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Static and Switching Characteristics of 10 kV-class Silicon Carbide Bipolar Junction Transistors and Darlington

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Abstract. This paper reports the device design, fabrication and characterisation of 10 kV-class Bipolar Junction Transistor (BJT). Manufactured devices have been packaged in single BJT, two paralleled BJTs and Darlington configurations. The static and switching characteristics of the resulting devices have been measured. The BJTs (2.4mm² active area) show a specific on-resistance as low as 198 mΩ·cm² at 100 A/cm² and room temperature for a β_{Max} of 9.6, whereas the same active area Darlington beats the unipolar limit with a specific on-resistance of 102 mΩ·cm² at 200 A/cm² ($\beta=11$) for a β_{Max} of 69. Double pulse tests reveal state of the art switching with very sharp dV/dt and di/dt . Turn-on is operated at less than 100 ns for an E_{ON} lower than 4mJ, whereas the turn-off takes longer times due to tail current resulting in E_{OFF} of 17.2 mJ and 50 mJ for the single BJT and Darlington respectively when operated at high current density. Excellent parallelisation have been achieved.

Introduction

The research on Silicon Carbide (SiC) has made huge progress in the last 30 years. From the complete assessment of the material properties to the commercialisation of discrete devices a lot of efforts has been put. This has proven that the intrinsic properties of SiC can be exploited and are not just a researcher's fantasy. Nowadays the automotive markets are the ones pushing the production and devices on the range between 650 V and 1200 V have gone into mass production [1]–[6]. In this range SiC Metal Oxide Semiconductor Field Effect Transistors (SiC-MOSFET) is very appealing due to their superior performance even though less costly Si counterparts exist.

For higher voltages (3.3 kV and above) and applications like High Voltage Direct Current (HVDC) converters, Medium Voltage Direct Current (MVDC) converters and Modular Multilevel Converter (MMC) submodules SiC devices cost projections place them in second position compared to Si Insulated Gate Bipolar Transistors (Si-IGBTs), which are now considered to be a mature technology in the industrial environment. In order for SiC to become interesting in that voltage range, it has to offer better electric performance than Si-IGBT, improve the system reliability, meet the current rating requirements, while not drastically increasing the global cost of the converter. This means that, SiC devices for these applications have to have much lower losses and provide advantages in terms of switching speed. This is not an advantage for MMCs, but it could be interesting for Solid-State Transformer like in traction application. Also, the current ratings require device paralleling and improved gate/base control. System reliability has to be warranted and this is usually supposed to be the case since fewer devices need to be used in series, but gate oxide issues on MOSFETs still fail to convince. One way to overcome these issues, is to completely

get rid of the gate oxide by employing Junction Field Effect Transistors (JFETs) or Bipolar Junction Transistors (BJTs). JFETs are a good alternative to MOSFETs but the normally-on nature that confers them very low on resistance is unattractive to application engineers. On top of that, JFETs are unipolar devices and for high voltages (>15 kV) bipolar ones are to be preferred since they provide lower on-resistance when resistivity modulation is achieved [7].

BJTs seem to be a good alternative for high and ultra-high voltage devices since they are proven to benefit from resistivity modulation property [8]–[10]. They do not have any gate oxide which renders them free from the related issues and gives them a more compact form factor compared to MOSFETs. This means that for the same current rating, less bulk material is needed because the conduction happens fully on the volume as compared to the conduction of the channel of the MOSFETs, which can be considered as surface conduction with classical channel mobility reduction [11]. For both these reasons SiC BJTs can be more economical compared to same rating SiC MOSFETs. But this does not take into account the fact that the SiC MOSFET integrates a PiN diode intrinsically, whereas the BJT has to be paralleled with a diode in order to be used in converter applications. One of the drawbacks that has slowed down the development of BJTs is its control. Since one has to provide continuous current to keep the BJTs in on-state, the driver is slightly more complicated than the ones used for SiC MOSFETs [12], [13] and the losses that can be eliminated by the bipolar nature of this device can be transferred to the driver, at least partially [14]. Nevertheless, the potential of BJTs has to be explored for applications such as power converters for MVDC/HVDC and also for Surge Protection.

Experimental

Device design and fabrication. The BJTs have been manufactured on 4" N+ substrates after 3 layers of epitaxy have been grown. First the collector layer (drift layer) was grown with a doping of $7 \cdot 10^{14}$ and a thickness of 110 μm . Since this layer is the one responsible for the blocking capability of the device, it is in theory able to withstand 16.8 kV for an infinite plane junction. The optimal thickness and doping of the base layer has been determined to be $1.5 \cdot 10^{17}$ cm^{-3} and 1.5 μm respectively. The choice for such a thick base layer is made to ensure that the remaining base thickness after etching is enough to sustain the high electric field. The main information of the doping and thickness of the base and drift layer are resumed in Fig. 1.

