

Temperature Humidity Bias (THB) Testing on IGBT Modules at High Bias Levels

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Abstract

The temperature humidity bias (THB) test is a standard for accelerated life testing with respect to corrosion and other humidity driven degradation mechanisms. Usually, 1000 h tests at 85°C and 85% relative humidity are used to predict up to 25 years of operation and the bias is usually limited to 80 V in order to fulfil the respective standards asking for limited self-heating. However, it was suspected that a higher bias level is a more severe test condition and should be at least in the order of the typical DC-voltage. In this work a variety of 1700 V and 1200 V IGBT modules from different manufacturers were tested in THB at bias levels up to 90% of nominal voltage. The higher bias resulted in significantly more stress symptoms compared to the respective 80 V references. Depending on the devices under test particular degradation modes were measureable. The failure analysis yielded clear indications of electrochemical migration. Finally a test with 65% and 90% of the nominal voltage was employed to determine the acceleration due to bias. The result was a factor of about two and emphasises the fact that bias is indeed a strong acceleration factor. In fact, the reference samples biased with 80 V did not show degradation of the blocking capability, though, electrochemical migration has been identified there, too.

1 Background

Since its development in the 1980s the Insulated Gate Bipolar Transistor (IGBT) has achieved a key role in power electronic systems by combining the advantages of the bipolar junction transistor, i.e. high current density and low saturation voltage, with the simple isolated gate control of the MOSFET. Currently, IGBT power modules prevail in the voltage-range from a few hundred volts in medium power conversion systems, up to several kilovolts in industry, traction, and renewable energy applications in the multi megawatt range as well as transmission and distribution solutions reaching almost a gigawatt.

Although usually operated in air-conditioned cabinets more and more IGBTs have to perform under harsh environmental conditions with high ambient relative humidity (RH). In contrast to the traditional thyristor housings the IGBT modules are affected by the ingress of moisture because they are not hermetically sealed and moulding-compounds as well as silicone gels are not impermeable against humidity. Thus, moisture diffuses through the package and reaches the semiconductor chip. There a variety of corrosion mechanisms can occur, resulting in gradual degradation of the device's electrical performance and finally in a catastrophic failure of the chip. The situation becomes more challenging with miniaturisation, i.e. smaller distances between conductors and generally decreased component area.

1.1 Humidity Induced Failures

It is well-known that the penetration of moisture has a big influence on the reliability of semiconductor devices and

even a small change in RH can have a large effect on the devices' median time to failure t_f [1]. However, there is a variety of different deterioration mechanisms.

One class of mechanisms is "hydro-mechanical". Intruded humidity can build up a pressure inside the housing when the device is heated, e.g. during soldering. This may result in cracks in the package or delamination of the substrate ("popcorning") [2]. In some cases such effects can happen already due to hygroscopic stress built up in the plastic encapsulating material [3]. Usually, those effects are less critical for IGBT modules because in there the chips are covered with soft-mould, i.e. silicone gel.

The more important class of mechanisms is related to corrosion [4]. The way corrosion arises depends strongly on the materials involved as well as on the presence of contaminants. Moisture and high electrical fields within the package yield to leaching of ionic species. Typical examples are corrosion of copper and of solder joints. The chemical reaction between e.g. chlorine contamination and water can speed up the process massively [5]. Another variant is cranny corrosion due to hydrolysis. In those cases corresponding high temperature stress tests without humidity do not show any abnormality.

However, the most common mechanism occurring in electronic devices under high humid conditions is the electrochemical corrosion (e.g. metal corrosion). By formation of a closed nano-scale water layer (electrolytic solution layer) on the insulator surface linking two adjacent conductors with different potentials, a corrosion cell can build up [5]. For an IGBT chip the most critical region is the junction termination with the metallisation of the active area (cathode) and of the channel stopper (anode) be-

ing the adjacent conductors on different potential. The process starts with the decomposition of water (see Figure 1a) and the movement of the resulting ions according to their respective charge and the applied electric field. Dependent on the solution properties cathodic reactions may be oxygen reduction and/or hydrogen evolution (see Figure 1a), while at the anode metal is corroded off the electrode and the formation of metal complexes, salts, or oxides is possible [6].

