https://doi.org/10.1051/e3sconf/202338907016

Sensitivity to pressure and light of a depletion-mode field-effect transistor

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Abstract. There are presented the results of experimental investigation of sensitivity of field effect transistor in two-terminal connection mode with pinched-off channel to the impact of pressure and light. It is shown that the depletion-mode field effect transistor has a high sensitivity to pressure and light.

1 Introduction

The growing interest to micro-power semiconductor devices manifested by specialists in the field of microelectronics, optoelectronics and communication technologies is conditioned due to their excellent features: low power consumption, reliability, long life and high stability of their parameters.

From this point of view, field-effect transistors (FETs) having a wide range of connection modes are highly demanded.

In particular, for creation of structures with the maximum sensitivity are required FETs with the depth of p-n-junction, commensurated with the depth of penetration of the light radiation, and a special selection of the channel thickness will allow to give to structure the temperature sensitivity. Here the positive sign of the temperature sensitivity coefficient is formed due to the dependence of contact potential difference of p-n-junction from temperature, and a negative temperature coefficient sign — owing to dependence of the mobility of charge carriers in the channel from the temperature3.

Thus a variety of different of photoelectric and temperature properties of FET can be received by varying of concrete physical and technological parameters of structure itself and successful combining of its connection modes in conjunction with electro-physical parameters.

The present work is devoted to the study of tenso- and photo-electrical properties of silicon junction field-effect transistor in depletion mode, in particular, to ensure sensitivity to external influences such as pressure and light radiation.

To reach this our goal it is necessary to choose a universal parameter correlated with the region that responds to all these influences.

We have chosen as such a parameter pinch-off voltage interconnected with the thickness of space charge region located between channel and gate region whose thickness is

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controlled by the source-gate junction potential while potential itself is created by voltage of drain-gate junction.

The proposed choice is conditioned due to the many physical processes, like generation of minority carriers, change in capacitance, height of potential barrier are associated with the dynamics of the space charge region change.

2 Experimental samples

The investigated silicon junction field-effect transistor shown in Fig. 1a contains a low-resistance substrate of p-type with the bottom gate electrode and a high-resistance epitaxial n-type layer grown on the surface of substrate. Further on the surface of epitaxial layer formed ohmic contacts to drain and source regions, between which a channel is located.

The carrier concentration in the substrate and the channel is $1.0{\cdot}10^{19}$ cm^{-3} and $2{\cdot}10^{15}$ cm^{-3}, respectively.

The thickness of the channel is 1 μm, and length is 50 μm.

The investigated structures have a typical field-effect transistor sub-linear current-voltage characteristics with the maximal drain current of 1.8÷2.2 mA and the pinch-off voltage of 0.9÷1.3 V, Fig. 1b.

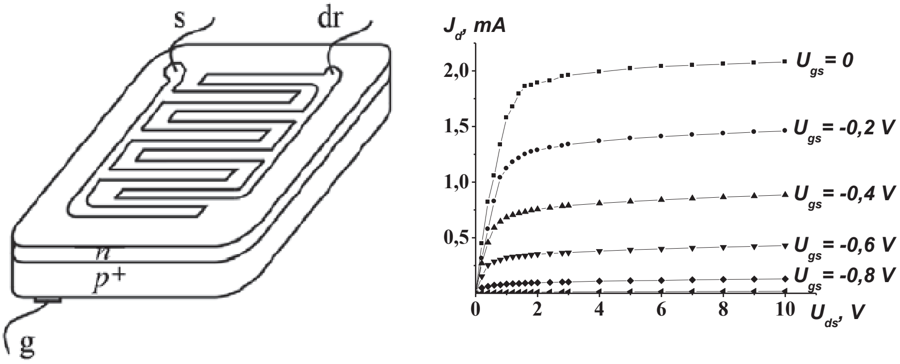

Fig. 1. Geometric design (a) and current - drain voltage characteristics (b) of the FET.

3 Experimental techniques

The electric circuit designed for direct measurement of the pinch-off voltage drop at the source-gate junction is shown in Fig. 2.

Power supply unit is connected to the drain-gate junction via microamperemeter. Herewith the potential generated at the source-gate junction is fixed by the second voltmeter.

As the drain voltage increases until the reach of pinch-off voltage, the voltage drop at the source increases linearly, and when the channel is pinched-off by the space-charge layer it becomes equal to the pinch-off voltage and is maintained at this level.

At a given work voltage impact on the channel of any factor (pressure, light or temperature) leads to a changing of source-gate junction potential, which is identified as mentioned above like the measuring parameter.

