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Physics-based Modeling of Packaging-related Degradation of IGBT Modules

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***Abstract*—This paper proposes an analytical model to fit degradation data of insulated gate bipolar transistor (IGBT), based on physics understandings. Different from the empirical and data-driven modeling, the revealed failure mechanism, crack propagation and metallization reconstruction leading to the smaller bond contact area and the increased resistivity respectively, have been fully considered. With the help of elaborate geometry equivalence for topside interconnection, an analytical equation is established to quantify the contact resistance, and its variation corresponds to the change of on-state voltage. Consequently, the equation build the bridge between these directly degradation-related indicators (crack, resistivity) and accessible data (on-state voltage, current). Moreover, a concise equation is formulated to analyze the crack propagation while fully considering the existing fracture mechanics theory. And another flexible equation is tailored to quantify the influence of the evolution of metallization reconstruction on resistivity. Finally, power cycling testings are conducted with different test conditions, these data verify the improved performance of the proposed model compared to the existing ones.**

***Index Terms*—degradation model, failure mechanism, insulated-gate bipolar transistor (IGBT), physics understanding, power cycling test**

I. Introduction

Degradation process modeling is a promising route for diagnostics and prognostics of IGBT and provides useful information to predict the remaining useful life [1]–[3]. And it also has the potential to reduce test time by achieving lifetime prediction based on the early-cycle data instead of conducting the test to failure [4]. Selecting the appropriate health indicator, and then quantitatively modeling is the general procedure of degradation modeling. In practical applications, electrical signals from the three typical external terminals of the device are generally collected to characterize degradation [5]–[7]. And two key factors, availability and sensitivity, need to be fully considered when selecting a suitable precursor.

As for the modeling methods, the existing models can be broadly classified into three categories: empirical model [2], [8], data-driven model [9]–[11], and physics-based model [12], [13]. For first model, some commonly analytical models, such as exponential, power-law and logarithmic equations etc. [8], can be selected empirically at the first glance when the data has obtained. For the second, some data-driven methods have been chosen, such as long short-term memory network [9], Kalman filter [10], auto regression integrated moving average neural network [11] and so on. Although these models are intuitively regard as black box, its essence is to improve the fitting results through more complex expressions. And, there are still many challenges to face, and one of them is the lack of interpretability. Additionally, test condition and heterogeneity among the devices have an important impact on the failure process of devices [14]. Even though good performance has been presented in the corresponding analyzed cases, there are still some challenges in implementing these models in different samples and operation conditions.

With the help of advanced equipment, for instance, scanning acoustic microscope (SAM) and scanning electron microscope (SEM), the failure mechanisms of IGBT are well revealed [15], [16]. This development promotes and facilitates physics-based modeling, which means that these mechanisms are fully considered and introduced during the modeling process. The microscopic changes are presented or even amplified in the external precursor, however, these micro-health indicators can not be measured directly. Therefore, how to establish the link between accessible macro-data and micro-health indicators becomes an important challenge.

In addition, the evolution of micro-health indicators plays an important role in the development of an effective degradation model. some prior assumptions for degradation mechanisms has certain limitations and even is not valid. For example, linear crack propagation and increase of equivalent resistance of the metallization layer is one of the possible scenarios [12], [17], and the assumption in [13] that the metallization layer ages from the outset contradict reality. Consequently, the reasonable and concise equation is essential for the evolution quantization of micro-health indicators. This paper proposes an analytical model to explore the degradation process of IGBT, which has the following distinctive contributions: a) the model bridges the accessible macro-precursor and degradation-related micro-indicators based on physics understandings; b) the governing laws of degradation physics are quantified via two reasonable and flexible formulas; c) the proposed model can more accurately fit the degradation data even under two different power cycling test conditions compared to the existing ones.

The rest of this paper is organized as follows. Section II presents the modeling details, which includes the linkage model between the on-state voltage variation and micro-health indicators (crack and resistivity), crack propagation model and resistivity evolution model. In section III, the power cycling test from two samples under two different test conditions is conducted, and the data pre-process is given. Section IV analyzes the effectiveness of the proposed model based on the obtained test data and compares with the existing ones. Concluding remarks are drawn at last.