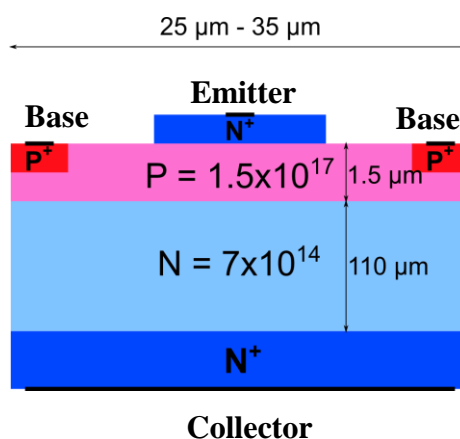


Fig. 1 – Drift region doping details.

The optimisation of the current gain is crucial for power BJTs. For this reason small and medium-sized ($0.75 \cdot 0.75 \text{ mm}^2$ $2.6 \cdot 2.6 \text{ mm}^2$) interdigitated devices were developed with 4 designs (geometry variations) and a cell pitch between 25 μm and 35 μm . The active area of the medium size BJTs is 2.4 mm^2 . The peripheral protection is an association of MESA and JTE that has been inherited from the 10 kV PiN diodes with same drift layer properties [15]. More details on the design and optimisation process can be found in [16].

Packaging. After on-wafer characterisation best performing medium sized BJTs from each design have been selected and packaged in high temperature custom package ISOPLUS from DeepConcept. For testing purposes, 4 hybrid devices were packaged, where 4 samples were used to make 2 paralleled BJTs and 4 other samples were used to make 2 Darlington. Extra care was taken to select the highest current gain (β) and the lowest parameter spread for the hybrid devices. Fig. 2 shows the packaging layout of a single BJT (a), paralleled BJT (b) and Darlington (c) on the left and the packaged device on the right.

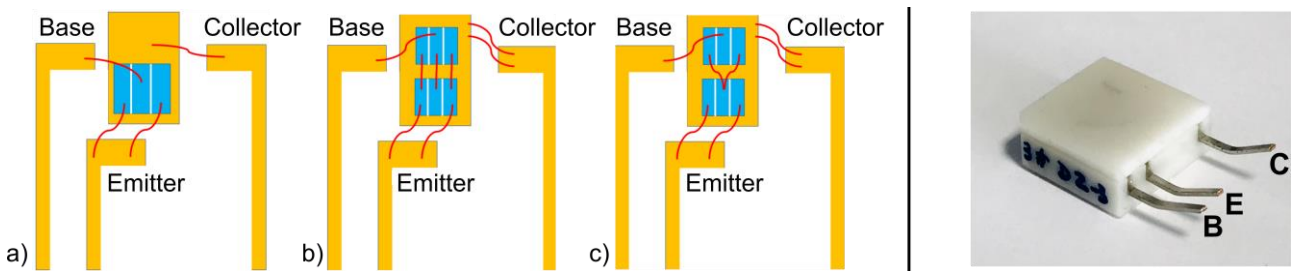


Fig. 2 – Packaging layout of a single BJT (a), paralleled BJT (b) and Darlington (c) on the left and the packaged device on the right.

Static characterization. Both forward and reverse characterisation, has been carried out on a Keysight B1506 for voltages up to 3 kV. The breakdown voltage has been tested on wafer in a vacuum chamber associated to a FUG 12,5kV SMU in series with a Keithley 6485 Pico-ammeter.

Switching Tests. Double Pulse tests were carried out on a custom test bench at room temperature. The test bench was not capable of thermal conditioning at the time of this study. BJTs were mounted on low-side, while a 4 mH air core inductor in parallel with a custom freewheeling diode was mounted on high-side. The freewheeling diode is made of two 1.7 kV SiC Junction Barrier Schottky diodes in series. The BJTs were driven by a GA15IDDJT22-FR4 driver [17] able to deliver a typical continuous current of 2 A on the base. The on-state and off-state voltages delivered by the driver are 5 V and -8 V respectively. Collector-Emitter voltage was measured through a Tektronix THDP0100 high-voltage differential probe. Collector current was measured through a 25 m Ω shunt in series with the BJT emitter, whereas the base current was measured through a Tektronix CT2 current transformer coupled with a P6041 probe. Tests were carried out on 2 paralleled BJTs and Darlington also. For paralleled BJTs, the GA15IDDJT22-FR4 driver was employed, whereas for Darlington a CPWR-AN10 Rev-C SiC MOSFET Isolated Gate Driver [18] was employed as the two base emitter diodes in series require at least 6 V to trigger the device.

