

Sulphur Related Corrosion in Power Modules and its Impact on the Switching Performance

Michael Hanf¹, Raffael Schnell², Sven Matthias², Nando Kaminski¹

¹University of Bremen, Germany

²SwissSEM Technologies AG, Lenzburg, Switzerland

Abstract

High power semiconductor modules, exposed to polluted (i.e. H₂S) and moist climates can experience corrosion at the packaging materials. Sulphur and copper will form Cu₂S-dendrites in the insulation trenches of the substrates, which are able to short the insulation distance. But, previous experiments pointed out, that modules with excessive dendrite growth are able to withstand high blocking voltages under DC-bias. While most IGBTs will operate under switching operation with fast transients, ohmic connections at insulation distances will change the situation tremendously. For this study, 1200 V silicon-IGBT-modules in a standard package were preconditioned in an accelerated corrosive gas test and will be operated in a switching test bench to verify corrosion related performance issues in active operation.

Keywords: IGBT, Power Electronics, Reliability, Corrosion, Robustness, H₂S, Hydrogen Sulphide, Humidity

INTRODUCTION

The extended usage of power electronic components in various applications has led to a wider spectrum of mission profiles and stressors within the useful lifetime of these parts. Especially frequency converters and power supplies are often exposed to harsh climatic conditions containing high relative humidity [1] or reactive pollutants like sulphur [2], which lead to a reduced service life. Many reliability investigations on power electronics are focused on silicone gel (Si-gel) potted power semiconductor modules and their degradation behaviour under harsh climates. Moisture induced aging of these devices is well studied and the failure mechanism as well as the influence on the electrical performance are documented [3].

For corrosion products related to ionic contamination, the situation is different and rather complex. If moisture and atmospheric pollutants like sulphur dioxide (SO₂) or hydrogen sulphide (H₂S) are present, copper-sulphide-dendrites are formed in the insulation trenches on the copper-ceramic-substrate [4, 5], leading to ohmic conduction paths between the copper pads. Under dry DC-conditions, the leakage current of the chip conceals the parasitic current through the dendrites and therefore, no sulphur related degradation can be measured [5]. Based on these experiments, standard industry silicon-IGBTs are preconditioned in accelerated tests and split into different groups to distinguish between degradation states and mechanisms. To verify critical operation conditions, an IGBT turn-off switching test at high currents is performed afterwards.

CLIMATE RELATED DEGRADATION OF IGBTs

Power modules are widely tested under accelerated conditions in lifetime tests with focus on environmental stressors such as temperature and relative humidity. Furthermore, a high voltage bias close to the nominal voltage (V_{nom}) increases the stress [6] and leads to a more application relevant testing scenario. While testing under high humidity, the chip interface is attacked and aluminium corrosion at the edge termination causes a reduction of the blocking capability [3, 6]. Beside the aluminium corrosion, electro-chemical migration (ECM) can be observed [6] due to contamination in the manufacturing process, where metals form a conductive path at areas of high electrical field. If the contamination level is low and the potting material shows a sufficient adhesion on the surface, aluminium corrosion is the predominant failure mechanism and no ECM can be found at substrate level.

If a reactive pollutant like H₂S is added to the test, the degradation mechanism changes dramatically and inflicts the copper-ceramic-substrate. To keep the explanation of the relevant reaction equations as basic as possible, a Cu-surface is used instead of a Cu₂O-layer on top of the substrates. Fig. 1 illustrates the situation in the power module with a direct bonded copper (DBC) substrate, covered with Si-gel [4]. Both, H₂S and H₂O are able to diffuse through the gel matrix and will react with the metallic packaging materials.

Similar to moisture, sulphur can be stored inside the gel and therefore, corrosion can occur much later than the actual contamination.

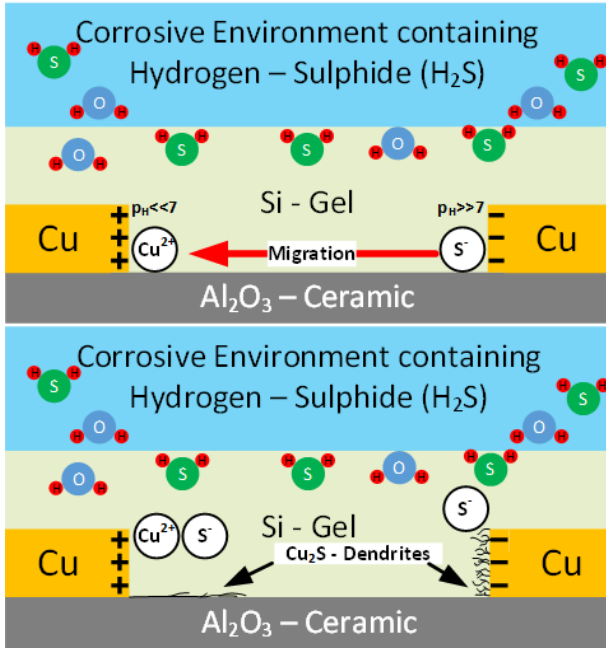
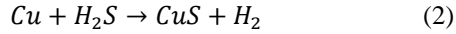
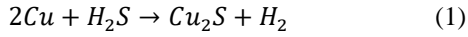
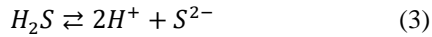


