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Identification of Failure Precursor Parameters for Insulated Gate Bipolar Transistors (IGBTs)

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Abstract— Insulated Gate Bipolar Transistors (IGBTs) are used in applications such as the switching of automobile and train traction motors, high voltage power supplies, and in aerospace applications such as switch mode power supplies (SMPS) to regulate DC voltage. The failure of these switches can reduce the efficiency of the system or lead to system failure. By identifying failure precursor parameters in IGBTs and monitoring them, a prognostics methodology can be developed to predict and avert failures. In this study, IGBTs aged by thermal-electrical stresses were evaluated in comparison with new components to determine the electrical parameters that change with stressing. Three potential precursor parameter candidates, threshold voltage, transconductance, and collector-emitter (ON) voltage, were evaluated by comparing aged and new IGBTs under a temperature range of 25-200°C. The trends in the three electrical parameters with temperature were correlated to device degradation. A methodology is presented for validating these precursor parameters for IGBT prognostics.

Index Terms—Failure precursor parameters, IGBTs, prognostics

A failure precursor is an event or series of events that is indicative of an impending failure [1]. A failure can be predicted by correlating changes in monitored precursor parameters. Failure precursor parameters can be identified by the following steps: performing the failure mode mechanisms and effects analysis (FMMEA) [2], accelerated aging, physical degradation analysis and electrical characterization. By identifying the precursor parameters and monitoring them, the extent of deviation or degradation from expected normal operating conditions can be assessed. This information can then be used to provide advanced warning of failures and for improving qualification of products.

In this article, three electrical parameters of the insulated gate bipolar transistors (IGBTs) were measured for aged (electrical-thermal stresses) and new parts in a temperature range of 25-200°C. The behavior of the three electrical parameters of the aged parts was compared with new parts to evaluate their potential as precursor parameter candidates.

I. INTRODUCTION

IGBTs are used in applications such as the switching of automobile and train traction motors, high voltage power supplies, and in aerospace applications such as switch mode power supplies (SMPS) to regulate DC voltage. The failure of these switches can reduce the efficiency of the system or lead to system failure. IGBTs have switching characteristics similar to a MOSFET and the high current and voltage capabilities of a bipolar junction transistor (BJT). The structure of an IGBT is similar to that of a vertical diffusion power MOSFET (VDMOS) [3], except for an additional p+ layer above the collector as seen in Fig. 1. The main characteristic of the vertical configuration is that the collector (drain) forms the bottom of the device while the emitter (source) region remains the same as a traditional MOSFET. Fig. 1 represents the schematic structure of the device used in this study. The majority carriers in this device are electrons. The additional p+ layer in the IGBT acts as a source of holes that are injected into the body (n- region) during operation. These holes enable quick turn-off by recombination with excess electrons that remain in the body of the IGBT after switch-off.

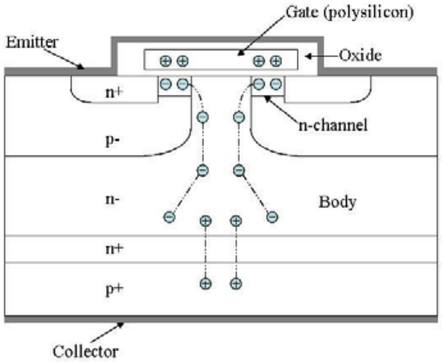

Fig. 1. Schematic of IGBT Operation.

Applying a positive voltage to the gate switches on the device when an inversion layer (i.e., a conductive channel) is created in the p- region just below the gate oxide allows for electron flow to take place. Electrons flow from the emitter through the conductive channel to the collector terminal. A positive voltage applied to the collector with the emitter at ground causes the injection of positive carriers from the p+ layer, which contacts the collector, into the body. This allows for conductivity modulation of the device, leading to a lower on-resistance compared to the power MOSFET. Since an

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IGBT is switched on by voltage rather than current, it results in faster switching speeds in comparison to BJT. As the conductivity of the device is modulated by charge injection from the p+ layer, it allows for lower on-state resistance than the power MOSFET. The punch-through IGBT used in this study has an additional n+ layer, called the buffer layer, above the p+ layer that contacts the collector terminal. The additional n+ layer leads to faster evacuation of the stored charges in the base of the IGBT. This reduces the current fall time and turn-off time for the IGBT.

