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PHYSICAL-TECHNOLOGICAL ASPECTS OF A MULTIFUNCTIONAL SENSOR BASED ON A FIELD-EFFECT TRANSISTOR

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ABSTRACT

The physical and technological criteria are presented for providing to the junction field-effect transistor sensitivity to external influences. It is shown that in the channel depletion mode by drain-gate voltage photosensitivity of drain-gate junction or temperature sensitivity of pinch-off voltage are greater than in the other modes.

KEYWORDS: field-effect transistor, pinch-off voltage, photosensitivity, channel thickness.

INTRODUCTION

Now the non-trivial modes of field and bipolar transistor operation are of great interest. It was found that a two-source transistor is very sensitive to deformation (Babichev et al, 2000). A field-effect transistor produced as a two-transistor cell with series-connected channels greatly amplifies direct and alternate signals (Karimov et al, 2015a). For a field-effect transistor to be sensitive to external actions, such transistor is proposed to operate in a mode of channel blocking by source-gate voltage and pinch-off voltage to be used as a measuring parameter (Karimov et al, 2015b).

This paper presents the field-effect transistor operation as a multifunctional sensor in a mode of channel blocking by source-gate voltage.

Field-effect transistor

A multifunctional sensor was produced on the basis of silicon. An epitaxial layer of the *n*-type conduction with the carrier concentration $2{\cdot}10^{15}$ cm^{-3} and the thickness 0.7-1.5 μm (its optimal values are presented in Table 2) was grown on a silicon p^+-substrate of 200 μm in thickness and with the carrier concentration $1{\cdot}10^{19}$cm^{-3}. Then the contact regions were formed by deposition of indium and silver through windows in a mask. The distance between source and drain, i.e. the channel length, was equal to 150-200 μm. On the back side of the substrate a continuous contact was formed by indium and silver deposition.

One of the design-technological features of the field-effect transistor under study is that the channel is accessible for external action (Fig.1). For the rapid reaction to changing temperature it is necessary that the substrate thickness should be as thin as possible, i.e. not 200 μm as we have but about 100 μm.

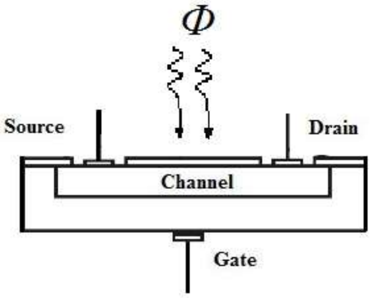

Fig.1: A structure of investigated field-effect transistor.

Main criteria for selection of parameters of field-effect transistor as a multifunctional sensor.

As shown in Fig.1, the junction field-effect transistor consists of a low-resistance substrate of the first type with the lower electrode of gate, an epitaxial (diffusive) high-resistance layer of the second type with the ohmic contact regions of source and drain; between them there is a channel of L in length and a in thickness that is $\sqrt{2}$ more than the initial thickness of the depletion layer of the p^+-n-junction. This thickness provides a value of the channel pinch-off voltage twice as large as the diffusion potential U_D, $U_{cutoff} = 2U_D$. The thickness of the depletion layer of the p^+-n-junction decreases with temperature increase or under light irradiation (Q, Φ). The substrate and the high-resistance layer can be both *n*- and *p*-type or vice versa. The sensor can be manufactured on the basis of germanium, silicon, gallium arsenide or on the basis of any semiconductors with a rectifying junction.

For optimal modulation of channel under external action, the pinch-off voltage is taken according the equality $U_{cutoff} = 2U_D$. As given in Table 1, for the zero shift the bulk charge thickness is 0.65 µm and the contact difference of potentials is 0.61 V. Then for the pinch-off voltage of 0.61 V we have x2 =1.22 V or for the reverse channel-gate voltage U_{reverse}=0.6 V we have the thickness W_{bchr}=0.90 µm, i.e. when the voltage increases twice as much the bulk charge region (bchr) increases as much as $\sqrt{2}$, which corresponds to the optimal thickness of the channel.

Table 1: Thickness of bulk charge layer vs. reverse voltage.

U_{reverse}, V	0.0	0.1	0.2	0.4	0.6	0.8	1,0	1.3	1.6
W_{bchr}, µm	0.65	0.70	0.74	0.83	0.90	0.97	1.04	1.13	1.22

Selection of the channel thickness within $\sqrt{2}$ of the bulk charge region thickness of the *p-n-*junction is due to the fact that for large thicknesses the field-effect transistor sensitivity to external actions decreases and for smaller ones there is a possibility of hysteresis formation when the pinch-off voltage increases and decreases under external actions because of enlarging or narrowing the bulk charge region caused by a sharp reduction in the carrier concentration near the p-n-junction boundary.