Figure 1: Mechanisms of H₂S-induced corrosion at a silicone-gel covered DBC-substrate, bias with high voltage

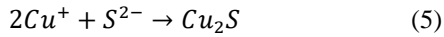
The Cu-surface is able to react with H₂S at high relative humidity and forms CuS/Cu₂S (copper sulphide) [7]:



The reaction to Cu₂S is thermodynamically more beneficial [7] and therefore, it is more likely to be found at the interface. The built-up surface layer will not cause major problems in the first place but the situation changes at the insulation trenches of the substrates, where a high electrical field is present and a galvanic cell can be formed. Referring to fig. 1, the H₂S molecule will reach the copper cathode through the gel and reacts to:



As a result of the high electrical field, the negatively charged sulphur ion will migrate to the anode:



The positively charged anode will form Cu⁺ (4) ions, which are attracted by the electrical field and will move towards the cathode. Due to the high concentration of sulphur ions in the anode area, the Cu-ions will react with the S-ions to Cu₂S (5). This leads to the growth of a dendritic structure from the anode to the cathode on top of the ceramic surface over time. These types of structures are able to grow over the full length of the insulation trench and reach the cathode [5]. The results from [5] indicated a secondary effect at the cathode, which is much faster than the anodic growth. In general, Cu₂O-dendrites on DBC-substrates covered with Si-gel are not reported as long as the adhesion is intact. Therefore, a classical ECM like described in [8] cannot explain the structure, because the Cu-ion itself is unable to reach the cathode to form a dendrite. Nevertheless, this

secondary structure at the cathode is present after a short exposure to high relative humidity and high H₂S-concentrations. Furthermore, this effect saturates over time and inflicts the complete cathodic area [5] from bottom to top of the pad. It is not reported, that these structures can grow across the full trench and therefore, this will be handled as a testing artefact, which is able to reduce the insulation distance by a certain amount.

Discussion:

The documented corrosion effects, related to high humidity, are widely accepted and there are solutions available to avoid this degradation on chip level [9]. While the humidity driven failure mechanisms are understood, the influence of ionic contamination changes the situation. The primary corrosion mechanism forms an anodic dendritic structure due to the high level of ions around the anode. This effect faces a threshold due to the time constant of diffusion through the gel and the growth starts after H₂S reaches the metallic interface. ECM in the presence of ionic contaminants is well documented [10, 11], but these experiments are performed without insulation materials on top of the metallic contacts. If a surface coating is applied and the adhesion is intact, ECM like in [10] will not occur in that manner. First of all, Si-gel can store a much higher concentration of H₂O [12] than the surrounding air and the same might be valid for the H₂S-concentration. Therefore, the high concentration will lead to precipitates [10, 11] and this results in anodic, rather than cathodic growth. In this case, the mechanism is described as an anodic migration phenomenon (AMP) [13] and is closer to the formation of conductive anodic filaments (CAF) [14], than to ECM-based dendrite growth.

As stated in [5], the impact of the resulting copper structures on the electrical behaviour is not conclusively identified. Even after excessive growth, the power modules in [5] were able to withstand their rated blocking voltage and the chip leakage current still covered the parasitic current of the AMP completely.

DESIGN OF EXPERIMENT AND TEST SETUP

When it comes to accelerated testing of power semiconductor modules, a DC-bias is generally used to stress the devices in an easily controlled way. For applications, this operation and stress conditions are not reflecting the actual mission profile and therefore, a corrosion product, which is uncritical under DC-conditions, might be a problem when it comes to switching events at high currents.

