IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 30, 2018, accepted December 21, 2018, date of current version January 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2018.2890022

Analysis and Modeling for the Real-Time Condition Evaluating of MOSFET Power Device Using Adaptive Neuro-Fuzzy Inference System

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This work was supported in part by National Key Research and Development Program of China under Grant 2018FYB0905800 and in part by the Venture and Innovation Support Program for Chongqing Overseas Returnees under Grant CX2018045.

ABSTRACT Aging has been generally regarded as one of the principal root causes of power device failure, due to it makes the performance of power device degradative, which will directly influence the electrical–thermal performances of the power device. Thus, it is essential to assess the condition to improve the operating reliability of power device. In this paper, a finite-element analysis (FEA) model of MOSFET is built for simulation. Then, the main impact of failure on the overall characteristics of the MOSFET power device will be discussed and analyzed based on the FEA simulation model of MOSFET. In addition, some suitable feature parameters that can indicate the condition of MOSFET are selected and a methodology is proposed for on-line evaluating the real-time condition without intruding the power device by recognizing the aging rate. In this method, MOSFET is deemed as a whole system considering only external feature parameters, and all feature parameters are classified as the inputs, while the aging rate is considered as the output. First, the feature parameters are extracted by especial measurement circuits, a model is built for evaluating the condition of MOSFET using the adaptive neuro-fuzzy inference system, and a reasonable evaluation criterion is established. Then, a case of practical application study for the monitoring method is illustrated based on the evaluation model. Finally, the real-time condition can be monitored, and the condition grade of aging can be evaluated so that the operator can take some measures to maintain the power device by means of this method. The results of a practical application validated the effectiveness of the proposed methodology.

INDEX TERMS Condition evaluating, MOFET, ANFIS, degradation grade, reliability.

I. INTRODUCTION

Usually a power device is comprised of several layers internally as shown in Figure 1 [1], [2], although these layers are usually made from the same process, their coefficient of thermal expansion is different from each other. Thus, different layers do not usually occur at the same rates of failure. Each layer of a power device may begin the operational mission profile with almost identical thermal and electrical parameters just at the beginning [1], but, throughout their operating life, it may develop variances resulting from uneven rates of degradation from aging. Differences in the electrical and thermal parameters of the individual layer can induce other failure mechanisms [3]–[6]. Thus, if each layer is subject to different load stress, they will undergo different thermal cycles, and hence, different degrees of thermo-mechanical fatigue from stress cycling due to coefficient of thermal expansion (CTE) mismatch between the die and the substrate. This means that the thermal resistance will change and the devices will thus operate at a higher junction temperature, which will in turn affect the thermal resistance of power device. For instance, usually the thermal resistances of the power devices typically increase as a result of solder joint fatigue due to electrical-thermal-mechanical arising [7]–[9].

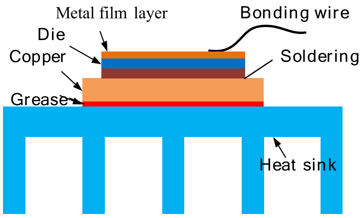

FIGURE 1. **Physical framework of power device.**

TABLE 1. **The structural dimensions of MOSFET (unit: mm).**

Layer	Material	Length	Width	Height	Radius
Silicon chip	si	14.24	10.48	0.2	--
Solder layer	96.5Sn3.5Ag	14.24	10.48	0.12	--
Metal film layer,	Al	14.24	10.48	0.004	--
Copper layer	copper	18.6	20.4	2.04	--
Sealing material	epoxy resin	19.9	26	5	--
Bonding wire	Al	--	--	--	0.18

As a result, the thermal resistance increase makes the junction or power losses become high [10], which will directly affect the overall performances of the power device. Thus, it is necessary for the power electronic system operator to assess the condition grade and enhance the real-time reliability of power device in practice

