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TÍTULO: Acerca de la medición de resistencia térmica de un misistor de potencia.

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RESUMEN. El artículo considera el método de determinación de resistencia térmica para un caso de transición de transistores MIS con un canal inducido. Se propone utilizar el voltaje de la fuente de drenaje como un parámetro sensible a la temperatura. Se describe el proceso de calibración de dependencia de la temperatura del parámetro. Se presenta el histograma de distribución de valores de resistencia térmica para transistores MIS de potencia.

PALABRAS CLAVES: transistor MIS de potencia, método de medición, resistencia térmica, caja de transición, parámetros sensibles a la temperatura.

TITLE: About Thermal Resistance Measurement of a Power Mis-Transistor.

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ABSTRACT: The article considers the method of thermal resistance determination for a transition-case of MIS-transistors with an induced channel. It is proposed to use the drain-source voltage as a temperature-sensitive parameter. The process of parameter temperature dependence calibration is described. The histogram of thermal resistance value distribution for power MIS-transistors is presented.

KEY WORDS: power MIS-transistor, measuring method, thermal resistance transition-case, temperature-sensitive parameters.

INTRODUCTION.

The service life of a power MIS transistor with an induced channel directly depends on the thermal MODE in which it is operated.

The choice of a standard thermal mode requires a complex evaluation of device various parameters. As a rule, when you perform the calculations, the averaged or limiting values of parameters from the transistor specification are used, which distorts the idea of its real capabilities. The reason is the technological spread of electrical and thermal parameters of semiconductor devices that inevitably arises during their production (Bespalov and Lysenkov, 2016; Bespalov, e al. 2017; Nezhad & Jenaabadi, 2014; Tabatabaei et al, 2014). Thus, it is necessary to monitor their electrical thermal parameters for the most efficient use of MIS transistors.

DEVELOPMENT.

Problem formulation.

One of the most important parameters of MIS transistor at a standard mode of operation selection is the thermal resistance of the transition-housing R_{thjc}. This parameter is directly related to the manufacturing quality of MIS transistor, which can be used to reject potentially unreliable devices.

Most modern detection methods of R_{thjc} have either low performance or low accuracy. Low productivity, as a rule, is conditioned by the need for preliminary calibration of the temperature dependence of the temperature-sensitive parameter in a thermostat. There are the methods that do not require calibration. However, such methods often involve the use of an average temperature dependence of the temperature-sensitive parameter, which inevitably reduces the accuracy of R_{thjc} determination.

Solution description.

The main informative parameters in the determination of R_{thjc} are the temperature of the transistor case T_C, drain current I_D drain-source voltage U_{DS}. The measurement of these informative parameters is not difficult. The main problem in the determination of R_{thjc} arises from the need to measure the temperature of the crystal T_j. This is due to the fact that the crystal is located inside the transistor case, and it is not possible to measure this parameter directly. The definition of T_j of a cased device is almost always realized by indirect methods (Niu and Robert, 2015; Niu and Robert, 2016; Toufik, e al. 2014).

Thermosensitive parameter.

The simplest method is to determine the value of T_j by static parameter of the current-voltage characteristic of the device, which has either a linear temperature dependence or a temperature dependence that can be reduced to a linear form. In particular, the temperature dependence U_{DS}, taken at a given constant current, has a nonlinear character, but on a logarithmic scale it acquires a linear form (Bespalov, et. al. 2012).

The temperature T_j is determined as follows:

$$T_j = T_{j0} + \Delta T_j \,, \qquad (1)$$

where T_{j0} is the temperature of the crystal in the initial state; ΔT_j — overheating.

Taking into account that $\ln(U_{DS})$ has a linear temperature dependence, the value T_j is determined as follows:

$$\Delta T_j = \frac{\Delta \ln(U_{DS})}{TK \ln(U_{DS})} \,, \qquad (2)$$

where $\Delta \ln(U_{DS}) = \ln(U_{DSh}) - \ln(U_{DS0})$, U_{DSh} — the value of the voltage on the transistor in a heated state, U_{DS0} — the voltage value, which is determined at the initial temperature T_{j0}, $TK \ln(U_{DS})$ — the temperature coefficient of the logarithmic drain-source voltage.