II. Analytical Degradation Model

Bond wire lift-off, aluminum metallization layer reconstruction, chip solder delamination, and baseplate solder delamination are the four major package-related failure mechanisms [13], [15], [18]–[20]. The corresponding position in IGBT and the micro performance are presented in Fig. 1. Typically, the latter two induce the junction temperature to rise and further aggravate the degradation process of the first two. The commonly open circuit of the device is mainly caused by the bonding wire lift off and the intuitive performance is a step change and the increases sharp of the on-sate voltage. The degradation model in this paper mainly focus on the degradation process caused by the former two, and the influence of junction temperature induced by the latter two can be decoupled through the temperature coefficient [15], [17]. And the proposed degradation model consists of two main parts: the mapping model between macro accessible data and micro degradation-related indicators (Part A), and the evolution model of micro-variables (Part B, crack and Part C, resistivity).

A. Contact Resistance Model

Several health indicators have been proposed in existing studies, which directly reflect the degradation of bond wire and metallization layer. However, it seems that on-state voltage is the best candidate, and the failure criterion based on it is formulated and widely accepted [21], [22]. Therefore, this paper chooses it as the health indicator. This on-state voltage is a summation of voltage of the semiconductor chip, the contact area, the bond wires, copper traces and the connection terminals [23]. Typically, among these different components, only the contact voltage between bond wire and metallization layer will change due to degradation.

The formulation and propagation of crack will lead to a reduction in contact area, and the micro reconstruction (grain boundary diffusion and grain extrusion) change the resistivity of the metallization layer [13], [19]. If these failure mechanisms are to be considered effectively in the modeling, the first step is to establish the link between these micro-variables and the on-state voltage. Commonly, the connection region shape of the bond wire is be equivalent to an ellipse [16], and the rectangle is also adopted in finite element model [24].

However, these two equivalences increase the difficulty of modeling, since at least two variables are required to efficiently calculate the contact area. This further makes modeling the crack evolution more complicate. Moreover, the existing widely accepted crack propagation model, the Paris model, only uses a single variable [25]. Therefore, in this paper, the circle is used to equivalent the bonding connection area, and the cylinder is used to equivalent the metallization layer, as shown in Fig. 2. In practice, current flows from the die to the

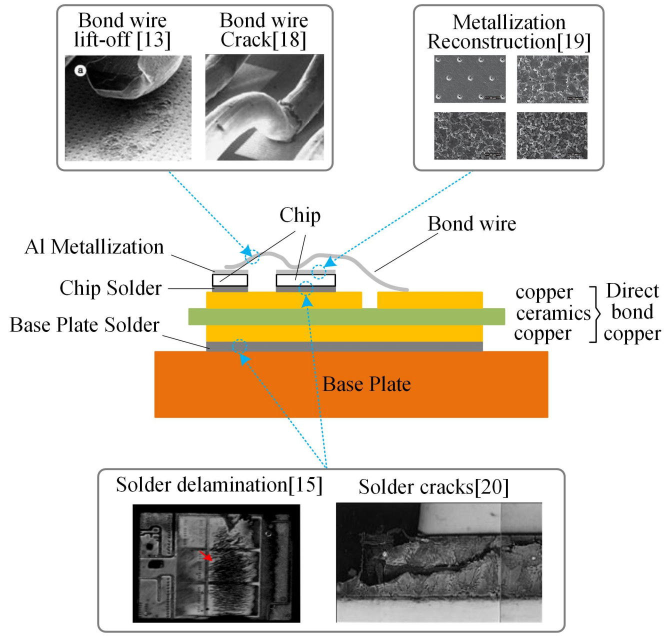


Fig. 1. Structure of IGBT module and the dominant failure mechanisms.

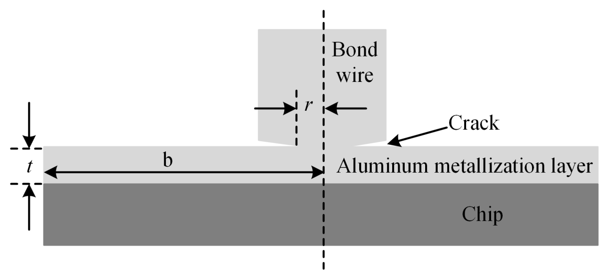


Fig. 2. Equivalent model geometry with circle and cylinder.

bond wires from the bottom up. The contact voltage is caused by the contact resistance, which mainly consists of two parts, namely the constriction resistance and the spreading resistance [13]. Based on Holm's relation [26], the constriction resistance can be expressed as follows

$$R_1 = \frac{\rho}{4r} \tag{1}$$

r represents the equivalent radius of contact area of the bond wire. ρ is the resistivity of material.