Many studies have been conducted to investigate the enhancement of the reliability of power device. Reference [11] presents a thermal network extraction methodology to characterize self-heating effect using two-port RF measurements. Reference [12] proposes a new precursor that can be used for online condition monitoring of power mosfet gate oxide degradation. Reference [13] describes a monitoring unit in an intelligent power module that detects internal thermal resistance changes, usually; a 20% increase of the internal thermal resistance from the junction to case is often accepted as the threshold. This model needs the internal temperature of the module, but in practice, it is very difficult to access the inside of power modules during operating, and the accuracy of measurements is affected by noise. Furthermore, in order to place the sensor to measure the internal junction temperature, the package must be uncovered, which is intrusive and can easily destroy the power device. Thus, this method is unfeasible for practical application. Thus, an alternative approach is therefore required to monitor MOSFET [14]–[18].

This paper provides an innovative methodology to supervise the MOSFET power device without intruding the MOSFET for real-time condition monitoring. Firstly, we consider the MOSFET power device as a whole system, there is no need to measure the junction temperature directly, as all feature parameters are regarded as the input into the MOSFET power device system. These parameters include the conducting voltage of V_{ds}, the conducting currents of I_d as well as case temperature, respectively, the aging rate is deemed as the output of MOSFET. Then, a model for evaluating the condition is built using ANFIS. The models can be used to forecast the real-time aging rate, at a given operating point; the real-time aging rate is directly associated with the working conditions and internal condition. Finally, reasonable criteria for the aging rate of power device based on the experiment are set reasonably. Once the predicted real-time aging rate is much higher than the normal aging rate, a system operator could conclude that the power device system is abnormal. Further, we can evaluate the condition grade of abnormal condition by recognizing which range the aging rate locates. Since all of the input and output parameters of the whole system for MOSFET can be measured or detected accurately, the electrical operating point can be tracked from the terminal measurements by measuring an individual MOSFET power device [19]–[22]. This method is feasible in practical application without any internal detecting and intrusion; experimental tests have verified the viability of this approach.

This paper uses simulations of MOSFET power device and experimental measurements to understand the impact of failure on module reliability. FEA is especially used to analyze the impact of failure including soldering fatigue and bonding wire lifting off variances on the overall performance. This paper is organized as follows: section II has explained how to build the FEA model and verify the FEA model, section III explains consequences of the main failure type for selecting the suitable feature parameters, section IV presents the experimental setup and build a prediction model for evaluation the condition grade, which is used to collect the feature parameters that are critical to monitor MOSFET power device. Section V introduces the practical application of the monitoring method of the power device based on ANFIS, which is verified by the result. Section VI concludes the study.

II. FEA MODEL OF MOSFET

In this paper, we build the FEA model of IXFK80N60P3 power device whose package is TO-264 using COMSOL software, IXFK80N60P3 is made of metal film layer, silicon die, solder layer, copper layer, plastic sealing material, bonding wire and other materials as shown in figure1, whose structural dimensions is shown as table 2 [23]–[25]

The electrical parameters of some materials of MOSFET power device, such as R_{ds}, are related to the temperature, so the static characteristics of R_{ds} are measured by using the B1505A power device analyzer and temperature chamber in order to ensure and improve the accuracy of the FEA model, which is shown as Figure 2

Firstly, the measured data from Agilent B1505A analyzer is put into the finite element model, the discrete point is

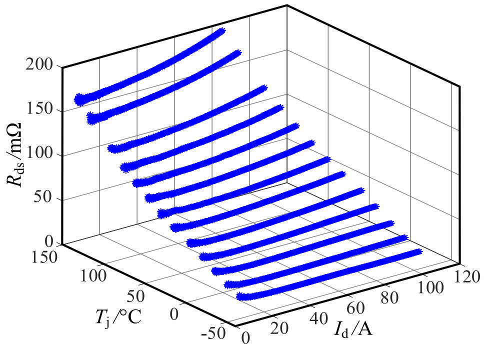

FIGURE 2. The relationship of conducting resistor R_d vs. I_d and T_j of MOSFET.

compensated which is performed by interpolation function, and the difference of die material is ignored. Then, using the resistivity calculation formula, the relationship between the resistivity ρ of the die and the conduction current I_d, temperature can be obtained as shown in Figure 3. Finally, the FEA model built is shown as Figure 4, the resistivity ρ is used to calculation of aging rate in the latter section 4 and 5.