For that purpose, 1200V IGBT-modules were preconditioned in an HV-H³TRB- and a single corrosive gas test to have different states of degradation. These preconditioned devices were operated in a turn-off switching test, the same that is part of the post production

Split	Quantity	Test Conditions	Test Time	Degradation
HV-H ³ TRB	8	85°C/85RH/80% V _{Nom}	2000h	Not measurable
H ₂ S-400h	2	40°C/93%RH/80% V _{Nom} / 50ppm H ₂ S	400h	Cathodic dendrites
H ₂ S-1000h	2	40°C/93%RH/80% V _{Nom} / 50ppm H ₂ S	1000h	Anodic & cathodic dendrites
H ₂ S-1500h	3	40°C/93%RH/80% V _{Nom} / 50ppm H ₂ S	1500h	Anodic & cathodic dendrites
Humidity Ref.	2	40°C/93%RH/80% V _{Nom}	1000h	Not measurable

Table 1: Overview of splits, quantities and test conditions. Split 1 (HV-H³TRB), will be just tested dynamically after the preconditioning.

testing to verify the influence of life time testing on the dynamic behaviour.

Devices under test

A 1200V/750A ED-Type IGBT-module (fig. 2) from *SwissSEM Technologies* was used for this investigation. These types of packages:

- ED-Type (SwissSEM)
- EconoDUAL (Infineon)
- LoPak (Hitachi Energy)
- Etc.

are preferable to use for this kind of testing due to the package design. First of all, these types come with a removable lit as well as a rather open package design. The removable lit, allows a sufficient monitoring of the corrosion state in intermediate measurements without damaging the devices. Furthermore, the corrosion rate can be enhanced by removing the lit in the corrosive gas test to expose the surface of the Si-gel directly to the environment [5].

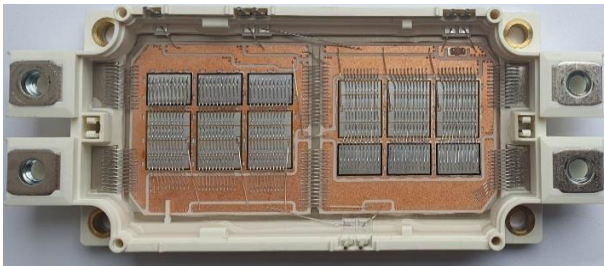


Figure 2: Device under test: ED-Type IGBT-module

Test procedure and setup

The corrosive gas testing is executed in a climate chamber according to IEC60068-2-43 at 40 °C, 93 % relative humidity (RH) and 50 ppm H₂S. Referring to [5], this climate shows a sufficient acceleration of the desired corrosion mechanism without triggering moisture induced degradation at the chip interface. Another interesting aspect is the calibration of the chamber with sensor elements. This is just useful, if the temperature is

≤ 40 °C, to allow the usage of chemical sensors directly in the chamber. The high relative humidity (> 90 %) will lead to an early degradation of the sensing element, but a measurement duration of at least 48 h is possible. Fig. 3 shows the calibration run for > 48 h with an analog gas- (measurement range up to 100 ppm), and a digital humidity sensor (RHT-sensor). While the temperature and relative humidity stabilises after ~ 1 h, the gas concentration is not fully stable over this test time. This can be explained by the critical relative humidity in this climate, which slightly exceeds the limit of the sensor and at 40 °C, this sensor operated at the maximum possible temperature. Using the gas sensor beyond this time frame leads to insufficient results and is not done for this experiment. In contrast, the RHT-sensor with protected interconnections can last for much longer time periods. The climate verification was combined with a corrosion indicator calibration. Cu-strips were prepared according to IEC60068-2-60 and the weight gain as well as the weight loss are used as an indication for the corrosion rate. As described in [5, 7, 15], a Cu₂S-surface is formed when exposed to the harsh climate inside the chamber. The gain in material leads to an increase in weight and this is measured by a high-resolution scale (10 µg) before and after the test cycle. Furthermore, the corroded indicators were cleaned according to EN ISO 9226:2012 and a weight loss measurement was executed additionally.

Dendritic growth, i.e. a directed growth, is just possible under the presence of a high electrical field at the

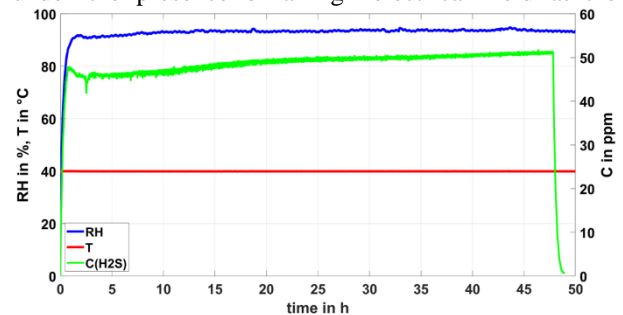


Figure 3: Calibration measurement of climatic conditions inside the chamber with H₂S- and RHT-sensor

