UDK621.3:(53+54+621+66), ISSN0352-9045

Informacije MIDEM 37(2007)1, Ljubljana

ON-RESISTANCE OF POWER MOSFETS

Janusz Zarębski

Gdynia Maritime University, Department of Marine Electronics

Key words: MOSFET, silicon carbide parameters, R_{ON} resistance.

Abstract: The paper concerns the problem of modelling of the drain-to-source ON-Resistance (R_{ON}) of power MOSFETs. Two kinds of the transistor structures: VDMOS and CoolMOS made of a silicon and a silicon-carbide are considered in the paper.

Upornost močnostnih MOSFET tranzistorjev v prevodnem stanju

Kjučne besede: MOSFET, parametri silicijevega karbida, upornost R_{ON}

Izvleček: V prispevku prikažemo probleme modeliranja upornosti izvor – ponor, R_{ON}, močnostnih MOSFET tranzistorjev v prevodnem stanju. Opišemo dve tranzistorski strukturi: VDMOS in CoolMOS izvedeni v siliciju, oz. silicijevem karbidu.

1. Introduction

Currently, silicon power MOSFETs are one of the most intensive developed and modified devices intended mainly for power converters.

The substantial drawback of the considered class of power devices is their relatively high value of the drain-to-source ON-Resistance (R_{ON}), what often results in unacceptable values of the energy losses at the high values of the drain current. The value of R_{ON} depends on both the values of the device breakdown voltage and the semiconductor parameters. The decreasing of R_{ON}, especially in the high-voltage power MOSFETs, is the very important challenge for the producers of these devices. This task can be reached by developing new structures (e.g. CoolMOS transistors), as well as by using advanced (wide band-gap) semiconductor materials, e.g. silicon-carbide (SiC).

The paper presents the estimation of influence of the impurity doping of the epitaxial-layer of the selected power MOS transistors (VDMOS, CoolMOS) on their drain-to-source ON-Resistance. The considerations are performed for two semiconductors: silicon and the most popular polytypes of silicon carbide.

2. The theoretical dependences

Power silicon MOSFETs (Fig. 1) are commonly used in electronics and energoelectronics in the voltage range from about fifteen up to one thousand volts. The main component of the switch-ON resistance (R_{ON}) of high-voltage VDMOSTs is the resistance represented by the epitaxial layer. The fundamental relation of R_{ON} on the breakdown voltage (U_{BR}) is /1/.

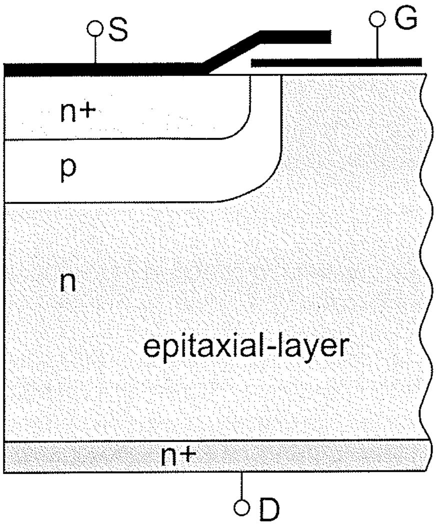

Fig. 1. *The considered structure of the VDMOS transistor*

$$R_{ON} = \frac{4 \cdot U_{BR}^2}{\varepsilon_0 \cdot \varepsilon_r \cdot \mu \cdot E_c^3} \qquad (1)$$

Where: μ - electron mobility, ĺ$_0$ - the permittivity of free space, ĺ$_r$ - relative permittivity, E_C - critical electric field are a semiconductor parameters.

It is seen, that R_{ON} increases strongly with increasing of U_{BR} (to the second power) whereas it decreases for semiconductors characterized by higher values of μ and E_C (third power).

On the other hand, at a fixed value of the epitaxial-layer thickness, the higher voltage VDMOS transistor have to be lightly doped (it concerns the epitaxial layer) according to the dependence /1/.

$$U_{BR} = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot E_c^2}{2 \cdot q \cdot N} \qquad (2)$$

where N - doping concentration, q - elementary (electron) charge. In turn, lower doping concentration results in higher value of R_{ON}.

The new generation of power MOSFETs - named CoolMOS transistors (Fig. 2) described for the first time in /2, 3/, have been offered by Infineon Technologies since 1998.