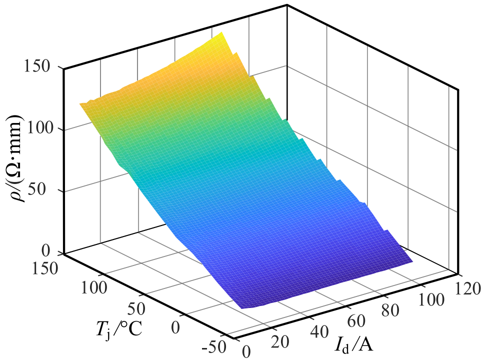

FIGURE 3. The relationship of resistivity ρ vs. I_d and T_j of MOSFET.

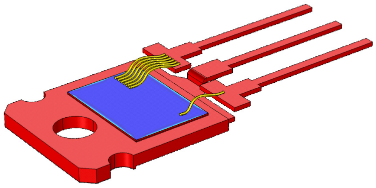

FIGURE 4. FEA simulation model of MOSFET.

To verify the accuracy and validity of the FEA model, Figure 5 gives the normalized conductivity of the device at gate voltage $V_{gs} = 10V$, the junction temperature $T_j = 25$ °C, and 125 °C, obtained by measurement, FEA simulation, and datasheet, respectively, it shows that output of the FEA simulation model has a good agreement with the output of datasheet and measurement. Thus, the simulation model of MOSFET established in this paper has a high accuracy so that we can effectively investigate the electrical, thermal and mechanical characteristics of MOSFET device to evaluate the reliability and condition of power devices using this model in the latter section 3.

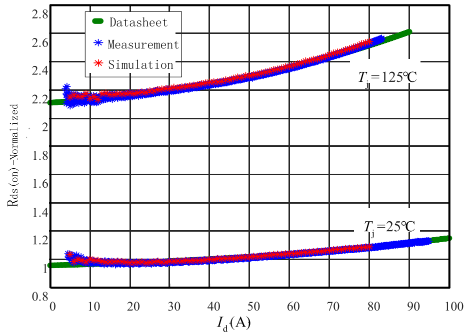

FIGURE 5. The output of MOSFET device.

III. ANALYSIS OF THE MAIN IMPACTION OF FAILURE ON THE OVERALL PERFORMANCE OF MOSFET DEVICE

In FEA simulation, the conducting current $I_d = 20A$, period $T = 20s$, duty ratio=50%, ambient temperature $T_a = 25$ °C, and the forced convection heat transfer coefficient of the copper layer bottom surface is 5000 W/ ($M^2 \bullet K$). it indicate that the soldering fatigue and bonding wire lifting off is the main failure type induced from the aging in simulation, so more attention is pay to the relative variation of the device's feature parameters with the process of soldering fatigue and bonding wire lifting off the relative change trend of the feature parameters of the device is reflected by the increase rate of the thermal resistance $\Delta Z_{jc}/Z_{jc}$ and the conducting resistance $\Delta R_{ds}/R_{ds,}$ which is defined as formula (1) and (2), respectively.

$$\Delta Z_{jc}/Z_{jc} = \frac{\Delta Z_{jc-measure}(i) - Z_{jc-initial}}{Z_{jc-initial}} \times 100\% \quad (1)$$

$$\Delta R_{ds}/R_{ds} = \frac{\Delta R_{ds-measure}(i) - R_{ds-initial}}{R_{ds-initial}} \times 100\% \quad (2)$$

where, $Z_{\text{jc}-\text{initial}}$, $R_{\text{ds}-\text{initial}}$ is the normal thermal resistance and normal conducting resistance of the power device at the same condition, respectively.

$Z_{\text{jc}-\text{measure}}(i)$, $R_{\text{ds}-\text{measure}}(i)$ is the real-time thermal resistance and abnormal conducting resistance of the power device at the same condition, respectively.

