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Aluminium corrosion in power semiconductor devices

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\section*{A B S T R A C T}

In this study, insulated gate bipolar transistor (IGBT) power modules were exposed to high voltage, high humidity, high temperature and reverse bias (HV-H\textsuperscript{TRB}) conditions until end-of-life (EoL). The limited lifetime of power semiconductor devices when used in demanding applications involving high relative humidity during operation is commonly reported to be associated with the design of the edge termination in power transistor or diode chips. A physics-of-failure (PoF) oriented methodology was adopted in failure analysis, including using lock-in thermography (LiT) for failure localisation and using an advanced microwave-induced plasma (MIP) decapsulation technique for the selective etching of the edge termination polyimide passivation film. A focused ion beam (FIB) was utilised to create a cross-section of the samples for both scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) analysis. The evidence gathered using the physics-of-failure methodology were compared with the results from advanced statistical analysis of the failure distributions in Weibull plots, including comparison of $\alpha$ and $\beta$ parameters. This analysis revealed correlation with the Weibull distributions and the results from the physics-of-failure. Aluminium corrosion products were systematically observed on guard rings (GR) and field plates (FP) showing that the migration of these corrosion products forming an electrical path between the guard rings that seems to be a major failure mechanism in high humidity environments when reverse bias voltage is applied.

\section*{1. Introduction}

Power electronic systems form the core technology of power conversion and power generation applications in both industrial and automotive environments. To fulfil the strict reliability requirements for these applications, the need for a physics-of-failure (PoF) oriented approach to evaluating reliability is widely recognised by the industry [1–3]. Especially harsh environmental applications (e.g. wastewater control, off-shore wind power converter and marine propulsion) require a careful consideration of humidity robustness in power electronic systems [4–6]. Humidity-induced failure mechanisms in power semiconductor devices (e.g. insulated gate bipolar junction transistors [IGBT] and freewheeling diodes [FWD]) have been studied extensively by multiple research groups in recent publications [4,5,7–10]. Several failure mechanisms have been identified in environmentally harsh environments (e.g. aluminium corrosion [7], copper/tin electrochemical migration [11], lead glass leaching [4] and copper sulphide dendrites [12]). In many of the recent studies, the relevancy and repeatability of these failure mechanisms is not clearly described; nevertheless, a handful of recent publications show evidence suggesting a failure mechanism provided by PoF-based analysis techniques [4–6,11]. In these recent publications, the IGBT/FWD chip edge termination (ET) robustness is clearly associated with being systematically involved in humidity-induced failure mechanisms. Furthermore, several publications have included ET region electric field simulations for IGBTs in both high humidity and dry atmospheric conditions [8,13], which suggests that there are much higher electric fields in the ET region when humidity is involved. Humidity can dramatically alter the ET electric field distribution, thus it plays a crucial role in power semiconductor devices’ humidity robustness [13]. Fundamental electrochemical descriptions of aluminium corrosion and the electrochemical migration (ECM) of soldering material splashes (i.e. copper and tin) in power semiconductor devices were already given some years ago [5,7]. A reliability demonstration test method, which is described in by European Centre for Power Electronics (ECPE) for automotive industry in...
ECPE Automotive Qualification Guideline (AQG) 324 as the High Humidity High Temperature Reverse Bias (H$^+$TRB) test [14], is commonly used to demonstrate humidity robustness in power semiconductor devices under operation [4,5,15]. There are also, other older standards (e.g. JEDEC A101) describing similar tests as H$^+$TRB tests and the primary difference is that in these older standards the maximum reverse bias voltage is $V_r < 80$ V, which is now generally accepted to be too low to generate commonly known failures in reasonable time to meet the end-of-life (EoL) conditions in power devices with nominal avalanche breakdown voltages of $V_{br(nom)}$ $\geq$1200 V [4,5,9,11,13]. Nevertheless, all commercial power semiconductor devices used in this study are assumed to have passed the low voltage H$^+$TRB test at 80 V. The H$^+$TRB test described in ECPE Guideline AQG 324 for automotive applications only suggests a high reverse bias voltage ($V_r$) values for silicon carbide (SiC) based devices in H$^+$TRB variant 2 [14]. On the contrary, ECPE Guideline Power Semiconductor Reliability for Railway Application (PSRRA) 01 states that a high voltage H$^+$TRB (HV-H$^+$TRB) test for railway applications requires that a minimum test voltage of $V_r$>1000 V for silicon (Si) based devices [15]. Generally, an HV-H$^+$TRB test requires a reverse bias voltage of $V_r$ = 0.8 x $V_{br(nom)}$; 80% of the nominal breakdown voltage, $V_{br(nom)}$, following high voltage requirements described in both the ECPE AQG 324 variant 2 [14] and ECPE PSRRA 01 [16] for the HV-H$^+$TRB tests [4,5,11]. In this paper, the work of the recent publications [4,5,11] is continued in order to improve the understanding of the associated electrochemical migration of aluminium guard rings (GRs) at the IGBT/FWD ET structure, a phenomenon denoted as aluminium corrosion [5]. This study describes the fundamental electrochemistry of the phenomena while providing sufficient PoF evidence by using advanced sample preparation and modern failure analysis techniques (e.g. lock-in thermography [LiT] localisation, microwave-induced plasma [MIP] decapsulation and focused ion beam [FIB] cross-sectioning).

