УДК 538.9

F. F. Sizov [1], **O. G. Golenkov** [1], **V. P. Reva** [2], **D. B. But** [1]

[1] Institute of Semiconductor Physics of Ukrainian NAS
41, Nauki str., Kiev-03028, Ukraine
E-mail: sizov@isp.kiev.ua

[2] Institute of Microdevices of Ukrainian NAS
3, Severo-Siretskaya str., Kiev-136, Ukraine
E-mail: reva@imd.org.ua

ELECTRICAL PARAMETERS Of Si *n*-MOSFET THz-DETECTOR: MATCHING WITH EXTERNAL AMPLIFIER

The influence of the external load resistance on voltage and current sensitivities of *Si n*-MOSFET THz detectors at radiation frequency ν=142 GHz is investigated. The noise level in the frequency band, which is needed for real-time imaging is specified. Investigated were transistors with the gate widths and lengths within 1×1 μm^2 and 20×20 μm^2. It is shown that internal resistance and external load resistance form the divider, the parameters of which are important for matching with read-out devices.

Keywords: THz detectors, field-effect transistors, matching amplifiers.

Ф. Ф. Сизов, О. Г. Голенков, В. П. Рева, Д. Б. Бут

ЭЛЕКТРИЧЕСКИЕ ПАРАМЕТРЫ ТГц ДЕТЕКТОРОВ НА КРЕМНИЕВЫХ n-КАНАЛЬНЫХ МОП-ТРАНЗИСТОРАХ С ВНЕШНИМ УСИЛИТЕЛЕМ

Исследуется влияние внешнего нагрузочного сопротивления на чувствительность ТГц детекторов на *Si n*-канальных МОП-транзисторах по напряжению и току при частоте излучения ν=142 ГГц. Описывается уровень шума в полосе частот, необходимый для отображения в реальном времени. Исследовались транзисторы с шириной и длиной затвора в пределах 1×1 μм^2 и 20×20 μм^2. Показано, что внутреннее сопротивление и внешнее нагрузочное сопротивление образуют делитель, параметры которого важны для согласования с устройствами считывания.

Ключевые слова: ТГц приемники, полевые транзисторы, согласующие усилители.

1. Introduction

Uncooled or slightly cooled THz/sub-THz broadband direct detection detectors on the base of 2D electrons in FETs (field-effect transistors) [1] are promising to be used in large arrays of low-cost systems. Reaching *NEP* between 10^{-10} and 10^{-11} W/Hz$^{1/2}$ they could be used in many low-resolution spectroscopy applications and active vision systems. They can be designed and manufactured as relatively large arrays with external or internal circuits for signal processing. Favorable semiconductor for these purposes is silicon.

Here, some characteristics of *Si n*-MOSFETs (metal-oxide FETs), as devices for registration of sub-THz radiation by arrays, designed and manufactured by 0.35 μm or 1 μm design rules, were investigated. Typical dimensions of these transistors were rectangular and square form with different gate width W and length L within 1×1 and 20×20 μm^2.

Parameters of FETs used as THz detectors, which are important for matching with signal processing devices, are input resistance R_L, amplifier intrinsic noise level U_{noise}, amplification bandwidth Δf and gain factor k_{amp}.

2. Detector model

Line coupling of *Si n*-MOSFET transistors for THz radiation registration [1–4] is similar to common-source circuit. The difference is the output signal, which is measured at transistor drain δU_D changes not with THz radiation frequency but corresponds to constant component which originate from nonlinear signal conversion in the transistor channel. For long transistor channel case the transistor drain rectified signal voltage response δU_0 is [1, 2]

$$\delta U_0 = \frac{U_a^2}{4 \cdot (U_G - U_{th})}. \qquad (1)$$

Here U_G is a gate voltage bias, U_{th} is a transistor threshold voltage, U_a is an amplitude of input signal in the channel under the THz radiation ($U_{in} = U_a \sin(\omega t)$). Expression (1) is valid for linear regime of transistor operation when $U_D < U_G - U_{th}$. Here U_D is a drain voltage, which in these experiments was equal to zero.

The signal direct component δU_0 is formed at short part near the source of transistor (< 100 nm) [1, 4], and the channel lengths of transistors investigated were within 1 and 20 microns. That is a reason why the signals at the transistor drain δU_D differs the signal direct component δU_0. As the channel resistance R_{CH} and the external load resistance R_L form the voltage divider (see Fig. 1a), the relation between δU_0 and δU_D can be written as

$$\delta U_0 = R_{CH} \cdot \delta I_D + R_L \cdot \delta I_D, \qquad (2)$$

where δI_D are the current changes in the channel under the THz radiation influence.

The maximum current δI_0, which can be obtained in the channel, can be estimated with the load resistor value $R_L = 0$ Ohm by expression

$$\delta I_0 = \delta U_0 / R_{CH}. \qquad (3)$$

In the readout integrated circuit (ROIC) design process for multielement detector arrays one should take into account the electrical parameters of detector and multiplexor (Fig. 1b). For this purpose an amplifier is used, which parameters depend on certain detector type.

