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The temperature dependence of subthreshold characteristics of Si and SiC power MOSFETs

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1. Introduction

Influence of the temperature on subthreshold characteristics of low-power MOSFETs (especially in integrated circuits) is an important factor in many applications. The design of extremely low power CMOS logic circuits, temperature sensors and subthreshold voltage reference subcircuits may serve as examples [1] – [5].

Relatively little attention is paid to the influence of the temperature on the subthreshold operation of power MOSFETs. Such devices find many important applications in modern power converters. Apart from conventional Si power MOSFETs, several types of SiC MOSFETs are commercially available at present, and their parameters are promising, although there exist some limitations connected with a relatively high density of dislocations and traps in SiO_2-SiC interface. MOS power transistors, in some specific conditions may operate in the subthreshold region with the gate to source voltage v_{GS} below and near the threshold voltage ($v_{GS}<V_{th}$ and $|v_{GS} - V_{th}|$ relatively low). The example of a such operation is switching the transistor between ON and OFF states with the need to minimize the swing of gate voltage. In such a case, the OFF state of a transistor may correspond to the subthreshold operation. Another example is the use of v_{GS} voltage corresponding to the sufficiently low drain current i_D, as a temperature-sensitive parameter in measurements of a device thermal resistance or an impedance. In such applications, the effect of the temperature on the subthreshold current-voltage characteristics may be essential.

The main purpose of this paper is to investigate experimentally the current-voltage characteristics of Si and SiC power transistors in the vicinity of the threshold for a wide temperature range, in particular the influence of the temperature on parameters responsible for the shape of these characteristics. Several types of Si or SiC power MOSFETs with a current rating from 4A to over 300 A have been selected and their current-voltage characteristics for the low current range at ambient temperature values from 20°C up to over 140°C have been measured. Values of the subthreshold swing coefficient ("nonideality factor") have been extracted from measurements.

In Sec. 2 some general remarks concerning subthreshold operation and interpretation of subthreshold swing coefficient of current-voltage characteristics in this region are presented. The exemplary results of current-voltage characteristics in subthreshold region for various temperatures and calculations of related parameters are shown in Sec. 3. The discussion of obtained results and some conclusions are given in Sec. 4.

2. Subthreshold operation of MOSFETs

It is usually assumed, that for values of the gate-to-source voltage near to the threshold, the drain current i_D consists of two terms: the main drift term, described usually by the quadratic current-voltage dependence, and the diffusion term observed mainly below the threshold.

$$i_D = i_{drift} + i_{diff} \tag{1}$$

The diffusion current is usually described by the formula [1] – [7]:

$$i_{diff} = I_s \cdot \exp\frac{v_{GS} - V_{th}}{n \cdot V_T}\left[1 - \exp\left(-\frac{v_{DS}}{m \cdot V_T}\right)\right] \tag{2}$$

where: V_{th} is the threshold voltage, v_{GS}, v_{DS} – gate-to-source and drain-to-source voltages, I_s and V_T are temperature-dependent coefficients ($V_T = kT/q$, T - absolute temperature, k – Boltzmann constant, q – elementary electric charge).

The second term in square brackets may be neglected for $v_{DS} > 4V_T$. The diffusion current i_{diff} described by the above equation is a dominant term of the drain current for voltages equal approximately or lower than the threshold voltage [5] – [7]. The Eqn. (2) with the second form in bracket neglected is similar to the current-voltage dependence of a p-n junction, where a diffusion current is a dominant term. The nonideality factor value $n > 1$ in p-n junction characteristics in a low current range is attributed to generation-recombination processes in a junction depletion layer.

The interpretation of n coefficient in the first exponent of subthreshold characteristics of MOS transistor is not uniform. According to References [1], [2], [5], [7], [8], this quantity (named a subthreshold swing coefficient or a body effect coefficient) is connected to the influence of the substrate polarization on i_D-v_{GS} characteristics and is indirectly determined by the device geometry:

$$n = 1 + \frac{C_{dm}}{C_{ox}} = 1 + 3 \cdot \frac{t_{ox}}{W_{dm}} \tag{3}$$

where: C_{dm} and C_{ox} are capacitances of a depletion layer and an oxide respectively; W_{dm} and t_{ox} – depletion layer and oxide thickness.

According to many sources, for example [9] – [12] the shape of i_D-v_{GS} characteristics in the subthreshold region is strongly influenced by phenomena of trapping and detrapping of electrons, due to interface states in a semiconductor-dielectric structure such as Si-SiO$_2$ or SiC-SiO$_2$.

In particular, in [9] the formula for the subthreshold swing coefficient is presented in the form:

$$n = 1 + \frac{C_{dm} + C_{it}}{C_{ox}} \tag{4}$$

This formula is similar to (3), but the presence of the interface trap capacitance C_{it} in the numerator shows the strong influence of the trap density on the shape of i_D-v_{GS} characteristics in the subthreshold region, not predicted by Eqn. (3). According to references [9] – [12], by extraction of the coefficient n from measured device characteristics in the subthreshold, one is able to evaluate the interface trap density.