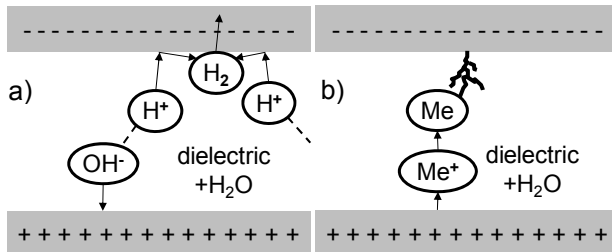


Figure 1 ECM between metallisation stripes [4]; a) Decomposition of water and metal corrosion, b) Metal migration and formation of a dendrite.

1.2 Electrochemical Migration (ECM)

Probably the metal corrosion itself would be less problematic for power devices. However, under the influence of the applied electric field the anodically dissolved metal ions will migrate towards the negatively charged cathode [4, 5]. There they are deposited and recombine to neutral metal atoms if the applied voltage exceeds the sum of the anodic and cathodic standard potential in aqueous solution [7, 8], which is always the case for reverse biased high voltage devices (see Figure 1b). The corrosive current is, thus, carried by electrons in the metallisation and by ions in the solution [8]. Because the metal ions move in the direction of the highest field they end up at inevitable field tips on the cathode side. This way they form dendrites, i.e. tree like structures, which deteriorate the insulation capability of the junction termination and, finally, lead to a catastrophic breakdown of the chip.

Altogether, the term electrochemical migration (ECM) refers to a three step process: Corrosion of one electrode, metal migration, and metal redeposition on the other electrode [4]. Depending on the specific situation each of the individual processes might be the limiting one and, thus, modelling of ECM is rather difficult. However, the progress of ECM is known to be influenced by the temperature, by the humidity, by process and service related contaminants, and by the electric field, i.e. the applied voltage in conjunction with the conductor layout [5, 8 - 10].

And of course ECM depends strongly on the metal(s) involved. A good example is the classification into so-called humid ECM, where an invisible thin film of moisture adheres to the surface, and wet ECM having a visible layer of water on top. Only silver (Ag) and copper (Cu) will start to migrate under humid conditions already, while other susceptible metals like nickel (Ni), lead (Pb) or tin (Sn) require wet conditions [9, 11]. Due to the required water layer the latter effect is less critical for IGBT

modules and the metallisation material aluminium (Al) usually used for power devices is supposed to show quite weak ECM because of the formation of a self-protective layer. However, a semiconductor module contains a lot of different materials and there might be more but still unknown factors influencing ECM [8].

2 Accelerated Life Testing

2.1 Necessity for THB Testing

Accelerated stress testing is the only way to get an estimate about the long-term reliability of devices still within their qualification phase. Usually, 1000 h tests are used for predicting up to 25 years of operation. To achieve the necessary acceleration the (environmental) test conditions have to be much harsher than the usual operation conditions. Obviously, the acceleration factor is most critical and the higher stress level must not trigger additional but irrelevant failure modes.

Proper acceleration models are required to calculate the test conditions necessary to assure a minimum time to failure or vice versa, the time to failure based on certain test conditions. Ideally, the acceleration model is based on the knowledge of the underlying phenomenon and consists of physical parameters. However, those parameters are sometimes difficult to obtain or the involved mechanisms are too complex to be modelled from first principles. Therefore, the usual approach is to fit experimental results collected under well-defined test conditions and verify the result with actual field-data. Of course, it is essential to know the main factors that limit the lifetime during operational life and to satisfy the laws of physics, so most fitting models contain a “physical core”. Furthermore, meaningful and well-defined test standards are required to have a close-to-reality prediction. In case of the test for corrosion and ion migration, the temperature humidity bias (THB) test is deployed for decades and its standard conditions are 85°C and 85% RH (85/85), to stay at normal pressure and not to trigger additional failure mode like in the so-called pressure-cooker test at temperatures > 100°C and significant overpressure.

