Room Temperature Terahertz Plasmonic Detection by Antenna Arrays of Field-Effect Transistors

V. V. Popov¹,²,*, N. Pala³, and M. S. Shur⁴

¹Kotelinkov Institute of Radio Engineering and Electronics (Saratov Branch), Russian Academy of Sciences, Saratov 410019, Russia
²Saratov State University, Saratov 410012, Russia
³Integrated Nanosystems Research Lab, Department of Electrical and Computer Engineering, Florida International University, Miami, Florida 33174, USA
⁴Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA

We show that dense field-effect-transistor (FET) arrays can effectively couple to incoming terahertz (THz) radiation without using supplementary antenna elements. Intensive plasmon resonances can be excited in GaN-based dense FET arrays in the entire THz frequency range at room temperature due to strong broadband coupling of such devices to THz radiation and high electron density in the GaN-FET channels. An alternative way of increasing the operation temperature of plasmonic THz detectors up to room temperature involves a non-resonant plasmonic detection response in FET arrays. Strong photovoltaic THz response can be obtained in a dense FET array with an asymmetric gate in each individual FET unit of the array.

Keywords: Two-Dimensional Electron Gas, Plasmons, Terahertz Radiation, Field-Effect Transistor, Gratings, Antenna Arrays, Detection, Photovoltaics.

1. INTRODUCTION

Hydrodynamic nonlinearities in two-dimensional (2D) electron channels in the field-effect transistor (FET) structures enable detection of terahertz (THz) radiation via the excitation of the either natural plasma waves (plasmons) with a high quality factor or overdamped forced plasma oscillations in 2D electron channel. In the either case of the natural or forced plasma oscillations, THz photoresponse originates from the nonlinear dynamics of 2D electron fluid described by the hydrodynamic Eq. (1)

\[
\frac{\partial V(x,t)}{\partial t} + V(x,t) \frac{\partial V(x,t)}{\partial x} + \frac{V(x,t)}{\tau} + \frac{e}{m^*}E(x,t) = 0
\]

(1)

\[
e^{-\frac{\partial}{\partial t} N(x,t)} - \frac{\partial}{\partial x} j(x,t) = 0
\]

(2)

where \(E(x,t)\) is the in-plane electric field depending on the time \(t\) and coordinate \(x\) in 2D electron system, \(\tau\) is the electron scattering time, \(j(x,t) = -e N(x,t)V(x,t)\) is the density of induced electric current, \(N(x,t)\) and \(V(x,t)\) are the hydrodynamic electron density and velocity in 2D electron channel, and \(e\) and \(m^*\) are the electron charge and effective mass, respectively. There are two nonlinear terms in Eqs. (1) and (2): the second term in the Euler equation, Eq. (1), describing the nonlinear electron convection in 2D electron fluid and the current density term \(j(x,t) = -eN(x,t)V(x,t)\) in the continuity equation, Eq. (2). Generally, the term “convection current” describes the motion of electric charges in the absence of an external electric field (e.g., the motion of the electron bunches in an electron beam). In the non-linear electron convection described by the second term in Eq. (1), the electron charges built up in a certain point in the result of the plasma oscillations drift with the hydrodynamic velocity. Time average of the nonlinear current yields the detection signal. The nonlinear terms in Eqs. (1) and (2) are related to non-uniform electric currents inherent in the plasmon oscillations (either natural plasmon modes or forced plasma oscillations) and, hence, both nonlinear terms vanish in the case of a uniform oscillating current. For symmetry reasons, the photovoltaic detection response must be zero in 2D electron channel with identical boundary conditions at its opposite ends if there is no DC bias current in the channel. It means that a THz photovoltaic plasmonic requires some asymmetry of the transistor channel.

