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Characterization and comparison of 1.2kV SiC power devices from cryogenic to high temperature

Thibaut Chailloux^{1, a *}, Cyril Calvez¹, Dominique Tournier^{1, b},
Dominique Planson¹

¹ Laboratoire Ampère, INSA de Lyon, 21 Av. J. Capelle, 69100 Villeurbanne, France

^a thibaut.chailloux@gmail.com, ^b dominique.tournier@insa-lyon.fr

Keywords: SiC, BJT, MOSFET, JFET, cryogenic temperature, high temperature.

Abstract. The aim of this study consists in comparing effects of temperature on various Silicon Carbide power devices. Static and dynamic electrical characteristics have been measured for temperatures from 80K to 525K.

Introduction

Silicon has long been the dominant semiconductor for high-voltage power applications. Thanks to significant achievements in SiC technology (bulk material growth and SiC device processing), this semiconductor has reached a maturity level confirmed by recent reliability studies performed on both rectifiers and switches (JFETs, MOSFETs and BJTs). Besides, this semiconductor is supposed to have a wider operation temperature range than Silicon. It could be used in harsh environments, when temperature is very high, such as oil prospecting, or when temperature is extremely low, for instance in superconducting applications or in space.

In most cases, high voltage and high current capabilities of SiC based devices has been proved [1,2] for temperatures up to at least 450K. Previously, operation of 4H-SiC vertical JFETs has been demonstrated at high temperature [3] and cryogenic temperature [4], and in both cases SiC VJFETs have shown good results between 100K and 473K. Performances of the 4H-SiC BJT at 100K have also been studied [5].

Recently, some comparative studies between JFET, MOSFET and BJT over a wide range of temperature have been published [6,7]. This work is intended to follow-up these investigations and study in the same conditions, at both cryogenic and high temperature, with various SiC power devices.

Components characterized

The tests have been performed on various SiC components (BJT, JFET, MOSFET). Some of their ratings are gathered in Table 1. The chosen MOSFET is a CREE's CMF2012D, packaged in TO254 metal case (silver sintering). We used Semisouth's SJEP120R050 normally-off JFET, packaged in TO254 metal case and SJDP120R045 normally-on JFET, packaged in TO247 plastic case. The BJTs were BT1220AB supplied by Fairchild, packaged in TO258 metal case. We also characterized GeneSiC's GA16JT17, packaged in TO247 plastic case, and it has been included in this study.

Table 1: Ratings of investigated devices

Component	V _{max} [V]	I _{max} [A]	R _{ON} [mΩ] at 300K
MOSFET CREE CMF2012D	1200	42	80
JFET N-Off Semisouth SJEP120R050	1200	38	40 (90 at 400K)
JFET N-On Semisouth SJDP120R045	1200	48	45
BJT Fairchild BT1220AB	1200	20	25 (50 at 525K)
SJT GeneSiC GA16JT17	1700	16	110 (280 à 450K)

Measurements and results

Static characterization. Electrical characteristics ($I_{CE}-V_{CE}$ for BJT and $I_{DS}-V_{DS}$ for the others) have been measured by Kelvin measurement method with a B1505A Agilent curve tracer. The

pulsed measurements (100 μ s) greatly reduce self-heating of the device. A cryogenic chamber using liquid nitrogen (boiling temperature: 77.36K) has been used to set the temperature under medium vacuum (0.2Pa). The temperature was raised from 80K to 525K, by step of 25K.

On-resistance, threshold voltage (for MOSFETs and JFETs), current gains (for BJTs and SJTs) and leakage currents have been extracted. These are key parameters since knowing on-resistance and leakage currents is required to estimate conduction losses, threshold voltage and current gain are needed to drive the transistors properly.

Figure 1a shows the specific on-resistance for increasing temperature for a fixed gate voltage or base current (resp. 20V, 0.4A, 20V, 0V, 0.4A for MOSFET, SJT, JFETs and BJT). It was obtained by multiplying the measured on-resistance values by the die area of the device. Typically, the active area is used for this calculation, but this dimension could not be obtained for all of the devices. The specific on-resistance of the BJT is the lowest and the least temperature-dependent. It can be explained by modulation of the conductivity on drift region. The MOSFET specific on-resistance is high and varies a lot with temperature. The JFETs' specific on-resistance is the more temperature-dependent since it increases by 335% between 200K and 525K for normally-off JFET. This can be explained by a great phonon scattering, which reduces carrier mobility.

