

Cyclic temperature and humidity profile for mixed flowing gas tests of power semiconductor modules

J. Rautio¹, T. J. Kärkkäinen¹, J. Jäppinen¹, K. Korpinen¹, M. Niemelä¹, P. Silventoinen¹, J. Leppänen², J. Ingman²

¹ LUT University, Finland

² ABB Oy, Finland

Abstract— Reliability testing of power electronics in corrosive environments is relevant and topical as the devices are used in increasingly harsh environments that impose a risk of corrosion phenomena taking place. On components protected with silicone gel, resin, or other potting and encapsulation polymers the corrosive gases and humidity need to permeate through the protective layers before dendrite growth is initiated on the component surface. Testing packaged power semiconductor modules in a static temperature and humidity environment does not reflect fluctuating field conditions and may lead to erroneous conclusions e.g. when evaluating different potting materials. In this study, gas transfer through the silicone gel potting used in power semiconductor modules is expedited. Based on the properties of the gel, a cycling scheme for temperature and humidity is introduced to increase the gas permeation rate and so the dendrite growth rate.

Index Terms— Accelerated life testing, Corrosive environment, Power semiconductor module, Reliability.

I. INTRODUCTION

Corrosive gas testing of power electronic components and devices is a recent venture compared to the research done on consumer electronics and low voltage electronics motivated by an increasing number of corrosion problems associated with the RoHS directive taking effect in 2006 [1, 2, 3, 4]. Power electronic devices like frequency converters are subjected to a wide variety of environmental conditions and they are required to operate in harsher and harsher environments. Some application environments are especially harsh due to the presence of corrosive gases (e.g. wastewater plants, mines and various industrial complexes). As packaging densities become higher the electric field strengths driving electrochemical corrosion become greater. The corrosion can manifest itself as dendrites, a conductive corrosion product that grows in the direction of the electric field. The devices and components need to be designed to withstand harsh environmental conditions. Accelerated environmental testing is required for studying the reliability of devices in such corrosive environments and to verify that products can survive the intended operating environments.

Testing with corrosive gases is commonly done in controlled and static humidity, temperature, and gas concentration [5, 6]. The simplest corrosive gas test is a single gas test in which the design under test is exposed to

high concentration of single gas, commonly hydrogen sulfide (H_2S) [5, 7]. Another test method is mixed flowing gas (MFG) environmental test where a mixture of three or four corrosive gases together with high humidity form the corrosive environment. Using multiple gases allows synergistic chemical reactions and relatively high acceleration for the corrosion with lower gas concentrations compared to single gas corrosive testing that may yield unrealistic chemical reactions [8]. The gases commonly used are hydrogen sulfide (H_2S), sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and chlorine (Cl_2) [6]. Hydrogen sulfide is commonly found in mines, wastewater treatment plants, agricultural sites and petroleum and natural gas processing plants. Sulfur dioxide and nitrogen dioxide are mainly emitted by combustion engines and fossil fuel power plants. Chlorine gas is not found in nature but is used as a substitute for naturally found sources of chloride ions such as sea salt.

Power semiconductor devices are commonly packaged into large modules where the semiconductors are potted in silicone gel, silicone rubber or resin to protect the module from outside objects and dust and to increase the dielectric strength compared to air. None of these polymers offers hermetic sealing, instead gases can permeate through them [9, 10, 11, 12]. Fig 1 shows a simplified structure of a high power IGBT (Insulated gate bipolar transistor) module where the IGBT chips and the DBC (direct bonded copper) structure on alumina substrate are potted under silicone gel supported by a plastic enclosure. In this kind of structure corrosive gases and humidity need to permeate through the potting gel to reach the component surface where together with applied voltage they can cause dendritic growth [5, 7] and other humidity induced failure mechanisms [13, 14, 15, 16]. The dendrites grow on the alumina base following the direction of the electric field and may eventually bridge adjacent copper areas together. Bridging may cause a high-impedance short circuit in the module.

