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Dynamic HV-H³TRB Test on 3.3 kV SiC MOSFET Modules

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Abstract. In standard environmental reliability tests, Silicon Carbide (SiC) MOSFETs show excellent performance even compared to their Silicon counterparts. This raises the question if the SiC modules are robust and reliable under all circumstances in the field and against all failure mechanisms or only in the standard laboratory tests. The HV-H³TRB (High Voltage – High Humidity High Temperature Reverse Bias) test is the standard test for humidity reliability and SiC modules survive this test for several thousand hours, easily surpassing the 1,000 h qualification requirement. However, in field service the devices are exposed to steep voltage slopes (high dv/dt) instead of the DC voltage stress applied in a standard HV-H³TRB. In this work, a dynamic HV-H³TRB test was performed on 3.3 kV SiC MOSFET modules for more than 4,000 h with switched high voltages of 80% V_{nom}, only observing minor degradations and reversible blocking capabilities.

From DC to Dynamic

The standard test for humidity induced degradation of power semiconductors is the HV-H³TRB [1-3] and in recent years, more and more Silicon devices show excellent robustness in this test [4]. SiC MOSFETs can surpass this performance and survive the HV-H³TRB for several thousand hours, easily fulfilling the 1,000 h qualification standards [5-6]. In a previous publication [6] a comparative HV-H³TRB test with more than 6,300 h of testing time showed a higher reliability of SiC MOSFETs compared to Silicon IGBTs. Even after this time, no SiC MOSFET failed or even showed a degradation in their blocking capability, while every Silicon IGBT of the test group reached the failure criterion. Even the rather high voltage stress of 90% of the nominal voltage (V_{nom}) did not accelerate the test sufficiently to reach end-of-life of the SiC MOSFETs within the 6,300 h.

In [7] the impact of temperature, relative humidity (RH) and voltage on the test acceleration were investigated for SiC MOSFETs with the conclusion that temperature has a similar impact, relative humidity a lower impact and voltage acceleration a higher impact for SiC devices compared to Silicon devices. The test can be accelerated to reach end-of-life in a fraction of the test time required with the standard parameters of 85°C and 85% RH (85/85). Unfortunately, this moves the test even further away from field application conditions.

However, as one of the benefits of SiC MOSFETs is their fast switching leading to low switching losses, the stress introduced by the steep voltage slopes (high dv/dt) might be more harmful than a usual HV-H³TRB procedure with DC voltage stress only. High electric field changes due to the switching combined with field distortions caused by humidity in the silicone gel on top of the chip's junction termination establishes additional stress for the devices. Another point is the change in electro-chemical reactions due to the switched high voltage instead of DC voltage and therefore, the impact on corrosion and dendrites.

For some SiC devices, the dynamic HV-H³TRB was only mentioned as passed [8] and a first test approach was reported in [9] in which 3.3 kV modules were tested under switched conditions, but with a focus on overshoots during condensation conditions at rather low dv/dt.

Fig. 1. Left: Single chip 3.3 kV SiC MOSFET in an engineering package filled with silicone gel; right: test stack built up with three half-bridges mounted on air coolers, busbar connection realised with a humidity robust multilayer PCB and additional snubber capacitors for the overvoltage suppression.

To meet the high reliability demand of automotive applications for power semiconductors, the dynamic HV-H³TRB test is already proposed in the appendix of [3]. Parameters aimed for are a dv/dt higher than 30 V/ns and a switching frequency between 15 kHz and 25 kHz. A dynamic HV-H³TRB conducted until end-of-life and with comparable DC HV-H³TRB results is still pending and is the aim of this work.