2. Aluminium corrosion

According to recent publications, moisture can penetrate the silicone gel of power semiconductor packages [4,12,17]. A typical silicone gel thickness in power semiconductor modules is ca. 6 mm and its permeability is considered to be at the range of 10$^{-8}$ g/(cm-s-torr) and the associated moisture penetration time ranges from 12 to 24 h to reach 50% of the ambient humidity [18]. Furthermore, the moisture can diffuse eventually through the passivation films (within a few hundreds of hours) protecting the high voltage ET structures that are typically based on P-doped wafers with aluminium (Al) GRs and field plates (FPs) [4,8,10,19]. Two examples of moisture penetration paths are shown in Fig. 1: (a) diffusion through the passivation film (e.g. polyimide) and (b) diffusion through a delamination (DL) path due to the loss of the adhesion of the passivation film. These have been discussed in several publications [5,8,10,17].

The corrosion of aluminium is an intensively studied phenomenon in electrochemistry, and some of the most accurate theoretical and empirical studies were already made in the 1950s [21]. All corrosion processes begin with the assumption of electrochemical overpotential due to the loss of the adhesion of the passivation film. These have been discussed in several publications [5,8,10,17].

The metal guard ring (GR) combined with a terminating field plate (FP) type edge termination topology of an FWD with its typical depletion region boundary (DRB) structure shows possible moisture ingress via passivation delamination (DL) or directly diffusing through the passivation, indicated by blue arrows, a similar process that described in [20].

![Fig. 1. The metal guard ring (GR) combined with a terminating field plate (FP) type edge termination topology of an FWD with its typical depletion region boundary (DRB) structure shows possible moisture ingress via passivation delamination (DL) or directly diffusing through the passivation, indicated by blue arrows, a similar process that described in [20].](image)

Fig. 1. The metal guard ring (GR) combined with a terminating field plate (FP) type edge termination topology of an FWD with its typical depletion region boundary (DRB) structure shows possible moisture ingress via passivation delamination (DL) or directly diffusing through the passivation, indicated by blue arrows, a similar process that described in [20].
on thermodynamic data of electrochemical reactions and begins by defining the relationship between electrochemical cell potential and ion concentrations (e.g. pH) by the Gibbs free energy, \( \Delta G \) \cite{25,31}, or as a Nernst equation:

\[
\Delta G = G^0 + RT \ln(K) \rightarrow E = E^0 + \frac{RT}{nF} \ln(K),
\]

where \( G^0 \) is the free energy change in standard state, \( R \) is the gas constant, \( T \) is the temperature in Kelvin units, \( K \) is the equilibrium constant (i.e. the concentration ratio between oxidation and reduction species), \( n \) is the number of electrons, \( F \) is the Faraday’s constant and \( \lambda = \ln(10) \) \cite{25}. The free energy in the standard state can be defined via the chemical potential difference between the cathodic and anodic sides. This can be generally written as the sum of products between the stoichiometric coefficients \( \nu \) and electrochemical potential \( \mu \) \cite{25,32}.

The electrochemical free energy potentials of the relevant chemical elements depicted in Eq. (1) through to Eq. (7) are described in \cite{22,33}. Using Faraday’s law, the standard electrochemical potential \( E^0 \) can be solved using this assumption:

\[
E^0 = -\frac{\Delta G^0}{zF} = -\sum \nu_i \mu_i^0 \frac{1}{zF},
\]

where the sign of the stoichiometric coefficient \( \nu_i \) is determined for each reaction element (i.e. it is positive for oxidised elements and negative for reduced elements) while the magnitude of \( \nu_i \) is the molar number of the element in the reaction \cite{25}. After solving the standard electrochemical potential \( E^0 \) for the reaction, one can combine Eqs. (8) and (9) into:

\[
E = \sum \nu_i \mu_i^0 \frac{RT}{nF} \ln(K),
\]

where the associated values for \( K \) can be generally written as a product of each chemical element’s concentration \( [c_i] \) to the power of the stoichiometric coefficient \( \nu_i \):

\[
K = \prod [c_i]^{\nu_i}.
\]