*Author to whom correspondence should be addressed.
Resonant plasmonic detectors have been recently studied. The frequency of the gated plasmons (confined in the FET channel under the gate contact) is given by:

\[ \tilde{\omega}_p \approx \sqrt{\frac{e^2 \tilde{N} d}{m^* (\varepsilon + \varepsilon_s) \varepsilon_0}} q \]  

where \( \tilde{N} \) is the equilibrium sheet electron density in the gated part of the channel, \( d \) and \( \varepsilon \) are the thickness and dielectric constant of the barrier layer, \( q \) is the plasmon wavevector, and \( \varepsilon_s \) is the permittivity of vacuum. The gated FET region forms a resonant cavity for the gated plasmons with the wavevector of the gated plasmon being determined by the gate length and by the boundary conditions in the channel under the gate edges. For identical boundary conditions at opposite edges of the gate, the wavevector of the fundamental gated plasmon mode is \( q = \pi/w \), where \( w \) is the gate length.

Both gated and ungated plasmons can exist in a FET with the gated and ungated 2D regions. The frequency of the ungated plasmons is given by:

\[ \omega_u = \sqrt{\frac{e^2 N d}{m^* (\varepsilon + \varepsilon_s) \varepsilon_0}} \]  

where \( N \) is the equilibrium sheet electron density in the ungated channel and \( \varepsilon_s \) is the dielectric constant of the substrate. The length of the ungated part of the electron channel and the boundary conditions at its ends determine the wavevectors of the ungated plasmons. For identical boundary conditions at opposite ends of the ungated channel, the wavevector of the fundamental ungated plasmon mode is \( q = \pi/W \), where \( W \) is the length of the ungated channel. In actual transistor structures, the gated and ungated plasmons become coupled and can interact with each other. In particular, the ungated plasmons excited as a result of the gated-plasmon scattering at the ends of the gated region of the channel (the so-called plasmon-plasmon intermode scattering) can cause a large broadening of the gated-plasmon resonance linewidth.

The gated plasmons are more attractive for practical applications because the gated-plasmon frequency can be effectively changed by varying the gate voltage enabling tunable THz detection. Resonant detection takes place at \( \omega \approx \tilde{\omega}_p \) for high quality factors of the plasmon resonance (\( \tilde{\omega}_p \tau_p \gg 1 \), where \( \tau_p \) is the plasmon relaxation time). In this case, the natural plasma wave is bouncing to and fro in the gated part of the FET channel. The plasmon relaxation time is determined by combined contributions of the electron scattering in the channel, plasmon-plasmon intermode scattering, and the plasmon radiative decay. The electron scattering time decreases with increasing the temperature. Therefore, high quality factor, \( \tilde{\omega}_p \tau_p \), needed for the resonant plasmonic detection can be reached at room temperature only for relatively high electron concentrations in the FET channel (corresponding to high plasmon frequencies). For small equilibrium electron density \( \tilde{N} \) (i.e., small plasmon frequency), inequality \( \tilde{\omega}_p \tau_p \gg 1 \) becomes valid, and non-linear behavior of the forced plasma oscillations excited in the FET channel enables non-resonant detection at THz frequencies \( \omega \gg \tilde{\omega}_p \). Such situation occurs, for example, when the equilibrium electron density in the FET channel decreases for the gate voltages \( U_g \) such as \( U_g \rightarrow U_{g0} \), where \( U_{g0} \) is the FET threshold voltage. The non-resonant plasmonic detection has no fundamental temperature limitations and can be realized in a broad THz frequency range. Non-resonant broadband plasmonic detectors can be used for THz imaging, while the resonant plasmonic detectors characterized by electrical tunability in a broad THz frequency band can be used for THz spectroscopy.

