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Research Article

Effect of Temperature on Electrical Behavior of 4H-SiC and 6H-SiC Double-Gate (DG) MOSFETs in 130nm Technology

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Abstract

The effects of temperature on the electrical properties of double gate DG-MOSFETs transistors in 4H-SiC and 6H-SiC technologies have been investigated and compared with single gate SG-MOSFET transistor using 130nm technology and BSIM3v3 model. In which the equivalent electronic circuits have been used for the two models (Series and Parallel) of the DG-MOSFET transistor. The current-voltage-temperature (I-V-T), transconductance-temperature (gm-T) and On/Off current ratio-temperature (ION/IOFF-T) characteristics have shown that the DG-MOSFETs are strongly affected by the temperature variation, especially the SG-MOSFET and DG-MOSFETs in 6H-SiC, as well as the DG-MOSFET transistor (Parallel model) in different semiconductor technologies is very sensitive to temperature variation compared to other transistors. The results obtained allowed the ability to predict the thermal behaviour of these transistors, and how effective are these devices in the very high temperature applications in a range from -200°C to 650°C. In addition, these transistors operate under low voltage and low power.

Keywords: 4H-SiC, 6H-SiC, 130nm Technology, BSIM3v3, I-V-T, g_m-T, I_{ON}/I_{OFF}-T

1. Introduction

The different physical properties of semiconductors are related to temperature change in naturally. That's why all designs and feasibility studies of semiconductor devices have to take into account normal working temperature range [1]. Silicon carbide (SiC) a wide bandgap material, considered as one of the basic semiconductors for making the electronic devices that are working with high power, high frequency and high temperature [2] due to its better physical properties such as a high saturation velocity of electrons, a high breakdown field and a high thermal conductivity [3].

In submicron and nanoscale technologies, Double-Grille Metal-Oxide Semiconductor Field-Effect Transistors (DG-MOSFETs) appear to be attractive alternatives compared with the Single-Gate Transistors (SG-MOSFETs) as they can reduce the Short Channel Effect (SCE) on the electrical behavior of SG-MOSFET [4]. In addition, they make it possible to dimension future SG-MOSFET transistors down to few tens of nanometers in size [5].

In recent years, recent studies have shown that the SG-MOSFETs Transistors in silicon carbide submicron technology work well in low voltage, low power, high frequency and high temperature [6-7]. The DG-MOSFETs transistors in 4H-SiC and 6H-SiC 130 nm technology also proved high electrical performance by investigating of the different static characteristics at room temperature of these transistors [4]. However, the effect of temperature on the performance of these transistors has not been studied in this latest work.

In this paper, the influence of temperature on the electrical behavior of DG-MOSFETs transistors will be studied in 4H-SiC and 6H-SiC technologies with 130nm technology in order to operate at low-voltage, low-power and high temperature, based on the SG-MOSFET transistor by BSIM3v3 Model and using two equivalent electronic circuits of DG-MOSFET transistor Series (Model 1) and Parallel (Model 2) models. To perform this study, the current-voltage (*I-V*) characteristics will be simulated at 27 °C and 100 °C. As well as the study of the transconductance (g_m) and I_{ON}/I_{OFF} ratio in the temperature range -200°C to 650°C. Then a comparison will be made between the different SG-MOSFE and DG-MOSFETs transistors of 4H-SiC and 6H-SiC technologies in this temperature range. The PSpice software was used to simulate the effect of temperature on the different characteristics of these transistors.

2. DG-MOSFETs transistors models

Figure 1 shows the two equivalent electronic circuits models (series and parallel) of DG-MOSFET transistor based on the SG-MOSFET transistor [4]. As shown in Figures. 1(b) and 1(c), the two models of DG-MOSFETs transistors are based on the same SG-MOSFET transistor. The series model (Model 1) of a DG-MOSFET transistor is essentially a series arrangement of two separate SG-MOSFETs as shown in the Fig. 1(b). For the parallel model (Model 2) of DG-MOSFET transistor, two SG-MOSFETs transistors are connected in parallel as shown in the Fig. 1(c).

