DC characteristics and parameters of silicon carbide high-voltage power BJTs

Joanna Patrzyk, Janusz Zarębski, Damian Bisewski

Gdynia Maritime University, Dept. of Marine Electronics, Morska 83, 81-225 Gdynia, Poland

E-mail: j.patrzyk@we.am.gdynia.pl

Abstract. The paper shows the static characteristics and operating parameters of the bipolar power transistors made of silicon carbide and for comparison their equivalents made of classical silicon technology. The characteristics and values of selected operating parameters with special emphasis on the effect of temperature and operating point of considered devices are discussed. Quantitative as well as qualitative differences between the characteristics of the transistor made of silicon and silicon carbide are indicated as well.

1. Introduction

High-voltage silicon bipolar power transistors (BJTs) have been known for decades and are still evolving. In the mid-nineties of the last century in the world's technological laboratories has begun intensive work on getting power BJT transistors made of silicon carbide (SiC) - a material which properties make many operating parameters and characteristics of SiC devices have features better than silicon counterparts of these devices.

Silicon carbide, compared with silicon, has about 2.5 times larger width of the band-gap, a much smaller value of the intrinsic carrier concentration at room temperature, more than three times larger thermal conductivity and the SiC junction has 10 times larger value of the critical electric field strength than silicon one. Favorable properties of silicon carbide make the SiC components, in comparison with the silicon devices, have better values of operating parameters, for example: greater voltage strength, better thermal properties and shorter switching times [1, 4].

In the literature, a lot of information about the characteristics and parameters of the silicon carbide power devices, which appeared previously on the market for example: Schottky diodes and transistors: MESFET, MOSFET and JFET can be found and are presented in [8, 9, 10, 11, 12].

In contrast, literature information relating to the characteristics and parameters of SiC power BJTs are rather poor. Static and dynamic characteristics of these devices are presented and discussed in [1-3], characteristics of SiC BJTs working at high temperatures are presented and discussed in [4] and selected operating parameters are considered in [5, 6, 7].

The market offers in terms of the considered class of semiconductor devices has been changing rapidly. The new generation of bipolar power transistors made in the technology based on silicon carbide appeared on the market in 2005 (TranSiC), whereas the company GeneSiC introduced a new technology of super junction bipolar transistors SJT made of silicon carbide, and the United Silicon Carbide company promises starting the production of SiC BJT transistors at the turn of the year 2016/2017.
Producers of semiconductor devices do not provide in the catalog data of considered class of SiC devices a lot of characteristics and parameters useful for engineers-designers of electronic circuits and systems.

It is worth to notice that the temperature dependences of certain characteristics and parameters differ not only quantitatively but also qualitatively from similar characteristics and parameters of the silicon power bipolar transistors.

In the paper the authors present the results of their own measurements of current-voltage characteristics and parameters of the BT1206AC SiC bipolar power transistor made by TranSiC. The influence of the ambient temperature, the collector current and the collector-emitter voltage on the leakage current, the saturation voltage and the current gain factor ($\beta$) is presented and discussed. In particular, the influence of the self-heating phenomenon on characteristics of the investigated transistors are considered. For comparison, the characteristics of the 2SC5294 Panasonic silicon transistor is presented as well.

2. Results of investigations
The research subject is power BJTs made of silicon and silicon carbide mounted in a standard TO-247 package. The values of the most important parameters of these transistors are shown in Table 1.

| Manufacturer | Type  | $V_{CEO}$ | $I_{Cmax}$ | $P_{max}$ | $T_{jmax}$ | $\beta$ |
|--------------|-------|-----------|------------|-----------|------------|---------|
| TranSiC      | SiC   | 1200 V    | 6 A        | -         | 175°C      | 35 (V$_{CE}$$=$2,5 V, I$_{C}$$=$4 A) |
| BT1206AC     |       |           | 120 W      | (T$_{c}$$=$25°C) | 150°C     | 12 (V$_{CE}$$=$5 V, I$_{C}$$=$10 A) |
| Panasonic    | Si    | 600 V     | 20 A       | 120 W     |            |         |
| 2SC5294      |       |           |            |           |            |         |

As seen from Table 1, the SiC BJT has a 2 times larger value of the permissible collector-emitter voltage $V_{CEO}$, as well as 25°C higher value of permissible junction temperature $T_{jmax}$, in comparison with the Si BJT. The current gain factor $\beta$ of the SiC BJT has 3 times higher value than the silicon transistor, however, it should be noted that this parameter is determined for different operating points of the considered transistors under. Unfortunately, the manufacturer of transistor made of silicon carbide, did not disclose the value of permissible power loss $P_{max}$ for the semiconductor device.

