A Step Toward High Temperature Intelligent Power Modules Using 1.5kV SiC-BJT

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Abstract. Looking back to the development of inverters using SiC switches, it appears that SiC devices do not behave like their silicon counterparts. Their ability to operate at high temperature makes them attractive. Developing drivers suitable for $200^\circ C$ operation is not straightforward. In a perspective of high integration and large power density, it is wise to consider a monolithic integration of the driver parts for the sake of reliability. Silicon is not suitable for high ambient temperature; silicon-on-insulator offers better performances and presents industrial perspectives.
The paper focuses on a SiC BJT driver: it processes logical orders from outside, drives adequately the BJT to turn it either on or off, monitors the turn-off and turn-on state of the device, and acts accordingly to prevent failure. SiC BJT imposes specific performances different from the well known ones of SiC JFET or MOSFET. The paper addresses a preliminary analysis of a SOI driver, anticipating the behavior of SiC-BJT and the change in behavior at high temperature. A discret driver as been design and fabricated. Elementary functionnal blocks have been validated, and a BJT conveter successfully operated at high temperature with high efficiency ($\eta = 88\%$).

Introduction

Several investigation teams are currently working on the development of high temperature power switch, sensors and packaging issues. Silicon devices have reached their theoretical limits.

SOI technology giving a margin to temperature operation of up to $225^\circ C$ [1]. SiC devices are pushing up both high temperature and high voltage silicon limits, as wide band gap devices (SiC and GaN) are promising solutions for the fabrication of high temperature switches. However, only power side devices have been developed so far and both driver and signal conditioning issues are not specifically addressed. Drivers are usually based on silicon discrete or integrated devices, and system architectures are constrained by thermal limitations. Amplification and drivers still remains a major point to be solved for high temperature normally-on and normally-off devices.

In order to reduce thermal stress for high temperature applications, and to match severe operating conditions (as high as $500^\circ C$), new converters architecture must be foreseen, implying the developpement of high temperature intelligent power modules (HTIPMs), including both power switch and its driver. The conception of such a new architecture implies to identify limiting key points of each elements of the energy conversion chain : from control to driving block and high voltage power switches.

High temperature integrated circuit (MOSFET amplifier operating at 300 $^\circ C$ [2]) have been successfully fabricated. Since then, several high temperature sensors, switch and converters have been designed. A JFET monolithically integrated power converter has been presented [3], however this work addresses only the output power stage and include neither protection feature nor dead-time control. Even if for highest temperature range (300 $^\circ C$) no mature technology addressing both device and system is right now commercially available, it is reasonable to define new converters topologies and BJTs driver based on SOI in a first step.
As a first step, next section presents BJTs static characterization, in order to determine required thermal and electrical characteristics of a high temperature driver.

BJT characterization and driver design

Among all SiC power switch (being either unipolar or bipolar), one must consider devices features to design an appropriate gate driver. Indeed, the knowledge of power switch gate equivalent impedance, transient gate supply current, reverse and forward characteristics and temperature impact of all those parameters is mandatory to design a reliable high temperature BJT driver.

Preliminary static BJT characterization Static SiC-BJT characterizations have been performed in order to get optimal driving condition, and to check the impact of the temperature on BJT gain among others. Temperature has been limited to 125 $^\circ C$ in order to avoid silicon top-gel SiC-BJT module degradation. Specific package solving this problem are currently fabricated and will be soon characterized. As inferred from Fig.1, the specific on-resistance is increased by a factor of 1.4 for a temperature increase of 100 $^\circ C$ while the current gain $\beta = Ic/Ib$ decreases by a factor 1.43 (33 downto 24).

