A High Voltage IGBT and Diode Chip Set designed for the 2.8kV DC Link Level with Short Circuit Capability extending to the Maximum Blocking Voltage

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A High Voltage IGBT and Diode Chip Set designed for the 2.8 kV DC Link Level with Short Circuit Capability extending to the Maximum Blocking Voltage

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***Abstract*—This paper presents the experimental characteristics of a high voltage IGBT and diode chip set designed for safe operation under hard switching conditions at the 2.8 kV DC link level. The fundamental goal of the design is a low cosmic ray induced failure rate for diodes as well as IGBTs at the DC link level. At the same time all the common requirements of low static and dynamic losses as well as wide SOA under turn-off, reverse recovery and short-circuit conditions are fulfilled. The blocking capability of these devices exceeds 4.5 kV by far.**

I. INTRODUCTION

In the design of high power semiconductor switches it has been common practice to develop components for specific voltage classes characterizing the maximum blocking voltage [1]. These blocking requirements have for a long time determined the silicon wafer material specifications, i.e. the thickness and resistivity. For a given blocking voltage, say 4.5 kV, the designer had a limited freedom in the choice of these two parameters. This has led to the creation of so-called punchthrough and non-punchthrough devices for one and the same blocking voltage class. For applications in power inverters, each of these blocking voltage classes is complemented by a corresponding DC link voltage, which is typically some 50 to 60 % of the maximum blocking voltage to accommodate the inductive overvoltages; for example, a 4.5 kV device is typically expected to operate at 2.8 kV DC link voltage.

With the discovery of a new cosmic ray induced failure mechanism some years ago [2], this classic design procedure has become obsolete, since devices designed in such a manner failed with excessively high rates at the DC link voltage they were expected to operate at. High power applications, in particular traction, have always imposed extreme requirements on low failure rates and long operation life cycles of the power semiconductors. The quest for low failure rates has further reduced the freedom

in the choice of silicon wafer properties: besides guaranteeing a specified blocking capability – 4.5 kV for the device discussed here – maximum electric fields at operating voltages – the 2.8 kV DC link voltage in the case of inverter applications – are no longer allowed to exceed tight limits. The criteria for the definition of silicon wafer properties imposed by the cosmic ray failure mechanism have been found to be more stringent than the ones deduced from the maximum blocking voltage requirement. Many components had to be redesigned for acceptably low cosmic ray induced failure rates by lowering the internal electric field maximum with the result of increased static and dynamic losses.

This fact is distressing for both manufacturers and users of conventional high power devices such as thyristors, diodes and GTOs, since diminishing performance of a mature product is 180^{o} out of phase with the common sense of “improvement” in the technical world. Even more disturbing, it might be a show-stopper for the just emerging high power IGBT technology. This is because the IGBT with exclusive injection from the anode reacts more critically to an increase of the wafer thickness than devices with injection from both electrodes like thyristors, GTOs and diodes. Moreover, IGBTs might be more susceptible to cosmic rays since the cathode cell array with a multitude of cellular p-bases induces electric field peaks considerably higher than the maximum field of a one-dimensional pn-junction in a diode, at the same blocking voltage. Injection enhancement at the cathode of advanced IGBTs [3], which is kind of a weak substitute for a cathode emitter in a bidirectionally injecting device, leads to a decrease of the on-state voltage drop. This effect could compensate for the increased static and dynamic losses of IGBTs designed for low cosmic ray induced failure rates. At present, such IGBT structures have not yet reached maturity.

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To shed some light on this topic, the present paper reports on a development of a high power IGBT and diode chip set designed for a low cosmic ray induced failure rate of 2 to 5 FIT per chip (failures per 10^9 hours of operation) at a DC link voltage of 2.8 kV and at room temperature. The IGBT sports a planar cathode structure.

II. Si Substrates for low Cosmic Ray Induced Failure rates of power semiconductor Devices

All types of high power semiconductor devices subjected to a high blocking voltage are affected by cosmic ray induced failures. The failure rate is a strong function of the applied blocking voltage and depends also on temperature. In accelerated field tests empirical relationships between failure rates and applied blocking voltages and the related maximum electric fields in the devices have been determined [2]. Based on such data , Si wafer thickness and resistivity were chosen to yield a failure rate of 2 to 5 FIT per chip at 2.8 kV DC link voltage and at room temperature. The same n-doped NTD Si wafers were used for diodes as well as IGBTs neglecting the supposed increased susceptibility to cosmic ray induced failures of IGBTs.