Substituting (2) into (1), we obtain the expression to determine the temperature of the structure in the heated state:

$$T_j = T_{j0} + \frac{\Delta \ln(U_{DS})}{TK \ln(U_{DS})} \,. \qquad (3)$$

Thus, the peculiarity of the objective determination of T_j for a specific transistor according to formula (3) is an accurate measurement and determination of three parameter values: the initial temperature of the crystal T_{j0}, which in the state of the initial thermal equilibrium can be considered equal to the initial temperature of the shell T_C, the voltages on the transistor $U_{DS\,h}$ and $U_{DS\,0}$, and $TK \ln(U_{DS})$. An accurate measurement of discrete voltage values $U_{DS\,h}$ and $U_{DS\,0}$ during the tests is not difficult. Also, there is no difficulty to obtaining the information about the temperature T_C.

For an objective determination of T_j it is important to determine accurately $TK\ln(U_{DS})$ of a specific MIS transistor. This is due to the fact that $TK\ln(U_{DS})$ of even one type of MIS transistors can differ substantially.

The definition of $TK\ln(U_{DS})$ is reduced to the measuring of two values of voltage in an open state when the test current flows for two different a priori known values of the crystal temperature. Then, according to the obtained data, they determine $TK\ln(U_{DS})$ by the following formula:

$$\mathrm{TK}\ln(U_{DS}) = \frac{\ln(U_{DSh}) - \ln(U_{DS0})}{T_{jh} - T_{j0}}. \tag{4}$$

When the instrument is tested, the first temperature point T_{j0} can be determined by measuring the temperature T_C before heating. The temperature of the crystal will correspond to the temperature of the MIS transistor case, since the device is in a state of thermal equilibrium between all elements of the structure, and there are no internal sources of heating. The voltage U_{DS0} is measured when a test current flows, the amplitude and the duration of which does not lead to the heating of a semiconductor structure.

The second temperature point T_{jh} can be obtained after the transistor heating. After the turning off of the heating current, the crystal of the transistor is heated more than the housing. The thermal time constant of the crystal τ_j is much smaller than the thermal time constant of the body τ_C. Consequently, after the time interval (3—5) τ_j the temperature of the semiconductor structure will be approximately equal to the temperature of the transistor case. By measuring the value of T_C after the end of the transient thermal process in the semiconductor structure, the second temperature point T_{jh} can be obtained and $U_{DS\,h}$ can be measured at the same test current as in the first case (Avenas, et al. 2012).

Main stages of thermal resistance determination.

The determination method R_{thjc} proposed by the authors suggests a sequential execution of two stages: measuring and calculating. At the first stage, they determine the electrical information parameters and the temperature of the tested transistor body. At the second stage, they determine the temperature dependences of the informative parameters and the thermal resistance of the transition-body. All these stages are performed in one test cycle. The time diagrams of the test cycle are shown on Figure 1.

The first stage in its turn is divided into two successive sub-stages:

1) the heating performed in the interval t_0 - t_2;

2) the cooling, carried out in the interval t_2 - t_3.

During the heating stage, they develop the test signals of direct current and heating current pulses through the tested transistor. This step is designed to measure informative parameters for the determination of R_{thjc}. At the stage of cooling, additional values of informative parameters are measured for the determination of $TK\ln(U_{DS})$.