The spreading resistance can also be quantified:

$$R_2 = \frac{w\rho}{2\pi t}\left[\frac{b^2}{b^2 - r^2}\ln\left(\frac{b}{r}\right) - \frac{1}{2}\right] \tag{2}$$

b and t are the equivalent radius and the thickness of aluminum metallization layer respectively.

It can be seen that when r gradually decreases with degradation, the contact resistance will increase. In addition, the resistivity increase caused by the reconstruction of the metallization layer is mainly reflected in the spreading resistance, therefore, a coefficient w is introduced to reflect the corresponding degradation. When the contact resistance variation is multiplied by the current, the on-state voltage variation will be obtained. In this way, the degradation-related micro-variables and accessible precursor have been established, and the next step is to model and analyze the evolution of these two micro-variables.

B. Crack Propagation

The Paris model is commonly accepted to describe the propagation of crack (a) [25]. However, highly-accurate modeling depends on some information, for example, the length and height of specimen [17]. These detailed geometric dimensions is difficult to access for most researchers and applicants, and the expression is more complicated. To meet this challenge, in this paper, a more simple and flexible equation is proposed to describe the evolution of a. Based on the Paris model, a general conclusion can be obtained, that is, the crack propagation rate is closely related to the current crack length, the evolution process of a can be described concisely as

$$\frac{da}{dN} = k_1 a^{k_2} \tag{3}$$

According to the corresponding mathematical transformation, the quantitative expression of the equivalent radius of contact area of the bond wire r can be obtained

$$r = r_0 - k_1 \left(cycle\right)^{k_2} \tag{4}$$

where r_0 is the initial value of r, k_1, and k_2 are the parameters to be determined.

C. Resistivity Evolution of Aluminum Metallization Layer

The linear evolution model is utilized in some degradation modeling literature [12], [17]. However, this assumption is significantly different from the trend revealed by some mechanistic failure literature. Fig. 3 shows the resistance variation in the Al metallization layer of IGBT under power cycling test [19], IGBT under repeat high power dissipation short-circuit operations [27], and metal-oxide-semiconductor field-effect transistor (MOSFET) under power cycling test [28]. Where R indicates the monitored resistance of Al metallization layer, R_0 represents the initial value. It can be seen that the evolution presents obvious non-linearity.

Therefore, a flexible expression is needed to describe various possible nonlinear changes. In this paper, the following equation is tailored to describe the degradation of the metallization layer. By adjusting the three parameter values, both linear and various non-linear degradation processes can be depicted.

$$w = k_3 \left[1 - exp\left(-\left(\frac{cycle}{k_4}\right)^{k_5}\right)\right] + 1 \tag{5}$$

where k_3, k_4, and k_5 are the parameters to be determined. When the device is not degraded, the value of w is 1.

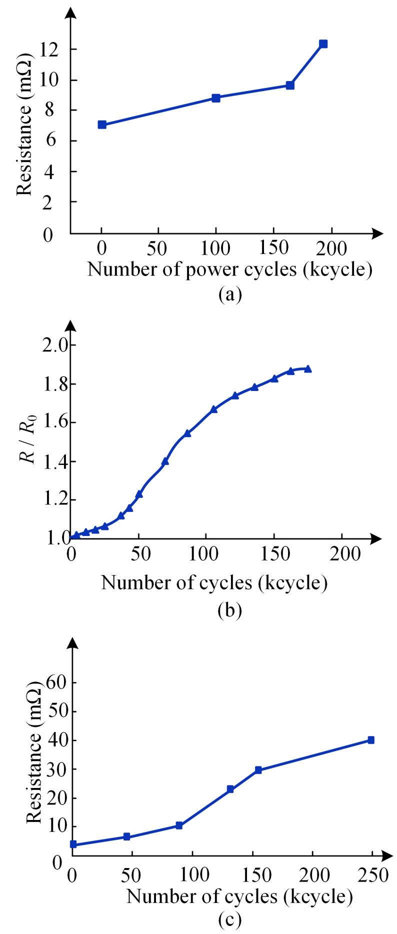


Fig. 3. Evolution of resistance of the Al metallization layer as a function of the number of cycles. (a) IGBT under power cycling test [19], (b) IGBT under repeat high power dissipation short-circuit operations [27], (c) MOSFET under power cycling test [28].