Figure 1b shows the threshold voltage of the three field effect transistors for increasing temperature and figure 1c shows its relative difference between threshold voltage and its value at 300K.

$$\varepsilon(T) = \frac{V_{th}(T) - V_{th}(300)}{|V_{th}(300)|} \quad (1)$$

The MOSFET threshold voltage has a high negative temperature coefficient: it decreases by 46% between 300K and 525K and increases by 197% between 300K and 80K. This diminution of the threshold voltage for an increasing temperature can be explained by an increase in the intrinsic carrier density and carrier trapping at the SiO₂/SiC interface.

Furthermore, the threshold voltage is linked to the channel doping concentration and geometry. This value depends on the P-Well doping activation. To confirm this assumption, MOSFET channel mobility extraction should have been done, as well as dopant energy activation. However no test structures were available to perform such an analysis.

The normally-off JFET threshold voltage decreases linearly with increasing temperature (54% between 80K and 525K) and the threshold voltage of the normally-on JFET seems to varies very slightly and only at very low temperature.

The MOSFET transconductance (Figure 2a) is almost constant over the whole range of temperature, while JFETs' are quite identical and decrease linearly with temperature (25% between 80K and 525K).

The current gains were obtained at a collector-emitter voltage of 4V and a collector current of 10A for the BJT and 6A for the SJT. The values for collector current have been chosen slightly below their nominal rating, since the devices were operating beyond their recommended operating area. The current gains of both transistors have a highly negative temperature coefficient. Between 300K and 525K, the BJT current gain decreases by 43% and SJT current gain decreases by 30% (Figure 2b). The decrease of the current gain with increasing temperature is due to an increase of the ionization of dopants, which decreases the efficiency of the emitter. This negative coefficient limits the risks of thermal runaway.

Leakage current of the MOSFET is minimal around 300K and increases very gradually between 300K and 525K (Figure 3a). The leakage current of the SJT gradually increases over the entire temperature range (Figure 3c). The leakage current of the BJT is minimal around 300K and increases when temperature increases up to 500K (Figure 3b). However measurements indicate a break in the curve, indicating that a mechanism of escape seems to activate when the temperature reaches 500K and causes significantly greater leakage at 525K. This may be due to a passivation fault.

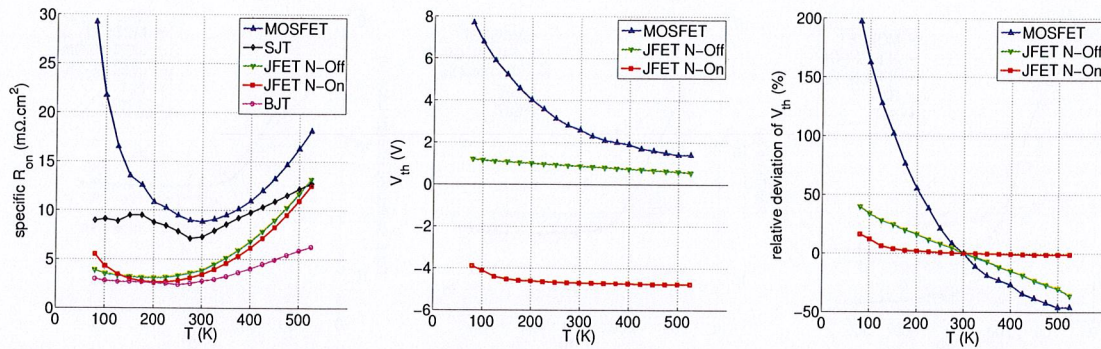


Figure 1: Static characterization. (a) Specific on-resistance (left). (b) Threshold voltage (middle). (c) Relative difference of threshold voltage with its value at 300K (right).

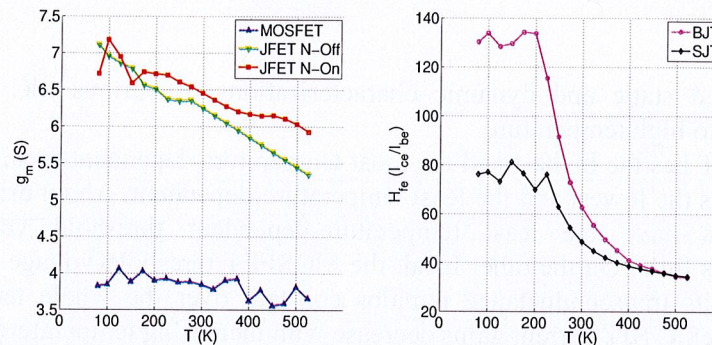


Figure 2: Static characterization. (a) Transconductance (left). (b) Current gain (right).