2.2 THB Acceleration Models

Various acceleration models based on different corrosion scenarios are proposed in literature. An overview can be found e.g. in [12]. However, only a few seem to be appropriate for the prediction of failures due to ECM.

DiGiacomo determined that an acceleration model useful for projection purposes is based on the theories of condensation, ionic migration and thermally activated mechanisms [7]. In the scope of his investigations on the migration behaviour of silver in encapsulated packages he developed the model

$$t_f = \frac{Q_c}{\beta \cdot J_{up}} \quad (1)$$

where Q_C is the critical amount of metal ions that must migrate to achieve dendrite growth across a gap and β represents the fraction of the active surface or degree of oxidation. J_{tip} is the current density at the dendrite tip. Despite of the physical description of the electrolytic migration phenomena, this model has low relevance because of the inclusion of physical parameters that are difficult to obtain [12].

Another approach goes back to the Arrhenius equation, which is the common approach to describe the quantitative dependence of a reaction rate on temperature. As the median time to failure t_f is inversely proportional to the reaction rate of the deteriorating process the equation for t_f reads:

$$t_f = A_1 \cdot \exp\left(\frac{E_A}{k \cdot T}\right) \quad (2)$$

In this equation A_1 is a fitting parameter, E_A is the activation energy for the chemical reaction, k is Boltzmann's constant, and T is the absolute temperature. It is important to note that the Arrhenius model includes temperature stress only, which excludes the possibility to model interactions with additional stress factors. This was included later by employing an Eyring equation:

$$t_f = A_2 \cdot T^\alpha \cdot \exp\left(\frac{E_A}{k \cdot T} + \left[\beta + \frac{\chi}{T}\right] \cdot S_1 + \dots\right) \quad (3)$$

Here A_2 is a fitting parameter and α , β , χ are constants representing the stress interactions. $S_1 \dots S_n$ represents the n different stresses, which would be considered to be e.g. relative humidity and voltage in case of the THB test. So the Eyring Model restates the Arrhenius equation more detailed with the disadvantage of a rapidly growing complexity and uncertainty by adding stress functions [12]. In 1968 Hornung took another approach refining the simple Arrhenius model for dendrite growth by taking into account the electrical stress [12], i.e. detailing A_1 of (2):

$$t_f = \frac{\alpha \cdot d}{V} \cdot \exp\left(\frac{E_A}{k \cdot T}\right) \quad (4)$$

Here α is a fitting parameter, d represents the spacing between electrodes, and V is the applied voltage.

However, the most wide spread approach is Peck's model [13 - 16], which was originally developed to calculate the usual requirements of 10% failures within 1000 h at 85/85. It is a statistical review of time to failure experiments of several decades (!) and is strictly based on the experimental observations [13, 15] as well as on the assumption of aluminium corrosion being the deteriorating process in moulded discretes. Nevertheless, it is widely accepted for modules, too. In 1986, Peck extended the simple Arrhenius model to include the influence of humidity:

$$t_f = A_3 \cdot RH^{-x} \cdot \exp\left(\frac{E_A}{k \cdot T}\right) \quad (5)$$

with the activation energy E_A in the range of 0.79 to 0.95 eV and the "empirical" or fitting exponent x of the relative humidity RH impact in the range of 2.66 to 4.64 [16]. Using (5) the acceleration factor of accelerated environmental test methods including THB and Highly Accelerated Stress Test (HAST or pressure-cooker test) [13, 15] can be easily calculated as the ratio between t_f at normal-use conditions and t_f at accelerated conditions:

$$a_f(RH, T) = \left(\frac{RH_a}{RH_u}\right)^x \cdot \exp\left(\frac{E_A}{k} \cdot \left[\frac{1}{T_u} - \frac{1}{T_a}\right]\right) \quad (6)$$

Herein, a_f is the acceleration factor of the test, RH_a the relative humidity at accelerated conditions and T_a the corresponding temperature, while RH_u is the relative humidity at normal-use conditions and T_u the corresponding temperature.