A problem with corrosive gas testing is that the test environment does not reflect real field conditions. The major difference is that on the field the ambient temperature and humidity the component or device sees changes and more importantly the microclimate on the component surface changes with heating of the component. As the component warms up the relative humidity inside the component and on its surface decreases. A conventional corrosive gas test, however,

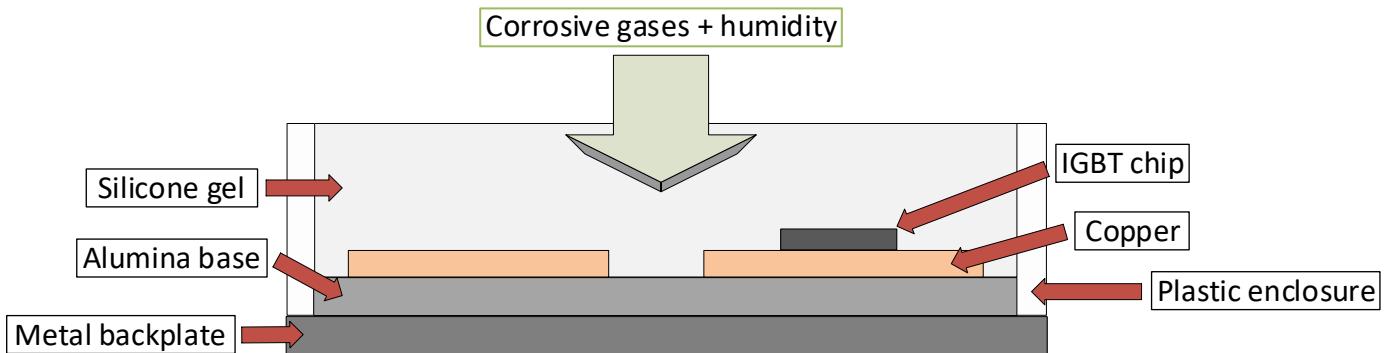


Fig 1. Simplified IGBT module structure and gas permeation through silicone gel visualized.

keeps the ambient temperature and humidity levels static for the entire duration of the test. Albeit accelerated, corrosive gas tests can take months to complete. The acceleration factor of the corrosion growth can be increased by making the environment more corrosive, for example by increasing the gas concentrations, temperature, or humidity [7]. However, accelerating the corrosion phenomena only happens after the water vapor and corrosive gases have permeated to the component surface. With elevated gas concentrations accelerating the dendrite growth rate is not an issue, but for example, with silicone gel potted IGBT modules the properties of the gel most likely dominate the aging leading to failure and so the test should be designed to accelerate the permeation instead. The permeation of corrosive gases through a polymer is a function of temperature and humidity [11, 17, 18], which can lead to a major discrepancy between corrosion phenomena caused by test and field conditions.

This paper proposes the use of a cyclic temperature-humidity test profile on corrosive gas tests to better account for encapsulation material properties. The effect of a cyclic temperature and humidity test profile to the corrosion phenomena of silicone gel potted IGBT modules compared to a conventional static temperature and humidity profile is investigated.

II. THEORETICAL FOUNDATION

Electrochemical migration that forms the dendrites is depicted in Fig 2. In IGBT modules the electrolyte layer forms between adjacent copper areas and allows ion migration to happen when the layer is complete. In non-condensing conditions the electrolyte is formed by thin monolayers of water that have adsorbed onto the alumina substrate [19, 20]. The number of layers depends mainly on relative humidity and surface properties: material, roughness, and impurities. It is to be noted that presence of impurities on the alumina substrate may cause condensation of water at less than 100 % relative humidity [17]. As the conductivity of the electrolyte increases with the number of adsorbed water layers, electrochemical migration is accelerated [20].