Results and Discussion

This section reports the characterisation results divided in static and dynamic characteristic. The results will be analysed and discussed further in this section. Throughout the paper the on-resistance is calculated as the ratio between applied collector emitter voltage and the resulting collector current. On-resistance does not refer to dynamic resistance that is calculated as the slope of the output characteristic.

Static characteristics. The BJTs, the paralleled devices and the Darlington have been extensively characterised. As shown in Fig. 3(a) the open base blocking capability of single BJTs shows a breakdown voltage of 5 kV, which is half of the targeted blocking voltage due to a faulty (higher than the optimal) implantation dose of the peripheral protection. Nevertheless, PiN diodes with same epitaxial layer have recently been designed with an optimised peripheral protection and successfully block 11 kV. This achievement can be applied to a future run of BJT to assure the targeted blocking voltage. On the other hand, the output characteristic at room temperature

presented in Fig. 3 – **The open base blocking capability of BJT 3#D5-3 a) and its output characteristics in b).** shows a healthy BJT saturation behaviour and an infinite Early voltage. The specific on resistance is calculated to be $198 \text{ m}\Omega\cdot\text{cm}^2$ at 100 A/cm^2 and a β of 9.6 for device 3#D5-3. The resistivity of the 10 kV SiC BJT reported in this study is 66% higher than that of 10kV SiC MOSFET reported in [19] and leaves room for improvement in a future run. However, the epitaxy of the BJT is highly oversized as its thickness is $110 \mu\text{m}$ as compared to the $85 \mu\text{m}$ epi of the MOSFET [19]. This means that a good part of the resistivity is due to the oversized epitaxy. Another aspect is the low injection due to low lifetimes in the drift region. At higher temperature the BJT might beat the unipolar limit and have a lower resistance than the MOSFET, but data on the 10 kV MOSFET at 150°C have not been found for comparison.

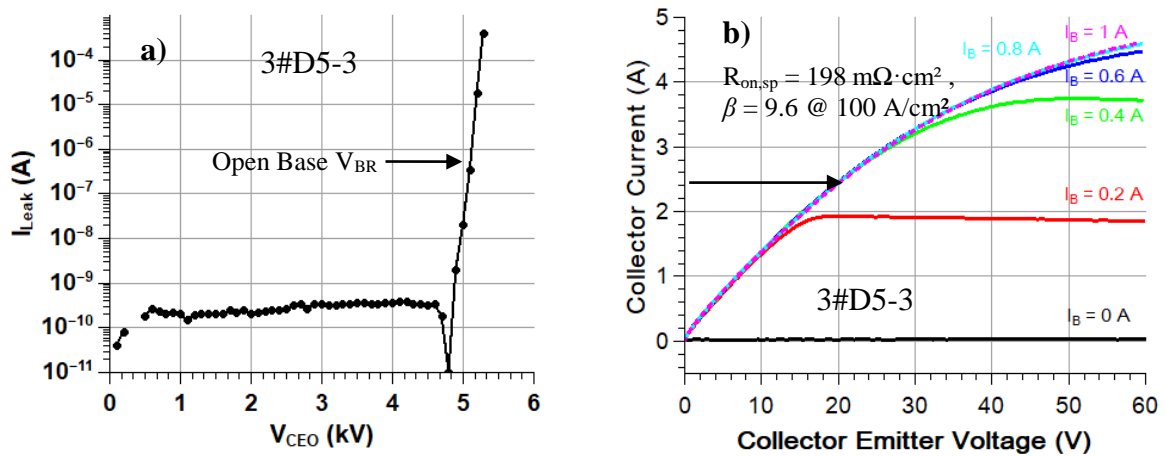


Fig. 3 – The open base blocking capability of BJT 3#D5-3 a) and its output characteristics in b).

Current gain as a function of collector current of BJTs with designs 2# and 3# have been selected and measured after packaging and are shown in Fig. 4(a). One can see the clear effect of the design (base and emitter width variations) as there are two distinct groups of β . Design 3# has the highest β , which peaks at 9.8 at just above 100 A/cm^2 and rapidly decreases for current densities higher than 133 A/cm^2 . The effect of high temperature is quite high as β_{max} goes from 8.5 at 25°C to 5.3 at 150°C for device 3#D2-3. Whereas the on-resistance increases from $201 \text{ m}\Omega\cdot\text{cm}^2$ at 25°C to $500 \text{ m}\Omega\cdot\text{cm}^2$ at 150°C . These values are far from the record-breaking β s published in literature, like $\beta_{\text{Max}} = 75$ for a 10 kV SiC SJT [9], $\beta_{\text{Max}} = 28$ for a 10 kV SiC BJT [20], $\beta_{\text{Max}} = 139$ for a 15 kV single cell SiC BJT [21] and $\beta_{\text{Max}} = 139$ for a 21 kV single cell SiC BJT [22]. The record for highest beta ($\beta = 256$ and $\beta = 335$ for (0001) and (000-1) crystal orientations respectively) is held by Miyake et al. [23], but the base layer is so thin that the open base break down voltage is limited to 600 V, which is far targeted voltage for MVDC and HVDC applications. The performance of the tested devices gives room for improvement, but the resulting β s were consistent throughout the wafers and the yield was above 50% in terms of β only.

