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The influence of humidity on the high voltage blocking reliability of power IGBT modules and means of protection

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ABSTRACT

High voltage IGBT modules are used in high power applications including traction, industrial drives, grid systems and renewables such as in wind-power generation and conversion. Many of these applications are subject to harsh environmental conditions and in particular when the inverter cabinets do not shield the power electronics, including the IGBT modules, from such conditions. As an example, IGBT modules can be exposed to severe humidity levels. In this paper we investigate the influence of the combination of humidity and high voltage on the blocking reliability of 6.5 kV IGBT and diode devices. An improved testing approach High Voltage, High Humidity, High Temperature reverse biased (THBHV-DC) when compared to classical THB is applied to assess the robustness of different termination designs and passivation stacks. Full description of the failure mode and of its correlation to the humidity induced electrical field modifications is also provided. This analysis offers an insight on the design and testing aspects which are of key importance to the development of environmentally robust high power IGBTs.

1. Introduction

Predicting the robustness of various power semiconductor designs for a planned lifetime of up to 30 years is very challenging, even more so since the conditions of the environmental impact are mostly not well understood. In many power electronics applications the IGBT modules are subject to harsh environmental conditions with severe humidity levels especially when the inverter cabinets do not shield the power electronics components. Also when the inverter is not always running under full load conditions and can be in idle or running in partial load which means that the temperature can rise or drop relatively fast. Due to that, moisture can penetrate into the IGBT modules during long idle periods of time and there are no high temperature levels to drive out moisture from the modules. Another aspect is that condensation can appear while having a temperature drop during operation, which can lead to severe changes in the material properties (e.g. dielectric properties of chip passivation and module encapsulation materials such as Si-gel). These undesirable modifications can have a negative impact on the electric field at the periphery of the semiconductor device and therefore cause an increased localized stress at the chip junction termination region. Therefore, it is crucial that the materials used for the IGBT module and the design of the power semiconductor including chip termination and passivation can cope with the increased stress levels.

2. Testing for environmental robustness

In the past, the standard THB (temperature humidity biased) test with 85% RH (relative humidity) and 85 °C was used at a reverse bias voltage of 80 V, with a typical test time requirement of 1000 h. This test promotes charge or ion movements due to increased moisture levels combined with relatively higher temperatures and voltages, which allows detection of instabilities caused by process variations or insufficient design margins. With such a standard test, decades of experience have been accumulated. However, for high power semiconductors, the 80 V applied reverse bias remains at a low level compared to typical voltages used in real power electronics converters.

It was shown that by increasing the applied voltage to more realistic values [1,2], it is possible to accelerate corrosion by electrochemical mechanisms which could play a more dominant role during field operation when compared to the classical impact of charge or ion movement. In the presence of high electric fields and enough reactant moisture ions at the chip surface, electrochemical corrosion can occur causing several materials like aluminum, nitride and even oxide compositions to change their structure and lose the main protective

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functionality. Hence, the well-known HTRB (high temperature reverse bias) when not combined with moisture, is not representative to quantify the device performance operating in a harsh environment.

A THB test with an increased collector emitter voltage, referred to as THBHV-DC or H^3TRB (i.e. High Voltage, High Humidity, High Temperature reverse biased) is the appropriate test to prove the robustness of the chip termination and passivation against humidity and high electric fields [3]. This test is typically performed in the standard controlled climatic environment and conditions of the well-established THB test while increasing the collector emitter voltage depending on the device voltage class up to 60–80% of the rated voltage.

3. Humidity impact on junction termination

This section provides an overview of the junction termination designs implemented in the investigated samples and a qualitative TCAD simulative analysis of the effect on the electric field distribution in humid environment. The robustness under THBHV-DC stress has been assessed for two different junction termination concepts. The IGBT employs a Variable Lateral Doping (VLD) junction termination while for the diode a floating guard ring (GR) junction termination is used, as sketched in Figs. 1 and 2 respectively. Both termination designs have a comparable width and use semi-insulating SIPOS material as first passivation layer. As protection against environmental and mechanical aging factors, a top passivation is added consisting of a stack of silicon nitride and thick polyimide (PI) for both devices.

Depending on the design, the electric field distribution and peak locations under blocking conditions are different for the IGBT and diode. Figs. 3a and 4a show the plot of the electric field contours for the 6.5 kV IGBT and diode terminations, simulated at 4.5 kV DC voltage Furthermore, Figs. 3d and 4d show the cutline at the nitride layer for the two different designs. To evaluate the possible changes in the electric field due to humidity exposure, the moisture absorption in the polyimide layer and the surrounding gel is accounted in simulation by an increased value of permittivity of a factor of 10 compared to a polyimide or gel without water content of a value of 3.4. Such an increase aims to represent the extreme case of having a water saturated layer as a water film directly in contact with the silicon nitride passivation.