The resulting values for \( K \) are collected for each equation in Table 1 together with the resulting \( E \) versus pH equation, which forms the reaction lines ‘a’–’g’ in Fig. 2a at the threshold concentration of \( [c_{Al}] = 10^{-4} \) mol/l \cite{22}. To solve \( \ln(K) \) for reactions involving either hydrogen ions (H\(^+\)) or hydroxide ions (OH\(^-\)), the hydroxide ions must be taken into special consideration by introducing the relation between pH and pOH described earlier. Based on the results displayed in Table 1, a major shift of reaction ‘f’ can be noted, caused by the separation of aluminium hydroxide Al(OH)\(_3\) with a partial re-dissolution, forming tetrahydroxoaluminate \([Al(OH)\(_4\)]^-\) anions \cite{28} can be noted (see Fig. 2b). It is also suggested to be the dominant aluminium corrosion product in an alkaline solution (i.e. closer to the cathode) \cite{34}. This shifts the reaction stability line closer to the neutral region when the temperature is elevated from room temperature to 85 °C, as depicted in Fig. 2a by vertical (orange dashed) reaction line ‘f’ (T = 85 °C). This can indicate that the reaction more probably occurs at elevated temperatures, but on the other hand, it can also induce anions to migrate to the neutral region before forming stable aluminium hydroxide. Furthermore, it should be noted that the reaction line ‘d’ (i.e. the transformation of aluminium ions into aluminium hydroxide Al(OH)\(_3\)) occurs at relatively low concentrations, which is in line with the assumption that aluminium ions Al\(^{3+}\) are not stable enough to migrate through the whole electrolytic solution from anode to cathode electrode \cite{15,28}. Based on the Pourbaix diagram, it is evident that Al(OH)\(_3\) can even directly form in a neutral solution \cite{15,22}. Nevertheless, when bias voltage is applied, a large pH gradient occurs between the electrodes \cite{35,36}, which can lead to reaction ‘f’ occurring closer to the cathode, electrode forming tetrahydroxoaluminate ions. These ions are reported to be stable enough to electrochemically migrate from the cathode to the anode electrode through the electrolytic cell \cite{5,15,28}.

3. Materials & methods

An HV-H\(^+\)TRB test is an Eol accelerated life test (ALT) that is used to verify power semiconductor device robustness during operation in a high humidity environment \cite{4,5,9-11}. In this paper, the empirical data was gathered from multiple HV-H\(^+\)TRB tests carried out by two different research groups, one at ABB Drives (denoted hereafter as ABB) in Finland and the other at the University of Bremen (denoted hereafter as UHB) in Germany. The test conditions used by these groups are close to identical: T=85 °C,rH=85% and \( V_F = 0.8 \times V_{F(nom)} \), primarily following two European Centre for Power Electronics (ECPE) guidelines: (a) automotive guideline ECPE AQG 324, variant 2 and (b) traction guideline ECPE PSRRA 01 for HV-H\(^+\)TRB tests \cite{14,16}. The test setup used by ABB was described thoroughly in earlier publications \cite{4,9}, and similarly, the test setup used by the UHB was described in \cite{5,7,11,15,17}. Maintaining reproducibility and repeatability throughout the testing procedure is crucial for gaining systematic and conclusive results without triggering irrelevant failure mechanisms. As a case in point, intermediate measurements during the reliability testing are critical in order to monitor the progress of the degradation mechanisms on all the samples individually. For this, well-defined pre- and post-conditioning is required. After the inbound measurements, the devices are stored in the climate chamber for 24 h under 85 °C and with 85% relative humidity to ensure a stable climate inside and outside the modules. The test voltage is ramped up after the pre-conditioning and the actual testing time starts as soon as the voltage reaches the desired value. If an intermediate time step is reached, the voltage is ramped down and...
situations where the lowest value (i.e. the weakest link) characterises $F$ from the test chamber regularly), a process that was discussed elsewhere.