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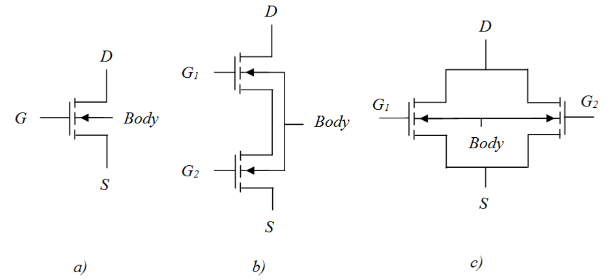


Fig. 1. a) SG-MOSFET transistor, equivalent electronic circuits of DG-MOSFET transistor: b) Series (Model 1), c) Parallel (Model 2).

The polarization symmetry ($V_{GS1} = V_{GS2}$) has been used to study the different characteristics of the DG-MOSFETs transistors. The relationships between the drain currents of DG-MOSFETs models and SG-MOSFET can be expressed as [4]:

$$I_{D(Model\ 1)} = \frac{1}{2} I_{D(SG-MOSFET)} \quad (1)$$

$$I_{D(Model\ 2)} = 2\, I_{D(SG-MOSFET)} \quad (2)$$

and

$$I_{D(Model\ 2)} = 4\, I_{D(Model\ 1)} \quad (3)$$

From the drain current expression of a SG-MOSFET transistor in saturation region and following a simplification, expression of transconductance can be written [6-8]:

$$g_{m(SG-MOSFET)}(T) = WC_{ox}v_{sat}(T) = \frac{1}{2}WC_{ox}E_{eff}\mu_{eff}(T) \quad (4)$$

From the expressions (1)-(2) and (4), the transconductance relations with temperature variation for these models can be expressed as:

$$g_{m(Model\ 1)}(T) = \frac{1}{2}WC_{ox}v_{sat}(T) = \frac{1}{4}WC_{ox}E_{eff}\mu_{eff}(T) = \frac{1}{2}\, g_{m(SG-MOSFET)}(T) \quad (5)$$

$$g_{m(Model\ 2)}(T) = 2\,WC_{ox}v_{sat}(T) = WC_{ox}E_{eff}\mu_{eff}(T) = 2\, g_{m(SG-MOSFET)}(T) \quad (6)$$

3. Results and discussion

3.1. Influence of temperature on output characteristic

Figures 2-a and 2-b show the evolution of drain current I_D as a function of the drain-source voltage V_{DS} of SG-MOSFET and DG-MOSFETs transistors in 4H-SiC and 6H-SiC technologies for two temperature values 27 °C and 100 °C with V_{GS}=1.2V. Naturally, all semiconductors physical parameters are related to temperature change. For the BSIM3v3 model, the velocity saturation and the mobility decreases with temperature [9], for this purpose the drain current of these transistors reduced when the temperature increases as shown in the figures 2-a and 2-b. The results obtained show that the DG-MOSFET transistor (Model 2) is characterized by a large decrease in saturation current in the temperature increase from 27 °C to 100 °C compared to the SG-MOSFET transistor, as well as the decrease in saturation current of the latter (SG-MOSFET) large compared to the DG-MOSFET transistor (Model 1) for the two technologies 4H-SiC and 6H-SiC.