A. THE IMPACT OF VOID IN SOLDER LAYER ON THE ELECTRICAL-THERMAL-MECHANICAL PERFORMANCE OF DEVICE

From the Figure 6 and 7, we can find that some parameters of power device increase with the increase of void resulted from the accumulation and development of aging in soldering layer. Furthermore, when void rate in soldering layer exceeds 30%, the void will significantly impact on the performance of power device.

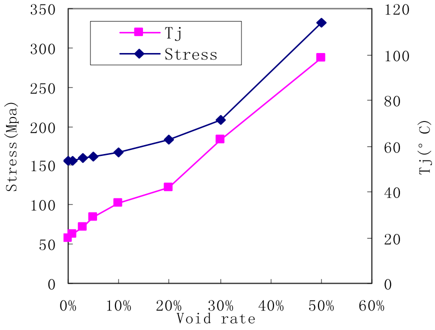

FIGURE 6. The relationship of stress and T_j vs. void rate of MOSFET.

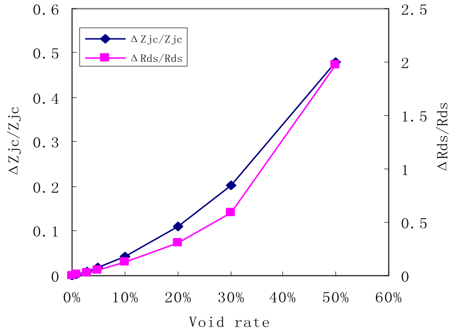

FIGURE 7. The relationship of $\Delta Z_{jc}/Z_{jc}$ and $\Delta R_{ds}/R_{ds}$ vs. void rate of MOSFET.

B. THE IMPACT OF SOLDERING LAYER DELAMINATING ON THE ELECTRICAL-THERMAL-MECHANICAL PERFORMANCE OF DEVICE

When the surface area of the solder layer delaminating is accumulated to a certain extent, the parameters such as thermal parameters, electrical parameters, and stress of the device gradually increase. When delaminating rate in soldering layer exceeds about 35%, the delaminating soldering layer will significantly impact on the performance of power device, which can be found from Figure 8. At the same time, Figure 9 shows that during the process of device solder layer lifting off, the increase of the electrical parameter $\Delta R_{ds}/R_{ds}$ is greater and more sensitive than that of the thermal parameter ΔZ_{jc} / Z_{jc}, which is easy to measure without removing the package of MOSFET power device. It also is found that the conduction current also has an effect on the $\Delta R_{ds}/R_{ds}$ of the aging device. The higher the current level, the larger the $\Delta R_{ds}/R_{ds}$ at the same aging stage.

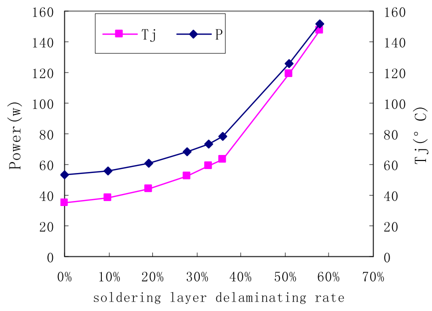

FIGURE 8. The relationship of power and T_j vs. soldering layer delaminating rate of MOSFET.

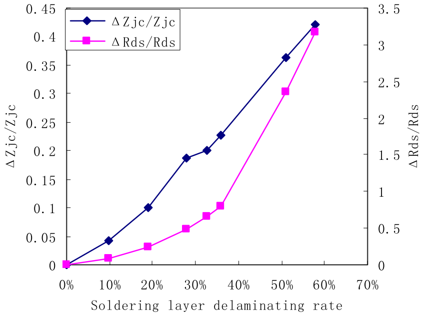

FIGURE 9. The relationship of $\Delta Z_{jc}/Z_{jc}$ and $\Delta R_{ds}/R_{ds}$ vs. soldering layer lift off rate of MOSFET.