In the UHB tests, intermediate leakage characteristics measurements were made (see Fig. 3) to see if there is a significant impact on the possible failure mechanism. In all the test samples, the failure statistics can obviously be shifted (accelerated or decelerated) due to the different failure mechanisms. Nevertheless, the failure statistics are assumed to provide comparable results in respect to failure statistics (Table 1), but this not considered to fundamentally change the resulting failure damage that might mask the cause of breakdown in the forensic mechanism and/or additional changes in experimental conditions. It may be noted that in the present tests, the test objects were withdrawn from the test just before actual failure. This was to prevent extensive drying process (at 50 °C / 10% relative humidity and lasting for at least 24 h) starts (see Fig. 3). The intermediate measurement of the remaining blocking capability must be done in dry conditions to avoid damaging the devices by, for example, electrical arcing.

The failure criteria of the ABB and UHB tests were varying (see Table 2), but this not considered to fundamentally change the resulting failure mechanisms. Therefore, tests carried out by ABB and the UHB are assumed to provide comparable results in respect to failure statistics and failure mechanisms. Nevertheless, the failure statistics can obviously be shifted (accelerated or decelerated) due to the different failure criteria; however, the Weibull fit parameter $\beta$ value can be studied to see if there is a significant impact on the possible failure mechanism. In the UHB tests, intermediate leakage characteristics measurements were also made using a curve tracer (CT) (i.e. the samples were removed from the test chamber regularly), a process that was discussed elsewhere recently using different samples [17]. The check for matching Weibull shape parameter $\beta$ is based on the principle that the data stem from various experiments with somewhat different ageing conditions. The Weibull cumulative probability density function $F(t)$ applies to situations where the lowest value (i.e. the weakest link) characterises the value of the object. Failures due to a single mechanism are supposed to be governed by two-parameter Weibull statistics, described by the $F(t)$ of failures:

$$F(t) = 1 - e^{-(t/\alpha)^\beta},$$  \hspace{1cm} (12)

in which $t$ is the time, $\alpha$ is the scale parameter and $\beta$ is the shape parameter. This relation is rewritten as

$$Z = \ln[-\ln(1-F(t))] = \beta \ln(t) - \beta \ln(a),$$  \hspace{1cm} (13)

in which $Z$ linearly depends on $\ln(t)$. Let $t_1 \ldots t_n$ be the ordered failure times of a sample of $N$ uncensored tests and let $Z_1 \ldots Z_n$ be the corresponding values of $Z$. To estimate $\beta$ and $a$, linear regression is applied to a suitable estimate of $Z$, as function of $\ln(t)$. The estimate (the ‘plotting position’) chosen here is the expectation value ($Z_i$), which is often approximated as [37]

$$\langle Z_i \rangle \approx \ln[-\ln(1 - (i - 0.44)/N + 0.25)].$$  \hspace{1cm} (14)

The plot of $\langle Z_i \rangle$ as a function of $\ln(t_i)$ is called a Weibull plot. The slope of the fit is $\beta$. In accelerated life testing, the stress is enhanced in order to reduce the failure time to an experimentally accessible value. Any times to failure, $t_{i,ref}$, in the reference situation will decrease to test times $t_{i,test}$ with an ageing process characteristic acceleration factor (AF) [38]:

$$t_{i,ref} = AF \times t_{i,test}.$$  \hspace{1cm} (15)

The AF is a function of both the rated and the enhanced stress. As all failure times are reduced by the same factor, the $\ln(t_i)$ data in the Weibull plot are shifted by a fixed amount, leaving the slope of the fit $\beta$ unaltered but changing the scale parameter:

$$\Delta t_{i,ref} = AF \times \Delta t_{i,test}.$$  \hspace{1cm} (16)

If under enhanced stress, the slope of fit changes significantly relative to the reference situation, there may be an unwanted change in the failure mechanism and/or additional changes in experimental conditions. It may be noted that in the present tests, the test objects were withdrawn from the test just before actual failure. This was to prevent extensive damage that might mask the cause of breakdown in the forensic evaluation. This withdrawal shortens the observed failure time slightly. It is assumed that the effect can be ignored. The same applies to the difference in criteria between the ABB and UHB tests that is shown in Table 1. In this work, both 1200 V and 1700 V rated chips were evaluated, while the chip technology for both IGBTs and FWDs was comparable in all the test samples. Nevertheless, it is assumed that the dimensioning and optimisation of the ET structures may be voltage-class dependent. All the tested modules were standard commercial IGBT modules, including an anti-parallel FWD biased in either single switch configuration (SSC) or half-bridge configuration (HBC). All the modules (i.e. samples) were standard plastic housing components that included silicone gel on top of the chips with an ET structure created using polyimide passivation. A similar passivation structure where aluminium (Al) metal lines were coated with multiple layers of thin films to
improve the adhesion and reduce the shear stress on the passivation structure, that is, Al/SiO2/SiN/PI, was described in a series of publications [39–41]. In this study, failed samples from all three test batches were randomly selected for the PoF analysis in order to verify whether all these failures show comparable failure mechanism regardless of the test setup and failure criteria. The failure analysis equipment used in this work involved electrical analysis conducted with a CT for leakage characterisation (before, during and after the test), and the CT results were used to select the reverse bias voltage level in order to localise the leakage hotspot to the failed samples using a LiT microscope. The samples selected for LiT analysis were prepared by an overnight bath in ARDROX-2312, a silicone gel removal chemical, in order to dissolve the soft gel from the IGBT modules. After the hotspot localisation, a MIP decapsulation equipment for polymide passivation removal in the chip ET region was utilised. Physical characterisation techniques also involved focused ion beam (FIB) cross-sectioning, both with and without MIP decapsulation, and standard scanning electron microscopy (SEM), from both the cross-sections and from the top view, combined with an energy dispersive X-ray spectroscopy (EDX) material analysis technique. Major parts in this failure analysis procedure have been discussed in detail in [4] with an exception to the MIP decapsulation technique that was described in other recent publications [42–44].