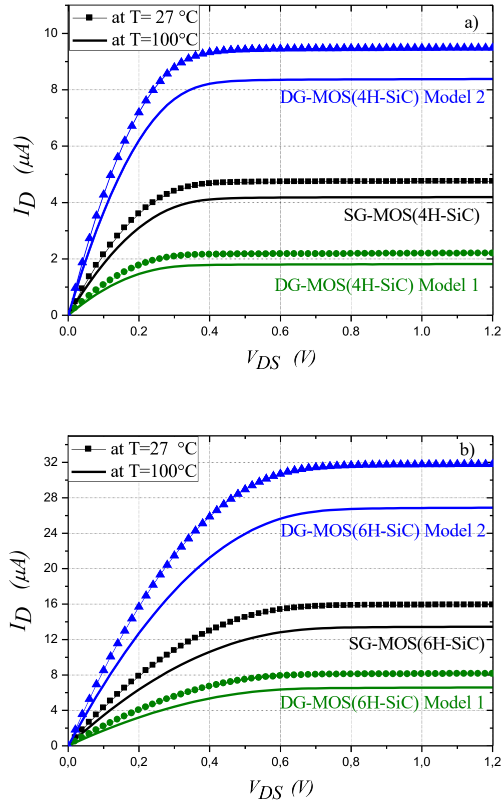


Fig. 2. I_D-V_{DS}-T characteristics of SG-MOSFET and DG-MOSFETs transistors in, (a) - 4H-SiC, (b) 6H-SiC technologies.

The output characteristics (Figure 2) are used to find the ratio between the difference in saturation current ΔI_{sat} and the difference in temperature ΔT.

$$S_{I_{sat}} = \left|\frac{\Delta I_{sat}}{\Delta T}\right| = \left|\frac{I_{sat}(T_2)-I_{sat}(T_1)}{T_2-T_1}\right| \quad (7)$$

Table 1 shows the saturation current sensitivity for the SG-MOSFET and DG-MOSFETs transistors in 4H-SiC and 6H-SiC technologies with V_{DS}=1.2V.

Table 1. Saturation current sensitivity for the SG-MOSFET and DG-MOSFETs transistors

Transistors / *Sensitivity*	*4H-SiC technology*			*6H-SiC technology*		
	SG-MOSFET	*DG-MOSFET (Model1)*	*DG-MOSFET (Model2)*	*SG-MOSFET*	*DG-MOSFET (Model1)*	*DG-MOSFET (Model2)*
$S_{I_{sat}} \left(\frac{10^{-2}\mu A}{°C}\right)$	0.753	0.507	1.521	3.42	2.11	6.71

The DG-MOSFET transistor (Model 2) is very sensitive to temperature variation compared to other transistors DG-MOSFET (Model 1) and SG-MOSFET for the different semiconductor technologies 4H-SiC and 6H-SiC as shown in the Table 1. This shows that the DG-MOSFET transistor (model 2) is highly influenced by the temperature variation. In addition, the various transistors in 6H-SiC technology are characterized by high saturation current sensitivity compared to the transistors in 4H-SiC technology. This could be attributed to the significant decrease in the drift mobility of 6H-SiC material with temperature compared to 4H-SiC [10]. These results show that the parallel DG-MOSFET transistor (Model 2) is very suitable for temperature sensors.

3.2. Influence of temperature on transfer characteristic

Figures 3-a and 3-b show the evolution of the transfer characteristics $I_D = f(V_{GS})$ of SG-MOSFET and DG-MOSFETs transistors in 4H-SiC and 6H-SiC technologies for two temperature values 27 °C and 100 °C with V_{DS}=1.2V.

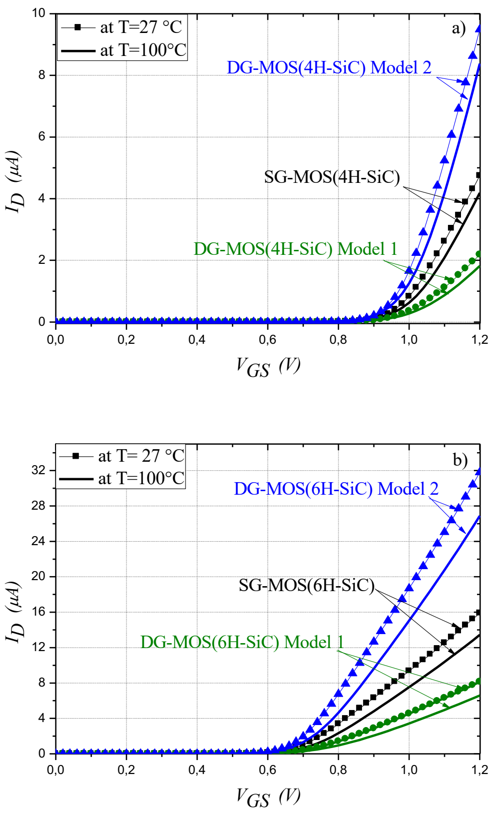


Fig 3. I_D-V_{GS}-T characteristics of SG-MOSFET and DG-MOSFETs transistors in, (a) - 4H-SiC, (b) 6H-SiC technologies.