Design of Experiment

The Devices Under Test (DUTs) for the dynamic HV-H³TRB are 3.3 kV SiC MOSFETs similar to those of previous publications [5-6] (see Figure **1**). They showed excellent robustness against the HV-H³TRB test over 6,300 h. These single chip modules are engineering samples with frame-based packages designed for research, but with materials used in the production line of modules for traction use cases. The interior of the package and the chip are covered with silicone gel.
Unlike standard HV-H³TRB, the complexity to perform a dynamic HV-H³TRB is significantly higher. Instead of a DC voltage, a pulsed voltage is required, which is generated either by the DUTs themselves (active switching) or by other devices to which the DUTs are connected (passive switching). Depending on the active or passive approach, the amount of DUTs can be easily increased and gate units (GUs) might not have to be inside the climate chamber. Another important point is the acceleration factor of possible degradation of the DUTs with active or passive switching. So far, the available and published test results do not indicate, if the DUTs degrade quicker with active or passive switching. Therefore, 6 DUTs were arranged into three half-bridges (see Figure **1** for the built up DUT group and Figure **2** for the schematic).

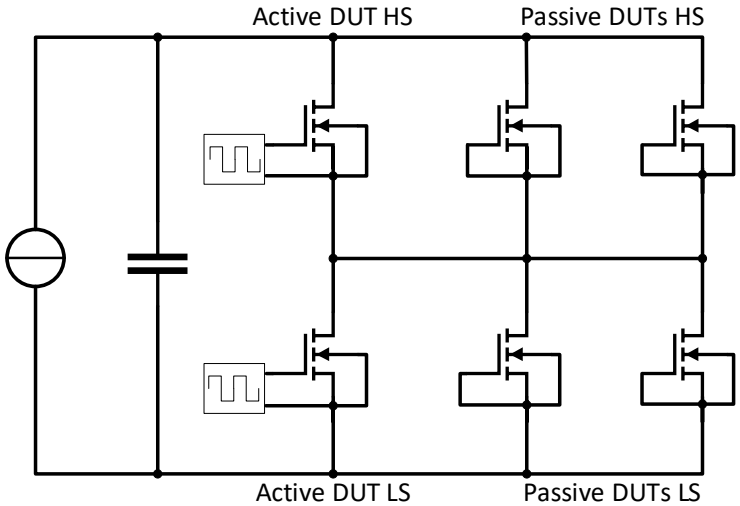

Fig. 2. Six DUTs arranged in three half-bridges, one half-bridge is actively switching with gate-units directly on top of them (HS: high side switch, LS: low side switch), the other two are passive half-bridges with their gates shorted to their source.

One half-bridge is actively switching with a GU at the gates, while the two other half-bridges have shorted gates and are subjected to the voltage slopes only passively. With no load current, the interconnections between the DUTs do not have to be copper busbars but can be achieved through a humidity robust multilayer PCB busbar with ceramic interlayers to ensure the high voltage insulation for the 3.3 kV devices even under 85% RH.

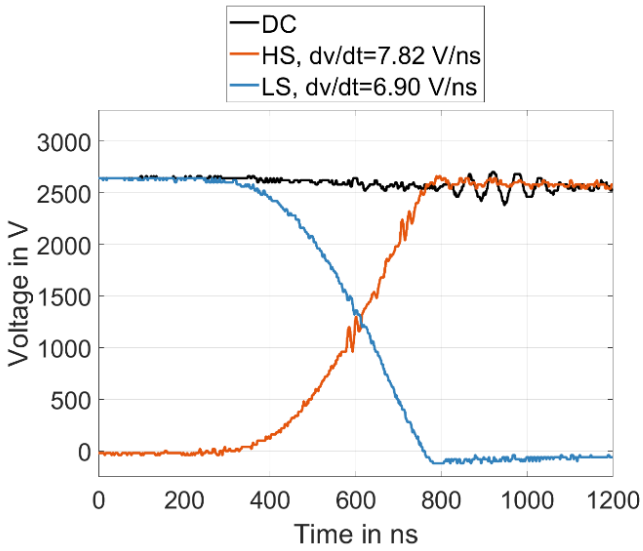

Fig. 3. Switching curves of the DUT stack, installed inside the climate chamber with parasitics like long DC voltage cables etc., achievable dv/dt of ca. 7 V/ns at 80% V_{nom} (2,640 V).