As mentioned above, a non-zero photovoltaic response can only appear in the presence of asymmetry in the FET channel. The simplest asymmetry of the channel was considered in the original theoretical paper, where it was assumed that one end of the channel is short-circuited while the opposite end of the channel is open. These boundary conditions yield the wavevector \( q = \pi/(2w) \) for the fundamental gated plasmon mode in Eq. (3). In practice, required asymmetry of a FET channel is typically ensured by connecting lumped circuit elements between the FET contacts and/or by asymmetric feeding of THz power into the device. However, the responsibility of a single-gate FET detector operating in the photovoltaic mode (with no DC drain bias current) still remains quite low because of weak coupling between the single-gate FET detector and THz radiation. Greater responsivity can be achieved in a FET driven into the current saturation regime. Nevertheless, the zero-current photovoltaic response is highly desirable for many applications (e.g., for THz imaging applications) due to reduced noise level and power consumption. Therefore, supplementary antenna elements are needed to couple sub-micron-size FET device to THz radiation in order to enhance the responsivity of the single-gate FET detector up to a value suitable for practical applications. It is worth noting that individual FETs in the focal plane arrays (FPA) used for THz imaging have to be electromagnetically decoupled in order to form different FPA pixels. In this case, a supplementary antenna element should be attached to each FET in the FPA in order to achieve good pixel responsivity.

In the grating-gate FET plasmonic detectors, a large area grating gate (comparable to or larger than a typical cross-section area of a focused THz beam) acts as an effective aerial matched antenna and, hence, supplementary antenna elements are not needed. While non-resonant THz detection in the grating-gate FET detectors based on GaAs heterostructures was demonstrated at room temperature, so far, the resonant detection condition \( \tilde{\omega}_p \tau_p \gg 1 \) could be satisfied only under cryogenic cooling.
In Section 2, we show that the pronounced THz plasmon resonances can be excited in a GaN-based grating-gate FET structure. In Section 3, we demonstrate that even more effective excitation of the plasmon resonances can be achieved in a dense array of individual GaN-FETs, even at room temperature. We demonstrate in Section 4 that a dense array of isolated FETs with an asymmetric gate in each individual FET in the array can exhibit broadband high-responsivity THz detection at room temperature without using supplementary antenna coupling elements. The main conclusions are summarized in Section 5.

2. PLASMON RESONANCES IN GaN GRATING-GATE FET STRUCTURE

The most intensive plasmon resonances in the grating-gate FET structure (see Fig. 1) can be excited if the radiative damping, $\gamma_{rad}$, of a respective plasmon mode is equal to its dissipative damping, $\gamma_{dis}$, caused by electron scattering in the FET structure channel.27 (This condition can be readily understood as the matching condition between the free-space impedance and the effective impedance of the grating-gate FET structure at the plasmon resonance frequency.27) When THz wave with its electric field polarized across the grating-gate fingers is impinged from the top of the structure, the maximal absorbance that can be reached at the plasmon resonance is $0.5(1 - \sqrt{R_0})$, where $R_0$ is the reflectivity of a bare substrate. (This expression for the maximal absorption was derived assuming that the thickness of the barrier layer is much smaller than the wavelength of the THz radiation, which is typically valid for grating-gate transistor structures.) Since the dissipative damping of the plasmon mode, $\gamma_{dis} = 1/2\tau$,27 increases with temperature, the matching condition $\gamma_{rad} = \gamma_{dis}$ of exciting the strongest plasmon resonances in the grating-gate FET structure can be satisfied at room temperature only for strong radiative damping of plasmons. The radiative damping of a plasmon mode is directly proportional to the electron density in the channel and to the strength of coupling between the plasmon mode and the incident THz electromagnetic wave.27 Hence, GaN-based heterostructures (with very high sheet electron densities in the device channels, above $10^{13}$ cm$^{-2}$) are especially promising for implementing uncooled grating-gate FET plasmonic THz detectors. High 2D electron density in GaN-based heterostructures plays a two-fold constructive role: (i) ensures the high-quality-resonance condition $\omega_{\tau} \gg 1$ at ambient temperature and (ii) enhances radiative damping of the plasmon modes upwards to the electron scattering rate required for strong coupling between the plasmon mode and the incident THz radiation.29

Strength of the coupling between the plasmon mode and the incident THz radiation also depends on geometry of the grating-gate FET structure. The coupling greatly increases in slit-grating-gate FET structures due to strong electric near field induced in narrow slits between the grating-gate fingers by the incident THz wave. Figure 2 shows the calculated THz absorption spectra of AlGaN/GaN grating-gate FET structure having 1-μm-wide grating-gate metal strips for three different grating-gate-slit widths and zero gate voltage. These results demonstrate quite pronounced and well-resolved fundamental and higher-order plasmon resonances at room temperature in the structure with sub-micron slits. For narrower slits, higher resonances are excited with larger amplitudes, since narrow grating-gate slits generate strong higher Fourier harmonics of the incident THz wave. As a result, quite pronounced higher-order plasmon resonances may be excited at high THz frequencies up to 7th resonance at about 10 THz (not shown in Fig. 2).