It is generally recognized, that SiC MOSFETs have very large interface trap densities which degrade a device performance, especially the carrier mobility in normal operation regions. According to formula (4), one may expect greater values of the subthreshold swing for SiC MOSFETs than for Si devices.

In some papers, for example [7], [8], the subthreshold slope S_t is used to describe the i_D-v_{GS} dependence, where i_D is a drain current in this region of operation:

$$S_t = \left(\frac{d(\log i_D)}{dv_{GS}} \right)^{-1} \tag{5}$$

Assuming description (2) for a drain current in the subthreshold, one obtains:

$$S_t = 2.3 \cdot \frac{n \cdot kT}{q} \tag{6}$$

therefore a coefficient n may be calculated from the slope of i_{diff}–v_{GS} dependence.

3. Measurement and calculation results

Several types of commercially available power MOSFET transistors made of Si or SiC have been selected and their DC characteristics measured in a wide temperature range (from the room temperature to over 140°C) and a wide current range including a subthreshold region. Drain-to source voltage is constant, $V_{DS} = 5\text{V}$. For such a value, the influence of a drain voltage on the diffusion term of a drain current is negligible. For the extraction of a diffusion current (expected to be the main term of a drain current in the subthreshold region) the difference current i_{EX} is calculated:

$$i_{EX} = i_D - A \cdot \left(v_{GS} - V_{th}\right)^2 \tag{7}$$

where the second term, being the ideal description of a drift current is easily identified from the graph of $i_D^{1/2}$ vs a gate voltage for medium currents. According to Eqn. (1), current i_{EX} should be equal to the diffusion current i_{diff}.

Dependencies of a current i_{EX} on a gate-to-source voltage presented in Figs. 1 and 2 are selected as typical for Si and SiC devices respectively. In the exemplary (but typical) characteristics of silicon MOSFETs (with a maximum permissible drain current 21 A), three regions may be observed. In the region of very low currents (visible only for the temperature 144°C, below 0.1 mA in Fig. 1), a current of a reverse biased p-n junction between the drain and substrate layers is a dominant term of i_{EX}. In the region of relatively high currents (above 20 mA in the exemplary plot in Fig. 1) the involved combination of drift and diffusion conduction results in changing the slope of *log*(i_{EX}) versus v_{GS} dependence. In the central part of plots in Fig. 1 (for currents below 20 mA), the shape of presented curves corresponds to the dependence predicted by Eqn. (2) and the dependence of *log*(i_{EX}) on a gate voltage is a straight line.

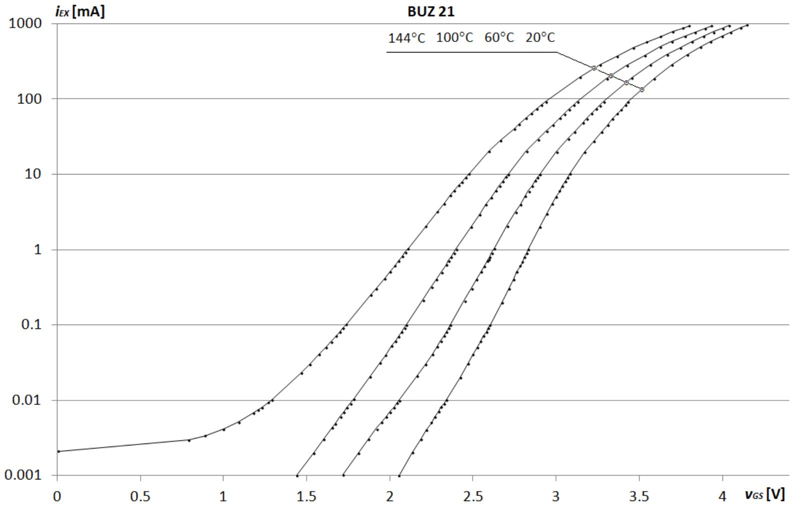

Fig. 1. The exemplary dependencies of a current i_{EX} on a gate-to-source voltage for a silicon MOSFET in the subthreshold region.