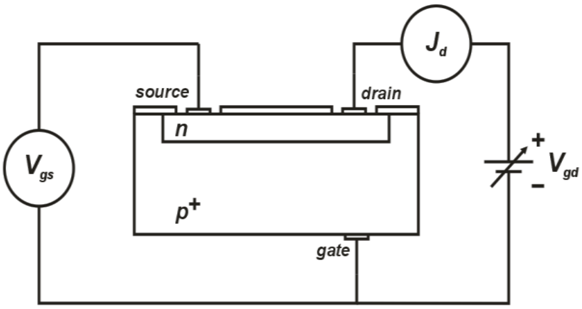

Fig. 2. Field-effect transistor connection circuit to study external influence.

Under illumination of channel in space charge region are generated electron-hole pairs which created photocurrent on the source-gate junction leading to the decreasing of resistivity of this junction that in turn causes to the decreasing of voltage drop and relevant increasing of current of the gate-drain.

4 The sensitivity to pressure of the depletion mode field-effect transistor

As shown in Fig. 3, studies have demonstrated that under the external pressure the voltage falling at the gate-source junction (pinch-off voltage) linearly decreases. Increasing of pressure from 0.027 g/cm^2 to 0.26 g/cm^2 leads to decreasing of pinch-off voltage from 1.2 to 0.86 V.

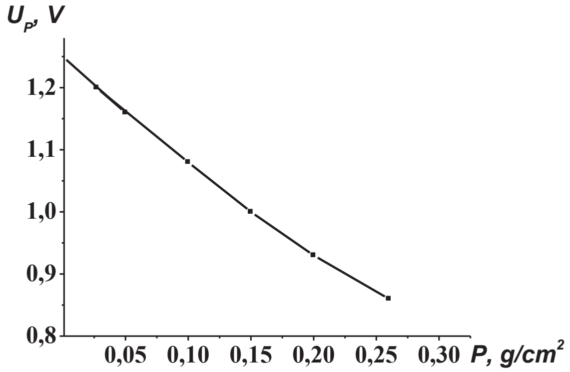

Fig. 3. Dependence of pinch-off voltage from pressure.

Thus, the coefficient of pinch-off voltage sensitivity to pressure (tenso-sensitivity)

$$\alpha_P = (U_P^2 - U_P^1)/(p_2 - p_1) \quad (1)$$

amounts 1.46 V/(g/cm^2) or 1.46·mV/Pa, which is two orders of magnitude higher than the stress sensitivity of the collector junction of a known bipolar transistor.

The observed decrease of pinch-off voltage of the channel with pressure growing can be explained by decreasing of the band gap of material of channel from pressure and increasing of dielectric permittivity of the material of the channel, which as seen from Eq.

(2) leads to increasing of initial thickness of the space charge region of p-n-junction of the gate

$$W_{SCR} = \sqrt{\frac{2\varepsilon\varepsilon_0 U_{diff}(N_{chan}+N_{gate})}{q\cdot N_{chan}\cdot N_{gate}}} \qquad (2)$$

that leads to a reduction of the thickness of channel's conducting part.

So, the increasing of pressure on the surface of the channel leads to even lower voltage for its pinch-off[5]:

$$U_P = \frac{N_{chan} q a^2}{2\varepsilon\varepsilon_0}\left(1+\frac{N_{chan}}{N_{gate}}\right) = U_{rev} + U_{diff} . \qquad (3)$$

Accordingly, dependence of the thickness of depletion layer from the reverse voltage can be determined by the following expression[5]:

$$W_{SCR} = \sqrt{\frac{2\varepsilon\varepsilon_0 (U_{diff}+U_{rev})(N_{gate}+N_{chan})}{qN_{gate}N_{chan}}} . \qquad (4)$$

In Eq. (2) and (4): ε and ε_0 - permittivity of semiconductor and vacuum, respectively; U_{rev} - voltage applied to the p^+-n-junction of the gate; N_{gate} - and N_{chan} - charge carrier concentration in low-resistant gate and high-resistant channel regions; q - charge of electron.

Thus, one can conclude that with increasing pressure on the channel the thickness of the channel's conducting region is reduced that, in turn, decreases of pinch-off voltage.

5 Photovoltaic properties of the depletion mode field-effect transistor

Fig. 4 shows the dependence of the voltage dropping on the source-gate junction from the drain-gate voltage.