The threshold voltage contributes to the electrical behavior of the transistors by its effect on the drain currents, the different characteristics and the sub-threshold operation of these transistors [4-11]. The threshold voltage decreases with the temperature variation of the SG-MOSFET and DG-MOSFETSs transistors in 4H-SiC and 6H-SiC technologies as shown in the I_D-V_{GS}-T characteristics. Thus, this decrease in the threshold voltage causes a change in the drain currents of these transistors. The results obtained show a very good agreement with the evolution of the threshold voltage as a function of temperature contained in the literature [11-12].

3.3. Influence of temperature on transconductance g_m

The transfer characteristic $I_D = f(V_{DG})$ is exploited to investigate the temperature effect on the transconductance g_m of a MOSFET transistor [6-8]. Figure 4 shows the transconductance evolution with temperature for SG-MOSFET and DG-MOSFETs transistors in 4H-SiC and 6H-SiC technologies. The temperature range -200 °C to 650 °C is chosen to make an objective study because the 4H-SiC and 6H-SiC materials are suitable for use in high-temperature applications [2-6-8-13].

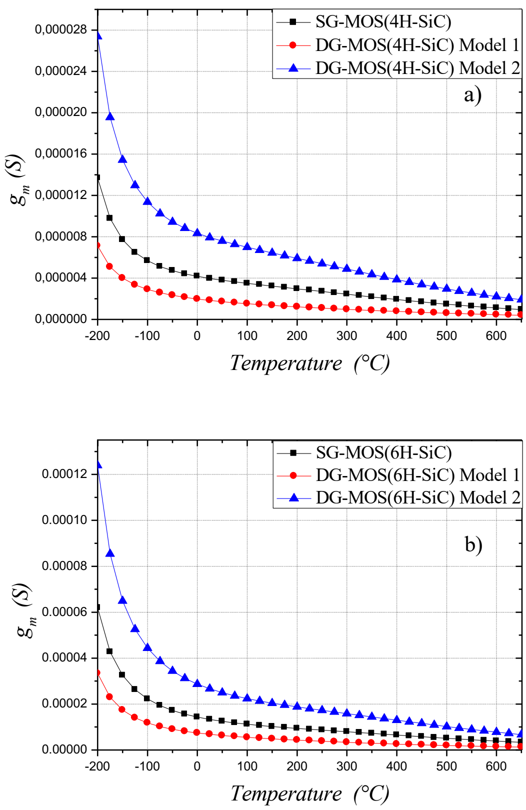


Fig. 4. g_m-T characteristics of SG-MOSFET and DG-MOSFETs transistors in, (a) - 4H-SiC, (b) 6H-SiC technologies.

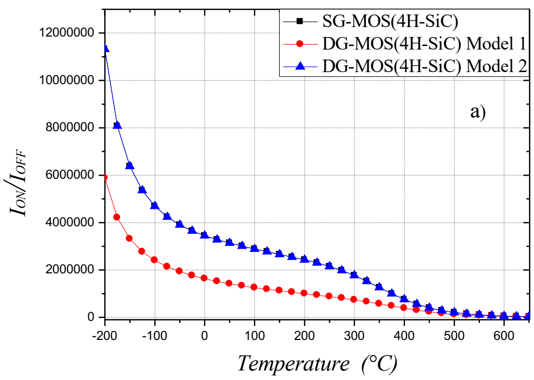
Expressions (4)-(5) and (6) show that transconductance g_m is related to carrier mobility and saturation velocity, the latter being electrical properties of 4H-SiC and 6H-SiC semiconductors which decrease with temperature variation [6-8-13] and so it follows that leads to a reduction in the transconductance whenever the temperature increases for the SG-MOSFET [6] and DG-MOSFETs transistors as shown in Figure. 4.