The following section presents author’s results of measurements of selected parameters and characteristics of both considered transistors obtained under isothermal conditions, it means, when the junction temperature $T_j$ of transistor approximately equals to the ambient temperature $T_a$, as well as under non-isothermal conditions in which the junction temperature of the semiconductor device may exceed, even significantly, the ambient temperature by self-heating phenomenon [13]. Isothermal measurements of the characteristics of the considered transistors were performed using a Keithley pulse measuring source type 2602, which minimized the influence of self-heating phenomenon on the measured characteristics of the transistor. In turn, the non-isothermal characteristics were made by "point by point" measurement for the transistors without heatsink in the thermal steady state conditions, which extended the measuring procedure, and a thermal steady state condition obtained even after 20 minutes. In addition, the temperature $T_C$ of the transistors cases was measured using a temperature meter TM-2000 equipped with a platinum probe Pt-100. This sensor was mounted on the transistors cases using a thermally conductive glue type AG Termoglue 10G. Figures 1-5 present the author’s results of measurements of the characteristics and parameters of considered transistors. The results of isothermal current-voltage $i(u)$ characteristics were compared with the catalog data.

Figure 1 presents the isothermal dependence of the current gain factor $\beta$ of the considered devices on the collector current at fixed value of the ambient temperature (Figure 1a) and on the ambient temperature at fixed value of the collector-emitter voltage and the base current (Figure 1b).
As seen in Figure 1a, in the transistor made of silicon, for the collector current value range up to approximately 1 A the dependence of $\beta(i_{C})$ is a monotonically increasing function, while for higher values of this current the considered parameter decreases. On the other hand, in the SiC BJT transistor, extreme value of $\beta(i_{C})$ exists at a value of $I_{C}$ equal to 9 A. The increase of the ambient temperature (Figure 1b) results in, increasing of the $\beta$ parameter value in the silicon transistor, while in the transistor made of silicon carbide – decreasing of the $\beta$ parameter value at the fixed value of both the collector-emitter voltage and the base current. Temperature coefficients of $\beta$ parameter for the Si BJT and SiC BJT are equal to 1.59 %/K and -0.52 %/K, respectively. Values of the temperature coefficient were determined using equation:

$$\gamma_{A} = \frac{A(T_{2})-A(T_{1})}{A(T_{2})-A(T_{1})} \cdot 100\%$$

where $A(T_{1})$ and $A(T_{2})$ represent values of $\beta$ parameter at temperature $T_{1}=25^\circ C$ and $T_{2}=130^\circ C$, respectively.
Figure 2a presents the output characteristics $i_C(v_{CE})$ of the SiC BJT, and Figure 2b - the output characteristics $i_C(v_{CE})$ of the Si BJT measured under isothermal conditions (points connected by solid lines) and under non-isothermal (points connected by dashed lines) at the fixed value of the base current and the ambient temperature.

Position of non-isothermal characteristics in comparison with their isothermal counterparts (considering the same value of the base current $i_B$) is qualitatively different for each of the investigated transistors. The junction temperature measured along the considered non-isothermal characteristics is growing, because of the device active power growth. However, because of the dependence of $\beta(T)$ presented in Figure 1, the non-isothermal characteristics of SiC BJT lie under their isothermal counterparts (current gain factor $\beta$ is a decreasing function of temperature), while in the silicon transistor, increasing temperature results in $\beta$ drop (Figure 1a) which causes that the non-isothermal characteristics $i_C(v_{CE})$ of the silicon transistor are located above their isothermal counterparts (Figure 2a).

In addition, the non-isothermal output characteristics of SiC BJT transistor also differ qualitatively from their isothermal counterparts. In the literature, such shape of the characteristics is called N-type, having regard to the phenomenon of avalanche breakdown, not illustrated in the Figure 2a.

Figure 3 shows the isothermal input characteristics of the both transistors measured in a wide range of the temperature at the fixed value of the collector-emitter voltage equal to 10 V.

![Figure 3](image_url)

**Figure 3** $i_B(v_{BE})$ characteristics of SiC and Si BJTs.

As seen, the transistor made of silicon carbide has more than three times higher value of the base-emitter voltage than the silicon transistor, at the same fixed value of the base current.

In the case of both considered transistors, as it was expected, the increase of the temperature causes a shifting of the input characteristics towards lower values of the base-emitter voltage. The temperature coefficient of base-emitter voltage at the constant base current (equal to 1A) for transistor made of silicon and silicon carbide is equal to -0.15 %/K and -0.05 %/K, respectively. Values of the temperature coefficient of base-emitter voltage were determined using Eq. 1, where $A(T_1)$ and $A(T_2)$ represent values of base-emitter voltage at temperature $T_1$ and $T_2$, respectively.
An important operating parameter of the transistor is the collector-emitter voltage in an ON-state ($V_{ON}$). Figure 4 presents the isothermal dependence of $V_{ON}(i_B)$ for the both transistors measured at two ambient temperatures.

![Figure 4](image4.png)

**Figure 4** $V_{ON}(i_B)$ characteristics of SiC BJT and Si BJTs.

As seen, in the both considered transistors the $V_{ON}$ voltage decreases with an increase of base current and increases with an increase of collector current. On the other hand, the temperature increase results in a decrease of the voltage $V_{ON}$ value in the silicon transistor (increase - in the silicon carbide transistor) at a constant value of the base and collector current.