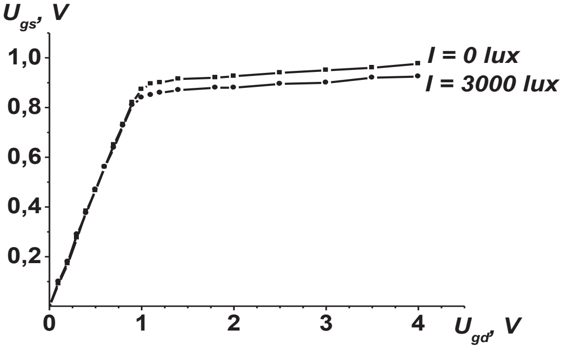

Fig. 4. Dependence of voltage dropping at source-gate junction from drain-gate voltage.

It`s seen, that voltage dropping on the source-gate junction changing from the work voltage to occurring of pinch-off mode enters the saturation.

The illumination of the channel by integrated light from halogen lamp with the wavelength 0.55 μm and intensity of 3000 lux leads to decreasing of voltage drop in the linear part of the plot in comparison with dark mode.

In the pinch-off mode of the channel, increasing of the intensity of light emission from zero to 7000 lux leads to pinch-off voltage drop from 0.89 to 0.76 V (Fig. 5).

Wherein the voltage photosensitivity

$$S_V = \frac{U_P^{I1} - U_P^{I2}}{I} \qquad (4)$$

amounts 18.5 mV/lux.

Analogically, reduction of the dropping voltage at the gate-source junction from 0.08 V to 0.073 V can be also observed at small fixed drain-gate operating voltage values (= 0.1 V) when the channel is illuminated by integral light emission with increasing intensity from 1000 lux to 7000 lux (see Fig. 6a).

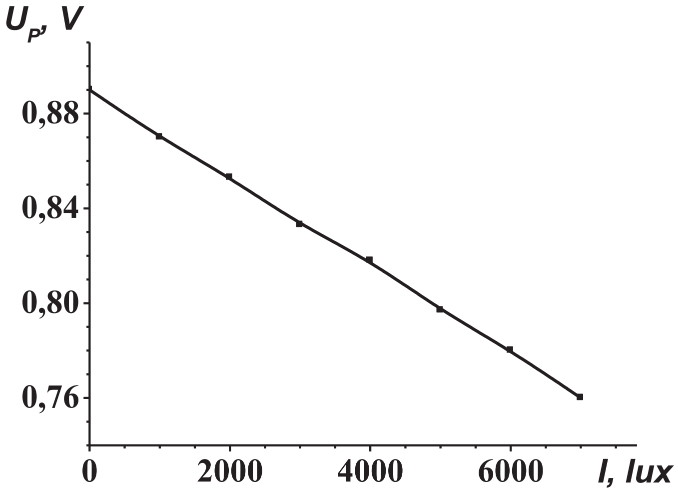

Fig. 5. Dependence of pinch-off voltage from light emission intensity.

One can say that in this case, similarly to that in the photodiode, the number of generated photo-carriers grows with increasing intensity of illumination, leading to increasing of the drain current from 14 μA to 18.5 μA (see Fig. 6b).

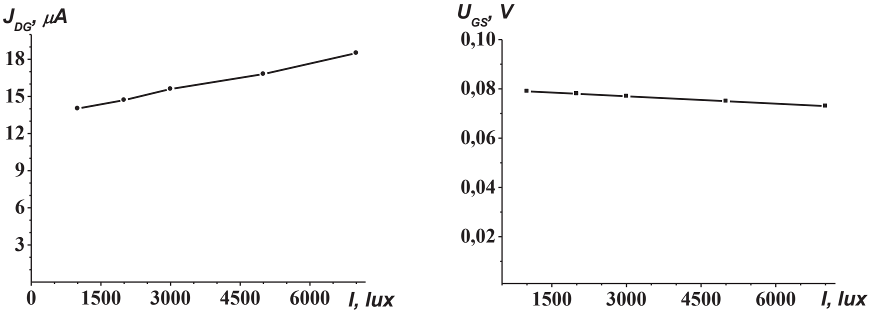

Fig. 6. Dependence of dropping voltage at gate-source junction (a) and drain-gate junction current (b) from light emission intensity at a fixed operating voltage.

The observed experimental photovoltaic characteristics of the field-effect transistor in the depletion mode of channel by the drain-gate junction voltage can be explained by the following mechanism: when the channel of the field-effect transistor is illuminated by light emission with energy of hν (larger than the bandgap) photocurrent generated at the source-gate junction reduces the dark resistance of the source-gate junction and, as a result, leads to decreasing of pinch-off voltage.

The higher is the light intensity; the lower is the resistance of the source-gate junction, and the voltage drop in it.

6 Conclusion

Thus, the depletion mode field-effect transistor under the influence of pressure and light due to its significant dependence on the initial thickness of the channel gets photosensitivity and pressure sensitivity depending on the pinch-off voltage while consuming significantly less energy than conventional diode structures.

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