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Investigating the solder mask defects impact on leakage current on PCB under condensing humidity conditions

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Abstract

This paper focuses on conducting a thorough investigation into the solder mask defects and their influence on the leakage current development in PCB under operating conditions. A practical commercial PCBA has been used as a reference to construct a realistic numerical model, integrating the solder mask layer through COMSOL software. Comprehensive investigations cover scenarios with and without pinholes, conducting precise electrochemical reaction simulations under critical electrical conditions for validation against experimental data. The outcomes notably reveal how pinholes level up leakage current (LC) and reshape its paths. To validate the proposed method, experiments under real operating conditions and humidity were conducted. The comparison between the simulation and experiments demonstrated the effectiveness of the numerical model.

1. Introduction

The rapid progress in power electronic technologies has led to their widespread adoption in various applications, including traction, photovoltaic (PV), and wind power systems. However, the operational environments of these applications often pose diverse and demanding challenges for power electronic equipment, compromising their reliability. Printed circuit board (PCB) plays a pivotal role in the reliability and performance of power electronic systems. It has been reported by [1] that up to 26% of failures in power electronics converter systems are attributed to issues with PCB. Among these failures, corrosion-related problems are particularly prevalent, especially when exposed to high humidity and contamination conditions.

Exposure to humidity conditions can trigger a wide range of failure modes linked to corrosion [2]. This occurs as a result of the formation of a water film with varying thicknesses on the surface of a printed circuit board assembly (PCBA). The presence of water film is a significant contributing factor to several operational failures, including corrosion modes like leakage current (LC), short circuiting, and electrochemical migration (ECM), as outlined in [3]. Specifically, the water film induces elevated levels of leakage current between adjacent opposite-biased pads on the PCBA, and further lead to ECM failure due to dendrite bridging [4]. The presence of a water layer under humidity is influenced by both the relative humidity (RH) level and the characteristics of the PCBA surface, more specifically the solder mask (also called solder resist) [3]. Acting as a thin polymeric coating deposited onto the FR-4 laminate, the solder mask serves as a protective layer, segregating conductive and non-conductive surfaces, and preventing short circuits and copper traces oxidization [5,6].

Recent industrial trends have strongly emphasized enhancing the ability of PCBs to withstand extreme temperatures and humidity. Evaluating this capability involves employing tests such as the temperature humidity-bias (THB) test, highly accelerated stress test (HAST), temperature cycling (TC), and high-temperature storage life (HTSL) [7,8]. Consequently, the rigorous testing and application conditions highlight the necessity of carefully selecting substrate and assembly materials.

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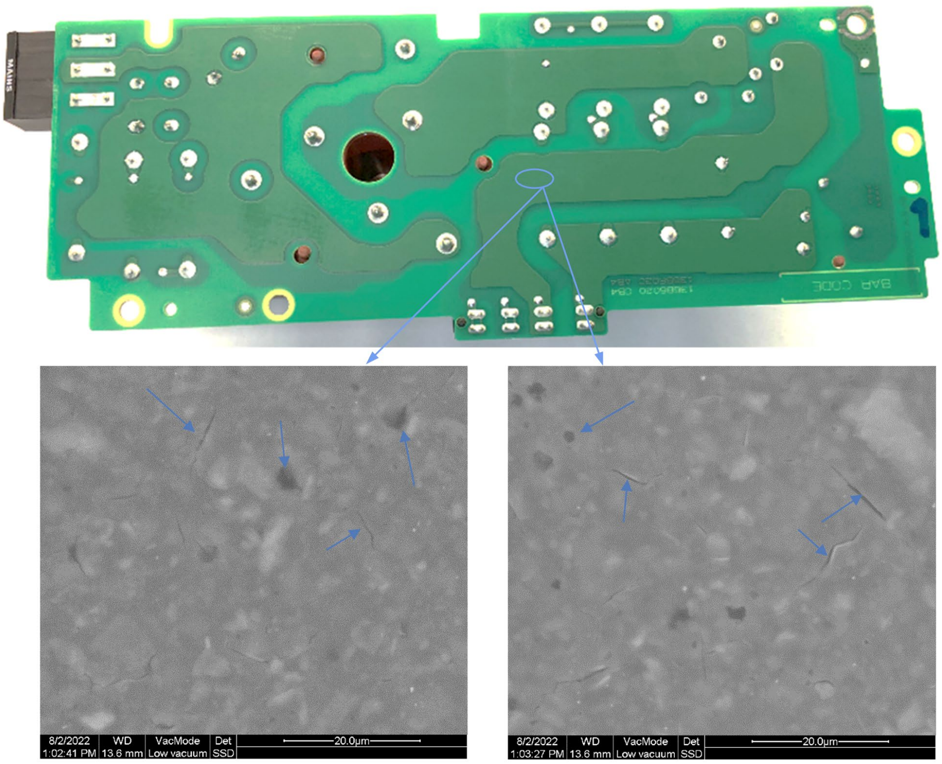