C. THE IMPACT OF BONDING WIRE LIFTING OFF ON THE ELECTRICAL-THERMAL-MECHANICAL PERFORMANCE OF DEVICE

The impact of bonding wire lifting off on MOSFET power device is different from that of delaminating and void in soldering layer. Figure 10 and 11 show that the bonding wire lifting off has a smaller effect on T_j and T_c regardless of whether the device is in a normal or aging condition. Only in case of one bonding wire left, there is a rather significant influence on the performance of power device, the main reason is that the resistance of the bonding wire is very low, with the increase of the number of bonding wire lifting off, the total resistance of the bonding wire in parallel gradually increases, and the total heat will increase insignificantly. So the bonding wire lifting off has little effect on the thermal resistance of the power device. With the increase of the number of lifting off wire, the maximum value of $\Delta R_{ds}/R_{ds}$ is only about 4 %, which is very difficult to be monitored. Thus, it is almost negligible in practice.

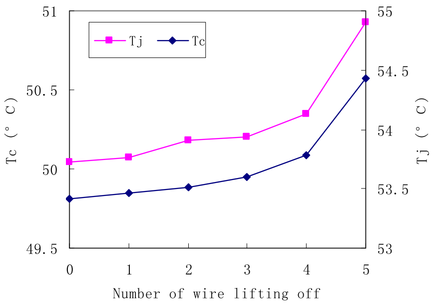

FIGURE 10. The relationship of T_c and T_j vs. number of wire lifting off.

In simulation, it also is found that the bonding wire failure usually occurs at the last 10 % of the remaining life. When the junction temperature fluctuates $\Delta Tj \geq 100$ °C, the bonding wire lifting off is the main failure cause of the device, but the MOSFET device usually suffers less temperature fluctuation

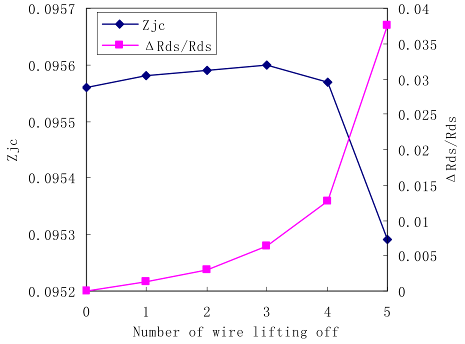

FIGURE 11. The relationship of $\Delta Z_{jc}/Z_{jc}$ and $\Delta R_{ds}/R_{ds}$ vs. number of wire lifting off.

in practice. Therefore, the lifetime of MOSFET device mainly depends on the solder layer reliability, it is better to monitor the aging grade of the solder layer for condition assessment.

IV. THE EXPERIMENT OF AGING TESTING

A. SETUP OF THE TEST RIG

Figure 12 shows a test rig built for a buck circuit containing MOSFET power device, comprised of DC power supply, one switching MOSFET, one diode, one inductive, one capacitive and one resistive load, some measurement instruments including, current probes (Tektronix TCP303, PR1030) and temperature sensors (Pico TC-08). An IXFK80N60P3 power device is used for this buck power conversion. The buck inverter was loaded by an R load on the output side with capacitance smoothing. The buck inverter is controlled from a real-time system programmed in LABVIEW. The case temperature is measured using a 2-channel Pico Thermometer which provides high accuracy (±0.01°C), with fast and synchronized data logging. The probes for the case and ambient temperatures are placed underneath the case surface of the module and next to the heat sink respectively.

FIGURE 12. The picture of experiment rig.

B. SELECTING OF THE FEATURE PARAMETERS FOR EVALUATION

From the physical structure of the MOSFET device (IXFK80N60P3, 600V/80A) as shown in Figure 13, it shows that the conducting resistance R_{ds} includes the internal resistance of the solder layer, die, and bonding wire. Therefore, the failure of anyone of them will cause changes in the conduction resistance R_{ds}. Thus, it is reasonable to adopt R_{ds} as the module failure feature parameter. According to the aforementioned simulation, it is known that the R_{ds} is related to the junction T_j and I_d. The T_j is related to the case temperature T_c. Therefore, I_d and the case temperature T_c is also the feature parameters

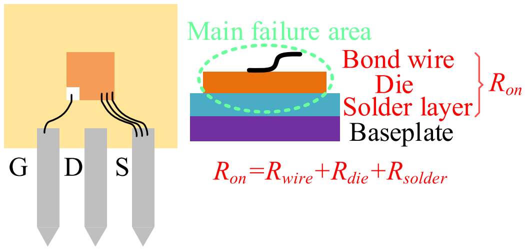

FIGURE 13. The physical structure of MOSFET.