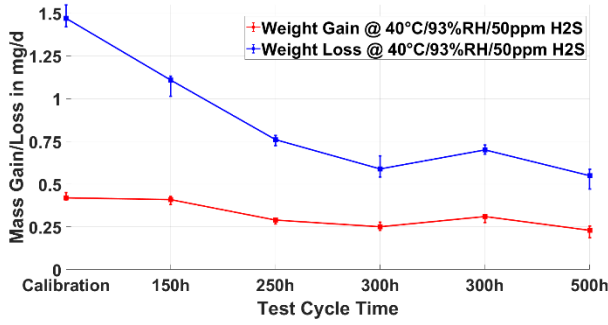


Figure 4: Corrosion monitoring with Cu-strips exposed to 40 °C / 93 % / 50 ppm H₂S.

interface. Therefore, a high-voltage (80 % V_{nom}) data acquisition system with eight separate channels was used to monitor the status of the devices and to execute a turn-off procedure in case of a failure. For this experiment, just the high-side switches were connected to high voltage due to the auxiliary collector layout of the substrate, which leads to another possible degradation path. An optical inspection after each test cycle (fig. 4 & 5) was done to control the corrosion state of the device. In tab.1, different corrosion states were separated with respect to the corresponding structure (fig. 1). In parallel, tests at 85 °C, 85 % RH, 80%V_{nom} and 40 °C, 93 % RH, 80 % V_{nom} were executed to have a reference under moisture stress only.

The preconditioned samples were tested in a static and a dynamic testbench to compare the electrical properties before and after the test. In the dynamic testbench, a turn-off event at 2·I_{CES, nom} is measured with an expected voltage overshoot reaching the total voltage of 1200 V. This procedure is a pass-/fail-test and will just verify the a fully operational condition after accelerated aging testing.

PRECONDITIONING RESULTS

Corrosion monitoring with Cu-strips

Fig. 4 shows the result of the corrosion monitoring with Cu-strips for all test cycles with the corresponding weight gain and loss. The calibration run was fully sensor monitored (fig. 3) and the test cycles up to 1000 h were observed with an RHT-sensor (the sensor failed in the last test cycle). Overall, the percentage weight loss per day is much higher than the measured weight gain. This can be explained by the brittle surface of the Cu-strips and the resulting mass loss inside the chamber. After each test cycle, Cu₂S-flakes were found all around the chamber and in the condensed water at the tester output. Furthermore, the gain and loss rate are nearly constant for test durations > 250 h. On the contrary, the calibration run at 50 h and the first test cycle at 150 h show a significant difference in the mass loss per day. The corrosion rate of Cu in H₂S containing moist air is highly non-linear due to the passivation effect of Cu₂O and Cu₂S. With increasing layer thickness, the supply of Cu is retarded and therefore, the growth rate is decreasing.

In [7], the growth rate is divided into a linear part and a parabolic part with respect to the metal surface over the test time. The same effect can be assumed for the results in fig. 4, with a highly decreasing rate from 50-250 h of test cycle time. Especially the first hours of testing have a high influence on the layer thickness [15] and the resulting corrosion products in the weight gain and loss measurement.

These measurements can now be used to generate an impression of the acceleration factor in relationship to the application relevant climatic conditions. Due to the lack of reliable field data with focus on H₂S-pollution, the corrosion categories defined in EN ISO 9223:2012 are used. The values from fig. 4 are used for a calculation of the corrosion velocity according to EN ISO 9226:2012:

$$r_{corr} = \frac{\Delta m}{A \cdot t} \quad (6)$$

As a result of the significant difference in the mass loss for shorter test cycles, Δm is averaged from the last four test cycles (similar loss rate) resulting in:

$$r_{corr} = \frac{\Delta m}{A \cdot t} \approx 3000 \frac{g}{m^2 \cdot a} \quad (7)$$

Tab. 2 shows the corresponding acceleration factors for Cu-corrosion based on the calculation (eq. 7) for each corrosion category according to EN ISO 9223:2012.

The acceleration factors in tab. 2 are of course just an estimate for the correlation between the testing and the application. But, with these categories, a corrosion state in the test can be extrapolated to the field, if the category is know. E.g. 1000 h in the test at the climatic conditions from fig. 3 & 4 would lead to a corrosion state similar to 14 – 30 years in category C4 (based on corrosion products with just one contaminant and constant conditions).