Fig. 1. PCBA under test (backside view) with close-up on solder mask with small cracks and pinholes.

In [9], several solder mask defects and deficiencies were addressed, including uneven surface, resist displacement, inclusions, missing resist, cracks, peeling, and wrinkling. [3] also discussed the significance of pinholes, which represent bulk surface defects of the solder mask varying in size from hundreds of nanometers to a few micrometers in diameter. With the existence of cracks/pinholes, the solder mask surface wettability will increase, leading to the spreading of the condensation layer and eventually bridging, thereby shortening the time of corrosion failure.

Relatively few studies have investigated the influence of solder mask defects and deficiencies on its humidity-resistant performance in harsh conditions. Consequently, this study employs finite element-based tools to simulate the pinholes presence on the solder mask surface and investigate its effect on the formation of leakage current in a commercial PCBA under condensing conditions.

The paper is organized as follows: In Section 2, the PCBA under test is introduced, providing a detailed description of the scanning electron microscopy (SEM) analysis results of a failed board after testing. Additionally, a brief explanation is given regarding how the condensation layer and the PCBA with solder mask defects are modeled in the simulation. Moving to Section 4, the simulation results are presented for both conditions: with and without pinholes. These results illustrate the potential paths of LC, with a specific focus on the risky regions where the LC could exceed the safety limit under high biased voltage and the presence of the condensation layer. By giving the comparison of the microscopy of the failure spot on the tested PCBA, and the simulation results within the same region, the effectiveness of the simulation model is discussed. Finally, the paper concludes with the drawn conclusions, as well as an outlook on future activities.

2. PCBA under test

The PCBA under test is as shown in Fig. 1, which is a commercial product designed to operate under $400V_{ac}$, with the potential of the tracks and pads/vias being categorized into three phases and protective earth (PE)/functional earth (FE). The PCBA is a four-layer type with the body of the board made of FR-4 material and four layers (top, two inner, and bottom layer) made of copper. The solder mask layer is liquid film type using green color, the smallest solder mask clearance is 0.10mm, and the via solder mask clearance is 0.00mm. The adopted surface finishing technique is hot air solder leveling (HASL).