III. Power Cycling Test and Data Pre-process

A. Power Cycling Test

AQG324 standard recommends that power cycling tests in seconds mainly cause topside interconnection failure, so this paper carries out this type of test and selects on-state voltage as the health precursor [22]. Fig. 4 shows the power cycling testing platform, and the test is carried out using mentor graphics power tester 1800A and the desired temperature and cooling capability can be achieved through the thermal control unit. As for the test strategy, a constant $t_{\mathrm{on}}/t_{\mathrm{off}}$ is adopted, and the current also keep constant. The conducted test conditions are listed in Table I, different test conditions are made to effectively validate the proposed model. And the power cycling tests are carried out on an Infineon FS25R12KT3 module. Although its configuration is sixpack, only one chip is chosen to test.

B. Data Pre-process

The proposed model from the perspective of physical mechanism can describe the whole failure process. Therefore, a

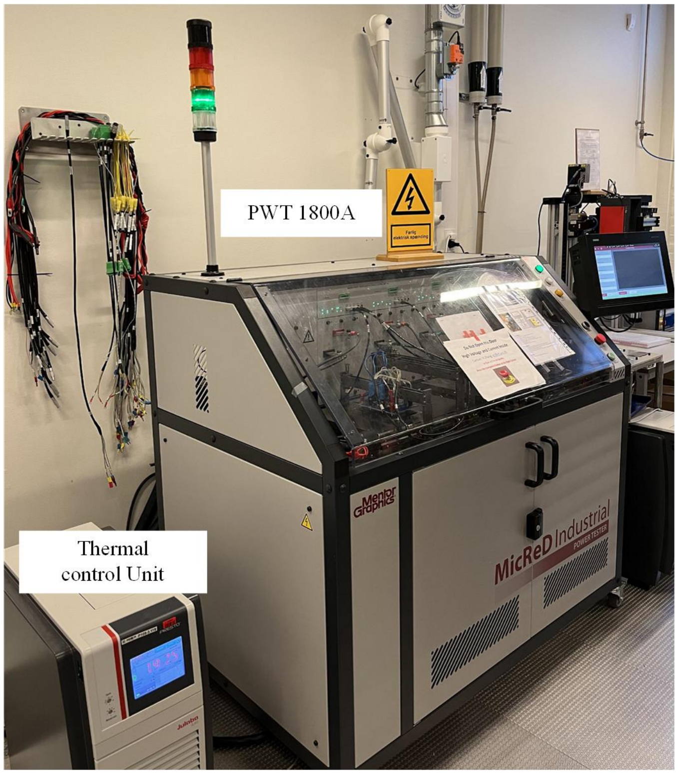


Fig. 4. Power cycling testing platform.

5% increase in on-state voltage increase, as recommended in AQG324, is not chosen as the failure criterion. And the testing was carried out until there was a sharp increase in the on-state voltage (V_{ce}), which means that the device is completely failure. Fig. 5 presents the raw data of two tested power modules. Before modeling and analysis, the collected raw data need to be pre-processed, which includes two steps.

Firstly, the on-state voltage increase due to effect of junction temperature (T_{j}) should be eliminated. Two factors, degradation and temperature, both lead to the increase of V_{ce}. However, the proposed model mainly focus on the first one. And during the test, both the on-state voltage and the maximum junction temperature are generally and effectively recorded according the requirements of IEC-60749-34 and AQG324. Therefore, the effect of junction temperature on V_{ce} can be eliminated according to the following equation [15] and is significant as shown in Fig. 5 when compares two curves.

$$V_{\text{ce}}^{c} = V_{\text{ce}}^{T} - \alpha\left(T - T_0\right) \tag{6}$$

where V_{ce}^{c} is the compensated V_{ce}, V_{ce}^{T} represents the monitored V_{ce}. T indicates the corresponding temperature of the sampled V_{ce}^{T}, $T_0$is the reference temperature. α denotes the temperature coefficient, which is extracted form I-V curves under different temperature.

Secondly, perfect data collection is difficult, and the outliers and some anomalous data points should be removed. In this paper, the experimental data are filtered with the tool from MATLAB, smoothing spline, which not only effectively extracts effective change information of V_{ce}, but also ensures the continuity of the obtained curve.