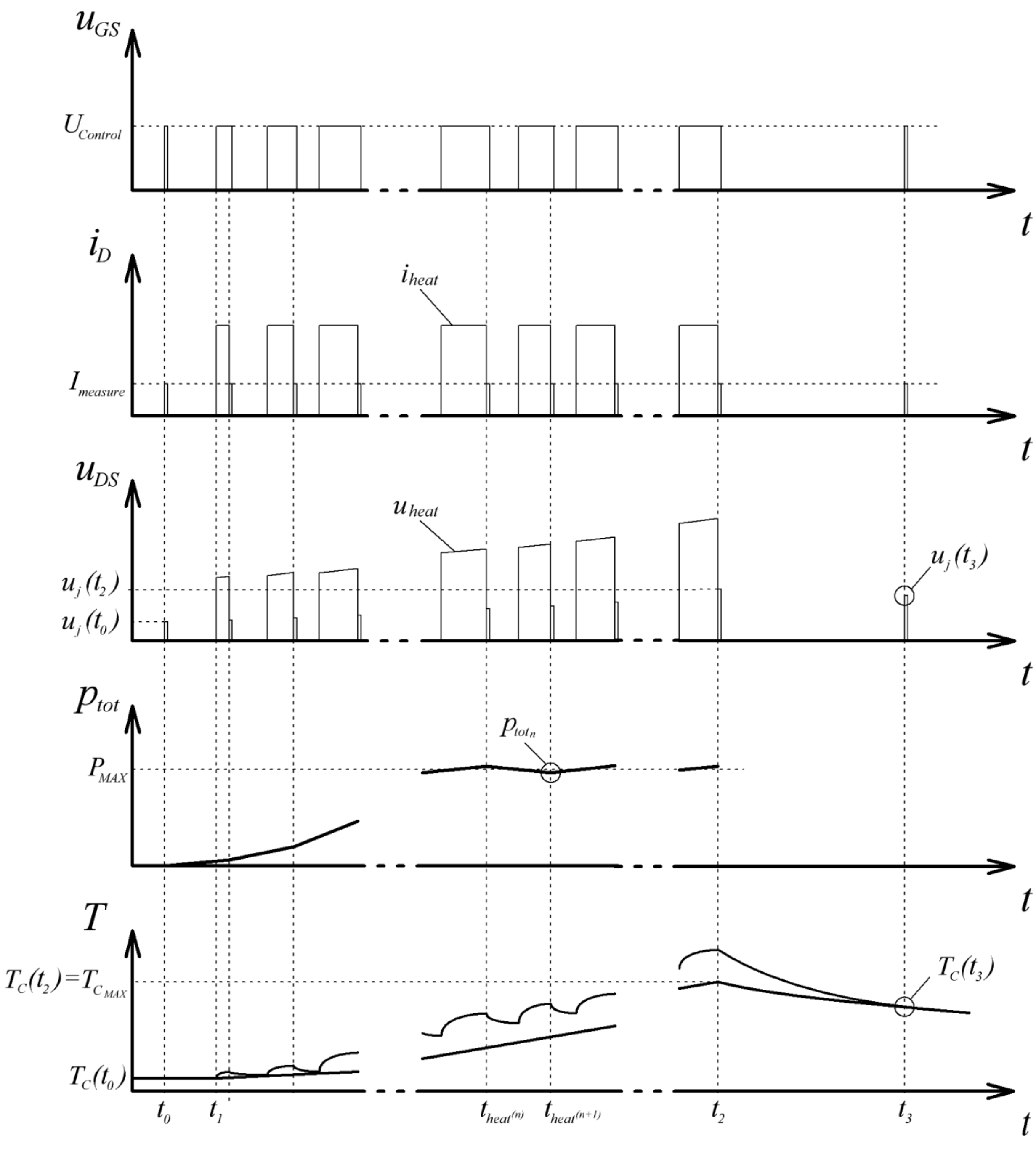

Figure 1. Time diagrams of test cycle.

Let's consider all the stages of the test cycle in more detail.

1. Heating stage.

1.1. At this stage, a measuring current pulse is passed preliminary through a selected channel of the test device in the open state. At that at the end of the transient processes, the values of the temperature-sensitive parameter $u_j(t_0)$ and the housing temperature $T_C(t_0)$ at the selected point of the device body are measured and stored at the time t_0. The duration and the amplitude of the current pulse are selected in such a way that its flow does not affect the thermodynamic equilibrium of the device. In order to measure the temperature of the body T_C a point is selected located under the center of the semiconductor crystal or in the center of the case base.

1.2. From the time t_1 until the moment of time t_2 the device is heated by passing the current of arbitrary shape through it, preferably rectangular one, $i_{heat}(t)$ in the open state. In time intervals $t_{heat^{(n)}} — t_{heat^{(n+1)}}$ the values of the heating current $i_{heat}\left(t_{heat_i^{(n)}}\right)$ and the device voltage drop caused by it $u_{heat}\left(t_{heat_i^{(n)}}\right)$ are periodically measured and stored and the average power $P_{tot\,n}$ is calculated, allocated by the device in the time interval $t_{heat^{(n)}} — t_{heat^{(n+1)}}$ as (Osman, 2016):

$$P_{tot\,n} = \frac{E_n}{t_{heat^{(n+1)}} - t_{heat^{(n)}}}, \tag{5}$$

where E_n is the energy of electrical losses in a semiconductor device within the time interval $t_{heat^{(n)}} — t_{heat^{(n+1)}}$ with the flow of heating current, defined as follows:

$$E_n = \sum_{i=1}^{m_n} \frac{u_{heat}\left(t_{heat_i^{(n)}}\right)\cdot i_{heat}\left(t_{heat_i^{(n)}}\right) + u_{heat}\left(t_{heat_{i+1}^{(n)}}\right)\cdot i_{heat}\left(t_{heat_{i+1}^{(n)}}\right)}{2} \cdot \left(t_{heat_{i+1}^{(n)}} - t_{heat_i^{(n)}}\right), \tag{6}$$

where m_n — the number of measurements in the time interval $t_{heat^{(n)}} — t_{heat^{(n+1)}}$, at that $t_{heat^{(n)}} = t_{heat_1^{(n)}}$, a $t_{heat^{(n+1)}} = t_{heat_{m_n}^{(n)}}$.