To evaluate the reliability performance of the

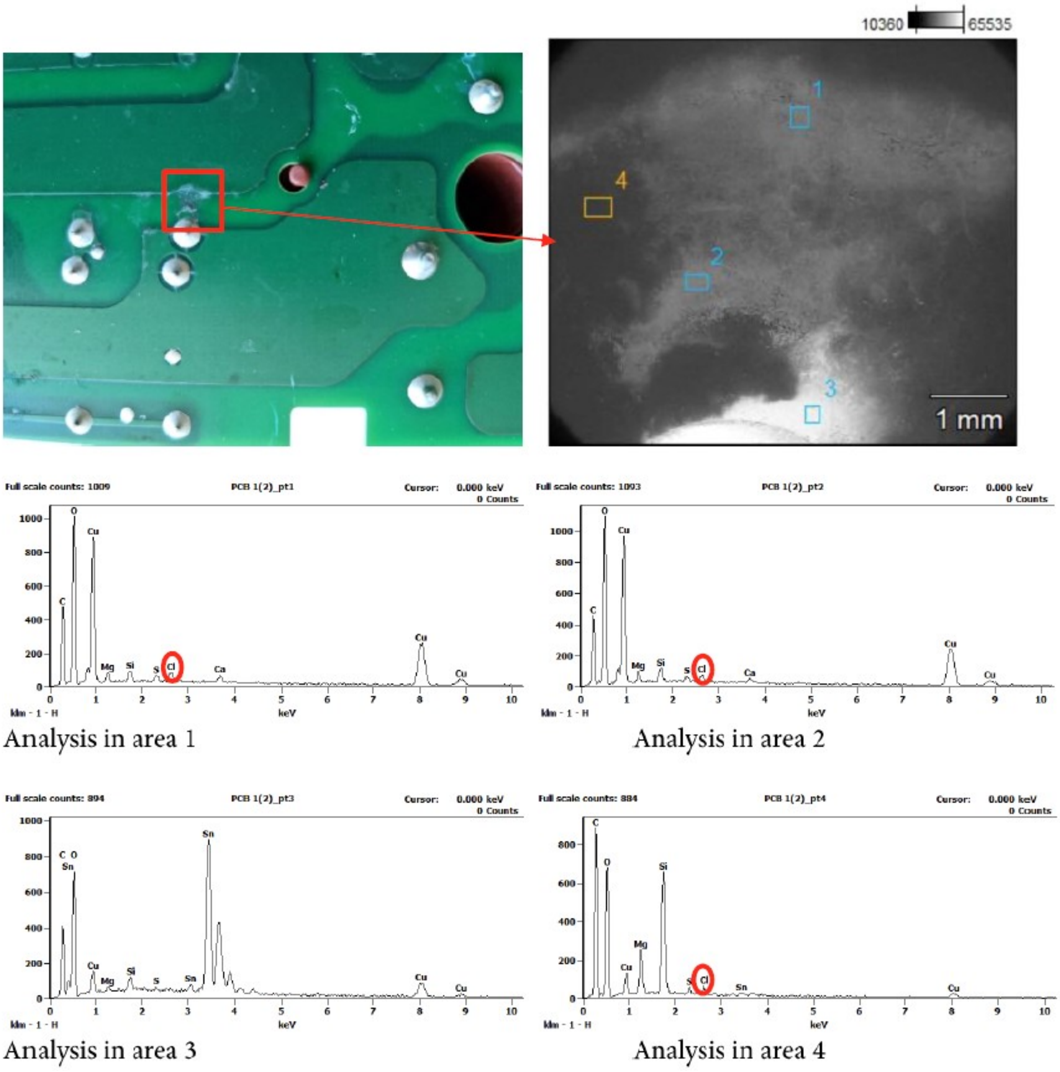

Fig. 2. FE-SEM analysis of the PCBA under test.

PCBA under critical environments, the DUT has been through several test cycles. Each test cycle consists of two test conditions. The first condition was the humidity exposure test at 70°C with 95% RH, where the PCBA was continuously fully powered and operated under realistic electrical working conditions. In the second condition, known as the temperature swing stress test, the drive was fully powered during the high-temperature step, while it was powered off during the low-temperature step.

The tested board underwent continuous testing until a malfunction occurred, followed by post-failure analysis that focused on examining the solder mask surface. SEM analysis revealed the presence of small cracks and pinholes in µm scale, on the surface and top edge of the solder mask layer of the PCBA, as shown in Fig. 1. The findings using field emission scanning electron microscope (FE-SEM), also confirmed the presence of chlorine on the PCBA surface, which originated from the PCB manufacturing process, is depicted in Fig. 2. To be noted, the presence of chlorine observed could contribute to the occurrence of ECM on the PCBA.