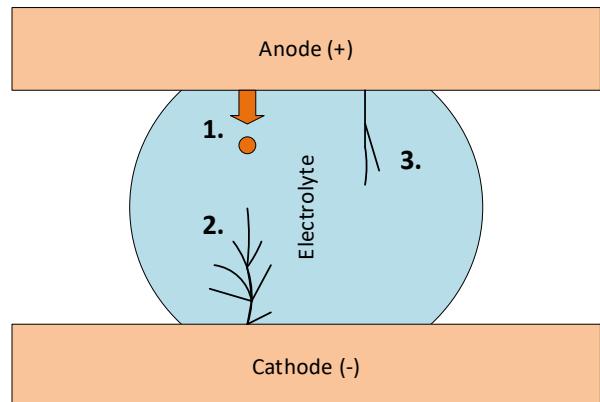


Fig 2. Electrochemical migration that takes place in the isolation trench of the IGBT module. 1. Copper ions dissolve to the electrolyte at the anode. 2. Copper ions migrate to the cathode where electrodeposition takes place, forming dendrites. 3. Anions formed by chemical reactions or by solution of corrosive gases migrate to the anode and electrodeposition takes place on the copper ions dissolved at the anode form stable compounds with the ions in the electrolyte, forming dendrites.

In accelerated corrosive gas tests, the highly corrosive environmental conditions must first reach the copper and alumina surfaces before electrochemical migration can begin. The corrosion process can be accelerated relatively easily with high corrosive gas concentrations compared to what is expected on the field. However accelerating gas permeation rate through the potting material, e.g. silicone gel or epoxy, is not as straightforward. The permeability coefficient P describing permeation of gases through a polymer is

$$P = DS \quad (1)$$

where D and S are the diffusion and solubility coefficients, respectively [21].

Solution of gases happens at the boundary between the polymer and the gas, after which diffusion happens inside the polymer. Diffusion and solubility coefficients are defined for a specific polymer-gas pair [11] and are affected by many parameters including properties of the gas such as molecule size and polarity and material properties of the polymer [11, 21].

In an environmental test the polymer is a part of the studied component or structure and so the polymer-gas

pair properties are not a controllable test parameter. The remaining environmental parameters affecting the gas permeation through the protective polymer layer that can be controlled are temperature and humidity [18, 22]. The effects of temperature and humidity on the gas permeation are not evident: polymers can show both increasing or decreasing permeability for gases when either parameter is altered [11, 21, 22]. The effect of relative humidity or water vapor is related to the amount of water absorbed into the polymer matrix and for hydrophobic polymers a decrease in gas permeability in humid environments is expected [18]. The silicone potting used in the example IGBT modules is hydrophobic and so relative humidity was decreased to increase the gas permeation on the cyclic test. The effect of temperature on the gas transfer through the specific silicone potting for each gas used in MFG test is not known but it has been suggested that at low pressure difference across the permeate it is more common that the permeation increases with increasing temperature [11].

The proposed cyclic test profile was designed to have a “dry and hot” step followed by a “wet and cool” step. During the dry step the corrosive gases permeate to the layer of interest under the silicone potting faster than in lower temperature humid conditions. The dendrites grow during the wet step with the formation of water monolayers to enable electrochemical migration [5, 23]. The wet step is cooler than the dry step because the operating temperature of the test chamber is limited by the absolute humidity of the exhaust air. The steps also mimic the field conditions more closely. As the devices are running under load it is not uncommon for the junction temperature of an IGBT to exceed 100 °C which heats the whole module and lowers the local relative humidity on the module surface. When the load decreases or is removed the module cools down to ambient temperature and the local relative humidity rises. If the ambient humidity is high, dendrite growth may ensue during the wet time. It’s not uncommon for power electronic devices like frequency converters to be used in non-air-conditioned spaces with elevated humidity levels.

A benefit over static high humidity corrosive tests is a possible decrease in failure mechanisms that are not under study. In recent work by M. Hanf et al. [7] it is mentioned that when testing IGBT modules under static high relative humidity several failure mechanisms were reported and most of them were related to chip degradation by humidity.