II. FMMEA OF IGBTs

FMMEA is a methodology for identifying potential failure mechanisms and models for all potential failures modes, and prioritizing failure mechanisms. The output of the FMMEA process is a list of critical failure mechanisms that help us identify the precursor parameters to monitor and the relevant physics of failure models to use to predict remaining life of the component. In the hybrid prognostic methodology being used in this research (described in Section VI), FMMEA is the first step in the analysis.

The failure modes for the IGBT can be in the form of short circuits, increased leakage current, or loss of gate control (inability to turn-off). The failure causes can be due to environmental conditions such as high temperatures or operating conditions such as high voltages.

Critical transistor failure mechanisms include hot electrons and gate-oxide breakdown. These mechanisms can result in excessive leakage current leading to increased standby power and an increase in transistor response time. The effects of these failure mechanisms can be observed in the form of degradation of certain key electrical parameters (e.g., transconductance, threshold voltage). The FMMEA for IGBTs is illustrated in Fig. 2. In this figure, only one critical failure mechanism for each site is listed and the analysis has been limited to die-level failures.

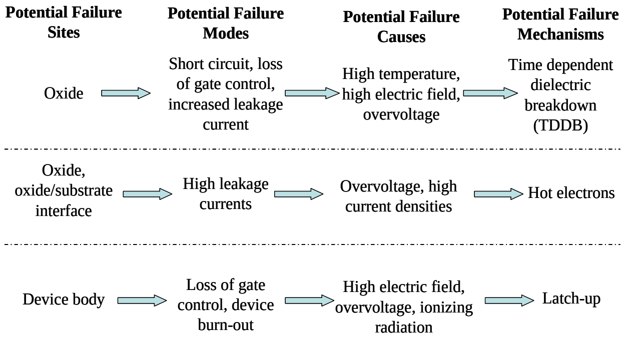


Fig. 2. FMMEA of IGBTs

The potential failure causes for the failure mechanisms as seen in Fig. 2 involve high electric fields and, for oxide breakdown, also involves high temperature. The IGBTs are subjected to electrical and thermal stresses that degrade the parts through the failure mechanisms of interest.

III. ELECTRICAL-THERMAL AGING

Accelerated aging on the International Rectifier IRG4BC30KD insulated gate bipolar transistors (IGBTs) used in this study was performed by Impact Technologies using a test board as shown in Fig. 3. The aging was performed by controlling the duty cycle and increasing the collector-emitter voltage.

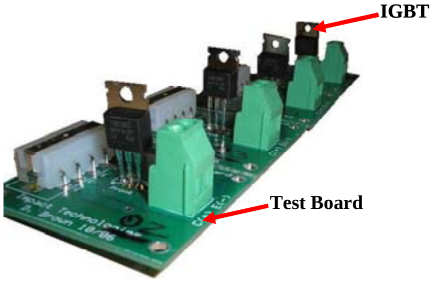


Fig. 3. Test board for used for accelerated aging [4]

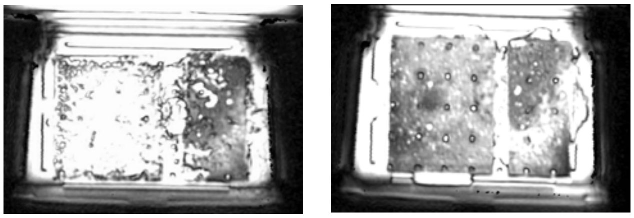
The collector-emitter leakage current was continuously monitored during the test. When latching of the IGBT was imminent, as was evidenced by the loss of gate control and increased collector-emitter leakage, the aging process was stopped. The collector-emitter voltage was increased from 4 to 6.5 volts during the test. The temperature at the transistor case reached close to 315^{o}C in a time period of about 45 minutes. There is a possibility of small differences in the test stoppage time and maximum temperature attained among the five IGBTs that were aged, leading to varying degrees of degradation in the parts. The IGBTs returned to a functional state after the aging exposure.