3. Modelling approach

3.1. Electrochemical reaction

This study utilizes the same electrochemical reaction modeling approach as established in the previous study [10]. During the manufacturing of PCBA, weak organic acids (WOAs) are utilized as activators in the solder flux system. Subsequently, residual WOA contamination can occur on the surface of the PCBAs after the soldering process. To replicate this contamination, the modeling methodology incorporates glutaric acid as one of the WOAs, with a contamination level of 100 µg/cm^2, closely resembling real-world application conditions.

In humid environments, the glutaric acid present on the surface of the PCBA dissolves within the condensation layer, serving as the electrolyte for the ensuing electrochemical reaction. In this process, the tinned pads function as the anode when a positive potential is applied, while the pads connected to the ground act as the cathode. As the electrochemical process unfolds between the anode and cathode, dendrites gradually form and extend. If a dendrite originating from the cathode successfully spans the gap and reaches the anode, it can lead to a short circuit. Importantly, prior to the occurrence of a short circuit failure, an initial localized corrosion takes place as a result of the electrochemical reactions at the electrodes and the ion transport through the water layer, preceding dendrite formation [11-13]. The level of LC generated before dendrite formation and short circuit acts as an indicator of the potential for corrosion-related failure, as higher LC corresponds to a higher rate of electrochemical reactions and metal ion dissolution at the anode, facilitating migration to the cathode for deposition. The same as in [10], the LC is modeled based on the main electrochemical reactions taking place at the electrode. The LC level is then utilized to evaluate the potential impact of solder mask defects on the humidity resistance capability of the PCBA in this study.

3.2. Numerical model

To investigate the impact of solder mask defects on the formation of LC in a practical PCBA subjected to condensing conditions, a numerical model was built using the COMSOL software. The model incorporated the Secondary Current Distribution–Shell interface, which effectively captured the charge transport within the condensation layer in the tangential direction. The condensation layer was represented in the model as a thin layer with a micrometer-scale thickness. Due to the thinness of this layer, it was assumed that the predominant flow of the LC occurred exclusively in the tangential direction. More specifically, the thickness of the condensation layer was set to be 1 µm, with an average electrolyte conductivity of 396 µS/cm to represent a corresponding relative humidity level in the environment.

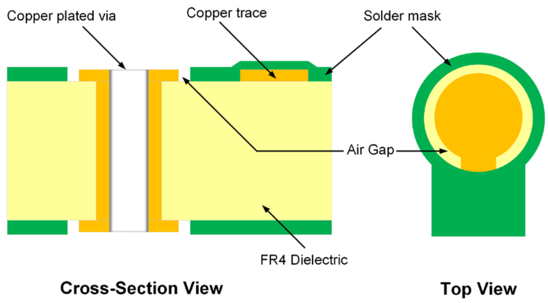

Fig. 3. Cross-section and top view of solder masks represented in the numerical model.

In the model's geometry aspect, an exploded view showcasing the PCBA's vertical structure is illustrated in Fig. 3. Since the two inner copper layers are embedded within the FR-4 material and are not in direct contact with the condensation, the numerical model only takes into account the top and bottom layers. These two layers were specifically considered as they are more susceptible to corrosion when the board is exposed to moisture and there have high voltage present between the tracks/vias. In order to closely replicate the original design, the solder mask was applied to cover all copper traces and vias, with the exception of certain intentionally exposed vias and copper areas, as presented in Fig. 4.