The special point of our multifunctional sensor is that if for the available thermosensitive field-effect transistor the negative temperature coefficient of the channel conduction dependence is suppressed owing to selecting the carrier concentration near the transition point of temperature sensitivity of mobility from high values to low ones (Karimov and Bakhronov, 1999) then in our case there should be photo-sensitivity and pressure-sensitivity besides temperature one. Those features can be provided if the field-effect transistor operates in a mode of channel blocking by the drain-gate voltage when with the raise in the working voltage before channel pinch-off the voltage drop on the source-gate junction linearly increases and then after pinch-off becomes equal to channel pinch-off voltage. For a specified working voltage the action of light or temperature (pressure) on the channel leads to changes in potential at the source-gate junction that is identified as a measuring parameter, as proposed in (Karimov et al, 2015b).

Experimental results and discussion

Under illumination of the channel in the bulk charge region of the gate-channel junction the electron-hole pairs are generated; they create a photo-current at the source-gate junction leading to a decrease in resistance of this junction, which results in turn in the voltage drop and in a corresponding increase of the drain current. An electronic scheme of how to measure the dependence of the voltage drop at the source-gate junction on external action is presented in Fig. 2.

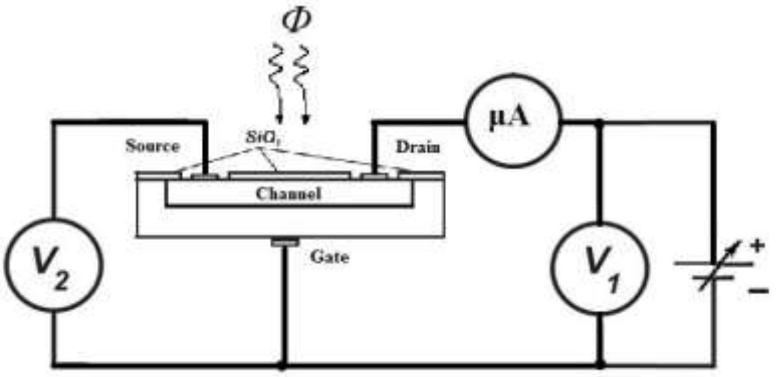

Fig. 2: A scheme of measuring the voltage drop at the source-gate junction in a mode of channel blocking by the drain-gate voltage.

As seen from the figure, the gate-channel junction operates in a diode mode or under illumination it operates similar to a photodiode. However, in principle it essentially differs from a photodiode. In the offered working mode of channel blocking the voltage at the drain-gate junction is two times and over more than that at the source-gate junction. When the source output is closed with the drain one (diode mode) it is transformed into a diode with a thin base.

As given in Fig.3, in the diode mode the reverse current up to 10 V does not exceed 1 nA and in the forward direction beginning with 0.7 V a sharp increase in current is observed and for the voltage 0.9 V the direct current is 9.75 mA. Accordingly, in the mode of channel blocking the so insignificant reverse current of the gate-source junction will not make effect on photocurrent generated under channel illumination.

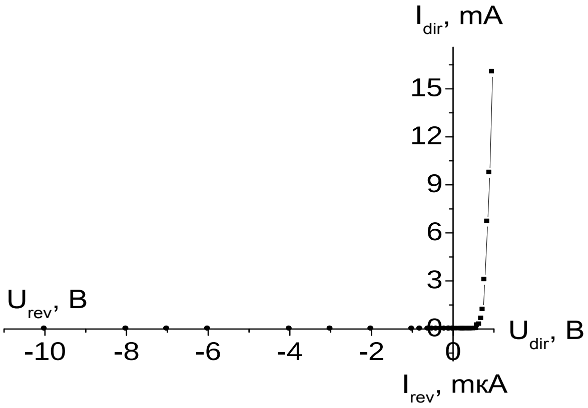

Fig. 3: The voltage-current characteristic of the drain-gate junction.

As shown by the investigation, in the short circuit mode when the gate and source outputs are connected with an ammeter the photocurrent increases almost linearly (Fig. 5, Curve 1) with the raise in the intensity of channel illumination by a halogen lamp. In the mode of channel blocking by the drain-gate voltage we have the photocurrent as large as twice (Curve 2).