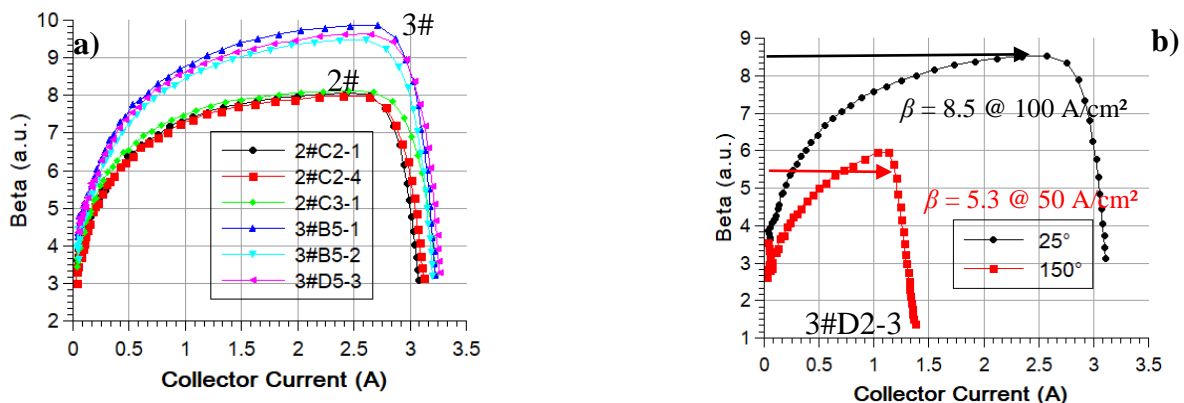


Fig. 4 – The β s of design 2# and 3# of the tested devices in a) and β of BJT 2#D2-3 at 25°C and 150°C in b).

An interesting aspect of BJTs is that they can be paralleled or used in a Darlington configuration. Parallelisation is useful when high current rating cannot be achieved with a single device, whereas Darlington is one way to lower the base current by multiplying the individual gains, but at the cost of a doubled V_{BE} voltage and a 3 V threshold voltage. Both these configurations have been tested and the output characteristics along with β s are presented in Fig. 5. Compared to the results in Fig. 4|a) the 2 paralleled BJT are capable of doubling the current without degrading β . This is a sign that current sharing is optimal. $\beta_{Max} = 9$ and $207 \text{ m}\Omega\cdot\text{cm}^2$ at 100 A/cm^2 is achieved, which is consistent with the results of a single BJT. As of the Darlington, $\beta_{Max} = 69$ and $102 \text{ m}\Omega\cdot\text{cm}^2$ at 200 A/cm^2 ($\beta=11$) has been recorded. The reduction of the specific on resistance is a result of high injection happening in the Darlington. The BJT does not show a clear bipolar behaviour for base currents up to 1 A. This result is encouraging as the specific resistance is 20 % lower than that of 10kV SiC MOSFET reported in [19] and lower than the unipolar limit of SiC. Experimenting with monolithic Darlington can yield devices with very low specific on resistance and double the current rating for the same active area.