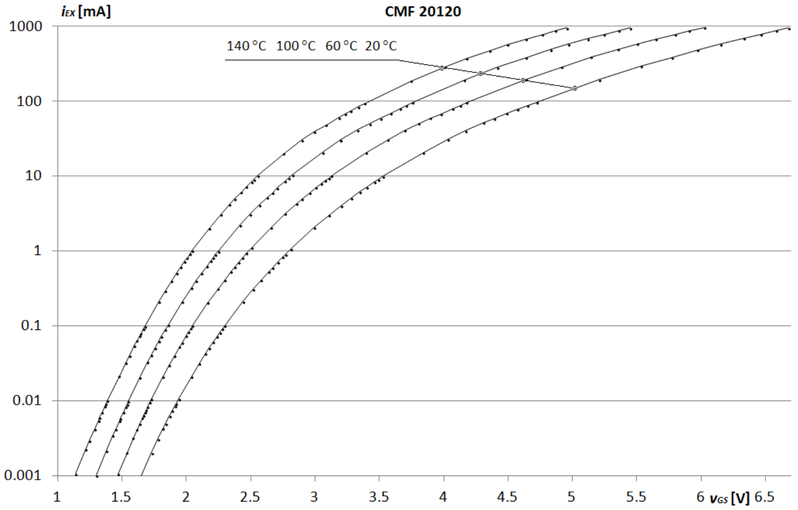

Fig. 2. The exemplary dependencies of a current i_{EX} on a gate-to-source voltage for a silicon carbide MOSFET in the subthreshold region.

Characteristics of SiC devices under investigations (see representative example in Fig. 2 for a device with a maximum drain current 33 A) are a little different. In the observed range of currents and temperatures, the term corresponding to the reverse conduction of a p-n drain-to-substrate junction is not visible. It is obviously a result of a high value of the bandgap of SiC. The region of characteristics corresponding to the description given by Eqn. (2) is relatively narrow, below 10 µA in the presented example. For a very wide range of a currents (10µA to 1A) the shape of current-voltage dependence differs from the prediction of Eqn. (2), therefore the conduction mechanism cannot be explained as a pure diffusion nor pure drift with a constant mobility.

Values of the subthreshold slope S_t calculated according to Eqns. (2) and (5) and the subthreshold swing coefficient n obtained from equation (6), corresponding to temperature values used in measurements are given in Tables I and II.

Table I. Subthreshold slope and subthreshold swing coefficient extracted from measurements of the exemplary Si power transistor.

T [K]	293	333	373	417
S_t [mV]	223	252	300	350
n	3.81	3.82	4.06	4.24

Table II. Subthreshold slope and subthreshold swing coefficient extracted from measurements of the exemplary SiC power transistor.

T [K]	293	333	373	413
S_t [mV]	260	235	262	250
n	4.48	3.56	3.55	3.06

For silicon MOSFETs under investigations, the dependence of the subthreshold slope S_t on the absolute temperature is nearly linear in accordance with Eqn. (6), therefore values of the subthreshold swing n for various temperature values are similar. For SiC devices the values of the subthreshold slope S_t seem to be independent of the temperature and consequently, subthreshold swing values calculated for various temperatures are different. As a consequence, Eqn. (6) is probably not a proper description of S_t for SiC devices.

4. Summary and conclusions

Dependencies of a drain current on a gate-to-source voltage in the a low current region for commercially available Si and SiC MOSFETs have been measured in temperature range from 20°C to nearly 150°C. Over 20 devices of several types, with maximum current ratings from 4A to over 300A have been investigated. The range of measured drain currents included very small values, down to 1µA. In this region the subthreshold operation takes place and a carrier diffusion is believed to be the dominant mechanism of conduction.

Typical results of measurements are presented in Figs. 1 and 2 for Si and SiC respectively. Substantial differences in the shape of measured i_D-v_{GS} characteristics between Si and SiC transistors are observed. Values of the subthreshold slope S_t obtained from measurements for Si devices are nearly proportional to absolute temperature, in accordance with Eqn.(6). For SiC devices, values of S_t obtained for various temperatures are nearly the same. Values of the subthreshold swing coefficient n extracted from the measured characteristics are surprisingly high – between 3.0 and 4.5 for Si and SiC devices.

5. References

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Abstract

In the paper, subthreshold characteristics of Si and SiC MOSFET power transistors in a wide range of current and temperature are considered. Representative examples of measured i_D-v_{GS} dependencies for temperatures from 20°C up to over 140°C are presented and discussed. Substantial differences of the shapes obtained for Si and SiC devices are observed. The subthreshold slope and subthreshold swing coefficient are extracted from measured curves for two types of devices and compared.

Streszczenie

W niniejszym artykule porównano charakterystyki w obszarze podprogowym tranzystorów mocy MOSFET z krzemu i węglika krzemu w szerokim zakresie prądu i temperatury. Dla reprezentatywnej partii tranzystorów przedstawiono i omówiono pomiary zależności i_D-v_{GS} w szerokim zakresie temperatur od 20°C do ponad 140°C. Dodatkowo zaprezentowano różnice w wartości nachylenia oraz wahania współczynnika w obszarze podprogowym od temperatury otoczenia dla badanych tranzystorów z Si i SiC.

Słowa kluczowe: MOSFET, tranzystor mocy, obszar podprogowy, zależność od temperatury