Originally, there was no voltage dependence considered for THB because the simple theory asks only for a minimum or "sufficient" potential difference to trigger hydrolysis and corrosion. On the other hand the voltage should not lead to significant (local) self-heating of the chip as the heat would drive away moisture and would slow down humidity related failure mechanisms. Therefore, the test standards ask for a maximum temperature increase (e.g. IEC 60068-2-67: 2°C) or a maximum power dissipation (e.g. IEC 60749-5: 200 mW). To fulfil all boundary conditions usually 80 V is applied in THB tests for power devices. In fact, some 10-20 years ago this was a challenge for HV-devices, but nowadays IGBT modules pass this test without problems. However, the potential distribution is believed to be a critical factor and 80 V is obviously a very low voltage level when it comes to HV-devices. Therefore, it is suspected that a higher bias level is the more severe test condition and, consequently, IGBT modules should be tested at 50 - 90% of the nominal voltage but not much higher to avoid cosmic ray failures. In order to model the influence of higher bias levels combining Hornung's and Peck's models might be a reasonable approach [10, 17, 18], though, it neglects interactions:

$$a_f(RH, T, V) = \left(\frac{RH_a}{RH_u}\right)^x \cdot \exp\left(\frac{E_A}{k} \cdot \left[\frac{1}{T_u} - \frac{1}{T_a}\right]\right) \cdot \left(\frac{V_a}{V_u}\right)^y \quad (7)$$

3 Experiments

3.1 Test System

The test system consists of a standard climate chamber and can include more than one DC-source for testing at different bias levels simultaneously. Because the leakage current is the best available state estimator of the reversely biased devices under test (DUTs), a galvanically insulated current monitoring system using fluxgate current transducers logs the current of the 16 separate test-channels. Figure 2 shows the schematic of the tester.

In case of a DUT failing, an IGBT phase-leg reduces the applied voltage to zero and a reed relay disconnects the respective test-channel from the bus bar before the phase leg reapplies the voltage. The phase-leg could also be used for testing with chopped voltage in case the self-heating of the devices is too high, but this option is not considered here. Of course, it is essential to control the climate such that strong condensation, i.e. additional leakage paths or even sparkover, is avoided.

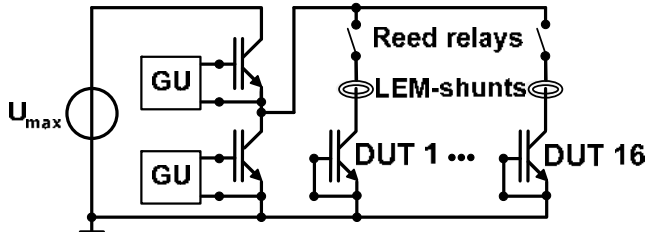


Figure 2 Schematic of the test system

3.2 Tested Devices and Experimental Procedure

A number of THB tests were carried out on a variety of standard IGBT-modules (mainly 62 mm, 190 mm x 140 mm, 130 mm x 140 mm) of the 1.2 kV and 1.7 kV voltage class with current ratings of 75 A up to 3.6 kA. As the devices had been produced by different manufacturers using different chip technologies, in particular different junction termination techniques, the blocking characteristics differed considerably with respect to leakage level and avalanche behaviour (sharp or soft breakdown). Prior to every THB an inbound test of the DUTs (and reference samples) was performed at RT using a Sony-Tektronix 370a curve tracer. The items were then arranged in the climate chamber and integrated in the test-circuitry. Subsequently, the chamber-climate was ramped-up to 85/85 conditions such that condensation on the surfaces of the DUTs was avoided. Only after the chamber climate had reached stable conditions, the bias voltage was applied.