As the time of wetness is decreased the failure mechanisms driven only by humidity are less likely to occur. The outcome is that more devices either fail to the expected failure of a short circuit caused by dendrite growth or they survive for the whole test duration and are comparable with each other. The humidity driven failure mechanisms are better studied with cheaper and easier to conduct high voltage, high humidity, high temperature reverse bias tests (HV-H³TRB) [13, 14, 16, 15, 24]

III. EXPERIMENTAL SETUP

Three mixed flowing gas (MFG) environmental tests with the same gas concentrations but different temperature-humidity profiles were conducted on this

study (Table 1). In the first test the temperature and humidity are constant. In the second test the temperature-humidity profile had two steps. The first step was 15 days and the second step 25 days long. The first step was “dry and hot” during which the temperature was set to the maximum allowed by the test chamber, 60 °C, at the driest controllable humidity setting. During this step the permeation speed of gases through the silicone gel is expected to be high compared to the second “wet and cool” step during which the corrosion process would take place as continuous electrolyte could form on the isolation trench. Additional benefit of the proposed profile is that the “dry and hot” step allows increase of testing temperature from 45 °C to 60 °C during the dry step compared to a static test where the absolute humidity of the exhaust air limits the maximum usable temperature.

In the third test the temperature-humidity profile went through the two-step cycle 4 times. Each step was 4 days and 22 hours long and the temperature and humidity were alternating between the same setpoints as in the stepped test while all other environmental parameters were kept constant.

TABLE I
ENVIRONMENTAL PARAMETERS OF THE MFG TESTS

Parameter	Test 1, static	Test 2, stepped	Test 3, cyclic
Length	40 days 20 hours	40 days	39 days 8 hours
Time of wetness	40 days 20 hours	25 days	19 days 16 hours
Temperature, °C	45	Dry: 60 Wet: 45	Dry: 60 Wet: 45
Relative humidity, %	85	Dry: 8 Wet: 85	Dry: 8 Wet: 85
H ₂ S concentration, ppb	900	900	900
NO ₂ concentration, ppb	2000	2000	2000
SO ₂ concentration, ppb	2000	2000	2000
Cl ₂ concentration, ppb	20	20	20
Ventilation factor, h ⁻¹	3.4	3.4	3.4

The power modules used in this study have approximately 5.5 mm thick silicone gel layer. The steps in the cyclic test were set to follow a 50% duty cycle and the step duration was based on a study where water vapor permeation through silicone gel was investigated [25]. It was found that for a gel thickness of 9 mm a relative humidity close to the ambient value is reached within 30 hours of exposure and for a thinner 5 mm layer in less than 10 hours [25]. The silicone potting material used in the modules under study is likely to show a difference in water vapor permeation, as the silicone potting material is not the same, which was considered on deciding the wet step duration. The step duration was set to greatly exceed the 30 hours to give adequate time for the formation of water monolayers to allow for electrochemical migration to take place.

The cyclic test started with a dry step and ended with a wet step. It is to be noted that the conditions were non-condensing even during the transition from one step to

another. When the temperature transitioned from “hot” to “cold” state the relative humidity was low and the modules were warm, preventing condensation. The humidity increased after the temperature had settled to a lower level. The study was conducted using a mixed flowing gas test chamber introduced in detail in [26].

Six IGBT modules with three half bridges in each were exposed to corrosive environment on all tests. In every other half bridge, the upper switch was reverse biased by short-circuiting the lower switch, and in the rest of the bridges the upper switch was shorted. The bias voltage was set to 1360 V, 80 % of the maximum rated blocking voltage of the modules. The heatsink backplates of the modules were connected to the negative bias to mimic connection to grounded heatsink on assembled devices. Each bias channel was connected to a leakage current monitoring system that disconnected the channel if leakage current reached a set limit value of 300 μA . This was also used as a failure criterion for the tests. The leakage current system was introduced in detail in previous work [26]. As mentioned in [7] the dendrite growth is not detectable from the leakage current unless it forms a short.

Dendrite growth on the IGBT module is not easily quantified as the growth length varies even within the same area of the module. For comparing the dendrite growth between three tests local maximum dendrite length was chosen: long dendrites that stand out from a shorter uniform-length dendrite growth were recorded for the analysis. The longest dendrites reflect the potential of a high-impedance short circuit forming.