IGBT-module preconditioning

The test matrix in tab. 1 is based on the optical corrosion monitoring after each test cycle. At 400 h of accumulated

Category	r _{corr,Cu} [$\frac{g}{m^2 \cdot a}$]	Acceleration Factor
C1	≤ 0.9	≥ 3333
C2	0.9 – 5	3333 – 600
C3	5 – 12	600 – 250
C4	12 – 25	250 – 120
C5	25 – 50	120 – 60
CX	50 – 90	60 – 33

Table 2. Corrosion categories according to ISO9223 with the corresponding acceleration factors for the chamber climate

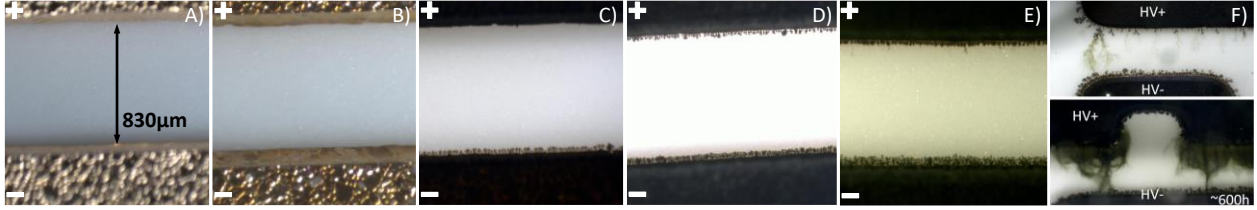


Figure 5: Preconditioned samples with different corrosion states in comparison to a reference state F) at the same climate [5]: A) Initial status, B) 2000 h HV-H³TRB at 85 °C / 85 % RH / 80 % V_{nom}, C) 400 h at 40 °C / 93 % RH / 50 ppm H₂S / 80 % V_{nom}, D) 1000 h at 40 °C / 93 % RH / 50 ppm H₂S / 80 % V_{nom}, E) 1500 h at 40 °C / 93 % RH / 50 ppm H₂S / 80 % V_{nom}

testing time, each sample showed the cathodic dendritic structures, described in fig. 1. Two samples with this specific corrosion state, showed in fig. 6 C), were removed from the test. In fig. 5 D), the final state after 1000 h of testing time is shown, with a clear evidence of beginning anodic growth as the main degradation mechanism. Due to the small amount of very short dendrites, the testing time for the remaining samples was extended up to 1500 h (fig. 5 E)). Overall, the growth rate is significantly lower compared to the result in [5] (fig.5 F)). In both test campaigns, comparable packages, the same test equipment (but different calibration) and the same climatic conditions were used. The only difference is the voltage class of the modules and the resulting lower test voltage. In [16], the electrical field is characterised as a predominant acceleration factor for ECM, with a defined threshold for every migration mechanism. A smaller electrical field can lead to highly delayed growth and might also change the composition of the resulting structures. In this case, the average insulation distance at the substrate is around 830 µm, which would lead to the following electrical field:

$$E = \frac{V}{d} = \frac{960V}{0.83mm} \approx 1150 \frac{V}{mm} \quad (8)$$

In the previous publication [5] on similar modules, the insulation distance was smaller and the bias voltage higher and therefore, the electrical field was 27 % higher. Furthermore, the surface of the substrate in fig. 5 is much cleaner (from the optical view) compared to the previous publication [5]. These factors led to the rather small dendrites and the overall high remaining insulation distances at the substrates even after 1500 h of exposure. The two humidity only splits showed no degradation after the preconditioning and the substrates just indicate a higher Cu₂O-surface thickness compared to the initial state (fig. 5).

POST TEST CHARACTERISATION

Static results

The samples of the corrosive gas testing as well as the humidity references at 40 °C and 93% RH were characterised before and after the treatment. Each sample was measured in a post-production test cycle and a