To study the degradation of the DUTs a number of intermediate measurements as well as a final test were carried out exactly like the inbound test at RT. Before those tests the DUTs were dried out in the chamber for several hours (≥ 12 h) at 50°C and 10% RH (NB: there was no drying for the initial testing). Of course, the drying interrupts the ECM or any other humidity driven effect going on but there was no other way to achieve results comparable with the initial data. Furthermore, additional experiments had shown that the humidity is back at the chip surface within hours after restarting the THB, so the influence on the end-of-life data should be small and worthwhile the additional information.

4 Results and Discussion

4.1 Degradation Monitoring

A typical read out of the leakage monitoring results is shown in Figure 3. Overall the leakage monitoring indicated two different failure modes: Type I is catastrophic breakdowns without any precursor (blue curve in Figure 3). In some cases this happened already after only a few hours of testing, but this is considered infant mortality maybe even due to another failure mechanism rather than the investigated wear-out. The failure mode type II is characterised by (irregularly) increasing leakage currents over a long period. The red curve in Figure 3 shows a case in which the devices survived the test time with significant signs of degradation, i.e. increased leakage. However, if the test goes on such devices will fail either parametrically exceeding the current limit set to 20 mA per test channel or catastrophically (maybe in a different mode than type I). Of course, it is possible that the two failure modes interfere, i.e. leakage increase followed by a sudden catastrophic breakdown of type I (black curve in Figure 3, confirmed by failure analysis).

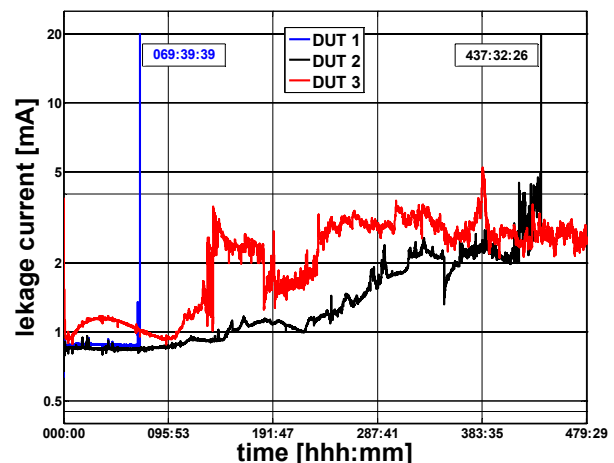


Figure 3 Typical leakage currents of three 1.7 kV 62 mm modules during highly accelerated (90 % of V_{nom}) THB

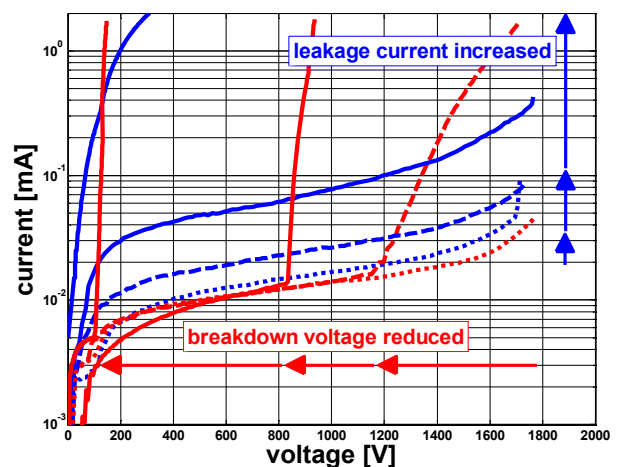


Figure 4 Types of degradation of blocking behaviour (at RT) during highly accelerated THB on 1.7 kV devices

Also the intermediate measurements yielded different ways of degradation. As indicated in Figure 4 there are two main variants, which are correlated to the junction termination (JT) design but NOT to the two variants in the leakage monitoring! Either there was pre-mature avalanche breakdown without significant leakage increase (red curves in Figure 4) or there was a general leakage increase (blue curves in Figure 4).