4. Results & discussion

During the HV-HTRB tests, online monitoring of the leakage current revealed excess leakage currents due to the deteriorated reverse bias blocking voltage characteristics in a similar way to the processes described in [4,5,7,9,11]. In this publication, the leakage characteristics were measured with a CT up to the maximum allowed voltage (i.e. 1200 V or 1700 V) for all IGBT modules both prior to and after the test. However, in a UHB test, the samples were removed from the chamber multiple times during the test in order to have better understanding of the leakage deterioration during the test, which is the same approach used in [11]. First, sample #13 was selected from ABB batch 1 for PoF analysis in this study in order to represent possible Al corrosion due to its major deterioration at blocking voltage (see Fig. 5a) that was observed on the outermost GR (or the FP), which was closer to the major burn mark in the ET region of a single FWD chip, and the damage can occur when the samples are not directly removed from the test samples from the test setup; the failed samples were only removed when the power supply current limitation (ca. 100 μA) was reached even though the actual failure criteria was limited dynamically for each test. Nevertheless, aluminium corrosion product migration between ET metallisation (on top of the insulation barrier) was be observed. Therefore, a further trial was carried out on ABB batch 8, where two failed devices – #52 and #54 – were taken into consideration. Based on the online leakage monitoring results, these two samples failed respectively at 528 h and 599 h during the test by reaching the failure limit described in Table 2. The leakage characteristics analysis conducted by the CT revealed a major deterioration in the breakdown voltage for both samples (see Fig. 5a for sample #54), and for #52, there was a clear short circuit observed. The visual inspection of sample #52 showed a major burn mark in the ET region of a single FWD chip, and the damage was considered too large for further analysis. Also, the LiT analysis of #52 showed a clear hotspot with very low voltage (< 5 V) in the burned region. The reason for such extensive damage is believed to be at least partially caused by the procedure in place for the removal of the test samples from the test setup; the failed samples were only removed when the power supply current limitation (ca. 100 μA) was reached even though the actual failure criteria was limited dynamically for each sample by doubling the original leakage current. Therefore, extensive damage can occur when the samples are not directly removed from the test setup after reaching the online monitoring failure criteria. A LiT

<table>
<thead>
<tr>
<th>Test name</th>
<th>Voltage class [V]</th>
<th>Failure criteria</th>
<th>Tested modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABB B03</td>
<td>1200</td>
<td>$I_r \geq 2 \times I_{ref} / V_{600} \text{ VDC}$</td>
<td>7 pcs</td>
</tr>
<tr>
<td>ABB B08</td>
<td>1700</td>
<td>$I_r \geq 2 \times I_{ref} / V_{6360} \text{ VDC}$</td>
<td>6 pcs</td>
</tr>
<tr>
<td>UHB B01</td>
<td>1700</td>
<td>$I_r \geq 10 \text{ mA} / V_{1360} \text{ VDC}$</td>
<td>8 pcs</td>
</tr>
</tbody>
</table>

It should be noted that in rare cases in all the batches, another mechanism was observed (early failures), and it can be seen in the number of suspended samples’ data that is shown in Fig. 4 and the number of suspended samples is denoted in the table as $r$ for each batch. These suspended data points statistically deviate from the rest of the population due to their earlier failure time. It should be noted that some additional samples were biased in HBC where early failures (suspended from the graph) were more common, and all these early failures were localised by the LiT or optical inspection of the IGBT chips. Based on these findings, it is assumed that these early failures depict another failure mechanism ($\beta<1$) that is not as common as the later failure mechanism with Weibull $\beta \approx 4 \ldots 5$. In this study, the primary emphasis is put on these later failures and currently no explanation is given as to why this second mechanism seems to be more common in HBC and typically localised to the IGBT chips (i.e. it is unknown why the IGBTs failed faster than the FWDs in some of these devices).

