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FEATURES OF THE TEMPERATURE PROPERTIES OF A FIELD-EFFECT TRANSISTOR IN A CURRENT-LIMITING MODE

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A study has been made of the physical processes in a field-effect transistor when its thermosensitive parameters, such as the direct voltage of the gate p–n junction and the cutoff voltage of the channel, are acted upon by temperature. It has been established experimentally that one can control the temperature-sensitivity coefficient of a diode-connected field-effect transistor.

Keywords: *field-effect transistor, temperature, dropping voltage, current limiting.*

Introduction. Imparting linearity to the parametric dependences of diode or transistor structures sensitive to external actions through the selection of a connection mode of these structures provide conditions for using them for their new purpose. For example, the existence of a linear relationship between the photovoltage and the radiation intensity of photocells in devices used for illumination measurement makes it possible to additionally use them as sensors reacting to the change in the intensity of light, in automatic equipment, in measuring and computer facilities, and in other today's devices. The possibility of exciting extra carriers in the *p–n* junction not only by light but also by ionizing radiation, i.e., by fast electrons, alpha particles, and gamma rays, enables one to use *p–n* junction devices as radioactive-radiation indicators or for direct conversion of nuclear power to electric power.

Furthermore, the necessity of using diode or transistor structures for their new purpose is dictated by the possibility of extending their functional properties. Thus, the use of structures with a rectifying *p–n* junction as a thermosensitive element makes it possible to solve the problem of measurement of temperature at hard-to-reach sites of motors and to determine the range of safe operation of high-power diodes and light-emitting diodes.

The presently known investigations have been carried out on rectifying diodes and bipolar transistors. It has been established from the investigation of KD503A- and KD102A-type semiconductor diodes that the temperature coefficient of conversion transconductance in them is 0.6–0.7 mV/^{o}C and they can be used as temperature transducers of an electric motor [1]. In [2], it is proposed that *p–n* junctions of D220-, KD522A-, and GD507A-type commercial diodes be used as temperature pickups. However, these diodes have large dimensions and capacity, which limits the possibility of using them in automatic equipment and devices of today's measuring facilities. The best temperature coefficients obtained for semiconductor diodes and a discrete bipolar transistor are 2.3–2.6 mV/^{o}C [3, 4]. However, up to now, there have been no data on investigations of field-effect transistors and mechanisms of control over the temperature coefficient of their parameters. The possibilities of using a field-effect transistor for its new purpose in nontraditional connection modes remain poorly known, too. For example, investigations of the possibility of using such transistors as two-terminal devices and temperature investigations of their properties in a channel-cutoff mode are to be continued.

In the present work, we give results of investigation of the possibility of using, as a thermosensitive element, the gate-to-source junction of a field-effect transistor with a *p–n* junction (with the example of KP303) in the modes of channel depletion and limited enhancement.

Prototypes. We investigated silicon-based epitaxial planar-junction and *n*-channel field-effect transistors (Fig. 1). The *p*-type region consisted of silicon doped with boron with a carrier concentration of $1 \cdot 10^{19}$ cm^{-3}. The channel represented an epitaxial layer of thickness a = 1–3 μm doped with phosphorus to a carrier concentration of

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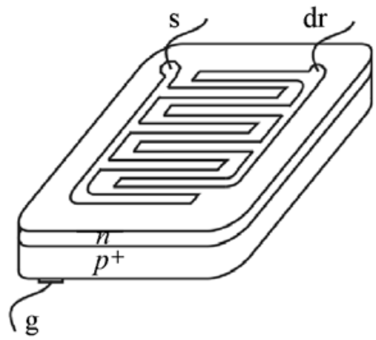

Fig. 1. Geometry of the investigated field-effect transistor: s, source; dr, drain; g, gate.

$1–2\cdot10^{15}$ cm^{-3}. The *p–n* junction capacity was 4 pF; the length of the *n*-type channel was 25 μm. Square 200 μm × 200 μm specimens with a contact area of the drain and the source of 0.00124 cm^2 was placed in a metallic casing. Their drain characteristics had a typical form; the drain current was saturated at a voltage of 2 V. With increase in the blocking voltage on the *p–n* junction the drain current decreased; the channel cutoff occurred at a voltage of 0.6–3.0 V, whereas the maximum value of this current was 1.85–2 mA. The transfer characteristics of the transistors in question are described by the quadratic dependence [5] and their maximum transconductance is 3.2 mA/V.