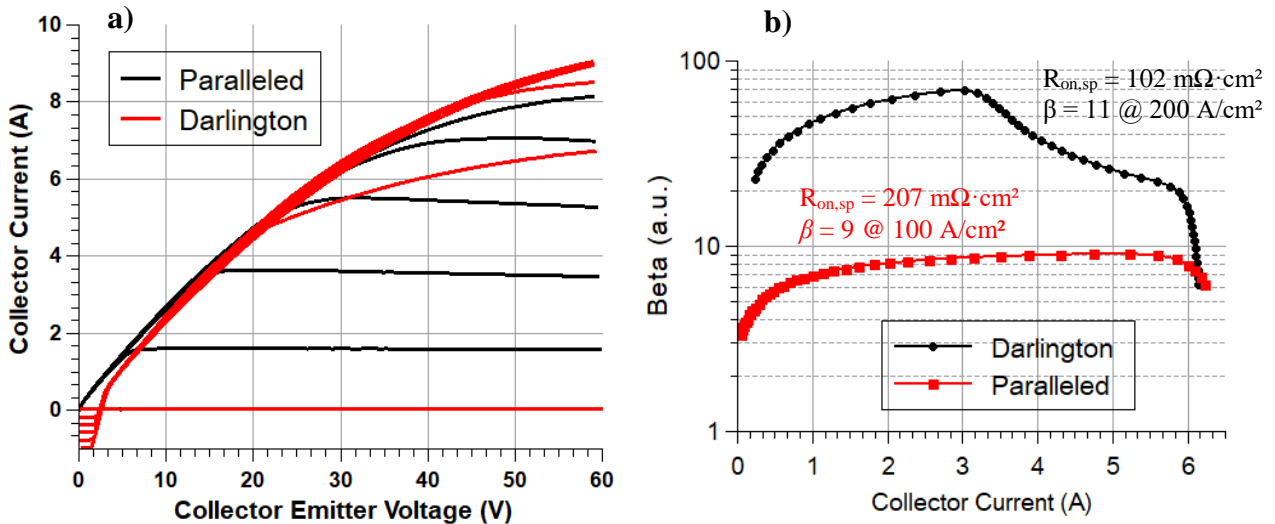


Fig. 5 – Output characteristics of the Darlington a) and β of the Darlington as opposed to that of the two paralleled BJTs b).

Dynamic characteristics. The 10 kV SiC BJT is meant to be used as a power switch. As such, the static characteristic is very important as it accounts for the conduction losses, but it also needs to perform when it comes to changing states (conduction to blocking and vice versa). The switching losses have to be well known, especially when the frequency is high, which is one of the main arguments in favour of SiC devices. In order to assess the switching behaviour of the studied devices the Clamped Load Inductive switching, also commonly called Double Pulse test, was carried out on single BJT (3#D5-3), 2 paralleled BJTs (3#P1) and Darlington (3#D1). Tests were carried out at room temperature with a maximum bus voltage of 3 kV. The applied peak current was kept under 20 A for 3#D5-3 (833 A/cm^2) and 3#P1 (417 A/cm^2), whereas for Darlington current was pushed up to 25A (1041 A/cm^2). As mentioned above, GA15IDDJT22-FR4 type driver was used for single BJT and paralleled one, whereas for a Darlington a CPWR-AN10 Rev-C SiC MOSFET Isolated Gate Driver. This choice was made due to the V_{BE} incompatibility of the Darlington with the BJT driver. The resulting switching waveforms show sharp turn-on and turn-off with good current handling capability.