To compare later test results with HV-H³TRB tested DUTs high voltages are needed, because the 50-50% duty cycle doubles the test duration if there is neither additional nor accelerated degradation due to the switching. With this DUT stack, pulsed voltages up to 80% V_{nom} can be achieved using DC link snubber capacitors to suppress the voltage overshoots (see Figure 3). Because of the engineering package, the existing HV-H³TRB test setup with long cables leading into the climate chamber and to minimize the need of additional devices inside the climate chamber like clamping diodes, which have to be also humidity robust, only rather low switching speeds are achievable. Voltage transients of about 7 V/ns were measured at 1 kHz switching frequency calculated between 10% and 90% of 2640 V. The recommended 30 V/ns [3] are unrealistic with these DUTs and the setup, due to overshoots and ringing.

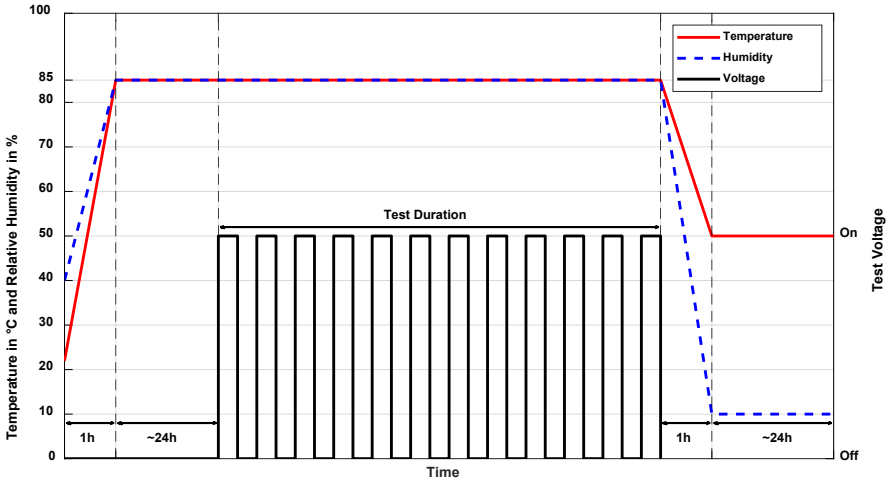

Fig. 4. Dynamic HV-H³TRB climate profile with a ramp up to 85/85 and after 24 h the turn-on of the switched test voltage, starting the actual test duration. A drying phase with 50°C & 10% RH for 24 h follows at the end before every intermediate measurement.