The amplitude and the hape of the heating current i_{heat} is determined based on the condition that the power dissipation in the crystal of the semiconductor device should not exceed the maximum average power of losses P_{MAX}, and the temperature of the housing base T_C satisfies the condition of transition temperature limitation $T_j < T_{j\,MAX}$, where $T_{j\,MAX}$ — is the maximum permissible transition temperature that does not exceed the limiting temperature with the margin of 20-30 ° C. The maximum average loss power is defined as follows:

$$P_{MAX} = \frac{k \cdot T_j - T_C}{R_{thjc(datasheet)}}, \tag{7}$$

where k is the safety factor of the crystal temperature, chosen from the condition $k < 1$; $R_{thjc(datasheet)}$ — the assumed or known thermal resistance value from the specification.

From the moment of time t_1 until the moment of time t_2 the calculated average power $P_{tot\,n}$, emitted by the instrument in the time interval $t_{heat^{(n)}} — t_{heat^{(n+1)}}$, is compared with the preset maximum allowable power for the device with the dissipated power P_{MAX} and when the value $P_{tot\,n}$ is less, equal or more than P_{MAX}, the average value of the heating current remains unchanged or decreases, respectively. The heating current is cut off at the time t_2 when the temperature of the semiconductor device body reaches 80-90 °C, after which the measuring current is passed through the device and the value of the temperature-sensitive parameter $u_j(t_2)$ is measured and recorded.

1.2 Cooling stage

In the natural cooling mode, the temperature of the semiconductor device decreases exponentially. Because of the difference in the heat capacities of the crystal and the device body, their cooling occurs with different thermal constants. The heat capacity of a semiconductor crystal is much less than the heat capacity of the body and at the time $t_3 >> t_2 + 3\tau$, where τ is the thermal constant of the semiconductor crystal of the device and thermodynamic equilibrium is reached. When this state is reached, the temperature of the semiconductor crystal becomes equal to the temperature of the housing, and cooling takes place with the same thermal constant. The pulse of the measuring current is passed through the device and the values of the temperature-sensitive parameter $u_j(t_3)$ are measured and stored when the measuring current and the temperature of the device body $T_C(t_3)$ take place, after which the thermal resistance of the transition-housing R_{thjc} is calculated as follows:

$$R_{thjc} = \frac{\dfrac{\ln(u_j(t_2)) - \ln(u_j(t_0))}{\mathrm{TK}\ \ln(u_j)} + T_C(t_0) - T_{C\,MAX}}{P_{tot_{YCT}}}, \tag{8}$$

where $u_j(t_2)$ is the value of the thermosensitive parameter of the semiconductor device at the time of heating current flow stop; $u_j(t_0)$ — the value of the thermosensitive parameter of a semiconductor device in its initial thermodynamic equilibrium; $T_{C\,MAX}$ — the value of the semiconductor device body temperature at the moment of heating current flow stopping; $T_C(t_0)$ — the value of the semiconductor device body temperature in its initial thermodynamic equilibrium; $P_{tot_{YCT}}$ — the average value of the loss power in the steady-state thermal mode during the heating process.

$\mathrm{TK}\ \ln(u_j)$ is calculated by the formula:

$$\mathrm{TK}\ \ln(u_j) = \frac{\ln(u_j(t_3)) - \ln(u_j(t_0))}{T_C(t_3) - T_C(t_0)}, \tag{9}$$

where $u_j(t_3)$ is the value of the semiconductor device thermosensitive parameter in the state of thermodynamic equilibrium within the cooling regime; $T_C(t_3)$ — the temperature of semiconductor device case in the state of thermodynamic equilibrium within the cooling mode.

The described method is implemented in the hardware-software complex ADIP-MDPT, intended for the diagnosis of power MIS-transistors. The system allows to determine the drain and gate current-voltage characteristics of transistors, the thermal resistance of the junction-case, to select the transistors with the required parameters, and also helps to develop the group connections of semiconductor devices (Bespalov, et al. 2015).

For the selection of transistors with the required characteristics in the control program, it is possible to sort the group of transistors according to the following parameters: open channel resistance $r_{DS(on)}$, transition-to-case thermal resistance R_{thjc} and the maximum direct current $I_{D\max}$. The number and order of parameter use during sorting is determined by the user. The information about the parameters is visualized by the means of histograms.