In the proposed temperature range, the parallel DG-MOSFET (Model 2) transistor is characterized by a transconductance 2 times and 4 times greater than that SG-MOSFET and series DG-MOSFET (Model 1) transistors respectively for 4H-SiC and 6H-SiC technologies as expected from expressions (4), (5) and (6).

From the figures 4(a) and 4(b), and when the temperature is less than room temperature, the g_m-T characteristic shows that the parallel DG-MOSFET (Model 2) transistor in 4H-SiC and 6H-SiC technologies is very sensitive to temperature compared with other models, and this is consistent with the results previously obtained (*I-V-T* characteristics).

3.4. Influence of temperature on I_{ON}/I_{OFF} ratio

The I_{ON}/I_{OFF} ratio is one of the most important parameters of the nanoscale transistors. The variations in transconductance by temperature indicate that the saturation current I_{ON} and leakage current I_{OFF} changes by temperature for the SG-MOSFET and DG-MOSFETs transistors. Therefore, it is necessary to investigate the influence of temperature variation on the I_{ON}/I_{OFF} ratio of these transistors. Figure 5 shows the I_{ON}/I_{OFF} ratio evolution with temperature for SG-MOSFET and DG-MOSFETs transistors in 4H-SiC and 6H-SiC technologies.



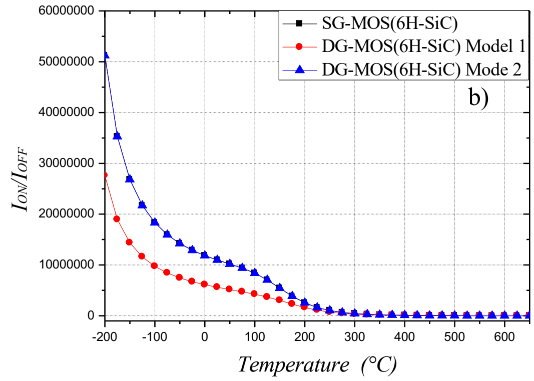


Fig- 5: I_{ON}/I_{OFF} ratio as a function of temperature of SG-MOSFET and DG-MOSFETs transistors in, (a) - 4H-SiC, (b) 6H-SiC technologies.

The results show that the I_{ON}/I_{OFF} ratios of the parallel DG-MOSFET (Model 2) and SG-MOSFET transistors are equal, and both are great compared to the series DG-MOSFET (Model 1) transistor in different semiconductor technologies (4H-SiC and 6H-SiC), and this ratio is also great for the different transistor models in 6H-SiC technology compared to the 4H-SiC technology at temperature range chosen as shown in the figures 5(a) and 5(b). In addition, when the temperature is less than 200°C, the I_{ON}/I_{OFF} ratio slope shows a rapid decrease with temperature variation for SG-MOSFET and DG-MOSFETs transistors in 4H-SiC and 6H-SiC technologies. This is not the case for T<200°C.

These results and behaviors show that the parallel and series DG-MOSFETs transistors in 4H-SiC and 6H-SiC technologies are very suitable for high temperature applications, this is consistent with the thermal properties of these materials, because they are very interesting materials in applications under high temperature [13-14].

4. Conclusion

In this paper, the impact of temperature variation on the electrical behavior of DG-MOSFETs transistors has been studied. In which the temperature dependent characteristics *I-V-T*, g_m-T and I_{ON}/I_{OFF}-T of these transistors have been investigated in detail in the temperature range from -200°C to 650°C. These transistors have been evaluated for 4H-SiC and 6H-SiC semiconductors and 130 nm technology using equivalent electronic circuits based on a BSIM3v3 model of the SG-MOSFET transistor. A quantitative comparison between series and parallel models of DG-MOSFET and SG-MOSFET has been presented. It has been found that the different electrical properties of these transistors are affected by temperature. The parallel model of the DG-MOSFET transistor in 4H-SiC and 6H-SiC technologies showed extreme temperature sensitivity; this advantage makes this transistor a suitable candidate for temperature sensors. A comparison with the 4H-SiC transistors has demonstrated superiority of the 6H-SiC transistors, this shows that 6H-SiC technology provides enhanced devices performance compared to 4HSiC technology for different transistors.

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