4.2 Failure Analysis

After opening the module's housings, the electrical failure analysis of each module was performed by checking the blocking curves of the individual IGBT and diode chips after cutting the respective bond-wires. Subsequently, the silicone gel was dissolved using BASF's Losolin® IV Selectipur. After cleaning the surfaces with alcohol, visual inspection using a digital microscope KEYENCE VHX-1000 was conducted.

Figure 5 shows the results of a highly accelerated THB on 1.7 kV 62 mm modules. The leakage monitoring showed significant differences between the individual devices. Some devices failed after a few hours (considered as early failures), while others survived the test duration of 500h, though showing leakage fluctuation. This result indicates that the failures are highly stochastic, which makes it difficult to investigate individual mechanisms and in this case impossible to extract quantitative results. However, there are indeed some remarkable findings. In this case the JT-design of the IGBT and the anti-parallel diode was completely different. All catastrophic failures of type I (red dots in Figure 5) could be attributed to the IGBTs showing molten spots in the JT area, while parametric failures of type II and leakage fluctuation (blue diamonds in Figure 5) could be attributed to the diodes showing dendrites growing from the active area metallisation over the JT (see Figure 6).

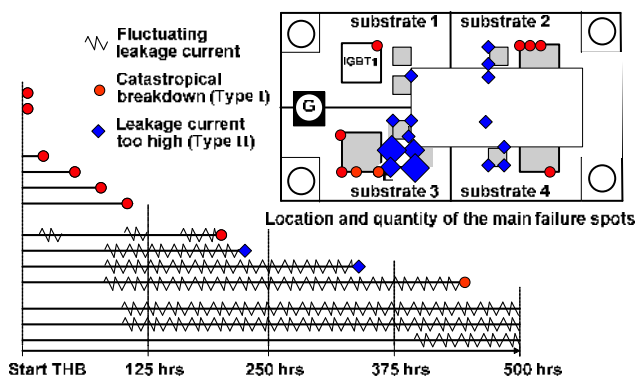


Figure 5 Results of the failure analysis of a highly accelerated (90% of V_{nom}) THB on 1.7 kV 62 mm modules

It looks like the ECM takes place in both JT-types and distorts the potential distribution but the thick passivation on the diodes prevents a direct breakdown to the silicon, while the thinner passivation of the IGBTs allows for direct breakdown. However, this assumption remains somewhat speculative as the failure analysis was not able to identify dendrites as the root cause for the catastrophic

failures of the IGBTs. It was also not possible to identify temporarily formed dendrites being responsible for leakage currents fluctuating with low amplitude. However, in literature it is usually assumed that dendrites form a parasitic current path and burn-off right again when the current gets too high there. Furthermore, it is assumed that a continuous increase in the leakage current superimposes the fluctuation behaviour due to the growth of substantial dendrites and may finally lead to a permanent short [5].

Another remarkable finding is the material of the dendrites (determined by EDX). The larger one in Figure 6 consists of copper (Cu) and some smaller consist of silver (Ag), while the chip metallisation is aluminium (Al)! So in accordance with theory it is not the Al-metallisation that was corroded and the copper and the silver have to come from a different source. This could be the DCB and the solder or alternatively the leads or terminals, though this would raise questions about how the material is transported to the JT. Because the dendrites grew only at the negatively biased active area metallisation and not at the positively biased channel stopper metallisation an artefact due to the failure analysis can be excluded with high probability (During failure analysis the aggressive Losolin dissolves some Cu/Ag from the said places and might have redeposited it somewhere else. In this case the dendrites should have grown at all metal-edges regardless of the polarity in the THB).

Interestingly, the 1700 V modules showed significantly more stress symptoms in high voltage THB than the 1200 V modules at the same stress level (same fraction of V_{nom} applied). This finding was independent of the manufacturer but is based on an arguable small variety of samples and tests. In any case, the THB tests with application relevant bias levels, i.e. 50% of V_{nom} or more, lead to much higher stress and faster degradation of the devices compared to the usual 80 V testing. In fact, reference samples tested at 80 V did not show any blocking degradation, though, Ag-dendrites have been found there, too!