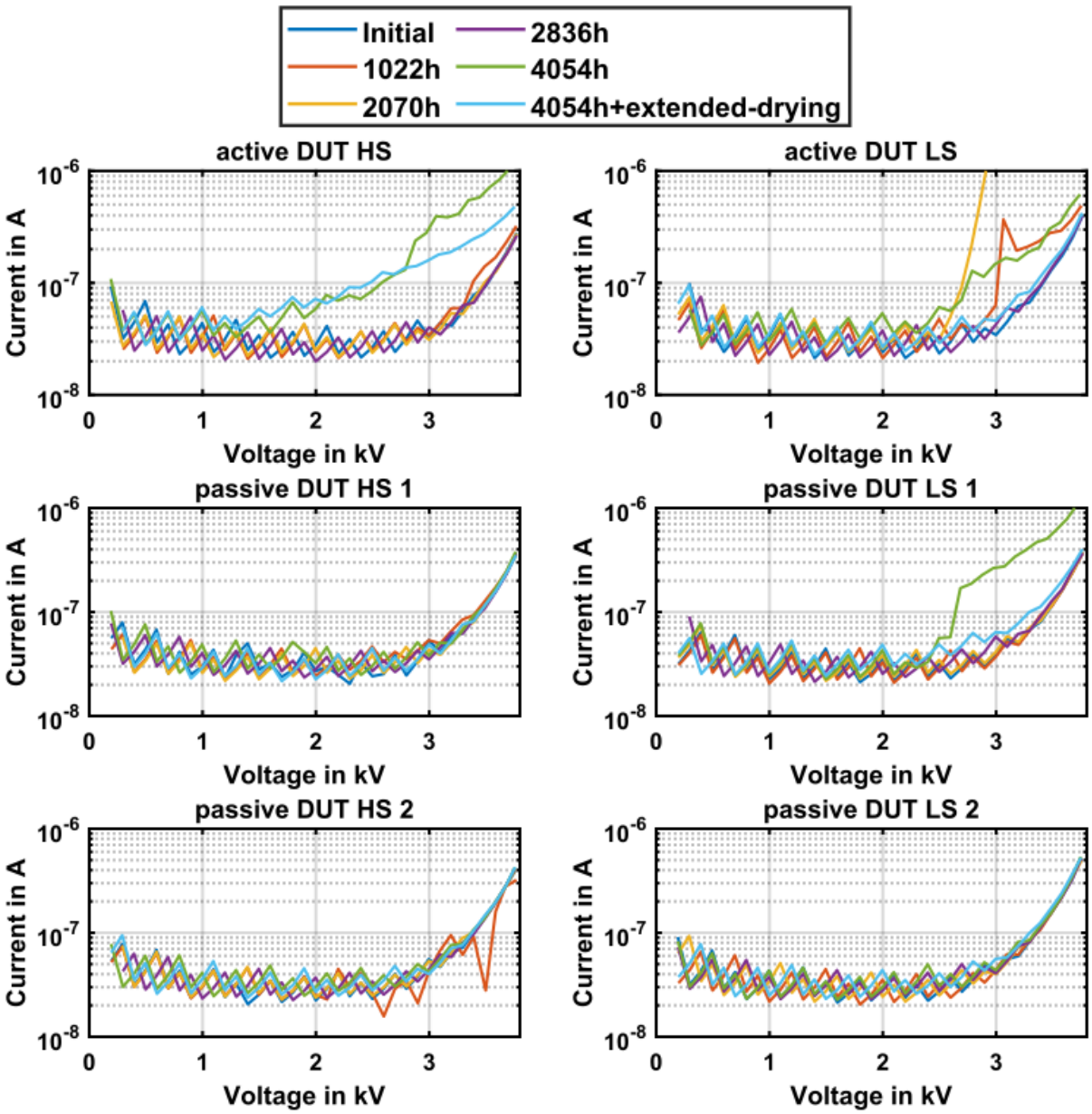

Fig. 5. Blocking curves of the DUTs, degraded active DUT HS even after extended drying, active and passive DUT LS before extended drying with a reduced blocking capability and passive DUT HS 1, HS 2 and LS 2 with no changes.

In [3] a switching frequency between 15 kHz and 25 kHz is suggested. At these frequencies, first tests with these DUTs show a too strong self-heating, which should be avoided according to the standards of H³TRB testing. Therefore, the switching frequency was lowered to 1 kHz with a duty cycle of 50-50% for this test. The test procedure is based on the standard HV-H³TRB procedure. After a ramp up to 85/85 within 1h the pulsed voltage is turned on after a 24 h soaking phase (see Figure **4**). With the voltage on the test duration starts. Intermediate blocking measurements are a proven method to detect humidity induced degradation and were taken after defined time steps to record the behaviour of the DUTs. Each intermediate measurement was preceded by a drying phase at 50°C and 10% RH for 24 h to ensure safe electrical measurements. The test was started with 50% of the nominal voltage (V_{nom}, 1,650 V) at first to cover early failures and was raised to 80% V_{nom} after 1,000 h.

Results

So far, 4,054 h of testing were completed and no module failed catastrophically yet. The “leakage” current is monitored, but is overlaid with oscillations caused by the switching currents, and is only used to detect a catastrophic failure of the DUT stack if the current exceeds the threshold of 50 mA. The intermediate measurements (IMs) were taken roughly every 1,000 h (1,022 h, 2,070 h, 2,836 h and 4,054 h) (see Figure ***5***). At first one active switching DUT showed a reduced blocking capability and two additional DUTs showed this behaviour in the last IMs. Two phenomena can be observed. Firstly, a reduced inception voltage, i.e. the voltage at which the leakage current starts to rise exponentially. Secondly, an increased leakage current compared to previous IMs, which is especially dominant for the active DUT HS. After the last IM at 4,054 h, an extended drying procedure at 85°C and 10% RH for more than 24 h was performed with the DUT stack to check if the deteriorated blocking behaviour is reversible. Except for one DUT, Figure ***5*** active DUT HS, with an only partially reversible blocking curve, all blocking curves returned to their initial measurements. This can be an indication of either residual moisture inside the silicone gel or possible delamination of layers at the junction termination that were filled with water layers and dried out only after the extra drying.