IV. RESULTS

By dendrite length measurements the cyclic test provides accelerated cathode dendrite growth rate compared to the static profile test and the stepped test despite using the same gas concentrations and having significantly shorter time of wetness. Dendrite length

varies quite a lot within the same test but the difference between cyclic and other tests is clear (Fig. 3). The mean length of recorded dendrites on the cyclic test was higher than the maximum length recorded on the static test for both the upper and the lower biased legs. On the stepped test a few dendrites reached a relatively long length, but they were more of an outlier. The stepped test showed a small number of dendrites that significantly exceeded the dendrite lengths recorded on the static test, but the distributions are close and there is less data available from the static test for drawing conclusions.

The variation in dendrite length within the same module is expected for a structure as complicated as the IGBT module. The isolation trenches are located around the module, some near the edges and some closer to the middle. The ambient gases mainly enter the package from the module edges through a seam between the module’s plastic body and a lid. There is some room between the silicone gel and the lid which should allow for the gas mixture to distribute on top of the gel somewhat evenly, but results indicate that gas permeation may be faster on the module edges. This could be because of imperfect adhesion of the silicone gel to the plastic walls. In addition, the copper edges from which the dendrites grow have differences in surface roughness which creates local differences in electric field strength. In addition, thickness of the electrolyte layer could have local maximums with impurities on the alumina isolation trench and would cause changes in the dendrite growth rate [4].

The isolation trench in the tested IGBT modules is approximately 700 μm wide and no short circuits due to dendrites were recorded on any of the tests. The measured dendrites grow from the side of the negative voltage potential (cathode) towards the positive (anode). The perpendicular distance from the tip of the dendrite to the copper edge at the base of the dendrite was used for characterization as lateral growth does not advance the

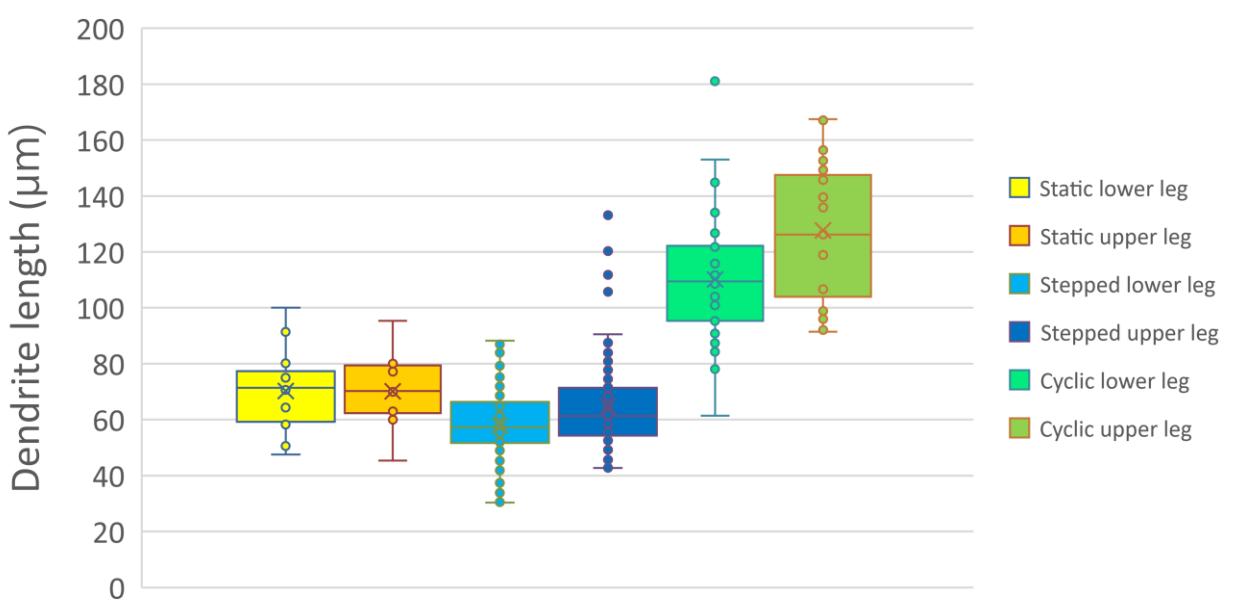


Fig 3. Box plot of local maximum dendrite length.

bridging of the isolation trench. In addition, this makes the length comparison easier and more equal.