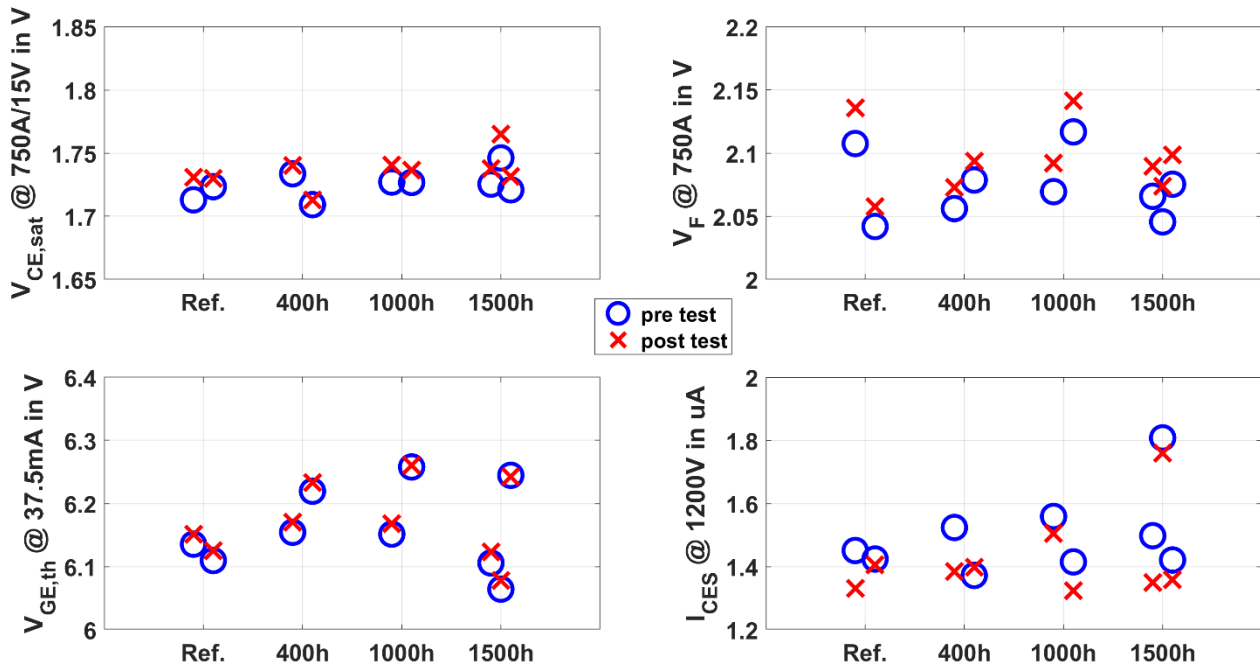


Figure 6: Static characterisation before/after the corrosive gas testing with H₂S (400 h, 1000 h, 1500 h) and the exposure to the same climatic conditions without gas supply (Ref.)



Figure 7: Setup for the soaking experiment with tested and new modules. An air sealed box is filled with water and stored in a climate chamber at 50 °C for 48 h.

selection of these values, taken at 25°C, are presented in fig. 6. The measurement values for the conduction losses of the IGBT as well as the diode are shifted to higher voltages across all samples. This is still within the normal scattering of these modules and with respect to the different corrosion states, a measurement artefact is most likely the reason for the deviation. No significant degradation was expected for these values as well as for the threshold voltage ($V_{GE, th}$). From testing under high humidity, the reduction of blocking capability is well known and reported [3, 6], therefore, an increase of I_{CES} at 1200 V could be a sign of decreasing insulation capability or corrosion at the chip interface. But, none of these can be stated at dry conditions by the data in fig. 6. The scattering in this measurement is attributed to the usage of a different measurement systems for the pre- and post-characterisation. Primarily, the semiconductors in

this package are robust enough to survive 2000 h at HV-H³TRB conditions and therefore, no chip degradation was expected at 40 °C / 93 %. Referring to [5], even excessive dendritic growth in a much more pronounced appearance is not significantly influencing the blocking capability. The corrosion states in fig. 5 show a low number of dendrites too small to successfully short an insulation trench.

The material composition (especially the metal concentration) of the dendritic structures have a significant influence on the conductivity and the chance of a breakdown event is higher in the presence of humidity [8]. This leads to another approach in measuring the blocking voltage, again after a soaking experiment under high relative humidity.

The setup is shown in fig. 7, where the contaminated modules are stored in an air tide, water filled box. At 50 °C, the air gets saturated with water over time and the modules can be soaked in humidity for a time period of 48 h. For the next characterisation loop, just the module with the longest and most dendrites were used and compared to a new module to distinguish between temperature-/moisture and corrosion driven effects. In fig. 8, modules without corrosion (one new module and one part of split: “Humidity Ref.”) are shown together with two modules from split: “H₂S-1500 h” and a HV-H³TRB sample. The significant difference in the moist and dry blocking curves is not just related to the higher temperature of 50 °C. Therefore, a temperature compensation [17] was used to shift the initial dry curve to 50 °C:

$$C = 2^{\left(\frac{T_{init}-T}{11K}\right)} \quad (9)$$

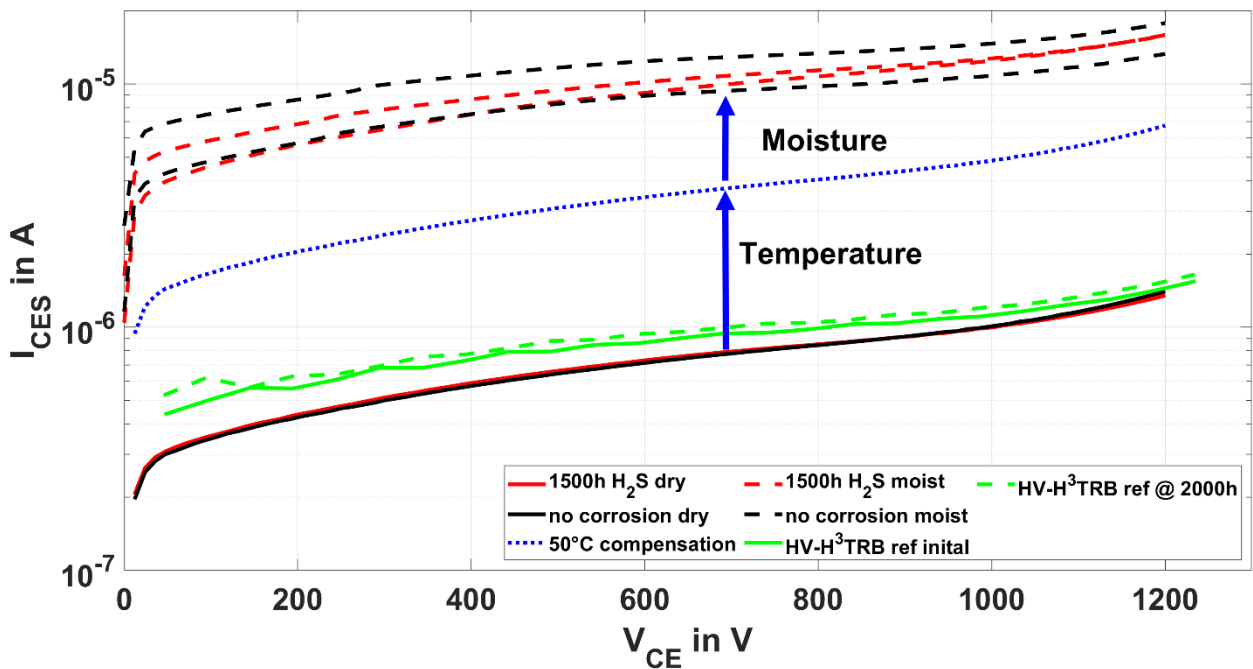


Figure 8: Blocking curves with dry and moist modules as well as HV-H³TRB reference. The measurement of the HV-H³TRB sample was performed in a different measurement range due to the expected degradation, which causes the off-set in the plot. The blue curve is the calculated 50 °C (eq. (9)) curve of a dry, new module.

Split	Quantity	Dry Test at 800V/1500A/125°C	Moist Test at 800V/1150A/50°C	Degradation
HV-H ³ TRB	8	8/8 passed	-	Not measurable
H ₂ S-400h	2	2/2 passed	-	Cathodic dendrites
H ₂ S-1000h	2	2/2 passed	1/1 passed	Anodic & cathodic dendrites
H ₂ S-1500h	3	3/3 passed	2/2 passed	Anodic & cathodic dendrites
Humidity Ref.	2	2/2 passed	1/1 passed	Not measurable

Table 3: Results of the switching test with high currents. The test is passed if the module is not destroyed in after the test procedure and the parameters were adjusted for the moist test to keep the voltage overshoot close to the nominal voltage.

The factor C is used as a multiplier for the leakage current and this can be utilised to shift the curve to higher temperatures. In fig. 8 this calculation separates the two different effects into a temperature and a moisture driven off-set. Nevertheless, all four measurements at a soaked state show a comparable behaviour and no clear tendency regarding the corrosion in the insulation trenches can be isolated. The only difference in the behaviour can be seen around 700 V for one of the corroded devices, where the curve shifts to a different slope.

In conclusion, the minor dendritic growth is not leading to any changes in the static behaviour. Even after the modules are stored under high humidity, no reduction in blocking capability can be attested.

Dynamic characterisation

To characterise the dynamic behaviour, a pass-/fail-test fulfilling a certain specification of the device is used. In this case, the device needs to be able to turn-off twice the nominal current at any time. As with the static characterisation, the measurement is split in a dry and a moist measurement. The results of these switching tests are shown in tab. 3 and all splits passed the procedure successfully.

The dry testing was executed at 125 °C (voltage overshoot limited to 1200 V) and an exemplary waveform of a humidity ref (40 °C/93 % RH/80 % V_{nom}) and a H₂S-preconditioned device is shown in fig. 9 (A). Both devices show the same waveform with comparable

dv/dt and overshoot. No signs of degradation can be seen from these curves and the modules were fully functional afterwards. Even modules with an HV-H³TRB preconditioning of 2000 h passed this test, which attests a very robust module design. Furthermore, the test under moist conditions, led to the waveforms in fig. 9 (B.)) with significantly increased oscillation at V_{CE}. The current was adjusted to ~1.5 I_{CES,nom} to control the voltage overshoot.