The in situ leakage current monitoring suggested an exceedance of the current limit at 278 h for sample #13 in ABB B01 (i.e. a failure). The leakage characteristics were measured after (the red line) with a CT and show major deterioration when compared with the measurements before the test (the blue line) in Fig. 5a. All the failed devices were physically intact after the test and visual inspection showed no damage within any of the chips or package structures. The breakdown voltage, $V_b$, deterioration is common to HV-HTRB tests and similar findings were made by [4,5,9,10]. Other parameters (e.g. threshold voltage, on-state resistance and gate leakage current) studied in an earlier publication were found to be constant during HV-HTRB test [9]. In this earlier publication the devices were pack-aged into TO-247 discrete packages and in this article all devices were packaged into modules, based on the analysis no large differences in electrical behaviour are observed. A LiT analysis revealed that the hotspot was generated close to the corner of one IGBT chip on the ET structure, which is consistent with the earlier findings for rectifier diode failures reported in [4]. However, in this case, the GR structures were clearly identified; even the likely hotspots in the ET insulation trenches were identified (see Fig. 5b). Finally, a FIB cross-section close to the hotspot was made and a SEM/FIB analysis was conducted (see Fig. 5c). This analysis revealed that Al GRs were oxidised on their surfaces. The worst damage was observed on the outermost GR (or the FP), which was closer to the positive potential ($V_r+$) due to the vicinity of the edge of the chip, as explained in [4]. There were clear signs of the migration of aluminium and possibly oxygen in the EDX analysis (see Fig. 5d).
analysis using 80μm resolution optics (see Fig. 6b) was carried out on #54 and two hotspots on the opposite corners of a single FWD chip were observed. It should be noted that a LiT analysis was also carried out on other samples from this batch and the failure hotspots were consistently localised in the FWD ET region. Sample #54 was selected randomly from failures that did not show a clear short circuit, since these samples were less damaged and were thus more suitable for PoF analysis, a selection process similar to that described in [4].

A further SEM from the top view revealed a crack in the polyimide (PI) passivation film beneath the hotspot, as can be seen in an overlay image of the hotspot using 5μm resolution optics on top of the SEM image (shown in Fig. 6c). Finally, a cross-section was prepared with JEOL JIB-4700F dual beam FIB equipment and, after several trials, only a corroded outermost GR could be seen and no large damage could be observed on the FP (see Fig. 6d).