Recognizing that pinholes can compromise the integrity of the solder mask and provide pathways for moisture and contaminants to penetrate the PCB solder mask, possibly resulting in corrosion-induced failures, led to the simulation of this solder mask

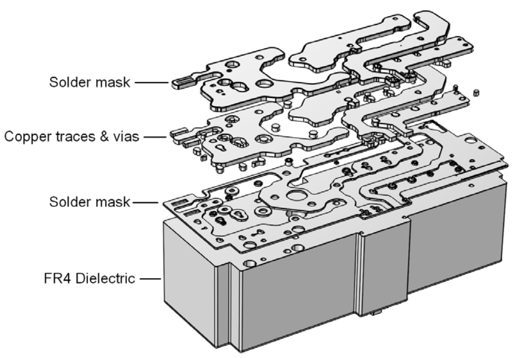

Fig. 4. Exploded view of the numerical model built in COMSOL (50x magnified along the Z-axis).

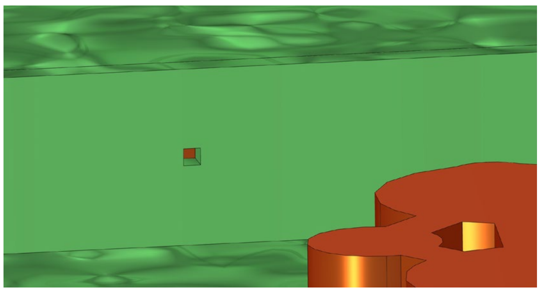

Fig. 5. Pinhole created in the solder mask, exposing the underlying copper (located on the edge of the track).

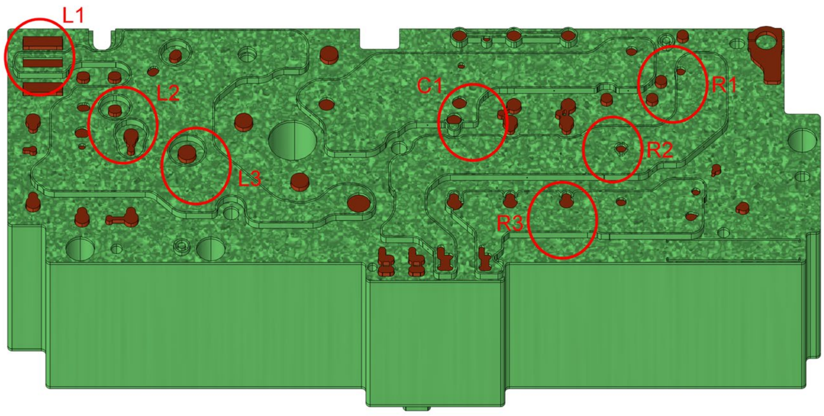

Fig. 6. Numerical model of the PCBA under test with pinholes created on the solder mask (backside view).

defect. Small unintended openings were deliberately created as pinholes in the solder mask, to expose the underlying copper traces to the condensation layer. A zoomed-in figure illustrating the pinhole with a width of 5 µm is displayed in Fig. 5.

In the simulation, both geometries with and without pinholes have been modeled. The geometry with pinholes including ten pinholes strategically placed along the edge of the traces and one pinhole on top of the solder mask is presented in Fig. 6, with tracks and vias being assigned to different potentials. The locations of the pinholes are more clearly visible in Fig. 12, appearing as small openings under the applied high voltage.

4. Simulation and experimental validation

To evaluate the potential paths of LC and identify the risky regions where the short circuit might mostly occur under real operating conditions, multiple COMSOL simulations were performed. Three different electrical conditions were applied to the tracks and vias as the PCBA under test is designed to operate under three-phase power. Since operational failures under condensation and high electric field are instantaneous, the study only concentrated on the most crucial conditions, specifically those with the highest potential differences among tracks and vias. Fig. 7 illustrates the potential distribution in the condensation/electrolyte layer for three specific