During the process of damage and aging of the solder layer, the electrical parameter $\Delta R_{ds}/R_{ds}$ increases evidently and it is more sensitive than ΔZ_{jc} / Z_{jc}. Although most of studies regard ΔZ_{jc} / Z_{jc} reaching up to 20 % as the indicator of the device failure. However, it is inconvenient to measure ΔZ_{jc} / Z_{jc}. In fact, it is more feasible to select ΔR_{ds} / R_{ds} as the indicator of the aging condition of the power device. The reason is that the solder layer is the main thermal conduction and conductive path for the loss of heat and current flow of the device. Therefore, the thermal resistance and resistance of the device are mainly affected by the aging of the solder layer, which causes the relative changes in the electrical, thermal and mechanical parameters.

It has been found that Z_{jc} increases with the development of aging in soldering layer, the junction temperature T_j and power loss of the power device also increase in FEA simulation. Usually I_d and T_c is unchanged, T_j increased significantly according to the output characteristic curve of the device as shown in Figure 5, it can be seen that when the MOSFET device is at a certain I_d, the conducting resistance R_{ds} is only related to the junction temperature T_j. so the more obvious junction temperature T_j increase, the more obvious the R_{ds} change, this change has a positive feedback process, the change relationship is shown in formula (3)

$$Z_{jc}\uparrow = \frac{(T_j - T_c)\uparrow}{(I_d^2 \cdot R_{ds})\uparrow} \Rightarrow \frac{(T_j \uparrow - T_c)}{(I_d^2)\cdot(R_{ds(I_{d,T_j\uparrow})}\uparrow)} \tag{3}$$

In short, the case temperature, conducting current I_d and conducting voltage V_{ds}, ΔR_{ds} / R_{ds} is selected as the feature parameters of MOSFET power device.

C. EXTRACTING OF THE FEATURE PARAMETERS FOR EVALUATION

The V_{ds} is measured by a circuit as shown in Figure 14, the case temperature is measured using a 2-channel Pico Thermometer, conducting current I_d is measured by a current probe.

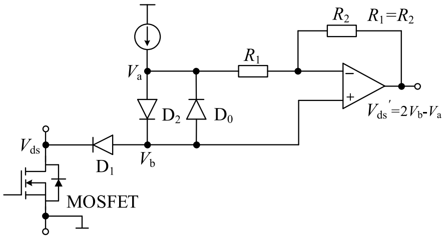

FIGURE 14. The measurement circuit of V_{ds}.

D. BUILDING THE EVALUATION MODEL USING ANFIS

In this section, a model is built for calculating the real –time aging rate by means of ANFIS [26], [27] with real measured data obtained from experiment described aforementioned.

The aging rate of MOSFET prediction system is a high non-linear system with significant variability of performance over time, the ANFIS generates a single-output Sugeno fuzzy inference system (FIS) and tunes the system parameters using the specified input/output training data. The FIS object is automatically generated using grid partitioning. The training algorithm uses a combination of the least-squares and back propagation gradient descent methods to model the training data set, so it is able to identifying the nonlinear system, which has demonstrated a good performance

Usually, the generalization ability of BP network is poor when the real value of device feature parameter exceeds the data range provided by the sample database, and the learning process converges slowly, the condition of power device can not be effectively evaluated by BP algorithm. SVM algorithm also has shortcomings in solving classification problem, and it is generally used in the field of classification with 2 grades and is not suitable for practical applications that require several grades of classification. When there are data with more dimensions, it consumes more memory of machine and takes a long time for calculation. However, the evaluation model based on the ANFIS algorithm can clarify the physical meaning of neural network nodes and weights, avoid their "black box" nature, and observe the intermediate results. Classification ability, learning ability, and convergence speed of ANFIS algorithm are very good. With strong logic reasoning and network generalization ability, it can accurately and effectively evaluate the condition grade of the power device. Thus, the ANFIS neural network is selected in this paper.