Experimental data.

Figure 2 shows the histograms of parameter values distribution from 36 IRF840 transistors of the same batch. For $r_{DS(on)}$ and R_{thjc} the minimum values were 0,715 Ohm and 0,833 W/°C, the maximum values were 0,750 Ohm и 0,95 W/°C, respectively. All transistors comply with the declared characteristics.

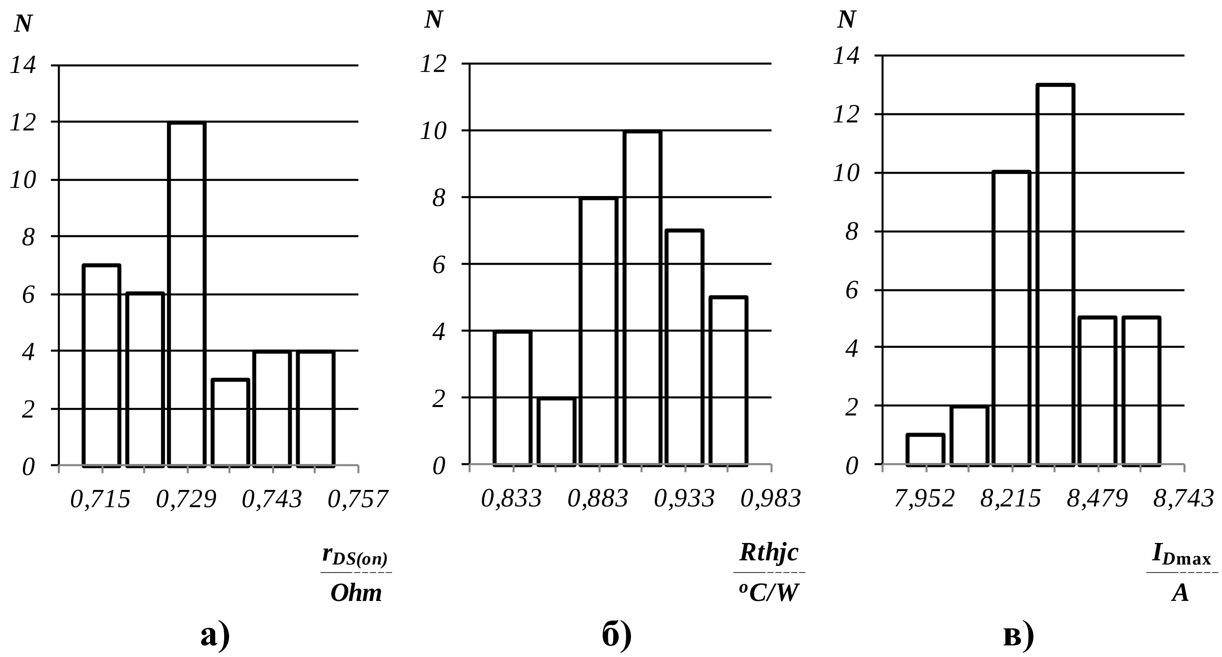

Figure 2. Parameter value distribution histograms from the transistors of the same batch:
а) channel resistance in the open state $r_{DS(on)}$;
б) thermal resistance of the transition-body R_{thjc};
в) the direct current maximum $I_{D\max}$.

The development of any product of power electronics includes the stage of thermal operation calculation of each semiconductor device that makes the part of it. For this calculation, the averaged or maximum values of the electric- and thermophysical parameters from the specification are used. The lack of information on the real values of the parameters will inevitably lead to the presence of potentially unreliable devices in the product, since their real crystal temperature will exceed the calculated one. Most often, a similar situation occurs in group compounds, when the devices with different combinations of electrical and thermal parameter values are applied for a group development (Bespalov, et al. 2015; Bespalov, et al. 2017; Muyambiri and Chabaefe, 2018; Videla, 2018).

Summary.

When transducers are designed based on MIS transistors, in view of the practical lack of objective information about the parameters and the characteristics of devices, such technical solutions are created that initially lead to their use efficiency decrease.

The obtaining of expanded information about the parameters and the characteristics of MIS-transistors at all stages of device life cycle will improve their quality and application efficiency significantly. Besides, the conduct of a continuous monitoring of the electric-thermal parameters of MIS transistors and the identification of potentially unreliable devices will allow to reduce the intensity of their failures in converters significantly.

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