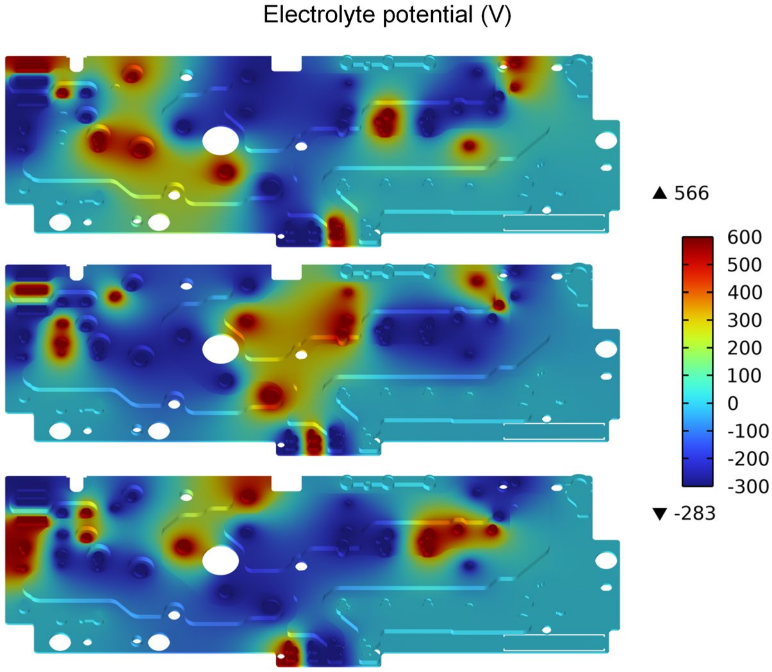

Fig. 7. Electrolyte potential distributions on the PCBA surface (without pinholes).

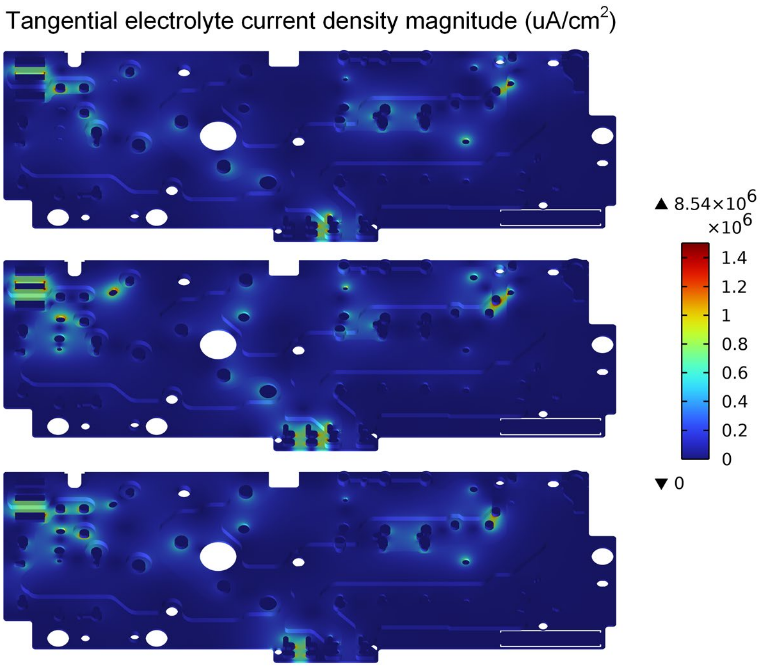

Fig. 8. Electrolyte current density distributions on the PCBA surface (without pinholes).

instances when the positive peak voltage is reached in one out of the three phases.

Correspondingly, under each electrical condition, the LC level and paths under the same humidity level (defined by condensation layer thickness and conductivity) have been identified and presented in Fig. 8.

To validate the simulation results, a humidity test was conducted by placing the PCBA test samples in a climatic chamber. The chamber maintained a constant relative humidity level of 95% RH and an air temperature of 70°C. The experiments were conducted over a period of 700 hours. Following the completion of the tests, seven regions of interest, as identified in Fig. 6, underwent extractions and conductivity measurements on the PCBA board. The measured conductivity values are detailed in Table. 1.