III. Experimental Results

A. Blocking Performance

The active area of both IGBTs and diodes is very close to 1 cm^2. Both devices have a planar field termination structure. Reverse I – V characteristics are shown for both devices in fig. 1. Breakdown voltages exceeding 6 kV at room temperature were measured for both types of devices.

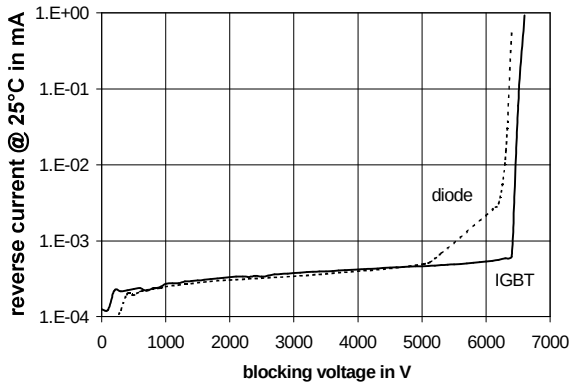
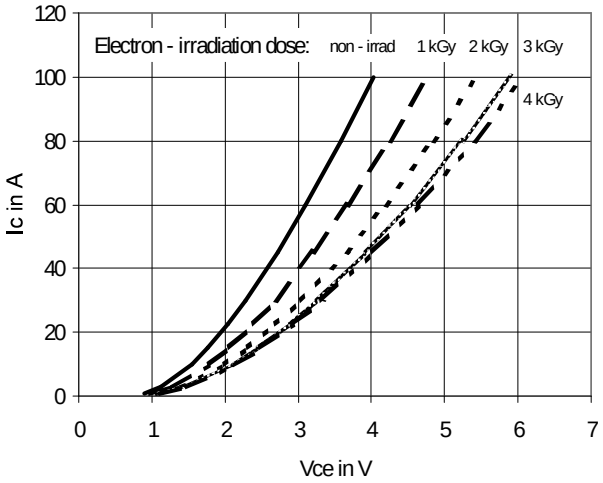


Fig. 1: Blocking characteristics of non-irradiated IGBT and diode chips at room temperature.

B. On-state characteristics

The strongly diverging requirements on lowest possible conduction and switching losses are particularly difficult to meet for the diode due to the very wide n-base imposed by the cosmic ray failures. An optimum compromize was achieved with a PIN structure exposed to a combination of irradiations for carrier lifetime adjustment using both homogeneous electron irradiation and local helium irradiation [4]. The homogeneous reduction of carrier lifetime caused by the electrons reduces the charge in the tail current phase during reverse recovery while the local carrier lifetime reduction induced by the He ions



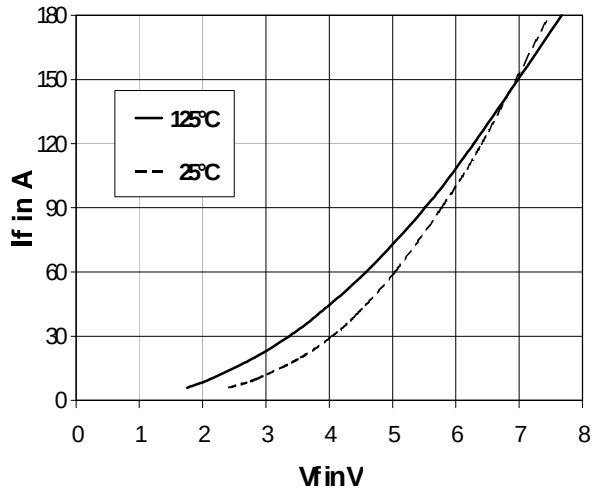


Fig. 2: 25 °C and 125 °C forward I-V characteristics of an irradiated diode chip.

Fig. 3: 125 °C forward I-V characteristics of electron-irradiated IGBT chips.

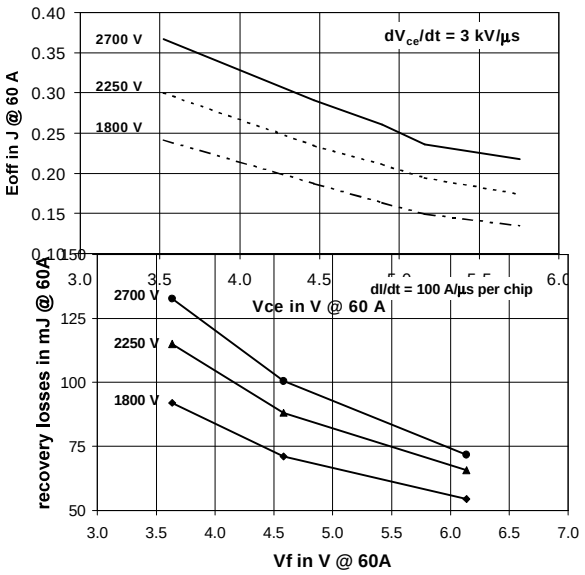
is optimized to yield a maximum reduction in the peak reverse recovery current and the peak power. The IGBT chip sports a planar cathode structure organized in a “see of cells”. IGBT dies were electron-irradiated in order to adjust the turn-off switching losses.