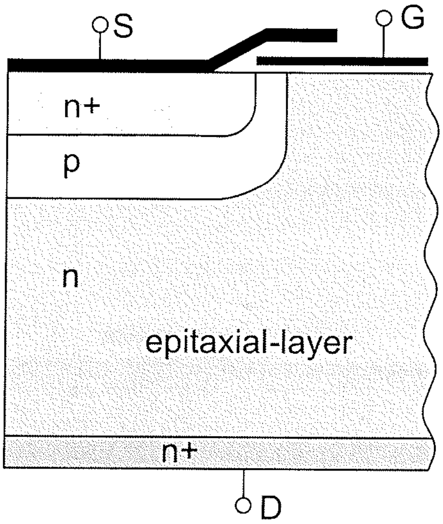

Fig. 2 The considered structure of the CoolMOS transistor

CoolMOS transistors (Fig. 2) belong to the class of superjunction devices presented in /4/. In CoolMOS transistors the epitaxial layer consists of parallely connected heavily doped n and p pillars of the width equal to d. At the drain-to-source voltage, typically higher than 30 ÷ 50 volts, the pillars become fully depleted by lateral extension of the depletion region from the p-pillar/n-pillar junction. On the other hand, the pillar-doping concentration depends on the pillar width. The thinner epitaxial-layer, the higher doped one.

The resistance R_{ON} and the breakdown voltage U_{BR} of the CoolMOS transistor are related by the following dependence /4/.

$$R_{ON} = 4 \cdot d \cdot \frac{U_{BR}}{\varepsilon_0 \cdot \varepsilon_r \cdot \mu \cdot E_c^2} \qquad (3)$$

As seen, R_{ON} resistance is proportional to U_{BR}, what means that CoolMOS transistors are especially attractive for high-voltage applications. On the other hand, narrower pillars, the lower R_{ON}, what have to result in the heavily dopped ones.

3. The semiconductors parameters

As seen from Eqs. 1 and 3, two semiconductor parameters: charge mobility and critical electric field are of the fundamental importance to determine the R_{ON}- resistance. In Table 1 the values of these parameters for silicon (Si) and three of the most popular polytypes of silicon carbide: 4HSiC, 6H-SiC and 3C-SiC are presented.

Parametr	Si	3C-SiC	4H-SiC	6H-SiC
$\mu \left[\frac{cm^2}{V \cdot s}\right]$	1400	900	700	400
$E_c \left[\frac{V}{cm}\right]$	3.10^5	$1,5.10^6$	$2.6.10^6$	$2,1.10^6$
ε_r	11,9	9,7	9,6	10

The values in Table 1 concern lightly doped semiconductors. As results from a lot of publications, assuming the fixed values of the considered parameters is a great simplification, because their values are a function of temperature, doping concentration, pressure, etc. Fig. 3 presents the dependences of μ(N) and E_C(N) for the silicon and silicon carbide, respectively.

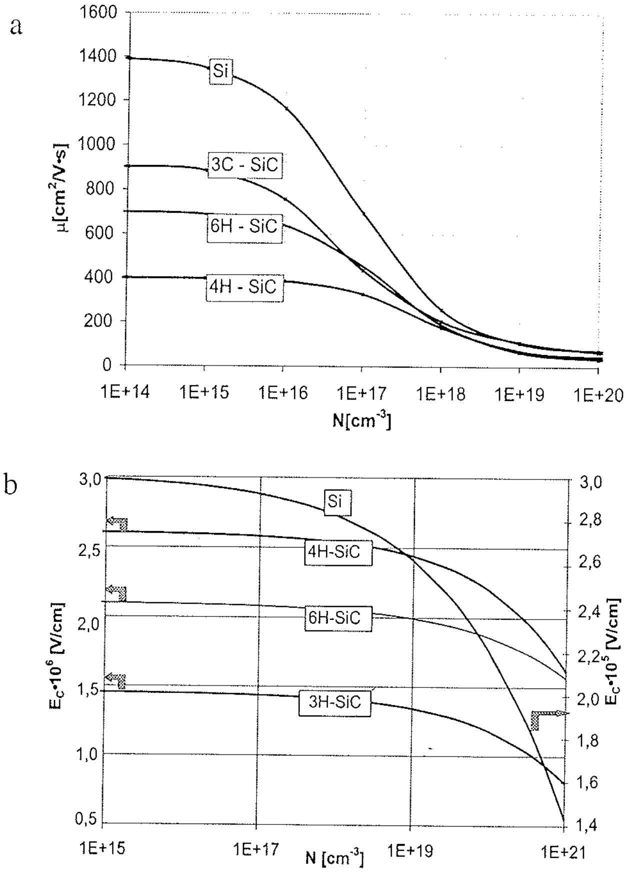

Fig. 3. Dependencies μ(N) and EC(N)