There seems to be a slight bias towards longer dendrite growth in the upper leg. The difference between upper and lower leg dendrites could result from one or both of the following reasons:

- 1) The isolation trenches may not experience similar electric fields because of geometrical differences.
- 2) In the studied module type the isolation trenches surrounding the upper biased leg are longer so there is larger area where dendrite growth can take place.

Because of the mentioned differences in module structure the dendrite length comparisons were made separately for high and low side legs. Only legs that survived the whole duration of the test without reaching the failure criterion were used for the comparison. This way the legs were biased for the same duration and the dendrites had equal time to grow.

The static profile test has a smaller number of eligible legs for the analysis because more of them failed from humidity-only related failure mechanisms of the IGBT or diode chips rather than from dendrite bridging of the isolation trench. Failure criterion of exceeding 300 μA leakage current was met with 11 out of 18 legs on the static profile test, 7 out of 18 legs on the stepped test and 5 out of 18 legs on the cyclic profile test. As hypothesized, the stepped and cyclic test profiles decreased the number of early failures to humidity driven mechanisms, that are not the primary focus of the corrosive gas test, as the time of wetness was significantly shortened.

Comparison of typical dendrite growth on each test is presented in Fig. 4. It was observed that corrosion growth

on side of the positive bias (anode) was not accelerated similarly on the cyclic test and in multiple modules was almost completely absent. The same observation was made in the stepped experiment. When anode dendrites were present in the cyclic or stepped tests, they looked darker and more prominent but not longer than those caused by the static experiment exposure, as seen in the figure. Judging by the decrease in length the phenomenon may be driven by humidity rather than the corrosive gases, or the chemical reactions that form dendrites on the side of negative bias start to dominate when the composition of the electrolyte changes as more ions are dissolved in the electrolyte solution.

The difference in cathode dendrite length between stepped and cyclic tests is interesting and hints that a single hot and dry step does not prime the isolation trench surface with enough gases for longest dendrites to form. It could be that the chemical reactions consume the ions faster than more are provided via permeation through the gel during the wet step or the chemical reactions driving the cathode dendrite growth may benefit from the changes happening on the electrolyte layer thickness and composition during humidity transients.

V. DISCUSSION

When studying packaged semiconductor modules with corrosive gas tests the packaging materials such as silicone gel potting end up being a major contributor to the observed progression of the corrosion. The same effects apply to corrosion in the field. The gel provides some protection against the environment although it is not its primary purpose. The so-called protection is based on how