The equidistant spectrum of plasmon resonances shown in Figure 2 is characteristic of the linear plasmon dispersion, see Eq. (3), which evidences the excitation of the gated-plasmon modes in the structure. The ungated plasmon modes in the FET channel under the grating-gate openings can also be excited in the grating-gate transistor structures (however, at much higher frequencies).31 Due to coupling between the gated and ungated plasmons, complex hybrid plasmon modes form in the structure.
The ungated regions of the 2D electron channel are very important for effective excitation of the gated plasmon resonances in the grating-gate transistor structure. Due to the oscillating charges induced by the incoming THz wave in the ends of the ungated regions of the channel, these regions act as electrical vibrators exciting the gated plasmon modes. As reported in Ref. [30] the intensity of the gated plasmon resonances decreases by two orders of magnitude in the grating-gate transistor structure with totally depleted ungated regions of the 2D electron channel. The effect of the ungated regions becomes dominant at the frequencies of the ungated plasmon resonances. This effect can be used for the enhancement of the higher-order gated plasmon resonances via exciting a “firing” ungated plasmon mode at the same frequency.

In spite of the strong interaction between the gated and ungated plasmons in the grating-gate transistor structure, the linewidth of either type of the plasmon resonances is determined by the electron scattering and radiative decay contributions only, whereas, in a single-gate transistor structure, the plasmon resonance linewidth can exceed the electron scattering rate by an order of magnitude due to the intermode plasmon-plasmon scattering. In contrast to the linewidth in a single-gate transistor, the interaction between the gated and ungated plasmons in the grating-gate transistor structure does not cause the plasmon resonance linewidth broadening but, instead, leads to the formation of a collective plasmon mode via synchronizing the plasma oscillations in all unit cells of the structure.

The radiative damping and dissipation of plasmon oscillations in a FET channel contribute comparably to the total linewidth of the plasmon resonance in the FET with a single-grating gate, which makes the excitation of strong plasmon resonances possible. The maximum absorbance reached at the plasmon resonance is 0.25 that is close to the maximal theoretical value of $0.5(1 - \sqrt{R_0})$ for $R_0 = 0.25$ characteristic for GaN substrate. For narrow slit widths ($L - w \leq d$ and $d \ll L$) the frequencies of plasmon resonances are the multiples of $2\pi/L$ but not the multiples of $\pi/w$ as for a single-gate FET structure. This leads to a blue shift of all plasmon resonances seen in Figure 2 for shorter periods of the structure (for the same width of a grating-gate finger). The physical reason for this phenomenon can be explained as the following. For narrow openings of the grating gate, the gate fingers effectively screen also the ungated regions of the channel due to the electric-field fringing effect and, hence, the structure becomes similar to that with a continuous gate in terms of the plasmon dispersion. For the same reason, the plasmon electric field also spreads out of the gated region of the channel and, for narrow openings of the grating gate, the collective plasmon mode distributed over the entire period of the structure forms in this case.

Figure 3 shows the measured THz transmission spectra in the AlGaN/GaN grating-gate FET structure with 2D electron channel and the grating-gate with narrow slits. Due to strong electromagnetic coupling between plasmons and THz radiation in the narrow-slit grating-gate structure, well pronounced plasmon resonances can be excited at elevated temperatures in a broad frequency range. Most of the grating-gate resonant THz plasmonic detectors that have been demonstrated (until now only based on GaAs heterostructures at cryogenic temperatures) employ a photoconductive THz response of the FET channel which needs applying DC drain bias current in the device channel. The responsibility of the grating-gate resonant THz plasmonic detectors increases linearly with increasing the DC drain bias current for relatively small bias current. The grating-gate FET structure is, in fact, an array of many identical FETs with a long common channel. However, strong drain current causes large