IV. PHYSICAL DEGRADATION ANALYSIS

Degradation analysis was performed to determine the effects of electrical-thermal aging on the package of the IGBTs. A non-destructive technique called scanning acoustic microscopy was used. Scanning acoustic microscopy analysis is used to detect delaminations and voids in plastic encapsulated microcircuits. This technique is sensitive to submicron thickness delaminations.

For the SAM analysis, the TO-220 package was placed with the heat-sink facing the transducer. A 35MHz transducer was used in the pulse-echo mode to obtain the C-scan image of the die attach interface to detect voids and delaminations in the die attach layer. Voids within the die attach and delamination between at the die attach interfaces appear as bright white areas in the CSAM image.

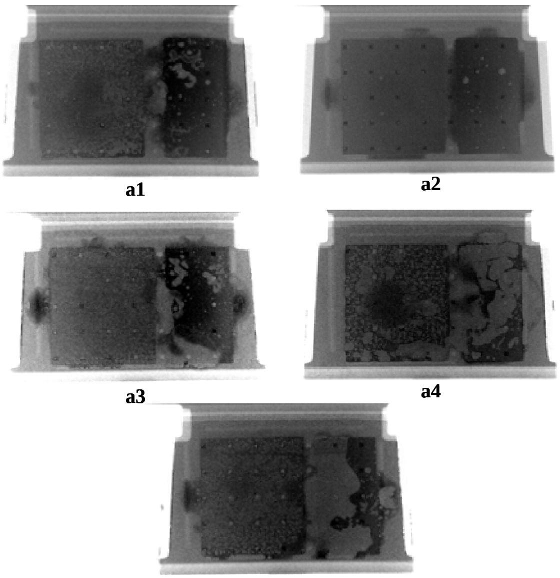
Two aged parts labeled “a1” and “a2” were selected for analysis. The C-scan images of these parts are shown in Fig. 4. This device is a co-pack wherein the IGBT (the large die on the left) and the free-wheeling diode are present in a single package. Part a1 was observed to have significantly more damage in the IGBT die-attach in comparison to part a2.



Part a1 Part a2

Fig. 4. C-scan images of IGBT parts a1 and a2

X-ray images of the aged parts are shown in Fig. 5. The X-ray images correlate with the CSAM images as observed by comparing the parts "a1" and "a2" in Fig. 4 and Fig. 5. The images show varying levels of die attach degradation in the other three parts too.



a1 a2 a3 a4 a5

Fig. 5. X-ray images of aged IGBT parts

During the aging, the parts were subjected to temperatures greater than the melting point of the die attach material which is a lead free solder. This could have led to localized melting of this layer leading to the degradation observed in Fig. 4 and Fig. 5.

V. ELECTRICAL CHARACTERIZATION OF NEW AND AGED IGBTs

Electrical characterization of aged and new IGBTs was performed by measuring the behavior of three electrical parameters of IRG4BC30KD IGBTs over a range of temperatures. The measurements were performed using the Tektronix high power curve tracer. Five new IGBTs were used in this study to form a baseline for healthy behavior. The behavior of five aged parts with different levels of damage was then compared with that of the new parts.

Due to inherent variations in the fabrication processes such as in the channel doping and oxide charge, the electrical parameters will be spread in a distribution, even in transistors that belong to the same production lot [5]. The results of the characterization of the five new parts were used for assessing the levels of change in electrical parameters due to aging. The sample size in these tests was not intended to be statistically significant.