As there are no catastrophic failures, Weibull analysis does not work and an alternative method is required to compare different test groups. In Figure **6**, the method is to extract the inception voltage values by defining an appropriate current level of the blocking measurement for each DUT and plot the median voltage with the corresponding 25 % and 75 % quartiles of the test group. This gives the development of the blocking capability over test time. In Figure **6**, test results of [6, 10] and the dynamic test are compared. As reference the Silicon IGBT groups of [10] are included to show test groups with catastrophic failures and no blocking capabilities left. The DC HV-H³TRB test group of SiC MOSFETs survived over 6,000 h at two different test voltages, one even higher as for the dynamic test, and show no reduced blocking capabilities or changes that can be reversed through drying. The dynamic test group on the other hand has a drop at 4,054 h, which still slightly remains after extended drying. This leads to the assumption that the dynamic testing influences the DUTs already at lower testing time compared to the DC testing. If the duty-cycle of 50% is considered, the dynamic test group has only about 2,000 h, in which the DUTs are exposed to voltage.

It remains open, if it is a problem of the switching, humidity induced degradation or something else that is triggered. This can be only fully understood with analyses of failed DUTs, that still need to be generated within the continuation of the test. In any case, the modules already fulfil twice the qualification requirements for a standard HV-H³TRB (4,000 h·50% duty cycle = 2,000 h net exposure time to DC voltage) even under these harsher conditions, in contrast to the gate units with failures after 2,000 h.

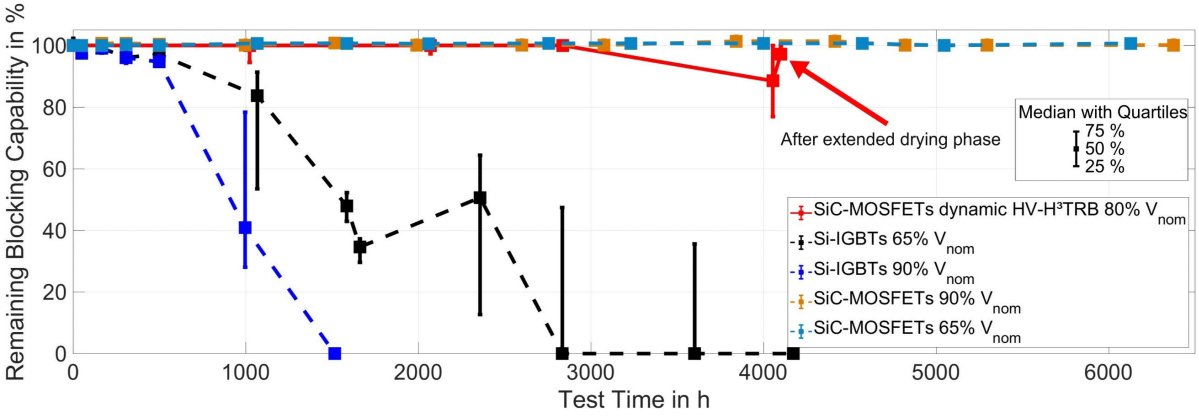

Fig. 6. Normalised remaining blocking capability over testing time for the DUTs and for comparison DUTs from previous publications [6, 10].

Summary

A dynamic HV-H³TRB test with 3.3 kV SiC MOSFET in engineering packages was carried out for more than 4,000 h of testing time. The DUTs were stressed with high temperature, high humidity and switched high voltage. Within the test time no catastrophic failures occurred, but some DUTs changed their blocking behaviour in intermediate measurements. Most of these changes could be reversed through extended drying.

Acknowledgements

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