These oscillations are a result, caused by the lower temperature of 50 °C and changed switching behaviour of the bipolar semiconductor chips. Nevertheless, an influence of corrosion or the exposure to high concentrations of H₂S is not confirmed due to the fact, that unused modules show a comparable switching waveform under moist conditions.

Discussion

The preconditioned modules showed just optical signs of non-critical (few, short dendritic structures) corrosion (H₂S-exposure) and this finding was confirmed by the static measurement. There is no permanent degradation at the metals measurable and even the insulation materials like the housing-plastic and the Si-gel are still able to perform under critical electrical load. The overall excellent operation under static conditions correlates with the dynamic behaviour at high current switching. In conclusion, a degradation effect, which is not measurable

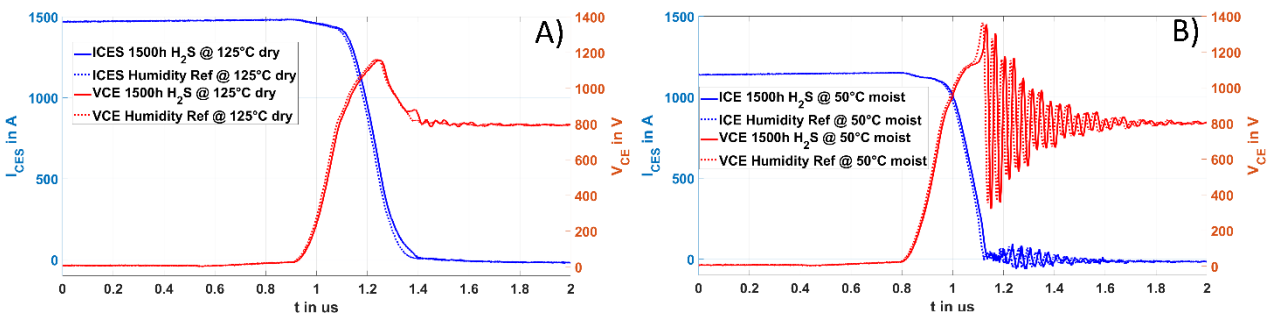


Figure 9: Switching curves of humidity and H₂S-preconditioned modules at 800 V:

A) dry conditions at 125°C and $2 \cdot I_{CES,nom}$ (1500 A),

B) moist conditions at 50°C and $\sim 1.5 \cdot I_{CES,nom}$ (1150 A), the switching current was reduced to limit the voltage overshoot

under static conditions has also a neglectable impact on the dynamic behaviour.

But, a change in the static behaviour can be achieved by a humidification preconditioning. If the IGBT-modules are moist, their blocking curves are shifted to higher leakage currents. The shift in the blocking curve is supposed to be not critical, since the nominal blocking voltage is still reached without any premature avalanche.

CONCLUSION AND OUTLOOK

In this study, standard IGBT-modules were preconditioned in harsh climate to evaluate the influence of corrosion products on the static and dynamic behaviour. The overall robust design of the modules prevented critical degradation after 2000 h of HV-H³TRB testing and the wide insulation distances on the substrates slowed the dendritic growth due to the H₂S exposure. Therefore, it was impossible to inflict enough degradation (in an acceptable time frame) to the devices to show a significant influence of the corrosion on the electrical performance. The tested module type performs excellent in these climatic tests and some of the design decisions can be regarded as improvements to inhibit certain corrosion effects. Especially the H₂S-induced dendritic growth at the substrates was prevented by the substrate design, which lowered the electrical field and decelerated the process. Summarised, the corrosion products were uncritical in the optical inspection and the same result was obtained from the electrical characterisation afterwards. Even modules with long testing times could withstand a high current turn-off event without failing and a significant influence of a high moisture content in the Si-gel could not be proven. This experiment could be executed for any Si-gel potted device type and if the corrosion products or the climate related degradation is measurable, the turn-off event might cause a different result. For applications in corrosive environments, the insulation distances inside the module should be considered if ionic contamination is expected in the surrounding air.

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Addresses of the authors

Michael Hanf, University of Bremen, 28359 Bremen, Germany, michael.hanf@uni-bremen.de
Raffael Schnell, SwissSEM Technologies AG, Lenzburg, Switzerland, raffael.schnell@swiss-sem.com
Sven Matthias, SwissSEM Technologies AG, Lenzburg, Switzerland, sven.matthias@swiss-sem.com
Nando Kaminski, University of Bremen, 28359 Bremen, Germany, nando.kaminski@uni-bremen.de