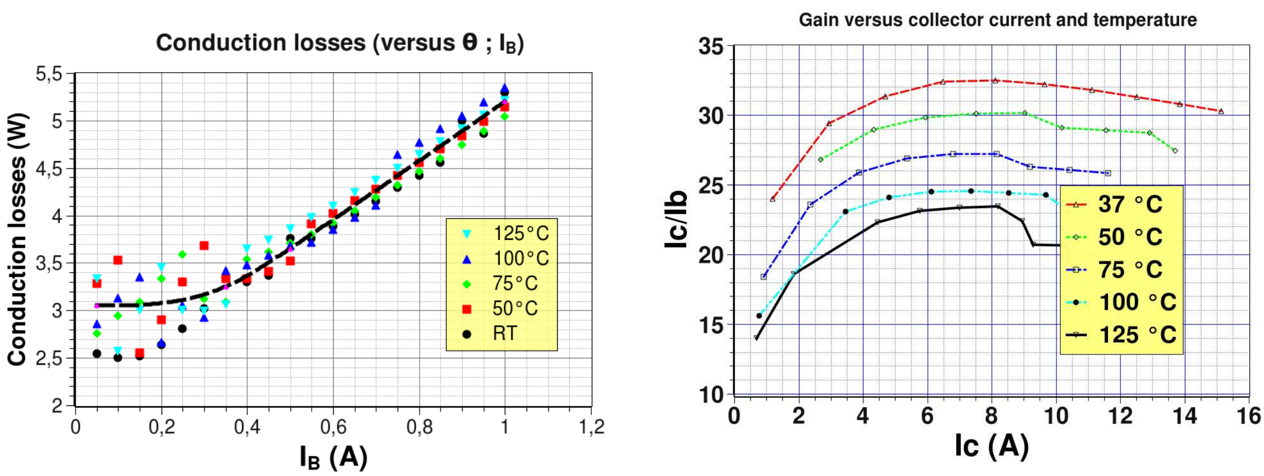

Fig. 1: Conduction losses dependence on temperature and base current (left), Current gain versus collector current depending on temperature (right).

One can conclude from Fig. 1, that for the BJT-nominal current ($I_N = 6A$), the optimal operating gain value (to minimize static losses) corresponds to a base current in the range of $200mA < I_B < 300mA$, corresponding to the maximal gain value. Thereby, no dynamic base current adaptation would be necessary on the driver side, to operate BJT at its higher gain value. The driver topology is thus strongly simplified since no temperature sensing and correction of side-effects are required.

Dynamic characterization Based on previous BJT characteristics, a discrete driver version has been designed, optimized and fabricated. The BJT specific driver has been partitioned into several functional blocks : positive and negative isolated auxiliary power supplies, short circuit protection by V_{CE-sat} monitoring, cross conduction protection. Switching waveforms (Fig. 2) show satisfying performances of “Driver /SiC-BJT” association. A short over-current applied on

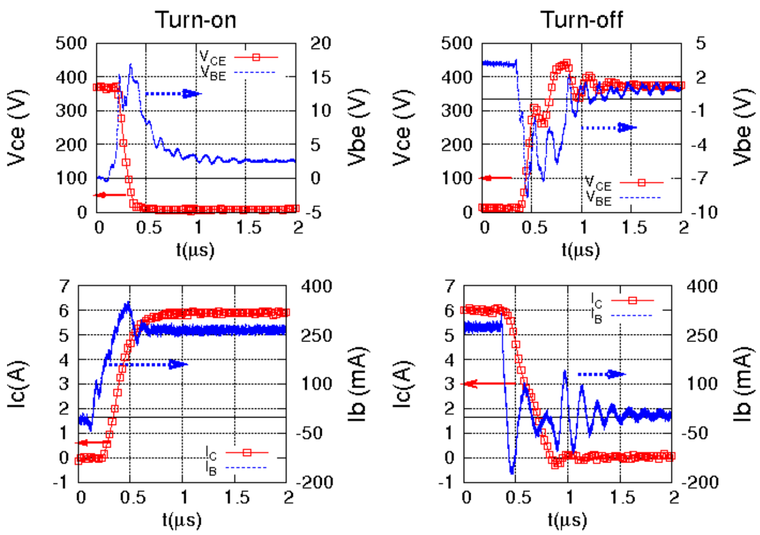

Fig. 2: Switching waveform : collector (left), base (right) using discrete driver.