As seen from Fig. 3 the value of the electron mobility is nearly the proper low-doped value for the doping concentration less than any critical value N_{Cr}, which for silicon (N_{CrSi}) is equal to 10^{14} cm^{-3}, whereas for silicon-carbide is much higher, e.g. for 4H-SiC we have $N_{Cr4HSiC}$ = 10^{16} cm^{-3}. The analogical observation (Fig. 3b) concerns the critical field, for which N_{CrSi} = 10^{15} cm^{-3} and $N_{Cr6HSiC}$ H" 10^{18} cm^{-3}, respectively.

4. Results

On the parameter values from Table 1, the dependences of $U_{BR}(N)$ for VDMOS transistors made of silicon (Si) and silicon-carbide (SiC) were calculated from Eq. 2 (Fig. 4). In turn, the dependence of $R_{ON}(U_{BR})$ for silicon and silicon-carbide VDMOS and CoolMOS transistors at three various values of the pillars width, corresponding to the same materials parameter values are presented in Fig. 5.

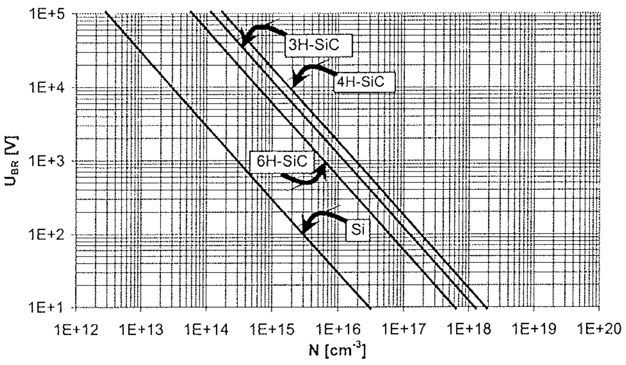

Fig. 4. Dependencies of UBR on N

It is seen from $U_{BR}(N)$ characteristics that for silicon transistors of the breakdown voltage higher than 20V, the doping concentration not exceed 10^{16} cm^{-3}, whereas the SiC transistors of the same U_{BR} value can be even one hundred times more heavy doped (N = 10^{18}).

The current technology allows to manufacture the silicon CoolMOS transistors of the pillar width equal to 5 μm. For examples, for the 1 kV CoolMOS transistor, assuming that $d/2 \sim 1/\sqrt{N}$ and d = 5 μm, the doping concentration can increase 10^5 times. Note, that the tenfold degreasing of the pillar with (d = 500 nm) results in the further hundredfold increasing of N doping until the value equal to 10^{21} cm^{-3} (for Si). As it is seen from Figs 4,5 the values of E_C and μ decrease considerably at the doping concentration N > N_{Cr}. So, this phenomenon should be taken into account, when the R_{ON} resulting from Eqs. (1,3) is calculated. For instance, in Fig 6 the dependence of $\Delta R_{ON}/R_{ON}$ as a function of U_{BR} of the form

$$\frac{\Delta R_{ON}}{R_{ON}} = \frac{\left[R_{ON}^{const.} - R_{ON}^{var}\right]}{R_{ON}^{const.}} \cdot 100\% = f\left(U_{BR}\right) \qquad (4)$$

for Si and SiC VDMOS transistors is presented. In this equation the resistances $R_{ON}^{const.}$ and R_{ON}^{var} are calculated with the use of the semiconductor parameters of the constant values (table I) and the values obtained from Fig. 3, respectively. To get the proper value of the doping concentration N corresponding to the selected value of the device breakdown voltage, the diagram shown in Fig.4 was used.