3. Experiment and discussion

In Fig. 2a as for example shown are the typical voltage signals δU_D at different load resistances R_L within 10^3 and 10^7 Ohm for transistors with channel width $W = 20$ μm and length $L = 1$ μm that were measured at room temperature influence of radiation with frequency ν=142 GHz and power density ~10^{-3} W/cm^2 at the samples location. No antennas to input THz radiation into FET channels were used. Current signals δI_D (Fig. 2b) were calculated according to the expression $\delta I_D = \delta U_D / R_L$.

Estimations of channel resistance and drain current δI_0 vs voltage U_G using the voltage divider model and Exp. (3) are shown in Fig. 3 for two transistors with different channel length.

Voltage signal maximum δU_D = 120 μV (see Table 1) is observed for samples with W = 20 μm and L = 20 μm. Current signal maximum δI_D = 2.4 nA (Table 1) is observed for samples with W = 20 μm and L = 1 μm.

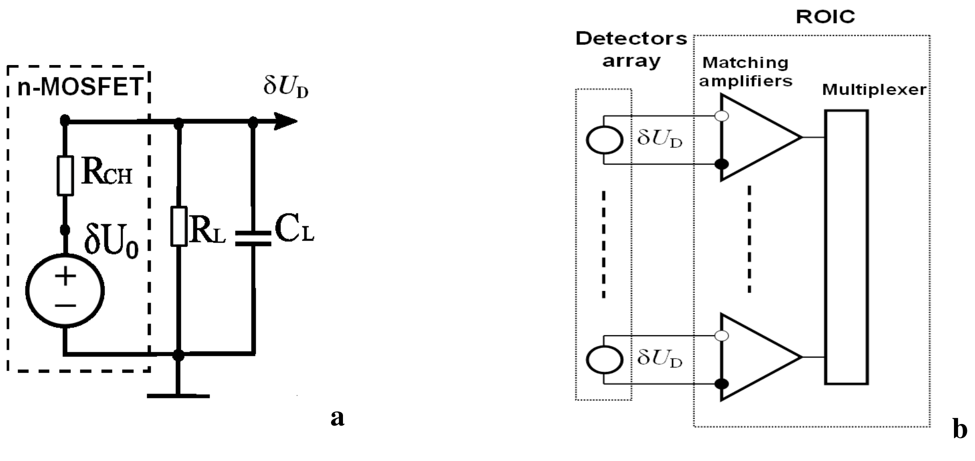
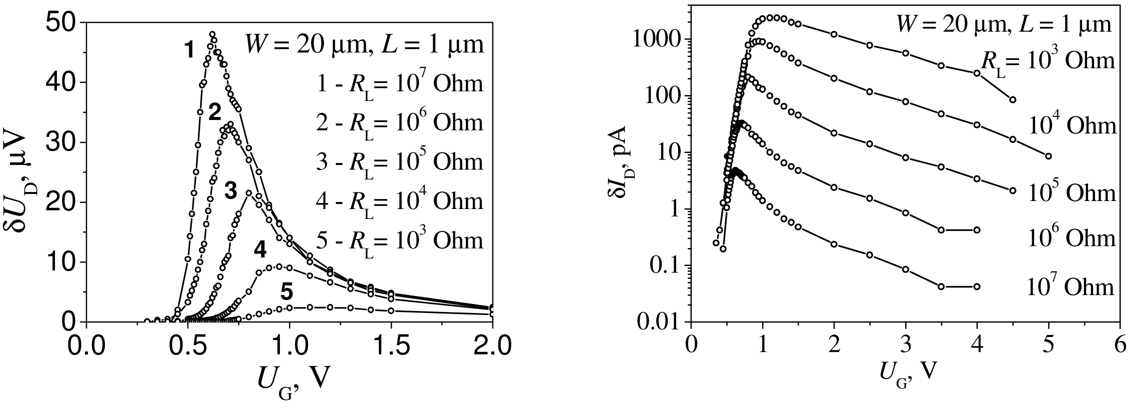


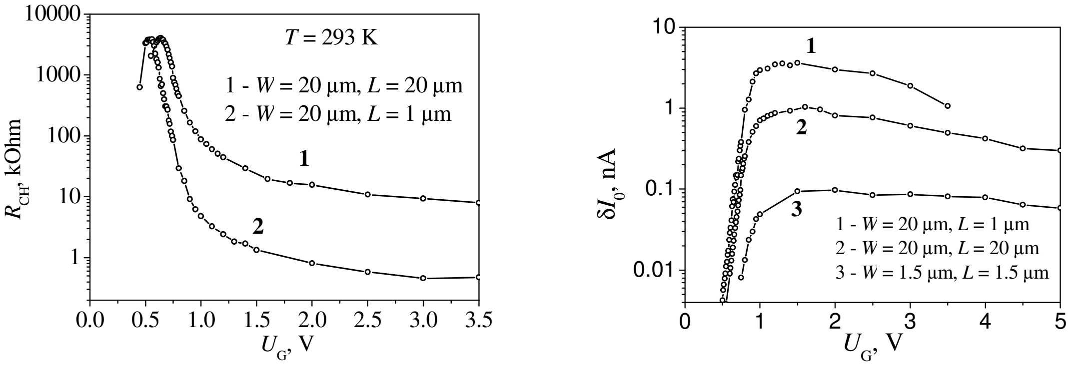
Fig. 1. Detector's equivalent circuit (*a*),
and schematic of the detector array connections with ROIC (*b*)