For the electrical characterization, the Temptronic thermal stream generator was used to subject the parts to temperatures ranging from 25^{o}C to 200^{o}C in steps of 25^{o}C. At every temperature step, three measurements were taken for each electrical parameter. The mean of the three measurements was used to plot the variation in electrical parameters with temperature.

A. *Threshold Voltage*

The threshold voltage is the gate voltage at which the IGBT turns on and collector current begins to flow. IGBTs have a negative temperature co-efficient for the threshold voltage as seen in Fig. 6. It is therefore easier to turn-on the IGBT at higher ambient temperatures. The increase in temperature leads to a decrease in the band-gap of the silicon, which reduces the threshold voltage. The threshold voltage reduces with an increase in temperature for aged as well as new parts. From the experiments, it was observed that the aged parts had a higher threshold voltage than the new parts across all temperatures. The difference between the average threshold of the new parts and the aged part a1 when measured at 25^{o}C was 10.5%, and this difference reduced to 9.7% at 200^{o}C. This suggests that temperature affects new and aged parts in the same manner.

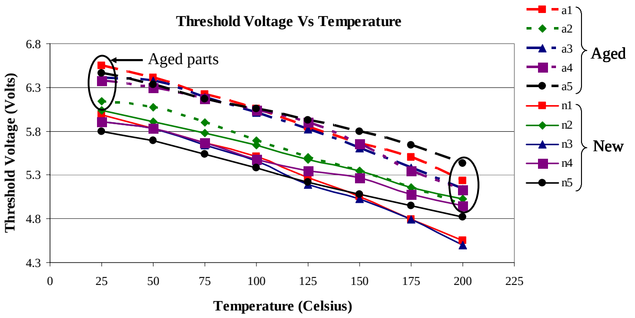


Fig. 6. Threshold voltage variation with temperature

B. *Transconductance*

Transconductance is the gain of the transistor and refers to the magnitude of output current (collector current) obtained for a given input voltage (gate voltage). IGBTs have a negative temperature co-efficient for transconductance as seen in Fig. 7.

The gain of the IGBT reduces with increase in temperature, and the output current from the transistor reduces for a given gate voltage. From the experiments it was observed that the transconductance for the aged parts was higher compared to the new parts. The difference between the average transconductance of new parts and the aged part a1 at room temperature was 8.2% and the difference reduced to 5.6% at 200^{o}C.

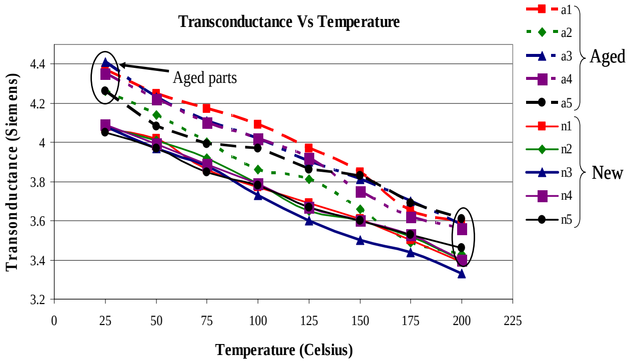


Fig. 7. Transconductance variation with temperature

C. *Collector Emitter ON Voltage*

IGBTs have a positive temperature co-efficient for the collector emitter ON voltage at high collector currents [6] as seen in Fig. 8. Thus, with an increase in temperature, the IGBT output current reduces due to a increased resistance. From the experiments it was observed that the collector-emitter ON voltage for the new parts was higher in comparison to the aged parts. The difference between the average collector emitter ON voltage difference and the aged part a1 was 9.9% at 25°C and the difference increased to 12.8% at 200°C.