Temperature Properties of the Investigated Transistors in the Mode of Direct Bias of the Gate *p–n* Junction. The input volt-ampere characteristic of the gate-to-source junction has a form typical of diodes. The gate current increases exponentially in the mode of direct bias of the gate-to-source junction. As the temperature increases, the volt-ampere characteristic shifts to the region of low voltages, which is due to the decrease in the contact potential difference (Fig. 2). This property can be used for creation of temperature pickups [6].

The change in the value of direct bias dropping across the gate-to-source junction, as is shown in Fig. 3, is taken as the thermosensitive parameter. The value of operating voltage is regulated by resistor R_1, whereas the current through the rectifying junction is limited by resistor R_2. The difference between a field-effect transistor and diode and bipolar transistor structures is that the thickness of the base region (channel) has a fixed value, whereas the concentration of carriers in the gate region ($N_g = 1\cdot10^{19}$ cm^{-3}) is two to three orders of magnitude higher than that in the channel region ($N_{chan} = 2\cdot10^{15}$ cm^{-3}), which guarantees the abruptness of the *p–n* junction.

Figure 4 gives the temperature dependences of the dropping voltage at different supply voltages of the diode through the resistor R_2, i.e., the current limiter. As is seen, at equal supply voltages (4.9 V), the temperature coefficients of the dropping voltage (curves 1 and 3) have the same value α = 2.5 mV/°C, and the decrease in the supply voltage causes the temperature sensitivity to reduce. The value of the dropping voltage is larger in the specimen with a lower U_{cut} (curve 1).

The observed difference in the temperature coefficients of the specimens is attributable to the mechanism of current transfer through the gate *p–n* junction, which is described by the expression [7]

$$I_{dir}^{con} = I_{sat}\left(\exp\left(qU_{p-n}/nkT\right) - 1\right). \quad (1)$$

Preservation of the constant current through the structure leads to a temperature dependence of the dropping voltage, consequently:

$$nkT = \frac{qU_{p-n}}{\ln\left(\dfrac{I_{dir}^{con}}{I_{sat}} + 1\right)}. \quad (2)$$

According to formula (2), the change in the direct-to-reverse current ratio created by changing the value of the bias voltage on the *p–n* junction leads to a change in the temperature coefficient $\alpha = \left(U_{dir}^{T_2} - U_{dir}^{T_1}\right)/(T_2 - T_1)$. In particular, the temperature coefficient α decreases from 2.5 to 1.72 mV/°C (Fig. 4, curves 1 and 2) as the bias voltage decreases; accordingly, recombination currents decrease. Since the direct current is limited and has a fixed value I_{dir}^{con}

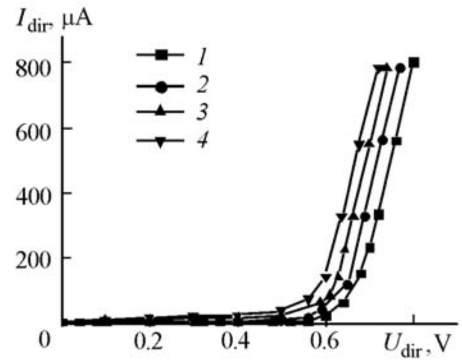

Fig. 2. Direct volt-ampere characteristic of the gate-to-source junction at different temperatures: 1) T = 30, 2) 40, 3) 50, and 4) 60°C.

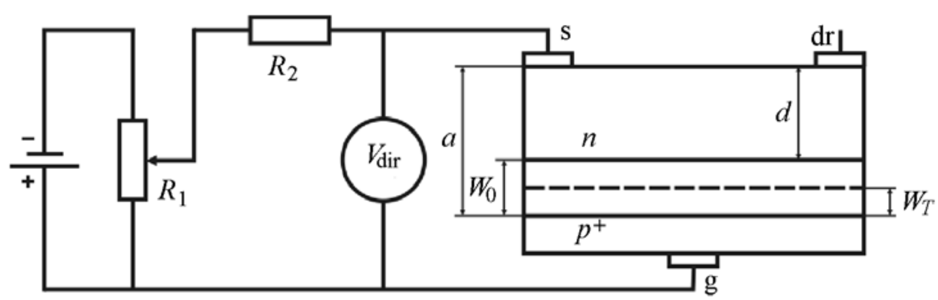

Fig. 3. Scheme of measurement of the thermosensitive parameter of the gate-to-source junction.

= I_{lim}, the voltage $U_{p–n}$ dropping across the $p–n$ junction will change in proportion to the temperature of the diode-connected field-effect transistor.