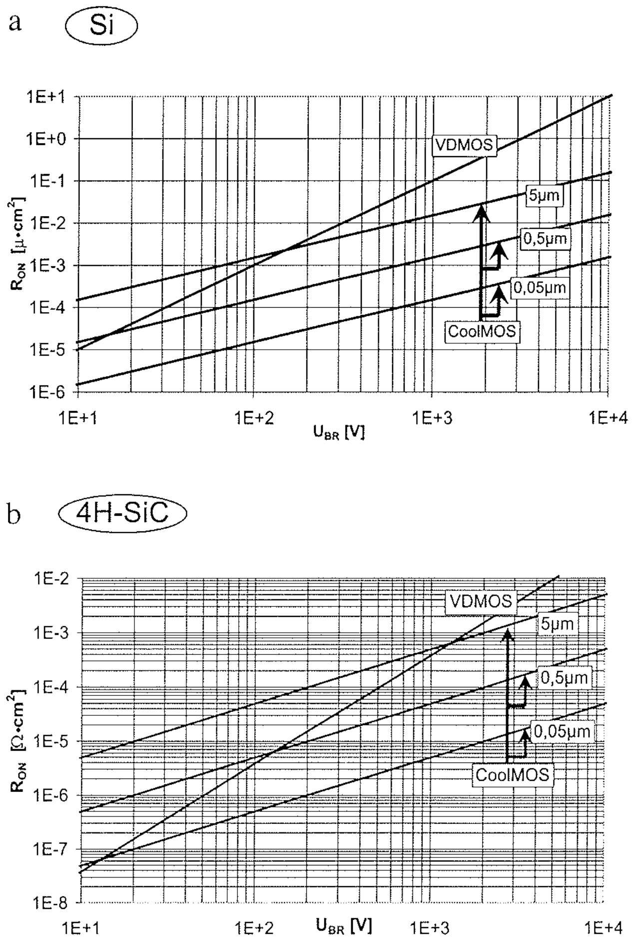

Fig. 5. Dependencies of RON on UBR

As seen, using the dependence $E_C(N)$ and μ(N) results in the higher values of the ON-resistance, what is of the great importance, especially for silicon-carbide devices.

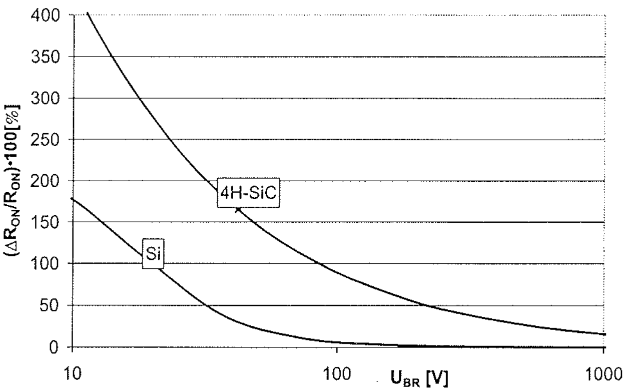

Fig. 6 Dependencies of ÄRON on UBR for VDMOS transistors

5. Conclusion

In the paper the problem of modelling of the drain-to-source ON-Resistance of silicon and silicon carbide power MOSFETs is discussed. Two kinds of transistors: VDMOS and CoolMOS, made of silicon and silicon carbide are considered. It was shown that ě(N) and $E_C(N)$ dependences should be taken into consideration while the R_{ON} resistance of the investigated power MOS transistors is calculated.

References

/1/ Baliga J.: "Power Semiconductor Device Figure of Merit for High-frequency Applications, IEEE Electr. Dev. Lett., Vol. 10, 1989, p. 455.

/2/ Lorenz L., Deboy G., Marz M., Stengel J., Backhofner A.: "Drastic Reduction ON-Resistance with CoolMOS", PCIM Europe ISSUE 5/1998, pp 250-258.

/3/ Deboy G., Marz M., Stengel J.P, Strack, Tihanyi J., Webber H.: "A New Generation of High Voltage MOSFETs Breaks the Limits of Silicon", IEDM Tech, Dig., p. 683.

/4/ Fujihira T.: „Theory of Semiconductor Super-junction Devices", Jpn, J. Appl. Phys., Vol. 36, pp. 6254-626

Prof. Janusz Zarębski
Gdynia Maritime University
Department of Marine Electronics
Morska 83, 81-225 Gdynia, POLAND,
Tel. ++48 58 6901599, fax ++48 58 6217353
E-mail: zarebski@am.gdynia.pl

Prispelo (Arrived): 10.08.2006 *Sprejeto (Accepted):* 30.03.2007