Figs. 3b, c and 4b, c illustrate the impact of dry and wet conditions and therefore increased permittivity of the ambient and of the polyimide layer while modifying the electric field distribution for the diode and IGBT termination by simulating the whole passivation structure presented in Figs. 1 and 2. The cutline parallel to the silicon surface in the silicon nitride layer shows the strong increase of the local electrical field peaks at each silicon ring location due to the increased permittivity of the polyimide and the ambient. The increase becomes larger when moving close to the active area. Fig. 4c and d shows the impact on IGBT VLD termination: the field peaks strength remains comparable to the dry peak but with a larger region of high electric fields which move towards the active area. In both diode and IGBT the electrical field does not decay to a negligible value at the outer edge of the termination but remains considerably high when compared to the dry conditions. As a qualitative outcome of the simulation results, an increased humidity

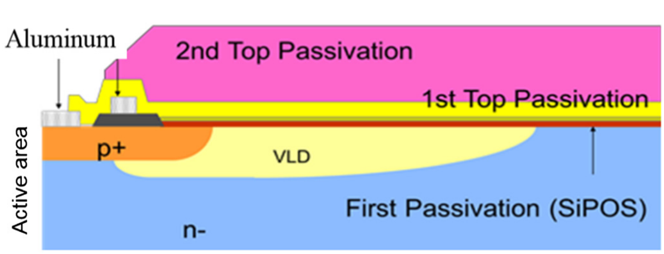

Fig. 1. IGBT with Variable Lateral Doping (VLD) termination and gate runner between active region and termination.

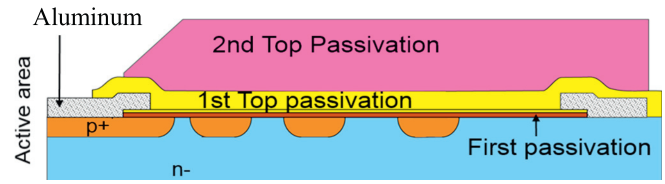

Fig. 2. Diode with floating Guard Ring (GR) termination.

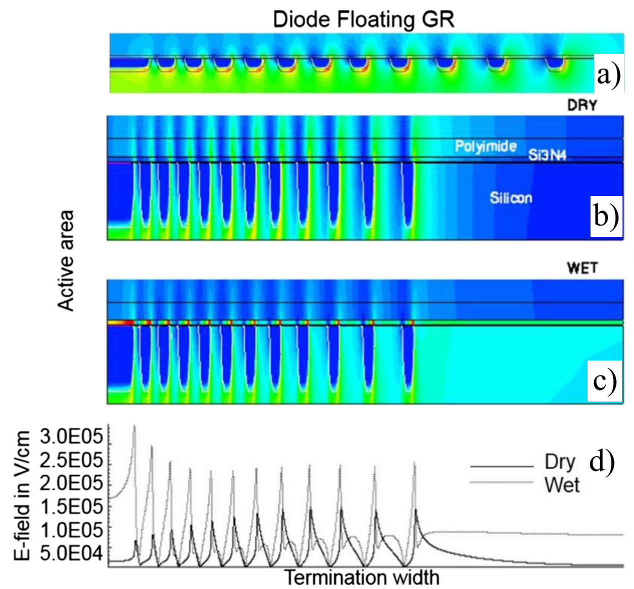

Fig. 3. a) Electric filed contour plot of the 6.5 kV diode simulation in reverse blocking at 4.5 kV (overview picture). Zoomed in electric field of GR termination without b) and with c) water absorption: d) cutline in nitride layer in the proximity of nitride/polyimide interface for b) and c).

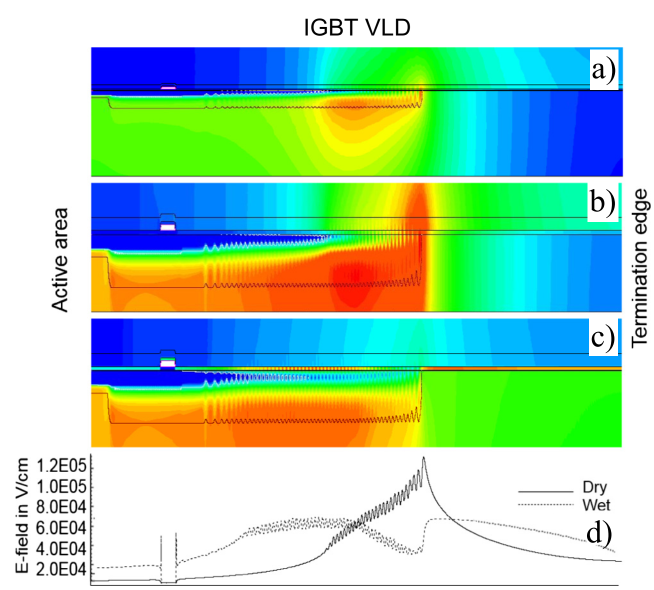

Fig. 4. a) Electric filed contour plot of the 6.5 kV IGBT simulation in reverse blocking at 4.5 kV (overview picture) with gate runner structure with gate emitter shorted. Zoomed in electric field of VLD termination without b) and with c) water absorption: d) cutline in nitride layer in the proximity of nitride/polyimide interface for b) and c).

content in the ambient (or encapsulating material such as silicone gel) and in the polyimide is expected to cause a strengthening of the electric field in the silicon nitride layer in the proximity of the active area and in