The applied (positive) voltage will be equal in value to the diffusion (negative) potential of the $p–n$ junction of the gate U_{d}, which is determined by its temperature [7]:

$$U_{\text{d}} = -\frac{kT}{q}\ln\frac{N_{\text{chan}}N_{\text{g}}}{n_i^2}. \tag{3}$$

This voltage decreases with increase in the intrinsic carrier concentration n_i as the temperature changes.

The difference between a field-effect transistor and a diode is in a fixed value of the thickness of the base region, i.e., the channel, which contributes to the base region being covered by the space-charge layer in a blocking mode, i.e., in a direct-bias mode, we also have processes caused by the recombination of carriers in a specific base region. In a regular diode, the base thickness is unlimited and offers series resistance relative to the $p–n$ junction, which, because of the additional voltage drop with change in recombination currents, makes the structure less sensitive to the contact potential difference. As applied to the field-effect transistor, one can attain maximum sensitivity where the thickness of the base region is determined by the value of the contact potential difference. Accordingly, the measurement accuracy will grow and the temperature coefficient will simultaneously increase when a material with a larger value of the contact potential difference (forbidden gap) is used.

In connection with the fact that a limited direct current through the $p–n$ junction ($I_{\text{dir}}^{\text{con}}$) is prescribed, the increase in the temperature causes the dropping voltage to decrease. The change in the direct-to-saturation current ratio ensures a controlled change in the temperature coefficient (see formula (2)). It becomes possible to identify the temperature coefficients of the specimens under study.

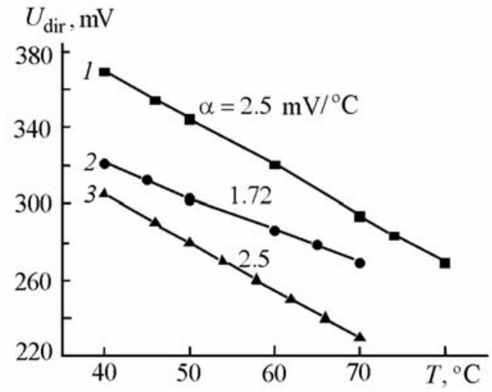

Fig. 4. Direct dropping voltages of a diode-connected field-effect transistor vs. temperature: 1) U_{cut} = 1.2 V and U_{spl} = 4.9 V, 2) 1.2 and 2.3, and 3) 2.2 and 4.9.

Thus, in the mode of direct-current limiting, a field-effect transistor with a *p–n* junction possesses temperature sensitivity determined by the mechanism of current transfer and by the controlled level of injection of carriers. The obtained value of temperature sensitivity of the direct dropping voltage (2.5 mV/^{o}C) compares well with the values occurring in diode and transistor structures, whereas the miniature structure of a field-effect transistor makes it possible to use it for determination of temperature in narrow gaps in various devices.

Temperature Properties of the Investigated Transistors in the Mode of Blocking of the Gate *p–n* Junction. The process of cutoff of the channel is the total capture by a space-charge layer, which can be determined by different methods. The classical method is when the operating voltage is fed between the drain and the source, whereas the blocking voltage is fed between the gate and the source. In this case two sources turn out to be series-connected and the ammeter connected to the drain keeps readings above zero, since in this case the current will flow through the drain-to-gate junction, and the ammeter of the gate shows the current through the gate-to-source junction. In this method, the equality of the channel current to the gate current is assumed to be the cutoff [8]. Another method is graphical and proposed by Richman [9]. It is implemented by constructing the plot of the square root of the drain current versus the gate voltage; the point of intersection of the extrapolated current and the voltage axis is assumed to be the cutoff voltage. The methods considered make it impossible to directly determine the cutoff voltage; therefore, this voltage cannot be used as a sensitive parameter.

The most convincing is the process of cutting the channel off the drain-to-gate blocking voltage by the space-charge layer, when the source lead is open. Since the drain current is not related to the leakage current of the gate, the current in the channel becomes zero. This method has been proposed by Wedlock and was implemented experimentally [10]. The electric circuit of this method is given in Fig. 5. According to this circuit, the operating blocking voltage is fed between the drain and the gate. The applied voltage is higher than the cutoff voltage. The process of measurement is as follows.

A high-resistance voltmeter is connected to the gate-to-source junction. At low voltages, the channel is open and the voltmeter voltage follows the drain voltage due to the ohmic conductance of the channel. With increase in the drain voltage there comes the instant of cutting off the channel which is completely filled with depleted layer, and the gate-to-source voltage takes on a fixed value that is equal to the cutoff voltage $U_{g-s} = -U_{cut}$. Since the current is absent from the channel, the boundaries of the depleted layer are equipotential, and the potential between the gate and the source is equal to the cutoff voltage.