a

b

Fig. 2. Drain voltage δU_D (*a*) and current δI_D (*b*) responses of *Si n*-MOSFET THz-detector vs the gate voltage U_G.



a

b

Fig. 3. Estimations of the channel resistance (*a*) and drain current δI_0 (*b*) vs voltage U_G using the voltage divider model

Table 1. Voltage δU_D and currents δI_D, δI_0 peak values for different transistors

Sample dimensions	W = 1.5 µm L = 1.5 µm	W = 20 µm L = 1 µm	W = 20 µm L = 20 µm
Maximum δU_D, µV	13.5	42	120
U_G, V	0.6	0.62	0.74
Maximum δI_D, pA	120	2400	830
U_G, V	1.4	1.1 V	1.4
Maximum δI_0, pA	135	3500	1000
U_G, V	1.5	1.2	1.5
R_{CH}, MOhm	>10	1.32	1.38
U_G, V	0.6	0.62	0.74

For output signals registration the relatively low voltages δU_D ($\le$ 1mV) of *Si n*-MOSFET THz detectors should be amplified. For typical data acquisition systems it is normally if maximum input signal U_{out} is above 1 V. In this case the gain factor k_{amp} should be $k_{amp} \ge$ $\ge 10^3 \div 10^4$.

For real-time imaging systems with detector's array, amplifier bandwidth Δf can be calculated as $\Delta f = F_{Rate} \cdot N_{lines}$, where F_{Rate} is frame rate, N_{lines} is number of lines in the frame. If $F_{Rate} = 25$ Hz and $N_{lines} = 320$ the bandwidth is $\Delta f = 8$ kHz.

For these detectors type the thermal noise is a principal one. Thermal noise U_{noise} was estimated as $U_{noise} = (4k_bTR_L\Delta f)^{1/2}$, where k_b is Boltzmann constant, T is temperature. Noise $U_{noise} = 12.9$ μV at $R_L = 10^6$ Ohm and $U_{noise} = 41$ μV at $R_L = 10^7$ Ohm for $\Delta f = 10$ kHz and $T = 300$ K. Therefore the dynamic range $DynR = 40$ dB can be attained only in the case of signal levels $\delta U_D > 1$ mV (which is possible with antennas applied) and with load resistances $R_L < 10^6$ Ohm.

4. Conclusions

Intrinsic (*n*-channel) resistance R_{CH} of *Si n*-MOSFET and external load resistance R_L form the voltage divider. Without antennas the response voltage maximum of these transistors is $\delta U_D < 120$ μV. Special design of the FET detectors (including THz antennas) can increase this value up to $\delta U_D \sim 1$ mV [1, 4].

To obtain maximum output signal $U_{out} > 1$ V the gain factor k_{amp} must be $k_{amp} > 10^3 \div 10^4$.

Estimated noise level is $U_{noise} \sim 41$ μV at $R_L = 10^7$ Ohm and $U_{noise} \sim 12.9$ μV at $R_L = 10^6$ Ohm, if amplifier bandwidth is $\Delta f \sim 10$ kHz. To obtain maximum signal-to-noise ratio an amplifier load resistance R_L should be chosen within $R_L = 10^5 \div 10^6$ Ohm

Real-time THz imaging system based on *Si n*-MOSFETs with dynamical range > 40 dB is possible when using special design of FET detectors. Amplifier bandwidth should be $\Delta f \sim 8$ kHz (is chosen for the frame frequency 25 Hz and the number of lines in the frame N=320).

5. References

1. *W. Knap, M. Dyakonov, D. Coquillat, et. al.* "Field effect transistors for terahertz detection: Physics and First Imaging Applications // J. IR, MM THz Waves, **30**, 1319 (2009).

2. *M. Dyakonov, M. Shur.* Detection mixing, and frequency multiplication of terahertz radiation by two-dimensional electronic fluid // IEEE Transactions on Electron Devices **43**, 380 (1996).

3. *W. Knap, F. Teppe, Y. Meziani, et. al.* "Plasma wave detection of sub-terahertz and terahertz radiation by silicon field-effect transistors // Appl. Phys. Lett., **85**, 675 (2004).

4. *A. Lisauskas, D. Glaab, H. G. Roskos, et. al.* Terahertz imaging with Si MOSFET focal-plane arrays // Proc. SPIE, **7215**, 72150J (2009).

15.09.2010