The model of ANFIS is used to predict the aging rate (f) defined as formula (4) and (5), which consists of the feature parameter of power device such as the conducting voltage of V_{ds}, the conducting currents of I_d. The model is designed by programming in MATLAB. About 95% of all 2875 set data from the experiment are used for training, they are presented to the network during training, and the network is adjusted according to the error across this training. 5% of the data are used for validation; these data are used to measure network generalization, and to halt training when generalization stops improving.

$$f = \frac{\Delta R_{ds}/R_{ds}}{(\Delta R_{ds}/R_{ds})_F} \tag{4}$$

$$R_{ds} = \frac{V_{ds}}{I_d} \tag{5}$$

where, $(\Delta R_{ds}/R_{ds})_F$ is the corresponding value obtained from the FEA model when the increase of $\Delta Z_{jc} / Z_{jc}$ reaches up to 20 %

Figure 15 shows the result of the aging rate calculation with ANFIS neural network. Making a contrast between the predicted and measured aging rate of power device, we can see that the performance of ANFIS model is good. As shown in table 2, the ANFIS model has a very low RMSE (root-mean-square error). Thus, this model has a very high prediction precision.

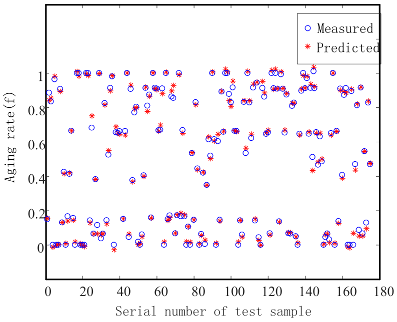

FIGURE 15. The predicted and measured aging rate.

TABLE 2. RMSE OF ANFIS model.

Algorithm	RMSE
ANFIS	1.21052e-0

E. SET UP THE EVALUATION CRITERIA

According to the data from the experiment set, the curve of $(\Delta R_{ds}/R_{ds})_F$ vs T_c and I_d in solder layer failure is obtained, as shown in Figure 16. From this figure, it can be seen that the higher the current is, the greater the increase rate of $(\Delta R_{ds}/R_{ds})_F$ become when the power device completely fails. From the aforementioned analysis, it can be seen that with the development of aging in solder layer, the higher the current is, the greater the T_j increase and the more significant R_{ds} increase, since there is a positive feedback effect between R_{ds} and T_j, and the $(\Delta R_{ds}/R_{ds})_F$ reaches up to the maximum value when it completely fails.

It shows that the failure curve of device is "bathtub" concluded by means of the statistical analysis of the failure data; condition monitoring is realized mainly by measuring the electrical and thermal parameters to judge the device's condition. the evaluation criteria of condition are shown in table 3, which is obtained by seeing the increase rate of thermal resistance to assess the condition grade of the device based on the mapping relationship between thermal resistance and conducting resistance.

The predicted and measured condition grade is get as shown in Figure 17 based on the evaluation criteria of

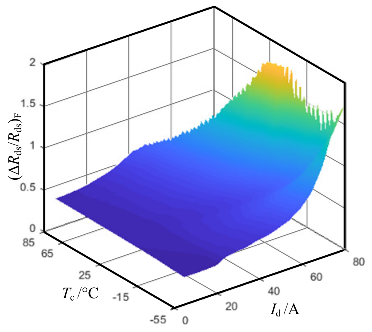

FIGURE 16. The curve of $(\Delta R_{ds}/R_{ds})_F$ vs T_c and I_d in solder layer.

TABLE 3. The evaluation criteria of condition.