At this point it became evident that the FIB cross-sectioning takes a relatively long time to cut through the polyimide (PI) passivation film, which can be up to 25μm thick. Furthermore, the area required to be processed was also large for a FIB, for example, 50μm x 120μm in size. Therefore, more accurate localisation of the failure was needed in order to be able to focus the process on a more localised region. Therefore, a trial to remove the polyimide selectively with an MIP decapsulation process (kindly offered as a demonstration by Jiaco Instruments, the company which manufactures the MIP decapsulation tools for sample preparation) [42–44]. The initial trial was carried out with sample #52, and the process seemed to be working properly. Therefore, the analysis from ABB batch 8 only provided limited evidence suggesting the existence of corrosion in aluminium GRs, and no aluminium corrosion product migration could be observed. Nevertheless, clear evidence suggesting aluminium GR corrosion and PI delamination suggests an ingress path for the moisture. In the UHB test the samples were regularly removed from the test chamber for intermediate leakage characterisation by a CT; this, on the other hand, can provide substantial thermomechanical cycles and CTE-mismatch induced stresses to both the chip ET and protective passivation structure [39]. Also, in the UHB test, online leakage current monitoring was used. Almost all the failed samples were selected for PoF analysis; the selection of the samples was based on the statistical data regarding the failure times with samples from different regions of the distribution (see Fig. 4). The CT leakage characteristics measurements revealed either a short circuit or a major deterioration in the breakdown voltages, similarly to earlier tests [4,5,7,9]. The LiT analysis revealed a hotspot on IGBT chips in some cases, but in the majority of the cases, they were found on FWD chips. When statistical failure data (see Fig. 4) is combined with this knowledge, the FWD chips seemed to fail later than the IGBT chips during the test. In the HV-H3TRB test where both IGBTs and FWDs can cause device failure, there is competition between failure mechanisms [45]. If an IGBT fails, the device fails and cannot be tested further; therefore,
when the FWD of the device would fail remains hidden beyond the fact that this failure time would have been longer than that of the failed IGBT. The hidden FWD failure time is termed as being censored or suspended from the IGBT module failure time statistics (see Fig. 4). This censoring time should not be ignored and must be considered when determining the respective FWD Weibull distributions [46]. For FWD data analysis, the IGBT failure times are the FWD censoring times, and likewise, the FWD failure times are the IGBT censoring times. A standard method for approaching this issue is to treat such cases with adjusted ranking in both parameter estimation and in plotting [47]; this was the approach used in the present research. From UHB batch 1, sample #10 was selected to be analysed by the PoF methodology in order to determine the possible failure mechanism since this sample seemed to show similar a deterioration of the breakdown voltage to that seen in earlier samples from ABB tests, and similarly, the failure time of 675 h suggested a similar mechanism (see green line with circle markers in Fig. 4). After the silicone gel removal was completed, the thermal hotspot was localised to the ET structure of a FWD chip using LiT. MIP was used to remove the polyimide passivation from the top of the chip ET region. A clear view of the ET structure was obtained, and a top-view SEM analysis revealed clearly identifiable and intact ET structures including those on aluminium GR. It should also be noted that some inorganic thin and brittle passivation structures (i.e. silicon nitride, SiNₓ) had cracked or peeled off during the sample preparation process. At the hotspot, clear local corrosion was observed on the aluminium FP ring and on the outermost GR structure, which is supported by the fact that the electric field local maximum is close to the FP [8] and, on the other hand, the shear stress maximum is to be most likely highest closer to the edge [39]. Therefore, the delamination of PI and deformation of aluminium rings is most likely higher in that region. However, the corrosion on FPs was much more extensive since the surface morphology had also deteriorated heavily on the FPs.

Similar signs of corrosion were observed on the outermost GR but even more locally at regions where signs of a possible migrated material at the insulation trench were observed. There were multiple similar regions in the proximity of the original hotspot that were observed by the LiT, and in all cases, some corrosion material had migrated locally at the insulation trench. With an EDX analysis conducted from the top view, it became evident that the aluminium had migrated into the isolation trench on top of the silicon nitride passivation film.

The aluminium GRs and FPs were heavily corroded since the oxygen content (especially on the FPs) was extremely large when compared with the non-damaged FP regions that had much higher aluminium content (see spectrums 1 and 5 in Fig. 7 table at at%). The contrast can be clearly seen from the top-view EDX maps of the Al shown in Fig. 7. A FIB cross-section also revealed that the oxidation had only taken place on the surface of the aluminium FP and GR while the inner bulk of the GR was still intact (see the contrast in the FIB cross-section image shown in Fig. 7). The bridging structure can be clearly observed to have grown from the edge of the FP towards the GR, as denoted by the white arrow in Fig. 7. This bridging structure primarily consists of aluminium (Al) and oxygen (O), as seen in point scan spectrum 3 in the spectrum summary table of the figure. This bridging structure is like the structure seen on ABB batch 1, sample #13, in Fig. 5. The passivation structure on top of the ET is consistent with the structure described in [39–41], including polyimide (PI) coated with SiNₓ on top of SiO₂, protecting the aluminium GR structures. It is not known at this point whether the adhesion deterioration of the passivation has caused moisture to penetrate the passivation structure or if the moisture has diffused through the passivation structure directly. According to the related literature, the PI film thickness is >5 µm, while the passivation films are in general <800 nm thick [39]. In Fig. 7c, the passivation film seems to be partially detached from the aluminium GRs or even cracked, which would support the fact that the ingress in the passivation structure plays a role in the moisture transportation to the GRs. Nevertheless, Fig. 7 shows that the bridging aluminium corrosion product in fact grows on top of the SiNₓ film, which would indicate that the silicon nitride film has cracked before the bridge was formed. It is suggested in [8] that corrosion of the nitride passivation film can play a crucial role in moisture penetrating the passivation structure. No conclusive evidence was found in the EDX analysis to support nitride corrosion as can be seen in Fig. 7, but it is a possible precursor to the aluminium corrosion.

The thermomechanical stability of a similar passivation structure was studied during thermal cycling in a recent article [39]; it can be noted that the underlying aluminium metallisation can wrinkle or ratchet during thermal cycling due to the thermomechanically induced stresses caused by the coefficient of thermal expansion (CTE) mismatch between the passivation materials and the aluminium metallisation. Nevertheless, during an HV-H²TRB test in principle, large thermal cycles should not be induced if the test conditions are constant. However, thermomechanical and electrical field simulations could reveal if an HV-H²TRB test could induce cyclic loading of the passivation structure. The origin of the bridging aluminium corrosion product seems to be close to the possible shear stress maximum and crack location described in [31].