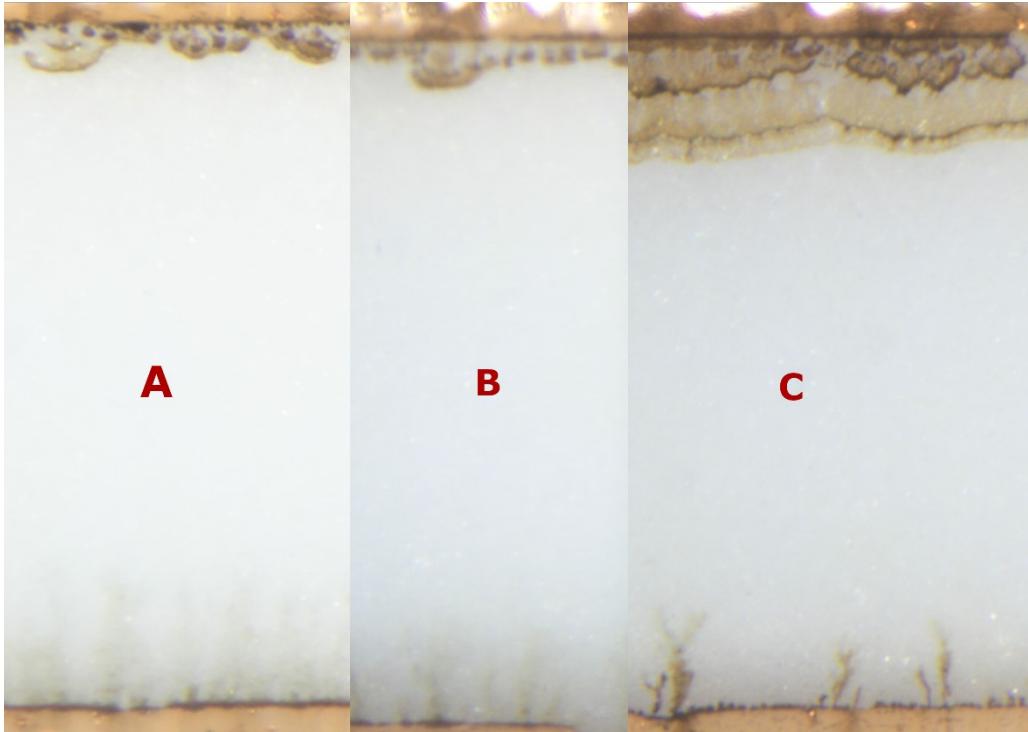


Fig 4. Dendrite growth comparison of static test (A) stepped test (B) and cyclic test (C). The top copper on each picture is negatively biased (cathode) and bottom positively biased (anode). All pictures are taken from the around same area of the module's upper leg. Blur is caused by the silicone gel on top of the dendrites.

slow the permeation rate of the gases through the materials is. A device may be able to survive short bursts of corrosive gas exposure because the potting material slows down the permeation enough that no gas reaches the module surface. Conversely a long-time exposure requires the materials to slow down the permeation of gases more.

The literature and results strongly suggest that gas permeation and so the corrosion test can be accelerated when the potting material properties are considered when deciding on test parameters. As the test durations of corrosive gas tests are relatively long, measured in tens of days for encapsulated components and devices, a small increase in acceleration can save multiple days.

Another direction for test profile customization is to consider the ambient conditions and load profile that the component or device sees on the field more closely. Using a warm and dry step already achieves this partly as the temperature of the IGBT modules during operation normally greatly exceeds the ambient temperature and relative humidity on the component surface is very low. Sadly, compared to the component temperatures commonly exceeding 100 °C during heavy loading the usable temperature range of commercial corrosive gas test chambers is low which limits properly recreating let alone accelerating gas permeation in potting materials where permeation increases with temperature.

The idea behind developing a cyclic test profile after the two-step test was that the chemical reactions may consume the gases faster than the gases can permeate through the silicone gel potting in wet conditions. This may not be the case with higher gas concentrations on a single gas test. Instead, a two-step test could cause longer dendrite growth compared to a conventional static temperature-humidity profile test within the same test duration. However, the dry step duration should be studied profoundly to maximize the effect and minimize the test duration. Both the stepped and cyclic profiles should be investigated with single-gas tests.

To achieve maximum dendrite growth rate on cyclic tests the step durations should be investigated further as long dry step could saturate the gas concentration on the component surface after which no more permeation happens. In turn, too long wet steps may decrease the ion concentration of the electrolyte enough to slow down the corrosion process.

The hypotheses mentioned need to be investigated in the future and the acceleration of dendrite growth estimated and quantified further.

VI. CONCLUSIONS

A cyclic temperature-humidity profile for mixed flowing gas corrosive tests was introduced. The profile is designed to highlight the vulnerabilities of IGBT modules stemming from the gas permeation characteristics of silicone gels. The proposed temperature-humidity profile takes into account polymer-gas specific transfer properties that are dependent on temperature and relative humidity.

The cyclic test was found to accelerate dendrite growth on the side of the negative bias compared to otherwise identical tests with a static and two-step temperature-

humidity profiles. An added benefit was found: the number of humidity caused failure mechanisms that were not under study was reduced as time of wetness was shortened.

By the findings with a tailored temperature-humidity profile it is possible to accelerate the corrosion phenomena in potted or encapsulated semiconductor modules and possibly shorten the test duration if it is of interest. A similar process of customizing the test profile can be used for other components with a gas permeable potting, encapsulant or enclosure.

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