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**Fig. 2.** Absorption spectra of AlGaN/GaN grating-gate FET structure with 1-μm-wide grating-gate metal strips for three different slit widths: 0.1 μm (curve 1), 0.3 μm (curve 2) and 0.5 μm (curve 3) at room temperature ($\tau = 2.27 \times 10^{-9}$) for zero gate voltage. $U_g = -3$ V, $d = 8$ nm (after Ref. [30]).

**Fig. 3.** (Color online) Transmission spectra of the slit-grating-gate AlGaN/GaN FET structure measured at temperatures from 77 K to 295 K for $U_g = 0$. The spectra are referenced to the transmission spectrum of the identical AlGaN/GaN structure without metal grating gate. The grating gate has the period $L = 1.5$ μm and slit width ($L - w$) = 0.35 μm (after Ref. [29]).
voltage drop across a long channel of the grating-gate FET and, hence, different unit cells of a large-area grating-gate FET structure turn out to be under different effective gate voltages. As a result, the net responsivity of the grating-gate FET plasmonic detectors decreases for strong drain currents and hence remains quite moderate.\(^{25}\) (Substantial enhancement in responsivity of the grating-gate FET detector can be achieved by combining it with on-chip micro-bolometer element involving a potential barrier under an isolated finger in the split-grating gate\(^{39–42}\) and/or by placing the detector on a thin membrane substrate.\(^{40,43}\)

For symmetry reason, strong photovoltaic THz response (which occurs without applying DC bias current in the structure channel) can take place only in the grating-gate FET structure with an asymmetric unit cell.\(^{44}\) As shown in Section 4, strong photovoltaic THz response at room temperature can be also obtained in a dense array of individual FETs (with separate 2D electron channels) provided that the gate position is asymmetric in each individual FET. The antenna characteristics of a dense FET array are considered in the next section.

3. PLASMON EXCITATION IN GAN FET ARRAY

As shown in Section 2, a narrow-slit (typically, sub-100-nm-wide) grating gate has to be fabricated in order to excite strong plasmon resonances in the grating-gate FET structure with a common 2D electron channel. An alternative way of effective coupling THz radiation to the plasmons in a FET channel is arranging individual FETs in a one-dimensional (1D) dense array. The period of a dense FET array is much shorter than THz wavelength at the plasmon resonance frequency. Different FETs in the array have separate 2D electron channels and combined intrinsic source and drain contacts (see Fig. 4). This design allows for effective excitation of the plasmon resonances over a broad THz frequency band in a structure having the characteristic lateral dimensions of a micron scale. In an earlier paper\(^ {45}\) it was suggested that coupling between plasmons in the FET channel and THz radiation might be more effective if FET units were arranged in an array. (Also see even earlier relevant paper,\(^ {46}\) where periodic ohmic contacts were alloyed into 2D electron channel producing an array of 2D electron diodes.) It was anticipated in Ref. 45 that the plasmons in an array of FETs should absorb (or emit) THz radiation at least by a factor of the number of FET units in the array as stronger as a single-unit FET. However, it was recently shown\(^ {47}\) that the coupling between plasmons and THz radiation in a dense FET array can be strongly enhanced well beyond that trivial estimation due to a cooperative effect of synchronizing the plasma oscillations in all FET units in the array.

Figure 5 shows the calculated THz absorption spectra of the FET array with separate electron channels for two different array periods and two different gate lengths and zero gate voltage in each FET unit. These results demonstrate that in such a structure, the intense fundamental and higher-order plasmon resonances up to the 8th resonance at 20 THz (not shown in Fig. 5) can be excited with comparable amplitudes at room temperature. All resonances are shifted to higher frequencies for shorter gate length as predicted by Eq. (3).