the base allows fast turn-on (Fig. 2-right). Driver turn-off block permits V_{CE} over-voltage limitation ($\Delta V_{CE} = 90V$) as inferred from (Fig. 2-left). Minor impact of temperature on switching performance has been measured (turn-on increases of 20% for 150 $^\circ C$ temperature augmentation while turn-off is reduced more or less of the same order). Switching energy losses dependence versus temperature have been investigated and remains quite stable (above $3.5\mu J$ between room-temperature and 200 $^\circ C$). Turn-on losses increase consequently to on-resistance increase with temperature, while turn-off losses reduction is related to base-carrier-recombination enhancement with temperature.
A boost converter efficiency, operated at 150 $^\circ C$, has been measured (Fig. 3-right). Efficiency remains moslty stable ($\eta \approx 89\%$) for switching frequencies between $1kHz < f_{SW} < 200kHz$. Results are similar to various studies [4, 5, 6] highlighting BJT-converters efficiency in the range of ($83\% < \eta < 96\%$).

Discussion and Outlook

This paper focuses on a preliminary analysis of the driver functions (Fig. 3-left) required to drive properly a SiC BJT, investigating temperature impact on both static and dynamic performances. Functional blocks to be monolithically integrated have been successfully tested, SiC-BJT operating at high temperature (200 $^\circ C$).
An output-power stage able to provide stable base current has been designed. A fault detection circuit (BJT-saturation detection circuit) has been successefully tested. Using this discret

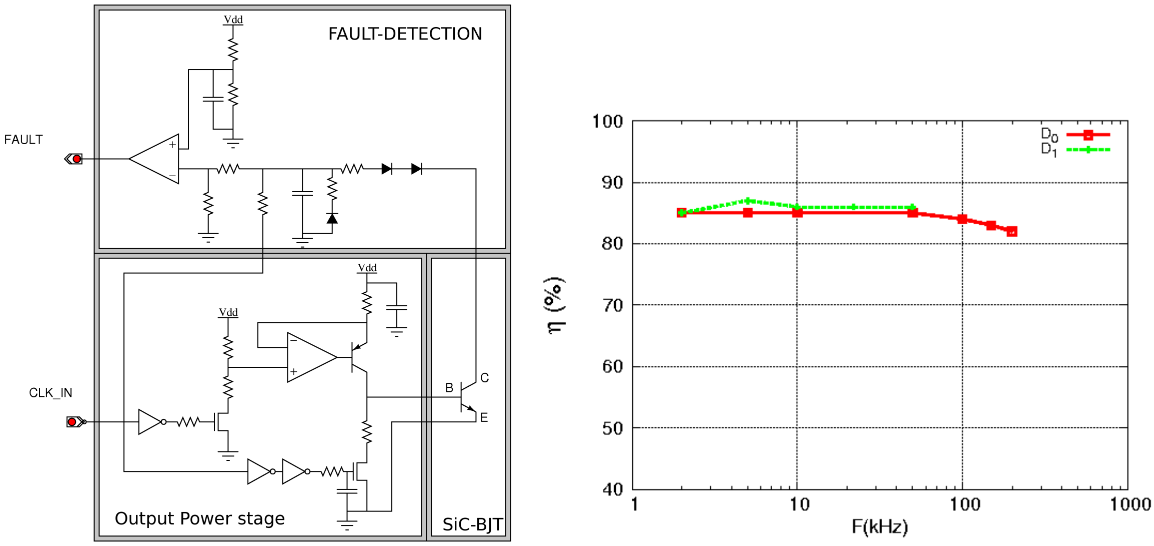

Fig. 3: BJT-driver functionnal blocks addressed in this study (left), Experimental BJT converter efficiency using two discret driver topologies (right) .

driver, low energy losses values have been measured ($E < 4\mu J$) and optimal driving conditions have been defined ($200mA < I_B < 300mA$), beeing almost temperature stable. It has been tested that transient base over-voltage enhanced turn-on and that a short negative base current pulse boost turn-off phase. Fully integrated SiC driver might be the ultimate high temperature solution. However, whatever material is chosen, the central question of the system schematic remains.
Based on previous static and dynamic analysis, a SOI BJT-driver is under design. After SOI prototype validation of studied functions, next step will be the integration of functionnal blocks using WBG technology to address high temperature applications.

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