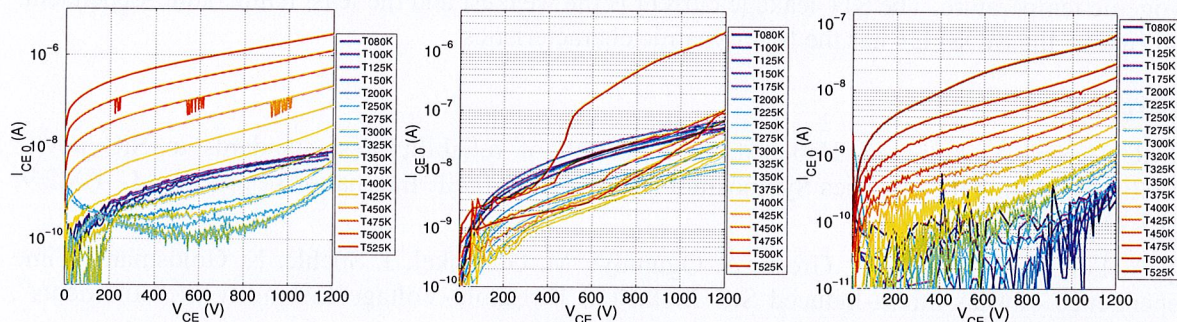


Figure 3: Leakage current. (a) MOSFET (left). (b) BJT (middle). (c) SJT (right).

Dynamic characterization. A Double Pulse Test setup, carefully designed to reduce the parasitic components that inhibit switching performance, and a Tektronix oscilloscope (DPO4014B) have been used. Drain-Source (resp. Collector-Emitter) voltage was measured with a Tektronix P5205 high voltage differential probe and Source (resp. Emitter) current was measured thanks to a 25mΩ T&M SDN100 coaxial shunt resistor. All transistors were driven by a IXDD614 low-side MOSFET gate driver and a 10Ω external gate resistor for MOSFET/JFETs and 33Ω for BJT/SJT. The transistors have switched 500V-8A.

The switching times were taken to be the difference between when the current is at 10% of its maximum value and voltage is at 10% of its maximum value. The losses were calculated as the integral of the instantaneous power between these two instants.

The rise time of the MOSFET increases with temperature between 300K and 525K while its fall time decreases. By the way, MOSFET seem to be the fastest of the characterized devices. For the four other components, switching times are quite constant when temperature rises from 300K to 525K (Figure 4). However the switching times of all transistors increase a lot at cryogenic temperature, maybe because of the increase in threshold voltage, which increases Miller plateau for a rather constant capacitance [8]. Among all transistors, the MOSFET has the least switching losses, due to fast switching.

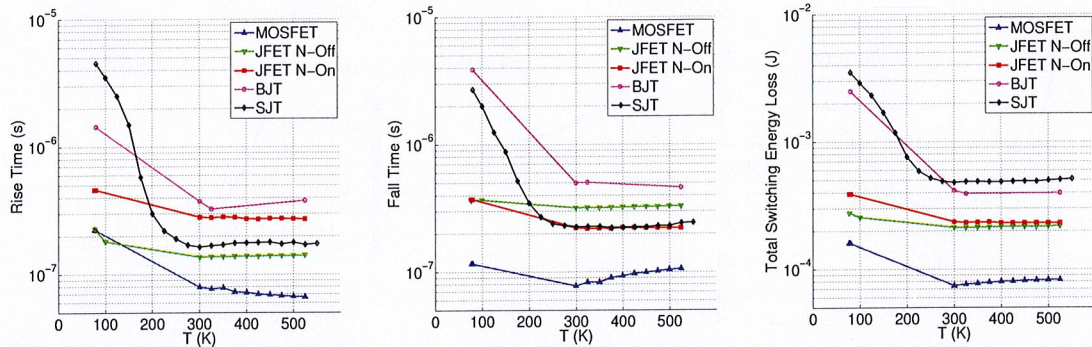


Figure 4: Dynamic characterizations. (a) Rise time (left). (b) Fall time (middle). (c) Total switching energy (right)

Conclusions

This paper presented static and dynamic characterizations of various SiC transistors from cryogenic temperature to high temperature.

The CREE MOSFET has the highest and the most temperature dependent specific on-resistance, while Fairchild's BJT is the lowest and the least temperature-dependent. About driving the devices, the Semisouth JFETs have the least temperature-dependent threshold voltage and their transconductance varies little. On the other hand, the MOSFET threshold voltage varies quite a lot with temperature but its transconductance remains constant over the whole temperature range. Fairchild BJT and GeneSiC SJT current gains decrease with increasing temperature but are however higher than gains of transistors in Silicon, and we can also notice that their gains are maximal at cryogenic temperature. The SJT leakage current is the weakest and the least temperature-dependent. And finally, the MOSFET has the best dynamic characteristics.

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