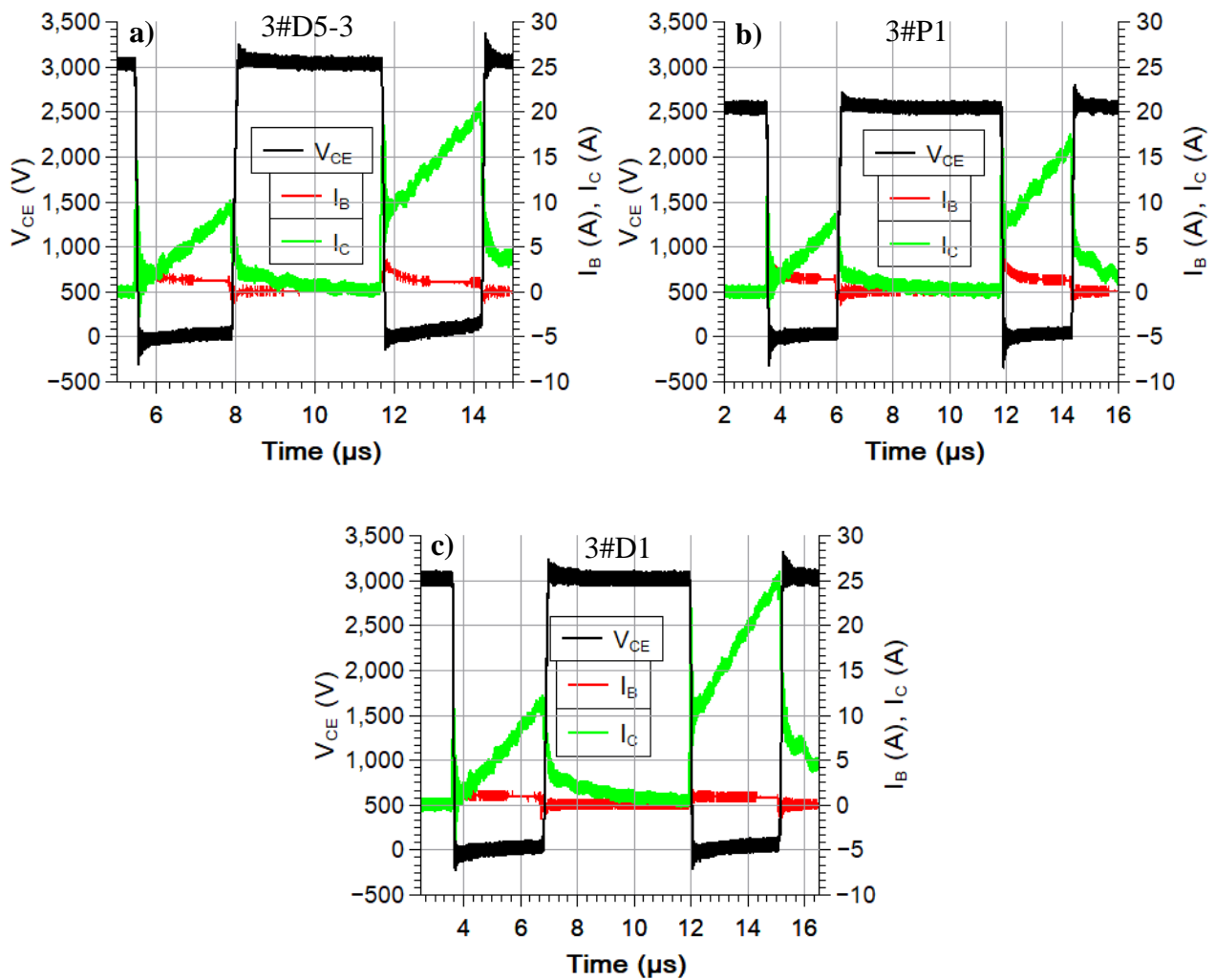


Fig. 6 – Full Double Pulse waveforms for BJT single 3#D5-3 in **a)**, paralleled 3#P1 in **b)** and Darlington 3#D1 in **c)** at room temperature.

Zooming in on the turn-on of these devices shows a state-of-the-art performance. As can be seen in Fig. 7, I_C t_{rise} and V_{CE} t_{fall} are inferior to 100 ns. Very high dV/dt and di/dt are recorded on the three devices even though they were subjected to very high current density (cf. Table 1). Turn-on energy lower than 4 mJ was extracted on the 3 devices. The current peak during the turn-on phase results from the capacitance of the freewheeling diode.