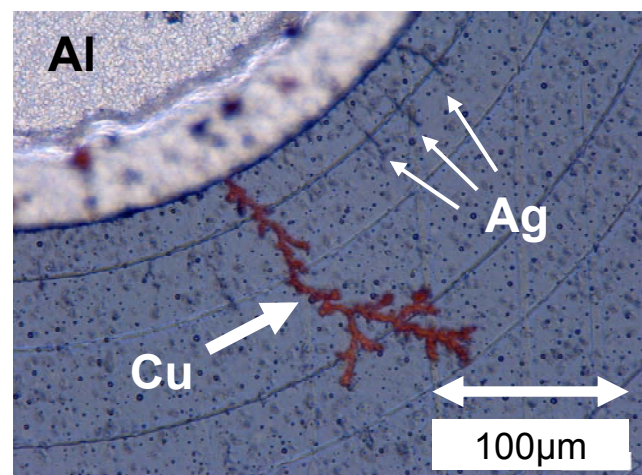


Figure 6 A Cu and small Ag dendrites found on the junction termination of a diode chip of a 1.7 kV 62 mm module. NB: Top left is the active area of the diode (anode), which is the negative electrode (cathode) in the THB test (see figure 1).

4.3 Statistics and Acceleration Factor

In order to investigate the influence of the applied voltage or rather estimate the acceleration factor of the voltage, 1200 V 62 mm IGBT modules with similar JT on the IGBT and the diode were THB tested at different voltages (65% and 90% of V_{nom}). The devices showed a blocking degradation behaviour with decreasing avalanche breakdown voltage (moving bend-off in the red case of Figure 4). Therefore, the remaining blocking voltage (position of the bend-off) was identified as the right measure to monitor the degradation by intermediate measurements. For blocking degradation behaviour with increasing leakage level (blue case of Figure 4) the leakage level at a certain voltage might be a better measure.

Figure 7 summarises the results of this test. The lines represent the median value of the remaining blocking voltage of 8 DUTs each and the error bars indicate the upper and lower quartiles. After about 900 hours the devices at highly accelerated conditions (90% V_{nom}) started to fail catastrophically and were dead 150 hours later (except from one device), while the first catastrophic failures at the more application relevant voltage level (65% V_{nom}) occurred well beyond 2000 hours and showed a similar decrease of the remaining blocking voltage in this area. Comparable to the observations reported in [4, 10], the ECM mechanism seems to take place in stages. At the initial stage the surface resistance of the insulator is reduced by contamination, which establishes conducting paths for metal ions released at the anode. Metal migration can form dendrites decreasing the spacing between the electrodes and if not killed by spark discharge right away they can further weaken the affected chip region by field distortions.

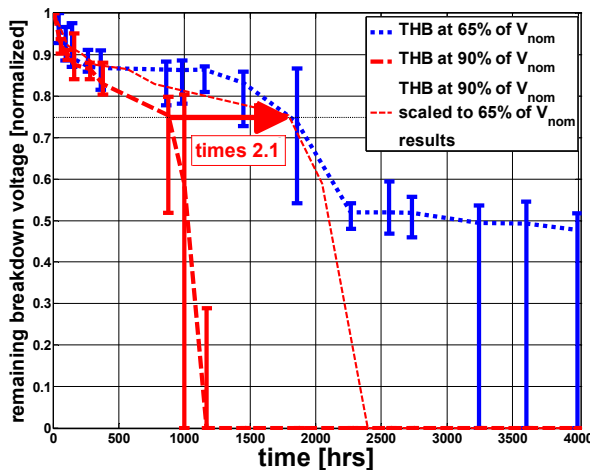


Figure 7 Degradation of the blocking capability during accelerated THB. Lower quartile, median, and upper quartile of the remaining breakdown voltage are shown for two different bias-levels (65% and 90% of V_{nom}).