Plasma oscillations in all unit cells of the FET array are excited with the same phase (and amplitude) dictated by the phase (and amplitude) of the incoming THz radiation. In an earlier paper\(^ {45}\) it was suggested that coupling between plasmons in the FET channel and THz radiation might be more effective if FET units were arranged in an array. (Also see even earlier relevant paper,\(^ {46}\) where periodic ohmic contacts were alloyed into 2D electron channel producing an array of 2D electron diodes.) It was anticipated in Ref. 45 that the plasmons in an array of FETs should absorb (or emit) THz radiation at least by a factor of the number of FET units in the array as stronger as a single-unit FET. However, it was recently shown\(^ {47}\) that the coupling between plasmons and THz radiation in a dense FET array can be strongly enhanced well beyond that trivial estimation due to a cooperative effect of synchronizing the plasma oscillations in all FET units in the array.

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wave. However, even without the incoming THz wave, the plasmons, once excited (either by a thermal or stimulated mechanism), oscillate in phase in all unit cells of the FET array shown in Figure 4 because the side metal contacts of the antenna are much higher than that of the 2D electron fluid because the free electron concentration in the metal is very high yielding plasmon resonance frequencies in the visible region.) Therefore, the plasma oscillations, though being confined in the 2D electron channel of each FET in the array, behave as a single plasmon mode distributed over the entire area of the array. The formation of this cooperative mode ensures strong coupling between plasmons in the FET array and external THz radiation.

As seen from Figure 5, the higher-order plasmon modes are excited much more effectively in such a dense FET array than in a FET structure with a common electron channel and a grating gate having the 100-nm-wide slits (see Section 3 and the dotted curve in Fig. 5). The physical mechanism of the higher-order plasmon mode excitation is entirely different in these two structures. In the grating-gate coupler, narrow slits generate strong higher Fourier harmonics of the incident THz field with wavevectors \( k_n \approx 2 n \pi / L \), where \( L \) is the period of the grating gate with \( n \) being an integer. Then these strong Fourier harmonics excite higher-order plasmon modes with the same wavevectors, \( q_n = k_n \), in the channel when the frequency of the incoming THz wave coincides with the plasmon mode frequency. By contrast, in the FET array with separate channels, the incoming THz radiation induces the oscillating charges of opposite sign across the vertical (typically sub-100-nm-thick) barrier gap between the gate and side contacts at each edge of the gate contact in every FET unit (see the inset in Fig. 4). These oscillating charges induce the electric fields with the same symmetry as in any plasmon mode excited under the gate contact in each FET unit with symmetric boundary conditions at the gate-contact edges. Hence, the plasmon mode is effectively excited when its eigen-frequency coincides with the frequency of the incoming THz radiation. Figure 5 demonstrates that a dense FET array serves as a super-broadband antenna effectively coupling incident THz radiation to the FET channels in the entire THz frequency range.

4. PLASMONIC DETECTION IN FET ARRAY

Room temperature THz plasmonic detection by a dense 1D array of individual identical FETs fabricated on the same chip was recently demonstrated. Although such detector array had no supplementary antenna elements, it had enhanced responsivity compared to that of an antenna coupled FET. The transistor structure was based on GaAs/InGaAs/AlGaAs heterostructure. The 2D electron channel was formed in a 12-nm-thick undoped InGaAs layer with 40-nm-thick AlGaAs carrier-supplying layer, and 400-nm-thick undoped GaAs buffer layer on the (100) surface of 450-\( \mu \)m-thick semi-insulating (SI) GaAs substrate (Fig. 6). A 60-nm-thick cap GaAs layer was doped \( n \)-type with Si up to \( 6 \times 10^{18} \) cm\(^{-3} \). The top surface of the mesa was passivated by deposition of thin silicon nitride layer. The electron density in the channel was \( 3 \times 10^{12} \) cm\(^{-2} \) with the electron effective mass \( m^* = 0.061 m_e \), where \( m_e \) is the free-electron mass, and the room temperature mobility was \( \mu = 5900 \) cm\(^2\)/V\cdots. The top metallization of the transistor structure was formed with 65-nm-thick Ti/Au/Ti by a standard lift-off process.