An important operating parameter of the BJT transistor operating in the cut-off state is leakage current flowing in the collector circuit referred to the terms of the established polarization of a control electrode. The most commonly presented by the manufacturer leakage current is $I_{CBO}$ current measured in a common base measuring set with an opened emitter.

Figure 5 presents the non-isothermal dependence of $I_{CBO}(V_{CB})$ of considered transistors measured for different ambient temperatures.

![Figure 5](image5.png)

**Figure 5** Dependence of the leakage current $I_{CBO}$ on the collector-emitter voltage of SiC BJT (a) and Si BJT (b).
As seen, the transistor made of silicon carbide is characterized by several dozen times lower value of $I_{CBO}$ current than the silicon transistor at the same, fixed values of collector-emitter voltage and ambient temperature. For example, the value of the considered parameter at 150°C and the voltage $V_{CB} = 600$ V in the Si BJT and SiC BJT is equal to 260 $\mu$A and 3.9 $\mu$A, respectively. Furthermore, it is presented that in the both considered transistors, the $I_{CBO}$ current strongly increases with an increase of the temperature.

3. Conclusions
The paper presents the results of author’s measurements of the selected static characteristics and operating parameters of the bipolar power transistor made of silicon carbide and for comparison the mentioned characteristics and parameters of the silicon counterpart of the considered device. In the case of considered transistors change both the junction and the ambient temperature due to self-heating phenomenon has an important impact on the characteristics of these semiconductor device.

The most important qualitative differences in properties of the BJT transistor made of silicon and silicon carbide are mainly due to the fact that the temperature dependence of the current gain factor in the first-mentioned transistor is a monotonically increasing function, and in the second - a monotonically decreasing function. As a result, the output characteristics presents a decrease of the collector current as the temperature increases only in the transistor made of silicon carbide. The occurrence of such a phenomenon may improve the thermal stability of the device and can also improve the reliability of electronic circuits containing such transistors.

The results of the measurements shown in the paper will be used by the authors in modeling SiC BJTs, and next – in a computer analyzes of electronic circuits containing power SiC BJTs.

4. References
[1] Sundaresan S, Jeliazkov S, Grummel B, Singh R 2013 10 kV SiC BJTs static, switching and reliability characteristics 25th International Symposium in Power Semiconductor Devices and ICs (ISPSD) 303–306
[2] DiMarino C, Chen Z, Boroyevich D, Burgos R, Mattavelli P 2013 Characterization and comparison of 1.2 kV SiC power semiconductor devices IEEE EPE 1-10
[3] Ahmed M M R, Parker A, Mawby N A, Nawaz P A, Zaring M 2008 Characterization of the static and dynamic behavior of a SiC BJT Power Electronics and Motion Control Conference 2472-2477
[4] Niedra J M, Schwarze G E 2006 Static and Switching Characteristics of a 4H-SiC Based BJT to 200°C International Conference on High Temperature Electronics (HiTEC 2006)
[5] Zhang Y, Zhang B, Li Z, Lai C 2008 Analysis of thermal characteristics of current gain for BJT-BSIT compound device International Conference on Communications, Circuits and Systems 1278 – 1281
[6] Buono B, Ghandi R, Domeij M, Malm B G, Zetterling C M, Östling M 2010 Modeling and characterization of current gain versus temperature of 4H-SiC power BJTs IEEE Trans. Electron Devices vol 57 704-711
[7] Chailloux T, Calvez C, Planson D, Tournier D 2014 Etude de différents transistors de puissance SiC 1.2kV des temperatures cryogeniques aux hautes temperatures Symposium de Genie Electrique (SGE’14)
[8] Zarębski J, Dąbrowski J 2011 Investigations of SiC Merged PiN Schottky Diodes Under Isothermal and Non-isothermal Conditions International Journal of Numerical Modelling: Electronic Networks, Devices and Fields vol 24 207-217
[9] Zarębski J, Bisewski D 2008 Modifications of the DC Raytheon-Statz model for SiC MESFETs International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, John Wiley& Sons vol 21 583-590
[10] Zarębski J, Bisewski D 2009 Modelowanie tranzystorów SiC-MOS Elektronika – konstrukcje, Technologie, zastosowania Nr 7 177-180.
[11] Gorecki K, Zarębski J 2008 The nonlinear compact thermal model of power MOS transistors International Conference of Microelectronics 196 – 199
[12] Na H J 2006 Fabrication and characterization of 4H-SiC planar MESFETs Microelectronic Engineering vol 83 160-164
La Spina L, d'Alessandro V, Russo S, Rinaldi N, Nanver L K 2009 Electrothermal behavior of highly-symmetric three-finger bipolar transistors *Bipolar/BiCMOS Circuits and Technology Meeting (BCTM 2009)* 21 – 24

[14] http://www.dacpol.eu/pl/elementy-polprzewodnikowe-z-weglika-krzemu/product/elementy-polprzewodnikowe-z-weglika-krzemu-1224

[15] http://www.alldatasheet.com/datasheet-pdf/pdf/108707/PANASONIC/2SC5294.html