The dynamics of change in the voltage on the gate-to-source junction as a function of the drain-to-gate voltage at different temperatures for one specimen of a field-effect transistor is shown in Fig. 6. As is seen, once the cutoff mode of the channel has been established, the voltage dropping across the gate-to-source junction acquires a constant value that is equal to the cutoff voltage of the channel.

Increase in the temperature causes the cutoff voltage to increase as is shown in Fig. 7. The temperature coefficient of the cutoff voltage $\alpha = \left(U^2_{cut} - U^1_{cut}\right)/(T_2 - T_1)$ of the field-effect transistor with cutoff voltage U_{cut} = 2.2 V

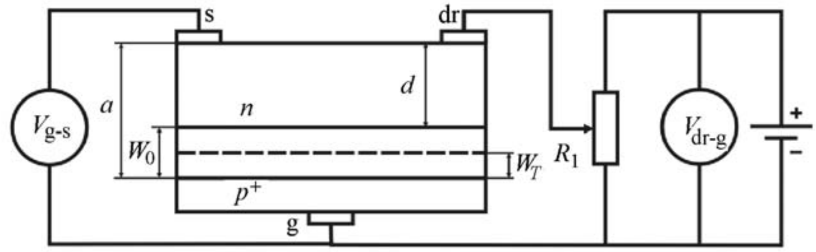

Fig. 5. Scheme of measurement of the field-effect-transistor U_{cut} [10].

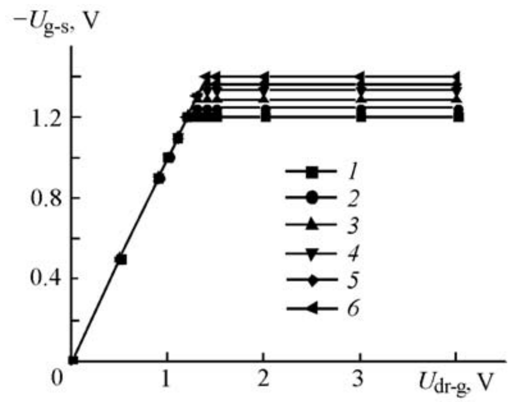

Fig. 6. Gate-to-source voltage vs. drain-to-gate voltage at different temperatures: 1) T = 30^{o}C, 2) 40, 3) 50, 4) 60, 5) 70, and 6) 80.

is equal to 1 mV/^{o}C, which is four times smaller than in the transistor with a lower cutoff voltage (U_{cut} = 1.2 V (4 mV/^{o}C)). The increase in the cutoff voltage of the channel with temperature is attributable to the decrease in the contact potential difference of the *p–n* junction (3) due to the increase in the intrinsic carrier concentration with temperature. As a result, the initial thickness of the space-charge region for U_{g-s} = 0 decreases:

$$W_{sp.ch.r} = \sqrt{\frac{2\varepsilon\varepsilon_0 U_d\,(N_{chan} + N_g)}{qN_{chan}N_g}}\,, \tag{4}$$

whereas the *p–n* junction increases:

$$C_{p-n} = \frac{\varepsilon\varepsilon_0 A}{W_{sp.ch.r}}\,, \tag{5}$$

which causes the thickness of the channel's conducting part to increase. Therefore, the channel cutoff requires even higher voltage:

$$U_{cut} = \frac{N_{chan}qa^2}{2\varepsilon\varepsilon_0}\left(1 + \frac{N_{chan}}{N_g}\right) = U_{cut}^{g-s} + U_d\,. \tag{6}$$

Thus, it is two parameters that change with temperature in the mode of channel cutoff: the contact potential difference and the thickness of the channel's conducting part.

The current drain in a field-effect transistor is known to be influenced by three factors: (1) mobility of the charge carriers in the channel decreases with growth in the temperature, which leads to a negative temperature coefficient; (2) the contact potential difference changes with positive temperature coefficient; (3) the channel's specific resistance changes with temperature. All the enumerated effects are associated to an extent with the voltage on the gate and influence the drain current and the cutoff voltage in the blocking mode.