Each FET in the array was biased by the same gate voltage applied to a common gate lead. All FETs in the array were electrically connected in parallel and, hence, had common source and drain leads. Individual FETs were densely arranged in the array interacting electromagnetically. The entire array of 192 similar FETs had the length of 3.6 mm. Terahertz radiation was incident normally upon the plane of the array from the top with the polarization of THz electric field along the direction of periodicity of the array. (As shown in Section 2, a dense array of FETs with the period much shorter that THz radiation wavelength is an effective super-broadband THz antenna that strongly couples each FET in the array to incident THz radiation.) The stem of T-gate in each FET of the array was shifted toward the source contact, which yielded the necessary asymmetry enabling strong photovoltaic response in each FET.

The DC photocurrent was measured between the source and drain leads of the array at liquid nitrogen temperature and at room temperature for zero DC drain bias current. Backward wave oscillator (BWO) was used as a monochromatic source of sub-THz radiation with the output power of about 1 mW in frequency range 0.415–0.72 THz. The terahertz radiation from the BWO was mechanically chopped at frequency 350 Hz and delivered
to the sample through an oversized circular metal waveguide with a tapered end focusing THz radiation onto the spot area of 6 mm in diameter (covering the entire FET array).

Figure 7 shows the measured photocurrent as a function of the gate voltage, $U_g$, at frequency 0.587 THz for $T = 77\,\text{K}$ and $T = 300\,\text{K}$. The source-to-drain conductance of the entire FET array as a function of the gate voltage measured at room temperature is also shown in Figure 7 by the dashed curve. As seen from Figure 7, the photoresponse greatly increases when the position of the T-gate stem is shifted to the source contact in each FET (see Fig. 6), the THz voltage, $U_{th}$, induced by the FET-array antenna is applied mainly between the gate and source contacts in each FET unit. Although different FETs in the array are coupled electromagnetically, the electron channels of different FETs are separated from each other. Therefore, the photocurrent $I_{ph}$ is generated in each FET independently of the other FETs in the array. Since all FETs in the array are connected in parallel, the measured photocurrent $\Sigma I_{ph}$ is the sum of photocurrents generated by every FET. Relating the measured photocurrent to the THz power incident upon the entire FET array area $3.6 \times 0.075\,\text{mm}^2$, the FET array photocurrent responsivity was estimated as 0.05 $\text{A/W}$ at $T = 300\,\text{K}$ for $U_g = -1\,\text{V}$ which yielded the photovoltage responsivity of $960\,\text{V/W}$ per a transistor. This is the greatest responsivity ever reported for uncooled THz plasmonic detectors. Neither a supplementary antenna coupler nor a DC bias current was applied for achieving such strong THz photovoltaic response.

The response of the chain of detecting FET connected in series is directly proportional to the number of FET in the chain (if each FET in the chain is biased by the same gate-to-source voltage) with the responsivity of the entire chain independent on the number of FETs. Therefore, it can be expected that 1D array of similar FETs connected in series can demonstrate the photovoltage responsivity of about 1 $\text{kV/W}$ at room temperature.

![Fig. 7. Measured photocurrent at different temperatures (solid curves) and the source-to-drain conductance (dashed curve) of the FET array as functions of the gate voltage (after Ref. [48]).](image)

5. CONCLUSION

Plasmonic THz detectors based on dense arrays of FETs with common and separate 2D electron channels can be effectively coupled to incoming THz radiation without using supplementary antenna coupling elements. Pronounced plasmon resonances can be excited in GaN-based dense FET arrays in the entire THz frequency range at ambient temperature due to strong broadband coupling of such devices to THz radiation and high 2D electron density in the GaN-FET channel. This paves a way to tunable THz plasmonic detection at room temperature. Strong photovoltaic THz response can be obtained in a dense FET array with an asymmetric T-gate in each individual FET in the array. Recent progress in the development of the plasmonic THz detectors based on dense FET arrays is very promising because these results open up possibilities for improving performance of uncooled plasmonic THz detectors.

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References and Notes

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