C. Dynamic characteristics

The differently irradiated IGBT chips from fig. 3 as well as the diodes were subjected to snubberless inductive switching experiments at different line voltages reaching the DC link voltage of 2.8 kV. The resulting trade-off curves (E_{off} versus $V_{ce,on}$) are shown in fig. 4 for the IGBT and in fig. 5 for the diode (E_{rec} versus V_f).

Fig. 4: 125 °C technology curves for non-irradiated and electron irradiated IGBTs at 60 A per chip and dV_{ce}/dt of 3 kV/µs.

Fig. 5: 125 °C technology curves for irradiated diodes at



60 A per chip and dI/dt of 100 A/µs per chip.

D. Turn-off capability of IGBTs

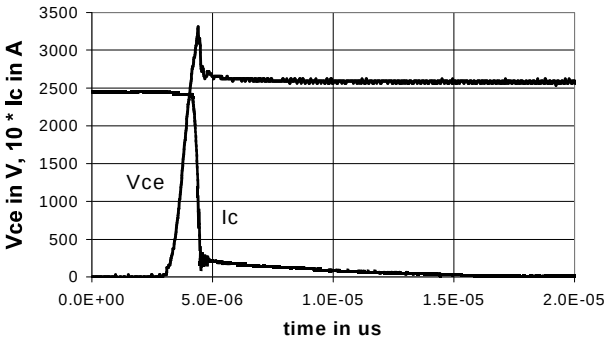


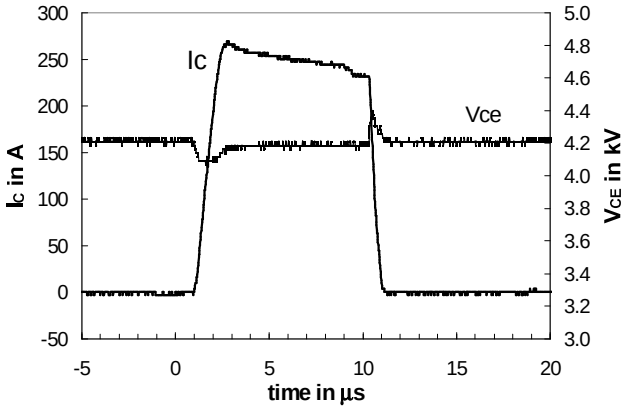
Fig. 6 demonstrates the maximum turn-off capability of IGBTs at a line voltage of 2700 V, which is close to the DC link voltage. One single IGBT chip is able to turn off safely up to 245 A at this voltage and the maximum power loss reaches 600 kW per chip or per cm^2. The maximum turn-off current per chip decreases when the line voltage is increased above 2700 V. We found the turn-off capability to decrease

Fig. 6: 125 °C IGBT turn-off waveforms of a single chip turning off 245 A versus 2700 V.

to 30 A at 4000 V line voltage. Thus, the maximum tolerable peak power during turn-off decreases also with the line voltage. As shown in [5], the use of local lifetime profiling with proton or helium beams improves this limit from 30 to 90 A per chip for very similar devices.

E. Short circuit capability of IGBTs

The turn-off limit of 245 A for these IGBTs coincides with their saturation current level at Vge = +15 V. This is a hint to a very high short circuit ruggedness,



which indeed was

Fig. 7: 125 °C short circuit waveforms of a single IGBT chip with more than 200 A and 4.2 kV. The peak power exceeds 1 mega-watt.

confirmed experimentally. Fig. 7 shows a successful turn-off under short circuit conditions (during 10 µs, line voltage is 4.2 kV and I_{sc} exceeds 200 A) for an IGBT chip; the peak power per chip under these conditions is approximately 1.1 to 1.3 mega – watts.