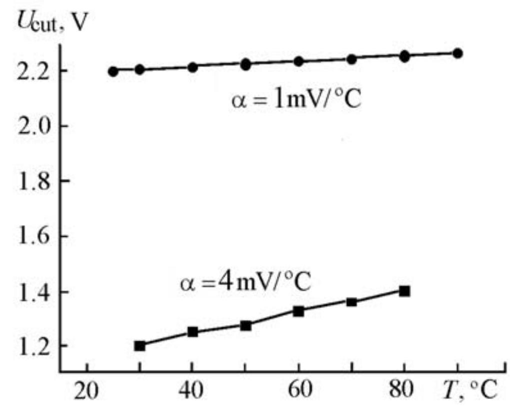

Fig. 7. Temperature dependence of U_{cut}: 1) U_{cut} = 1.2 V and 2) 2.

It should be noted that in the classical mode of blocking of a transistor, one cannot, in practice, record the process of cutting the channel off and the influence of temperature on it. Thus, the drain-to-source voltage, in the initial state, will be responsible for the current in the channel; when the blocking voltage is fed this voltage will be added to the drain voltage and the current through the drain-to-gate will prevail over the current of the gate-to-source junction, i.e., the ammeter connected to the drain will not show a pure channel current. The gate voltage assumed to be the cutoff will not correspond to the true value of the cutoff voltage, the drain and gate currents being equal. Thus, the procedure of determination of U_{cut} from the dependence of the drain current on the gate voltage is approximate and makes it impossible to use the cutoff voltage as the sensitive parameter.

In this aspect, the full coverage of the channel by a space-charge layer when the blocking voltage is fed between the drain and the gate meets the requirements of channel cutoff [10]. An equipotential field is created within the channel at a drain voltage higher that U_{cut}; the voltage in the field is equal to U_{cut} throughout the channel length. Here the temperature dependence of the internal diffusion field, which is directly related to the cutoff voltage of the channel, will act as the basic mechanism. As a result, the influence of the gate-to-drain current is excluded; no effects associated with the mobility of carriers and with the resistance of the channel manifest themselves. When the cutoff voltage is used as the thermosensitive parameter, the temperature coefficient is doubled compared to the mode of direct bias of the *p–n* junction.

CONCLUSIONS

1. A comparison of the temperature coefficients of the cutoff voltage to the temperature coefficient of the dropping voltage has shown that in both cases they are related to the quantity U_{cut}. In the direct-bias mode, the temperature coefficient is determined by the direct-to-reverse current ratio, i.e., its value is controlled. In the specimens with a lower U_{cut}, the dropping voltage has a higher value, which improves the measurement accuracy.

2. In the blocking mode, the lower the U_{cut} value, the larger the temperature coefficient. In the blocking mode, we have obtained a value of the temperature coefficient of 4 mV/°C, which is the highest in magnitude. This suggests that a field-effect transistor can serve as a temperature transducer in both the direct-bias mode and the blocking mode.

3. The temperature coefficients of a field-effect transistor are in inverse proportion to the thickness of the base region and they are physically controlled.

NOTATION

A, area of the *p–n* junction, cm^{-2}; a, total thickness of the channel, cm; C_{p-n}, capacity of the *p–n* junction, F; d, thickness of the channel's conducting part, cm; I_{dir}, current through the structure at direct bias, A; I^{con}, direct fixed current through the *p–n* junction, A; I_{sat}, saturation current of the *p–n* junction, A; I_{lim}, limited current through the p–n junction, A; k, Boltzmann constant, $J \cdot K^{-1}$; N_{chan}, doping concentration in the transistor channel, cm^{-3}; N_g, doping concentration in the transistor gate, cm^{-3}; n, ideality coefficient of the p–n junction; n_i, intrinsic electron concentration, cm^{-3}; q, electron charge, C; T, temperature, ^{o}C; U_{spl}, supply voltage, V; U_d, contact potential difference, V; U_{p-n}, bias voltage on the p–n junction, V; U_{dir}, direct-bias voltage, V; U_{g-s}, voltage dropping across the gate-to-source, V; U_{cut}, cutoff voltage, V; U_{dr-g}, voltage dropping across the drain-to-gate, V; W_0, initial thickness of the space-charge region, cm; W_T, thickness of the space-charge region as a function of the temperature, cm; $W_{sp.ch.r}$, thickness of the space-charge region, cm; α, temperature coefficient of the voltage dropping across the p–n junction, $mV/^{o}C$; ε, permittivity of the semiconductor; ε_0, vacuum permittivity, $F \cdot cm^{-1}$. Subscripts and superscripts: 0, equilibrium; con, constant; g, gate; s, source; dr, drain; chan, channel; lim, limitation; sp.ch.r, space-charge region; cut, cutoff; dir, direct; spl, supply; d, diffusion, sat, saturation.

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