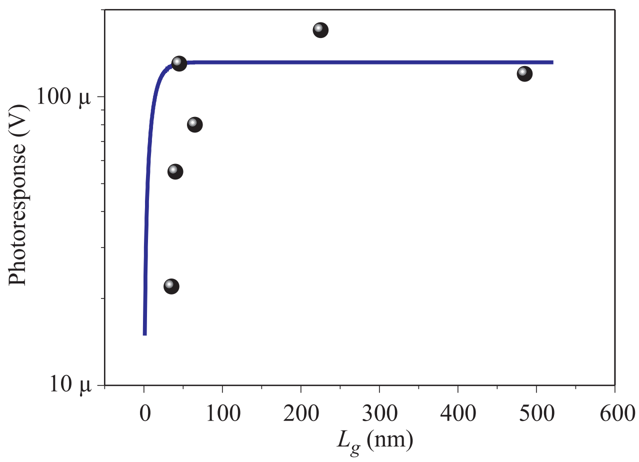

Fig. 4. Photoresponse of Si-MOSFETs as a function of the gate length.

4. Conclusions

In conclusion, we have demonstrated that HEMTs based on high electron mobility III–V transistors can show resonant detection at low temperatures. We observed that a relatively low quality factor of the resonant detection is not directly related to the mobility. A large broadening of the plasma resonances should still to be explained. At the moment, we could indicate that propagation of plasma oblique modes in the transistor channel could be responsible (at least partially) for the observed broadening. Understanding the origin of the broadening mechanism would open a way to construct resonant, voltage-tunable detectors, which would constitute a promising element of low -temperature spectroscopic systems. On the other hand, Si-MOSFETs are considered now as the most promising transistors for an integrated THz camera at room temperature. A relatively low mobility in MOSFETs at room temperature does not exclude their excellent signal/noise ratio exhibited by single nanometer transistors. Such a camera would be based on a non-resonant detection which offers also an advantage of the sensitivity to a broadband THz radiation. First demonstration of Si-MOSFET based camera in 2009 gives a hope to get such devices commercialized within next few years.

Acknowledgments

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