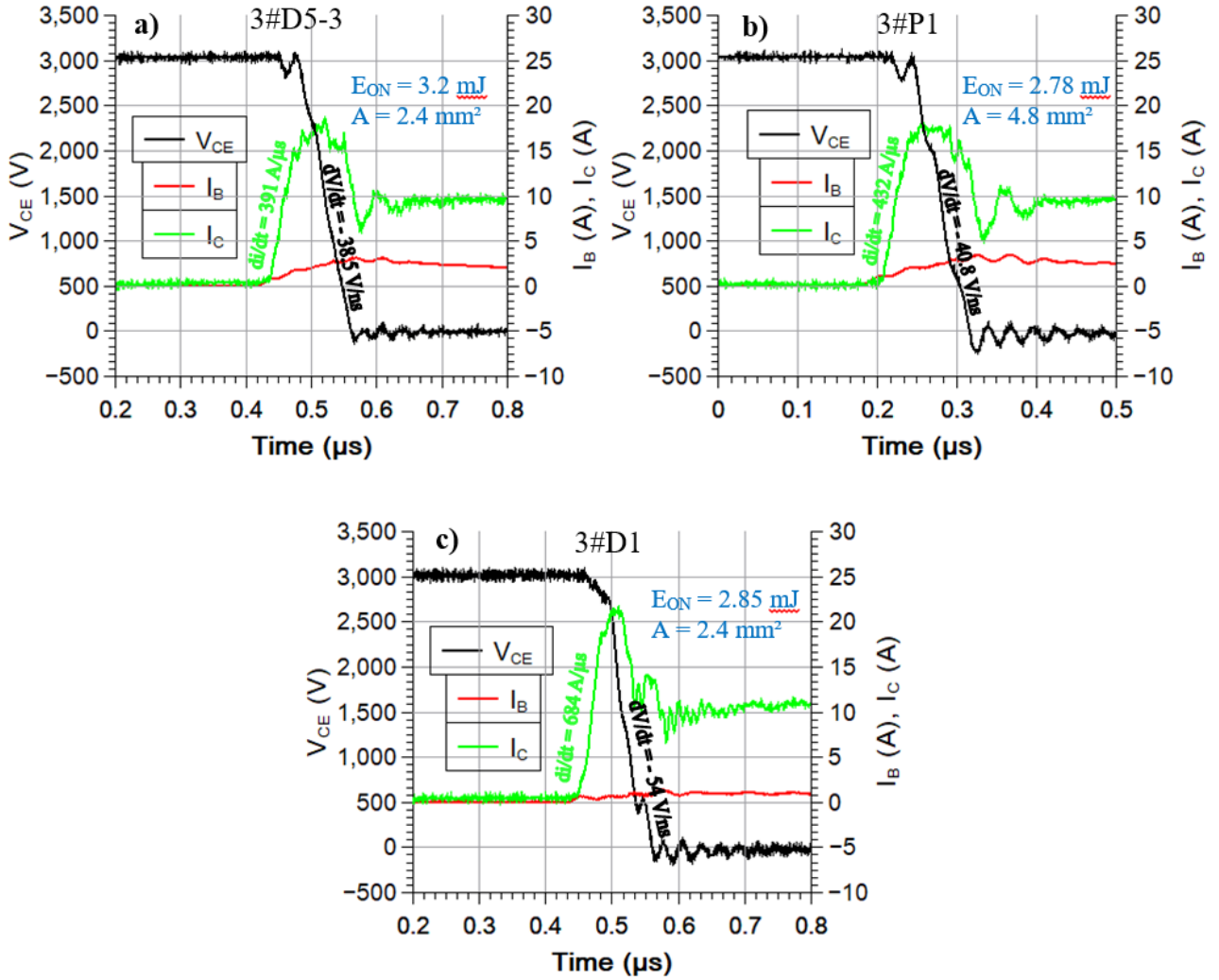


Fig. 7 – Hard turn on waveforms for BJT single 3#D5-3 in a), paralleled 3#P1 in b) and Darlington 3#D1 in c) at room temperature with a bus voltage of 3 kV and a turn on current of 10 A.

During the turn-off phase, reported in Fig. 8, one can notice that V_{CE} t_{rise} is lower than 100 ns for the 3 devices. The influence of the test bench parasitic elements is noticeable, since during the fall time of the collector current some oscillation is observed. I_C t_{fall} on the other hand exhibits an exponential decaying behaviour that could be related to the recombination of electron-hole pairs that constitute the plasma during bipolar conduction, commonly referred to as the tail current. In Fig. 6(c), the collector current takes around 5 μs to decay (between 7 μs and 12 μs), which results in a lifetime of 1 μs for bipolar conduction. This value is consistent with literature as some self-heating may occur in the device and produce an increase of the ambipolar lifetime that is reported to be 0.6 μs at 25°C [24]. Unfortunately, during these tests the test bench could not be used at higher temperatures. Bipolar conduction may be the slow decaying current that produces high turn-off losses compared to turn-on. In order to reduce this effect as much as possible, lowering the negative V_{BE} voltage should be explored in the future. This may increase the reverse recovery current in the base-emitter junction and thus enhance the recombination. The reverse recovery current of I_B is visible in Fig. 8 for the 3 devices. The bipolar degradation has not been studied in this paper and cannot be excluded since very high current densities were injected in the device. Repetitive switching tests and stress tests may be carried out in the future to investigate the potential bipolar degradation phenomenon.

Other papers in literature report outstanding switching performance [9], [20]. Nevertheless, comparing the actual BJTs and Darlington with the devices from literature would not be fair as the device in [9] performs only in unipolar mode and the device in [20] is tested only at 2 kV and 30 A/cm².