TABLE I
DETAILS OF TEST CONDITION

No.	Test conditions
Case 1	ΔT_{j}=100K, T_{jmax}=150°C, t_{on}=t_{off}=1.5s
Case 2	ΔT_{j}=100K, T_{jmax}=150°C, t_{on}=t_{off}=5.0s

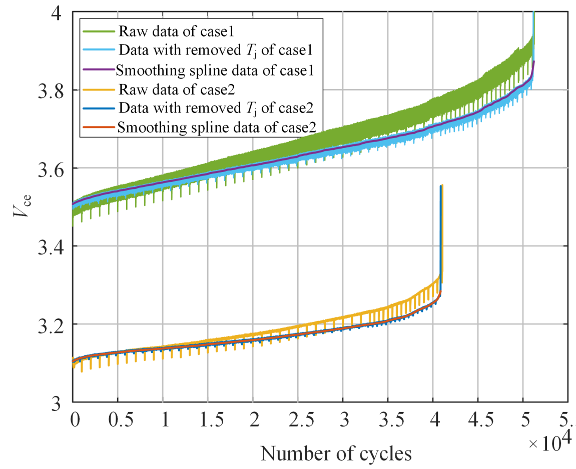


Fig. 5. V_{ce} curves of devices in two tests.

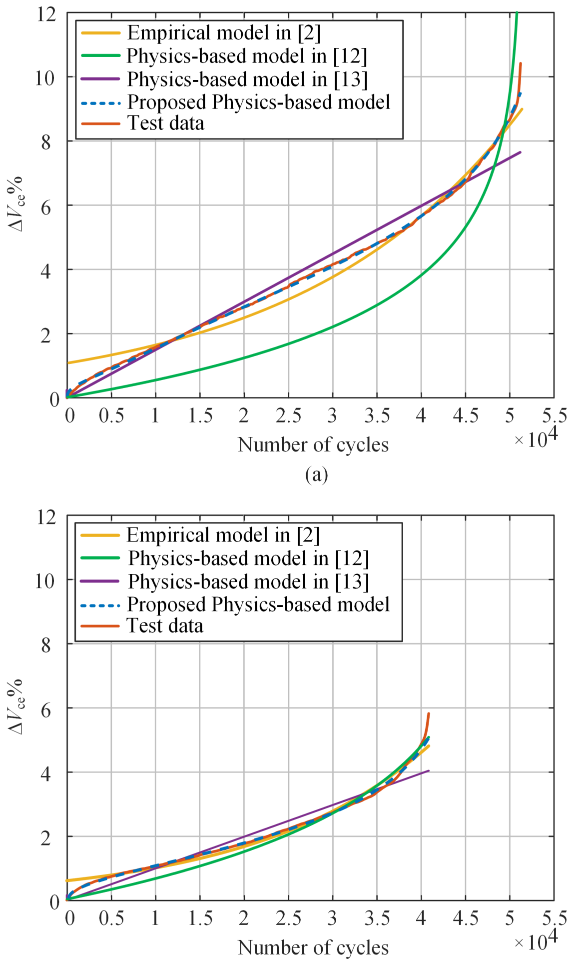
IV. Model Validation

To verify the effectiveness of the proposed model, three existing models are introduced and compared. One is the empirical model from [2], and another two are the physics-based models from [12] and [13]. Due to demonstrate the validity of the models for the whole degradation process, all tested data are selected for analysis, and unknown parameters in the models are obtained through regression analysis.

Fig. 6 shows the depiction of the degradation process with all models. It can be seen that the proposed model can maintain high consistency with the whole degradation process under two experimental cases. Moreover, the large variance in tendency projection is presented with the other three existing models. Comparing the physics-based model in [13] with the proposed model, it can be concluded that the assumptions that the cracks propagate linearly and the metallization layer ages initially, are not suitable for the case in this paper.

V. Conclusion

In this paper, an analytical model is proposed for degradation process investigation when the package-related failure mainly occurs in the aluminum metallization layer and bond-wire contact. The physics-based modeling bridges the macro-precursor and degradation-related micro-indicators. And the governing laws of degradation, which determine the accuracy of the model, are quantified via two reasonable and flexible formulas. As demonstrated in the comparison with existing



(b)

Fig. 6. Depiction of degradation processes based on different models under different test conditions, (a) case 1, (b) case 2.

models, the proposed model has a high-fidelity of the degradation process. And due to modeling from the physics-of-degradation perspective, the challenge of purely data-driven and empirical modeling, lack of interpretability, can be addressed. In addition, the acquisition of unknown parameters of the model only can be through regression analysis and does not rely on the availability of module packaging information, which indicates an end-user-friendly application.

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