Microelectronics Reliability 88–90 (2018) 447–452

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Humidity robustness for high voltage power modules: Limiting mechanisms and improvement of lifetime

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ARTICLE INFO

Keywords:
Power modules
Environmental testing
Accelerated stress tests
Reliability
Humidity
Robustness

ABSTRACT

During the last years applications for power modules with harsh environmental conditions have gained increasing importance. Static humidity tests with $T = 85\,^{\circ}\mathrm{C}$ and RH = 85% with high voltage have established as basic testing method for the humidity robustness of semiconductor power modules. The present work is showing the improvement of humidity robustness with respect to the established test methods. Electrical performance monitoring and analytic approaches to prove the results with respect to established work on the field of humidity testing.

1. Introduction

1.1. General motivation

The humidity robustness of semiconductor power modules has become a crucial factor in the overall reliability of systems running in an environment that allows exposure to outdoor conditions. Different mission profiles need to be assessed ranging from low load to high load, and also including idle state conditions. An example is provided in [1] for traction applications. The measured values for the temperature inside the converter cabinet during operation are roughly 5–10 K above the ambient conditions which can be a typical situation for low load conditions.

A general study on the reliability of wind turbines covering both offshore and onshore operation is presented in [2]. The expected limitation due to the end of life of interconnection technologies such as bond wires or solder connections could be excluded for an observation period of 11 years as a reason for the failure. Humidity-driven lifetime limitation of the power electronic system and its components is, alternately, of high relevance. Furthermore, a correlation between ambient temperature and failures is observed indicating an environmental influence. If so-called off-the-grid times are additionally influencing these failure rates as discussed in [3], needs to be further investigated in subsequent projects.

New technologies such as SiC-MOSFETS are also investigated regarding the influence of outdoor environments on inverter reliability [4]. Here, degradation effects regarding leakage current (I_{CES}) were observed in the outdoor applications compared to the indoor references. The author has pointed out in this paper that nowadays many industrial applications place the converter unit outdoors with exposure to harsh environmental conditions. Additionally, for many applications, an outdoor placement is obligatory and common as for certain types of solar applications.

The applications with direct contact to harsh environmental conditions are varied. Combinations with low-power dissipation due to low load operation or non-operation times also exist. The majority of these applications do not use any additional kind of protection against humidity exceeding the protection of normal IP (International Protection) classes. The necessity of a certain humidity robustness of semiconductor modules exists. The implication for life time estimation will be discussed at the end of this work.

1.2. State of the art test methodology

The H3TRB (high-humidity, high-temperature reverse bias) or THB (temperature-humidity bias) stress test with high voltage have already been discussed, and are generally accepted to prove the humidity robustness of IGBT modules (see [5]).

Zorn et al. discuss the effect that humidity can have in principle on an important electrical parameter, in this case the remaining blocking characteristic if a THB test at high DC voltage is applied. The findings prove that the test is sensitive in discerning technologies of different robustness (see Fig. 1). Furthermore, the paper describes in detail the underlying mechanism that can lead to such a deteriorating effect, and the improvement based on the failure-analysis results in addition to the electrical diagnosis.

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https://doi.org/10.1016/j.microrel.2018.06.043
Received 31 May 2018; Received in revised form 25 June 2018; Accepted 25 June 2018

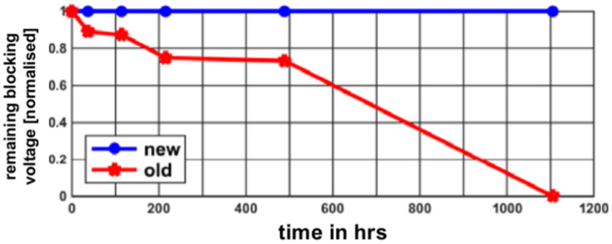

Fig. 1. "Reduction of the blocking capability over testing time. The awareness of humidity driven degradation has already led to significant improvements, here demonstrated for 3.3 kV IGBT modules." [1].

In the following chapters of this work, the H3TRB test at high voltage (HV-H3TRB) is applied to IGBT modules belonging to two different technology levels. Typical aging signatures are discussed in Section 2; the improvement generated by the latest technology development is highlighted in Section 3. Finally, a correlation between test duration and real-life operation times is estimated based on existing acceleration models.

2. Humidity robustness of 3,3 kV technology without additional humidity protection

2.1. HV-H3TRB tests

Before implementing measures to enhance humidity ruggedness, the robustness of an existing technology has been thoroughly investigated. To evaluate the humidity robustness of a 3.3 kV technology that is based on field-plate edge termination HV-H3TRB tests at a typical application voltage level of $V_{CE} = 1800$ V were performed.