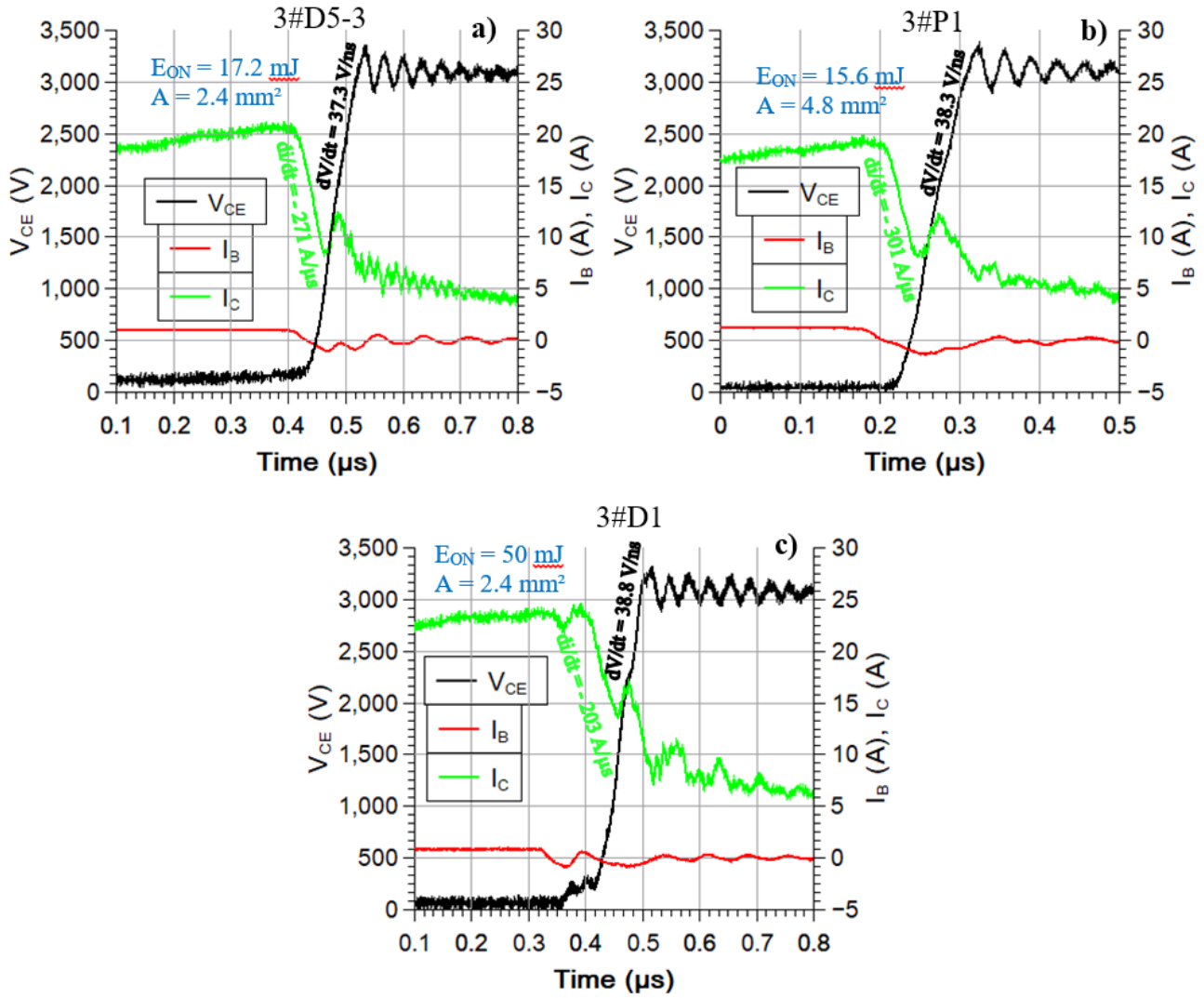


Fig. 8 – Hard turn-off waveforms for BJT single 3#D5-3 in a), paralleled 3#P1 in b) and Darlington in c) at room temperature with a bus voltage of 3 kV.

Table 1 – Main switching parameters of the single BJT, the paralleled BJT and the Darlington extracted from Fig. 7 and Fig. 8.

Turn-ON				
	J_C (A/cm ²)	dV/dt (V/ns)	di/dt (A/μs)	E_{ON} (mJ)
3#D5-3	417	- 38.5	391	3.2
3#P1	208	- 40.8	432	2.78
3#D1	833	- 54	684	2.85
Turn-OFF				
	J_C (A/cm ²)	dV/dt (V/ns)	di/dt (A/μs)	E_{OFF} (mJ)
3#D5-3	854	37.3	- 275	17.2
3#P1	397	38.3	- 301	15.6
3#D1	987	38.8	- 203	50

Summary and Conclusions

Static and switching characteristics of 2.4 mm² active are single SiC BJT, 2 paralleled SiC BJTs and SiC Darlington have been measured and reported in this study. Average β_{MAX} of 9.5 has been achieved for the third (3#) and best design. The specific on-resistance is as low as 198 m Ω ·cm² for the single BJT and 102 m Ω ·cm² for the Darlington. The peripheral protection has to be improved on a future run in order to block 10 kV. Turn-on is obtained for times inferior to 100 ns with very sharp dV/dt and di/dt . Turn-on energies lower than 4 mJ have been recorded. Turn-off has been successfully operated at current densities as high as 854 A/cm² and 987 A/cm² for the single BJT and Darlington respectively. This gave rise to current tail, which may be due to bipolar operation under high current injection condition. The Darlington packaging showed that a monolithic Darlington can be an interesting device for power switching applications.

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