To summarise, the possible moisture transportation scenarios are depicted in Fig. 1, showing the schematic cross-section of an FWD chip edge with a common GR+FP type ET topology that is also described in [15,20]. The delamination path for moisture is depicted in red in Fig. 1 and it can be noted that the delamination can also occur on the other edge of the chip, where the shear stress is believed to be the highest (as described in [39]). In an earlier publication, the results of hydrolysis on top of the passivation (only glass passivation samples were used in the study) were also described [4], but here it seems to be irrelevant since the damages are clearly localised beneath the passivation PI film.

During the test, the edge of the chip was exposed to the \( V_+ \) potential while the centre or active region of the chip were exposed \( V_- \) potential (see Fig. 1) [4]. Therefore, the electrolytic cell would form between the FP (the anode) and the outermost GR (the cathode) as
depicted in Fig. 2b. Based on the Pourbaix diagram of Al (see Fig. 2a), it is suggested that the following process could be responsible for the failure (similarly to the process described in [15]); the mechanism involves the formation of aluminium hydroxide with neutral pH, which could already begin to occur when the voltage bias is not yet applied during the stabilisation phase of the HV-H$^3$TRB test chamber. Finally, when the test begins and the bias voltage is applied, the aluminium hydroxide Al(OH)$_3$ film covers all GR and FP structures, especially those closer to the edge, where the moisture can penetrate from the interface between the chip and the film more easily (see Fig. 1).

Furthermore, on the GR side (the cathode), the [Al(OH)$_4$]$^-$ anions can migrate (as described in the earlier section) through the isolation trench all the way to the FP (the anode) where an extensive amount of Al$^{3+}$ is formed, and as a result, both of the corrosion products will pull each other together and finally form an aluminium hydroxide bridge that deteriorates the isolation of the ET structure [5–8,10,13,15]. Finally, it should also be noted that Fig. 2 depicts that [Al(OH)$_4$]$^-$ is stable in the larger pH region at elevated temperatures, and thus, it is believed that it can be stable enough to migrate from cathode to anode at elevated temperatures. Therefore, it is suggested that the higher the temperature and voltage, the higher the probability for the migration of aluminium anions [25,26].

5. Conclusions

This failure analysis was conducted on the failed IGBT modules gathered from multiple HV-H$^3$TRB tests carried out between 2016 and 2020 at two independent laboratories in Finland and Germany. An extensive failure analysis process (i.e. in situ/intermediate leakage and $V_{gs}$ measurements, and PoF methods) was developed to localise and analyse the failure mechanism in detail. An MIP decapsulation technique provided the essential possibility to selectively remove the passivation material without sacrificing the inorganic materials beneath it. With the help of an FIB cross-sectioning technique and SEM imaging, the failure mechanism was concluded to be related to aluminium corrosion at the chip GR structures on both transistors and diodes. The electrochemical migration of [Al(OH)$_4$]$^-$ (i.e. tetrahydroxosaluminate anions) is suggested to be associated with the mechanism via Eq. (6). This failure mechanism had been described by earlier studies [5]; however, PoF analysis and statistically relevant evidence had not been shown in such detail, partly due to the lack of access to the MIP technique and effective hotspot localisation techniques. For future work, hydrogen content should be analysed with some surface-sensitive material analysis technique (e.g. time-of-flight secondary ion mass spectroscopy) that can detect hydrogen, which was hypothesised to be associated with the resulting corrosion products [5]. Furthermore, the advanced statistical analysis techniques utilised during this study also suggest that aluminium corrosion is indeed a relevant failure mechanism in power semiconductor modules. Aluminium corrosion of the ET metal GRs should be considered when designing more robust power electronic systems for harsh environment applications where high ambient humidity levels are expected. The failure mechanism described in this article is suggested to be relevant for any voltage class beyond 1200 V range and should be considered especially in medium voltage applications due to the higher electric fields at the ET structures. Nevertheless, it is strongly suggested that metal GR and FP structures are either replaced by polysilicon structure or that the electric fields associated are reduced in power semiconductor devices, such as IGBTs and FWDs in general, as described in [6,8,10,13]. Further investigation of the electric field distribution in the ET region and the possibility of hermetically sealing the ET structure should not be overlooked if the situation is to be improved.

CRediT authorship contribution statement


Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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