During the test, the leakage currents of all modules in a parallel configuration were measured with an interval of ~1/(24 h). The leakage current was monitored both at the stress voltage (1800 V) and at an increased probe voltage of 2600 V that is only applied for short intervals of 60s. So no contribution to the aging mechanism has been assumed. In this way we ensured that fatigue mechanisms without relevance for a real application are not triggered. On the other hand, by measuring I_{CES} at 2600 V we obtained a very sensitive indicator for detecting fatigue of the IGBT module.

Fig. 2 presents the leakage current over test time. Up to 1000 h, no significant change in the current is visible, neither at 1800 V nor 2600 V. After 1000 h, the leakage current rises during continuation of the test. Both measured values 1800 V and 2600 V show a synchronous increase during the same time period. This seems to be a valid effect of an aging process. After ~1700 h, the test was ended and the modules were taken out of the test for an electrical and optical analysis.

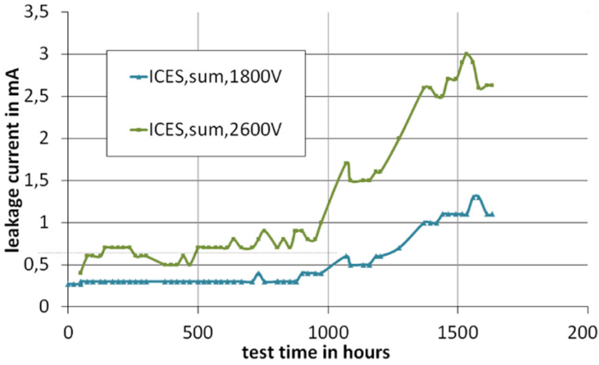

Fig. 2. Leakage current monitored over test time ($I_{CES}(t)$) for $V_{CE,test} = 1800$ V; green: current at 2600 V probe voltage; blue: current @1800 V stress voltage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

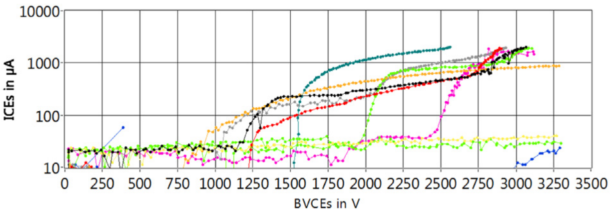

Fig. 3. IV characteristics after ~1700 h for the 1800 V test, different colors for different systems of a module.

After the stress test, the IV characteristics were measured within several hours after test end. Fig. 3. shows the IV characteristics after 1700 h of stressing at 1800 V. The blocking characteristics are significantly rounded. Nevertheless the modules are still able to block $V_{CE} > 3000$ V. This explains the capability to withstand $V_{CE} = 2600$ V until the end of the test.

2.2. Optical analysis

The modules were opened and the silicone gel was chemically removed from the top of the chips. Afterwards, the top imide layer of the chips was removed to investigate the aluminum structures of the edge termination.

Fig. 4 a/b displays an excerpt of the edge termination structure representing the IGBT dies. The pictures show a close-up of ~2 field plates for two stages of the corrosion. For the IGBTs, the corrosion started quite systematically on the side of the field plate directed to the outside of the chip. Most likely this is due to the higher electrical field strength at this location. The observed fatigue mechanism can be classified as a systematic effect.

For the diode, the aluminum structures also show corrosion (see Fig. 5). The corrosion affects both, the outer and the inner field plate and shows a higher contrast to the rest of the aluminum. For the diode, the corrosion takes place rather seldom compared to the IGBT, which can most likely be explained by the fact that the IGBT and the diode had a slight difference in their initial aluminum passivation layer. The lessons learned about the influence of design are exploited in the next step towards an ultimate robust edge termination (see Section 3).

2.3. Comparison of IGBT and diode

The results of the previous chapter lead to the educated guess that the IGBT and the diode behave differently with regard to stress time. Therefore a test with single-chip modules was done for a direct comparison. Three different groups were tested:

1) IGBT only
2) Diodes only
3) Full module with IGBT/diode (reference)

A bias of 2100 V was applied.

During the stress time the blocking characteristics were regularly

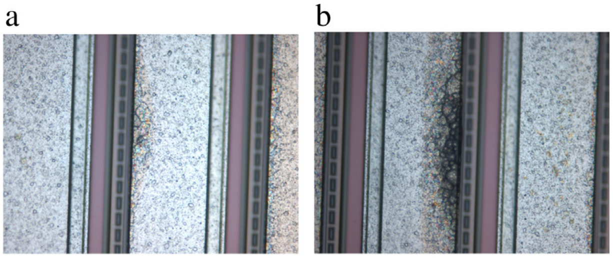

Fig. 4. a (left); b (right). Analysis after ~1700 h at 1800 V; corrosion on outer side of the field plate in two different progression states.