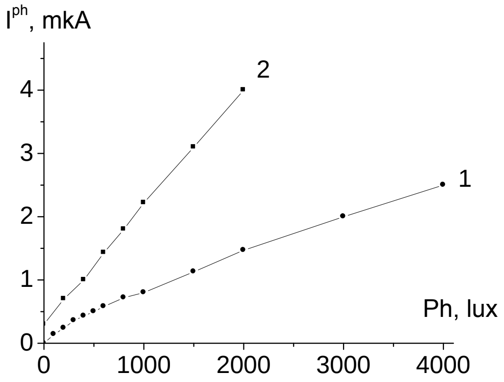

Fig. 4: The dependences of photocurrent on illumination intensity in the short-circuit mode and for channel blocking by the drain-gate voltage.

As far as the voltage drop is concerned, its value with the raise in illumination intensity significantly decreases for the small intensities of illumination and further non-linearly decreases and the dependence becomes weak. For the first region the sensitivity is 0.00025 V/lux and for the region 1000-2000 lux the photo-sensitivity is an order less and equal to 0.00002 V/lux.

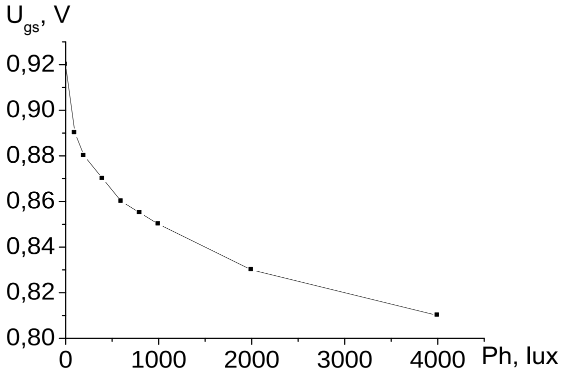

Fig. 5: The dependence of voltage drop at the gate-source junction on illumination in the mode of channel blocking by the drain-gate voltage.

The fact that the voltage drop at the source-gate junction is sensitive to illumination can be explained as follows. Channel illumination by n-type quanta with the energy greater than the bandgap leads to generation of non-equilibrium electron-hole pairs and an increase in illumination intensity to a decrease in the contact difference of potentials of the p-n-junction

$$U_{ph} = \frac{kT}{e} \ln \frac{n_n}{n + n_{ph}},$$

where n_{ph} - is the concentration of holes generated by photons under illumination of the n-region.

In turn, the photocurrent appearing at the source-gate junction reduces its resistance, which leads to a decrease in the dropping voltage as compared with the dark one.

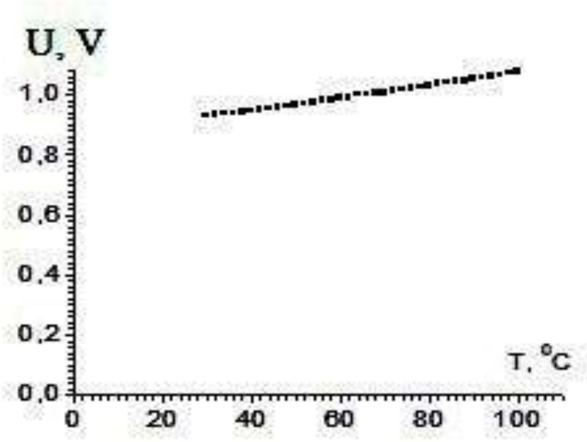

Fig. 6: The dependence of cutoff voltage on temperature.

In this mode the field-effect transistor under study has temperature sensitivity not less than that of diode structures but at the same time with the advantage of almost no energy consumption (Karimov et al., 2013). When the temperature increases from room one to 100^{o}C the pinch-off voltage increases from 0.92 V to 1.0 V. The temperature coefficient is 2 mV/degree, which is within the range obtained for the diode structures in the mode of direct current restriction up to 10 mA (Kurashkin, 2011).

CONCLUSION

Thus, it is experimentally shown that in the mode of channel blocking by the drain-gate voltage and the use as a measuring parameter of the pinch-off voltage the field-effect transistor with bottom gate and open channel has temperature and illumination sensitivity greater than that of other modes of operation. The power voltage is 2-5 V for the current less than 10 µA that is three orders less as compared with the diode mode.

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