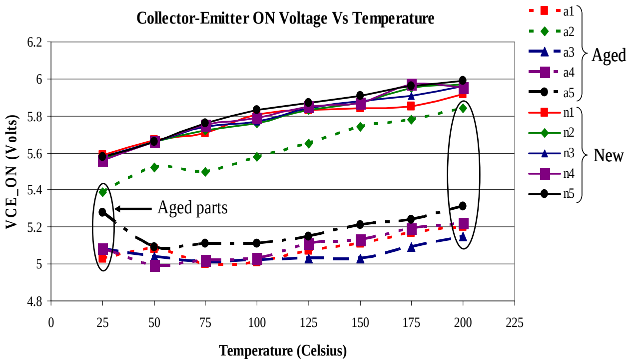


Fig. 8. Collector-emitter ON voltage variation with temperature

D. *Discussion*

From the temperature exposure results, it can be observed that the threshold voltage in aged IGBTs is higher than in the new parts. The positive shifts in threshold voltage are consistent with the presence of trapped electrons in the gate oxide [7]. Holes trapped in the oxide lead to a negative threshold shift while trapped electrons lead to positive shifts.

The tranconductance was observed to be higher in the aged parts compared to the new parts. This indicated that the aged parts output more collector current for a given gate voltage as compared to the new parts. This was also verified by the collector-emitter ON voltage results, which showed that the aged parts have lower resistance compared to the new parts.

The delaminations/voids observed in the X-ray analysis of the aged parts correlated to the trends observed in the evolution of the three parameters. For the collector-emitter ON voltage results shown in Fig. 8, the aged part a2 which had a less degraded die-attach in comparison to the other aged parts, followed the trend of the new parts. This suggests that the die-attach degradation is correlated to the collector-emitter ON voltage parameter.

The higher transconductance and lower collector-emitter ON voltages of the aged parts can be explained by noting that the transconductance and the collector-emitter ON voltages were measured at a gate voltage of 15 V and collector current of 16 A. At these relatively high currents, the degraded die-attach may have led to an increased temperature at the p-n junction above the collector. As the p-n junction has a negative temperature coefficient of resistance [3], an increase in the temperature at this junction will result in lowered resistance. This could explain the observed low resistance in the aged parts compared to the new parts.

This hypothesis was supported by the I-V characteristics measured at room temperature for gate voltages between 10 and 11.5 V for an electrically-thermally aged part “a1” and new part “n1” as shown in Fig. 9. At these gate voltages, high currents are output by the transistor. As observed, the collector current for the aged part was much higher than the new part for a given gate and a given collector-emitter voltage in the linear region. The linear region is defined as the region where the collector current is proportional to the collector-emitter voltage. The results as seen in Fig. 9 show that aged parts had lower resistances at high currents.

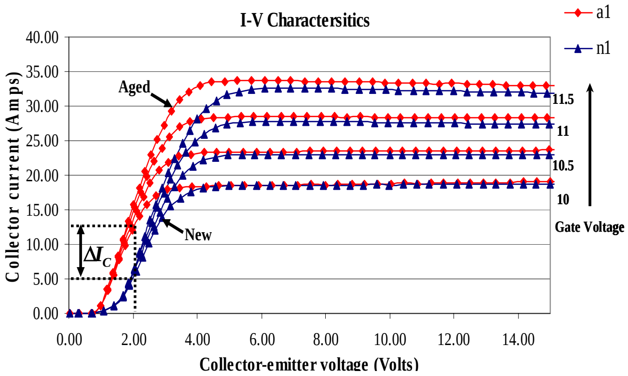


Fig. 9: I-V curves for aged and new IGBTs under high gate voltages

One would expect that at lower gate voltages and lower currents, the impact of the degraded die attach would not be as significant. The I-V characteristics measured at low gate voltages between 6 and 6.3 V support this view, as shown in Fig. 10.

As seen in Fig. 10, at lower gate voltages, the aged part had a lower collector current compared to the new part. The higher resistance of the aged part can be attributed to the trapped charges in the oxide that cause increased channel resistance. At these low currents, the degraded die attach has negligible impact.