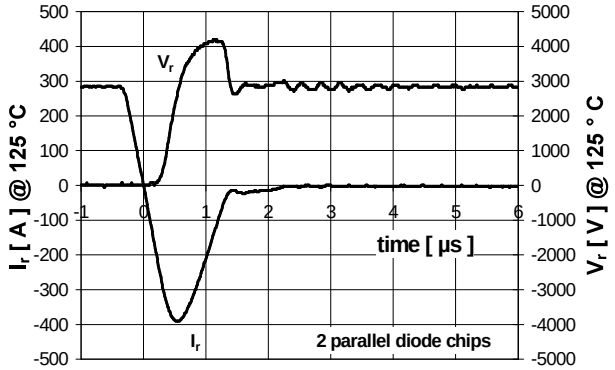


Fig. 8: 125 °C diode turn-off waveforms of 2 parallel diode chips. dI_c/dt exceeds 900 A/µs without destruction.

F. Diode turn-off capability

The diode's ruggedness is at the same very high level and therefore complements the IGBT perfectly. Proof is given with fig. 8, which shows current and voltage waveforms of a diode under reverse recovery. In this example, two parallel diode chips turn-off 290 A into four parallel IGBT chips against 2.8 kV at 125 °C. A single diode chip is able to handle dI/dt values of up to 450 A/µs without destruction. The maximum absorbed power during reverse recovery exceeds 600 kW per chip or cm^2.

IV. CONCLUSIONS

Regarding all the common requirements on ruggedness and various safe operation areas on a high power IGBT and diode chip set, we have demonstrated that the devices presented in this paper are apt to fulfil their job flawlessly at the DC link voltage of 2.8 kV.

But for how long ?

To say it with fig. 9, which shows measured cosmic ray induced failure rates at 25 °C per chip versus the DC blocking voltage for IGBTs and diodes designed according to old standards for the 4.5 kV voltage class and for the devices discussed in this paper : there is a difference of 1.5 to 2 orders of magnitude in the failure rates at the DC

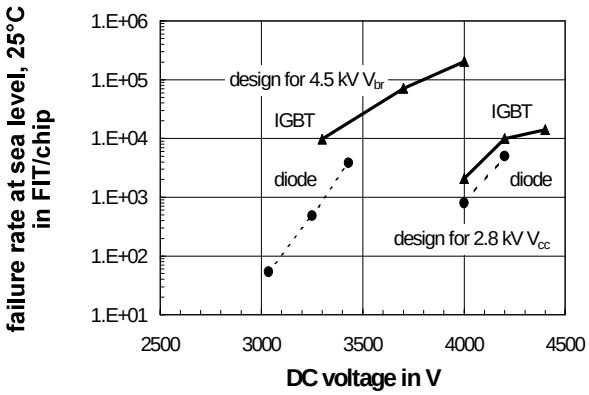


Fig. 9: Comparison of measured cosmic ray failure rates of IGBTs and diodes for 4.5 kV blocking and for 2.8 kV DC link voltage.

voltage of 4000 V and this difference will persist at 2800 V. Extrapolating the curve for the 2.8 kV DC link voltage design towards this voltage level [2] shows that the initial design goal of 2 to 5 FIT per chip has been met. In other words, approximately 50 devices designed conventionally would have failed in a given time interval while just one the advanced IGBTs would have been killed. The diodes reach even lower failure rates than the IGBTs (fig. 9).

Coming back to fig. 1, which showed the room temperature breakdown characteristics in excess of 6 kV, it can be said that according to old standards, the blocking voltage class of the presented chip set is 5.5 kV. Its electrical performance can therefore not be compared to devices designed for the 4.5 kV voltage class. There is further room for improvement of the blocking capability of high voltage IGBTs, for planar IGBTs as demonstrated in [5] and even more so for future IGBTs with strong plasma enhancement at the cathode.

The cosmic ray failure mechanism imposes similar costs in terms of increased static and dynamic losses on IGBTs as on other high power semiconductor devices such as thyristors, GTOs and diodes. It is for this reason that cosmic rays will not become a show-stopper for high power IGBTs. Most importantly, it's features highly esteemted by power system designers – the high input impedance allowing comparatively small gate drivers, it's short circuit withstand capability and it's robust turn-off performance making snubbers unnecessary – are unaffected by the design modifications imposed by the cosmic ray failure mechanism. Compared to other switch concepts (GTO, GCT, etc.), IGBTs will continue to become more attractive in the future at the pace of the advancement of semiconductor technologies for power IGBTs with injection enhancement at the cathode (IEGTs). Best of all, the progress achieved in high power silicon diodes lends a helping and reassuring hand on that way.

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