Aging rate	Condition grade
$0 \le f \le 0.15$	Normal (I)
$0.15 < f \le 0.35$	Slight aging (II)
$0.35 < f \le 0.55$	Medium aging (III)
$0.55 < f \le 0.75$	Serious aging (IV)
$0.75 < f \le 1$	Fault (V)

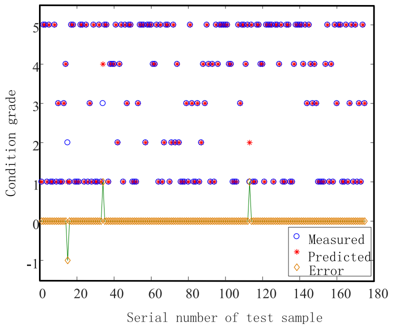

FIGURE 17. The predicted and measured condition grade.

condition, it can be seen that the predicted real-time condition grade is in good agree with the measured condition grade. There are three groups of data with level 1 condition level error, and there is no span beyond level 2 and above. This error is fully acceptable in assessment models and engineering applications. The accuracy of condition grade obtained by predicting the aging rate is as high as 98.3 %. Thus, the ANFIS model is effective.

Usually with more feature parameters and samples, the ANFIS model can predict aging rate better. The more sample data is used for ANFIS model training and building, the more precise the model will become. Thus, further study should be performed to make this model even more accurate and complete.

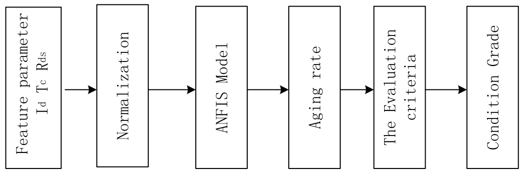

FIGURE 18. The flow chat of ANFIS evaluation.

TABLE 4. The verified result of condition grade in a practical application.

I_d (A)	20	20	20	20	20
T_c (°C)	50.0	52.17	56.25	62.54	66.98
R_{ds} (mΩ)	88.6	95.9	110.1	131.9	147.3
The actual condition grade	I	I	III	IV	V
The predicted condition	I	I	III	V	V

V. CASE OF PRACTICAL APPLICATION STUDY AND VERIFYING

Simulation and experimental results have shown that the aging rate (f) is affected by an increase of conducting resistance which is regarded as the reflection of performance degradation from aging. Based on this, a new method can be proposed to monitor power device by comparing the predicted real-time aging rate with the evaluation criteria. This methodology mainly consists of several steps as shown in Figure 18: collecting feature parameters of I_d, R_{ds} and T_c, normalizing the features parameters, building the prediction model using ANFIS, calculating the aging rate, looking up the evaluation criteria, assessing the condition grade. For a real application, it is designed so that all feature parameters will be recorded on-line during its operation. Thus, the evaluation should be preset in advance. During the operation, the features parameters will be collected periodically, e.g. every 1 or 2 weeks, to update the prediction model. If degradation occurs, its condition can then be monitored by recognizing the aging rate overtime the operating.

In a certain practical application, the parameters are measured and condition grade is verified as shown in table 4, it shows that the method proposed in this paper is feasible and, based on the result of the condition grade; the operator can take suitable operating strategies or maintenance measures.

VI. CONCLUSION

Simulation and experimental results verified that the failure influence the electrical–thermal-mechanical stress in different layers of power device power. Meanwhile, it will lead to the increase of thermal resistance, which directly affects the overall characteristics or performances of the MOSFET power device. This paper proposes an approach to monitor the condition and evaluate the condition grade of MOSFET power device using the estimation of aging rate. The external characteristics of power device are the reflection of internal condition, the inputs to this model consist of feature parameters at certain working points, and the output of the model is the aging rate, which is used as the indicator of internal degradation. The case study result shows that aging rate can be successfully estimated using ANFIS. The advantages and challenges of the method are analyzed in the paper and it is hoped that the study represents a forward step to develop a cost-effective technique to evaluate the condition grade for enhancing the real time reliability of MOSFET power device.

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