From the discussion above, it can be concluded that two mechanisms are in operation; the oxide damage that affects the threshold voltage, and the die-attach degradation which affects the transconductance and collector-emitter ON voltage.

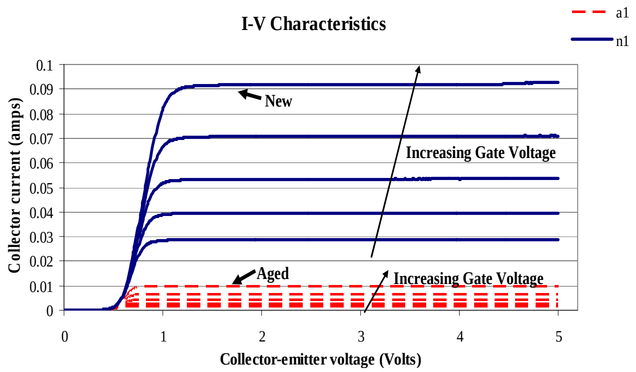


Fig. 10: I-V curves for aged and new IGBTs under low gate voltages

VI. HYBRID PHM METHODOLOGY

The hybrid PHM approach involves the identification of precursor parameters, determining their correlation with system performance parameters, continuous monitoring of product health, detection of failure trends and estimating the time to failure.

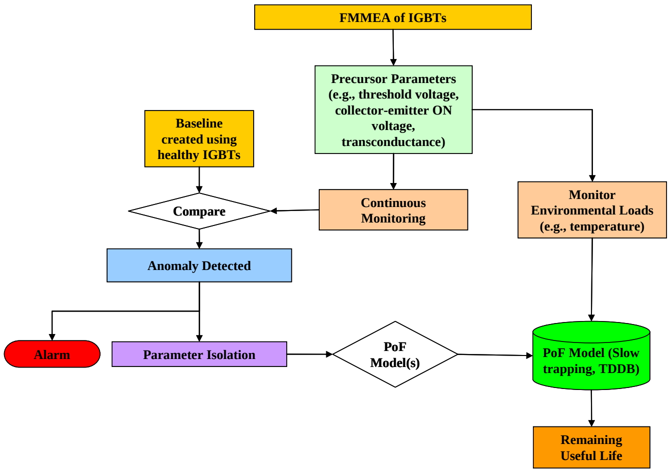


Fig. 11: Hybrid PHM methodology for IGBTs

The first step in the Hybrid PHM approach is to perform the FMMEA for the device and identify failure precursor parameters. Next, parameters that can be monitored in application are selected. These parameters are continuously monitored and compared with the baseline of healthy devices. An alarm is generated when anomalous behavior is detected. The parameters that contribute significantly to the anomaly are isolated. The isolated parameters and monitored environmental loads form the input to physics of failure (PoF) models that are subsequently used to estimate remaining useful life.

The hybrid component of this approach refers to the combination of the data-driven methodology used for parameter monitoring and anomaly detection and the use of PoF models to estimate remaining useful life. The proposed hybrid PHM methodology for IGBT prognostics is shown in Fig. 11.

VII. SUMMARY

The electrical-thermal stresses used to age the IGBTs leads to trapped electrons in the gate oxide resulting in an increase in the threshold voltage of the aged parts. The observed increase in the transconductance and reduction in collector-emitter ON voltage of the electrically-thermally aged parts is possibly a result of the observed degradation in the die-attach.

In this study, the first two steps outlined in the Hybrid PHM approach have been performed. From the behavior of aged parts under various temperatures, we have determined that the threshold voltage, transconductance and collector-emitter ON voltage are precursor parameters to IGBT failure as all three parameters show changes with increased degradation. A hybrid PHM approach, where these precursors are monitored in-situ and precursor trending data are input into Physics of Failure (PoF) models, will allow for anomaly detection and prediction of remaining life of these devices.

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