In addition, both test groups lost a bit more than 10% of their initial breakdown voltage within the first 200 hours. This effect was independent of the applied voltage! In case of the 65% V_{nom} group the effect is stable for about

1000 hours before a further degradation occurs and also the 90% V_{nom} group showed some kind of saturation before the catastrophic breakdowns started. Further experiments showed that the effect is irreversible, i.e. not reversible by baking-out the devices at 150°C for hours. There is no explanation for this effect yet but the finding emphasises the fact that a simple end-of-life test is insufficient to characterise the degradation behaviour.

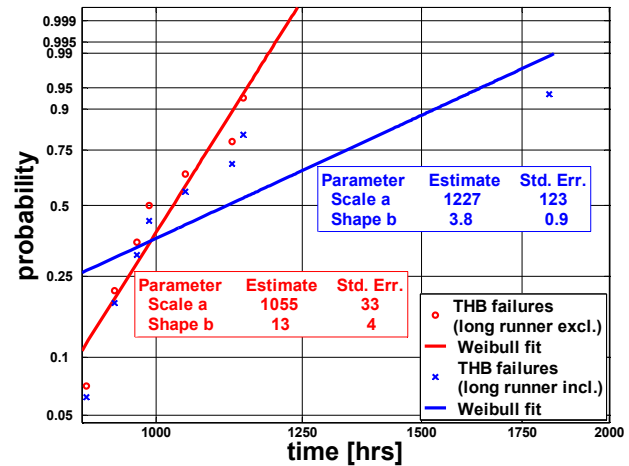


Figure 8 Weibull plot of the catastrophic failures of the 90% V_{nom} group of figure 7 with the long runner censored (red) or included (blue).

Figure 7 indicates that higher bias leads indeed to faster degradation. The thin curve there is the data of the 90% V_{nom} group scaled such that it roughly fits the data of the 65% V_{nom} group based on 0.75 remaining voltage. This yields approximately 1850 hours vs. 900 hours, so the acceleration factor due to voltage stress is approximately 2.1. The corresponding y-exponent of equation (7) is about 2.2 which is at least not contradictory to the results obtained on special test structures presented in [18]. Applying equation (7) to calculate the acceleration from 80 V to 65% V_{nom} would yield a factor of about 150. In other words, the 80 V test is indeed a strongly reduced stress level.

However, in the strict sense this result is valid for the tested devices only and, in addition, there remain some open questions. As the Weibull plot of the catastrophic failures of the 90% V_{nom} group in Figure 8 shows there is one device that lasts significantly longer. Without this device the shape factor would be 13 and with it the factor is only 3.8. Also the trend in the 65% V_{nom} group indicates a similar effect, as the remaining voltage levels off. A possible explanation could be more local self-heating due to the increased leakage. The higher temperature would reduce the effective humidity and would prevent or at least reduce further degradation. However, this is speculation.

5 Summary and Conclusions

THB at 85/85 conditions is the standard for accelerated life testing with respect to corrosion. In this work a variety of 1700 V and 1200 V IGBT modules from different

manufacturers were tested in THB at bias levels up to 90% nominal voltage. Higher bias was found to be indeed a higher stress compared to the usual 80 V testing, which is used to fulfil the respective standards asking for limited self-heating. For a particular 1200 V 62mm module an acceleration factor of about 2.1 was estimated when going from 65% to 90% of the nominal voltage. Applying the standard model for acceleration this would yield an acceleration factor of 150 between 80 V and 65%, so 80 V is apparently a strongly reduced stress and, in fact, reference samples bias with 80 V did not show degradation of the blocking capability. Furthermore, a simple end-of-life test as usually performed is insufficient to characterise the degradation behaviour. Long before the first devices fail catastrophically, there are clear signs of deterioration. However, the degradation progress depends strongly on the device technology, in particular, the junction termination design. The differences are detectable in leakage current monitoring and in the way the blocking curve deteriorates. The failure analysis yielded also quite different patterns as well as clear indications of electrochemical migration and dendrite growth already at 80V bias. However, the exact mechanisms are not fully understood yet and require further investigations.

6 Acknowledgement

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