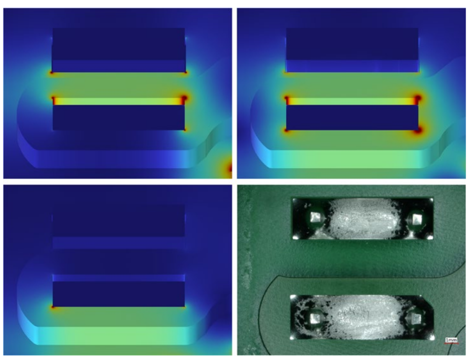

Fig. 9. Simulated current density and optical microscopy picture in region L1.

Table 1
Measured conductivity on PCBA sample after exposure[a]

Location on PCBA	PCBA Sample (μS/cm)
L1	32.90
L2	19.06
L3	20.60
R1	17.33
R2	17.99
R3	12.88
C1	13.56

[a]Reference: Millipore water's conductivity is 2.6μS/cm.

To be noted, there are several differences between the simulations and experiments, including but not limited to the following: 1) The electrolyte current density magnitude refers to the electrolyte domains, while the experimental measurements can only return the total current drawn at an electrode; 2) The condensation/electrolyte layer in the simulations is uniformly applied to the entire PCBA surface with consistent thickness, whereas real experiments may exhibit localized condensation, influenced significantly by the PCBA's surface wettability; 3) The potentials applied in the simulation are fixed at

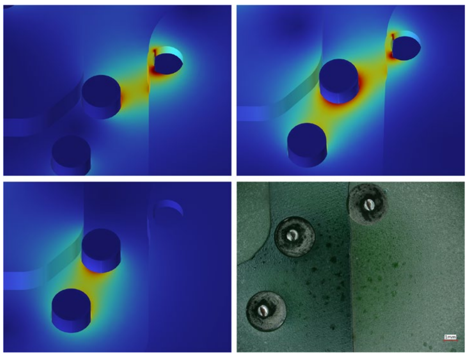

Fig. 10. Simulated current density and optical microscopy picture in region R1.

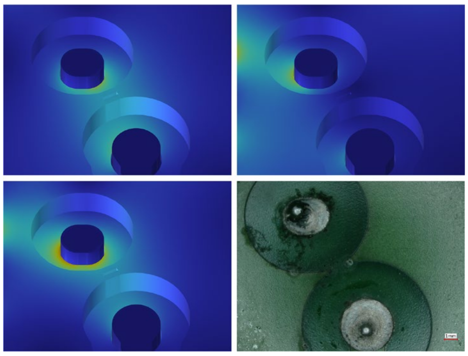

Fig. 11. Simulated current density and optical microscopy picture in region L2.

the maximum, while in the experiments, the input voltage is three-phase and time-variant.

For comparison, the simulated current density of the condensation under three electrical conditions and the corresponding optical microscopy images of the same regions are presented, respectively in Fig. 9-11. As previously discussed, the simulation results solely indicate the worst-case scenario and can serve as a design reference without giving the real LC value.

In the simulation results provided above, the solder masks were incorporated into the numerical model without introducing any pinholes. To illustrate the impact of solder mask defects on the LC levels and paths, the simulation outcomes for the model with pinholes will be presented and analyzed. Fig. 12 reveals the potential and current density distribution within the condensation/electrolyte layer of the numerical model, considering the presence of pinholes in the solder mask, under one of the three electrical conditions. Compared to the results shown in the first subfigure of Fig. 7 and Fig. 8, the presence of pinholes clearly indicates more biased copper areas exposed to the condensation and leads to the emergence of new LC paths and an elevation in the LC density within the region, which is identified as emerging more brighter areas in the simulation results.

Based on the findings of the FE-SEM analysis of the PCBA, it was ascertained that the pinholes within the solder mask are predominantly located along the track edges. In region C1, two pinholes were intentionally placed as close to the real case as

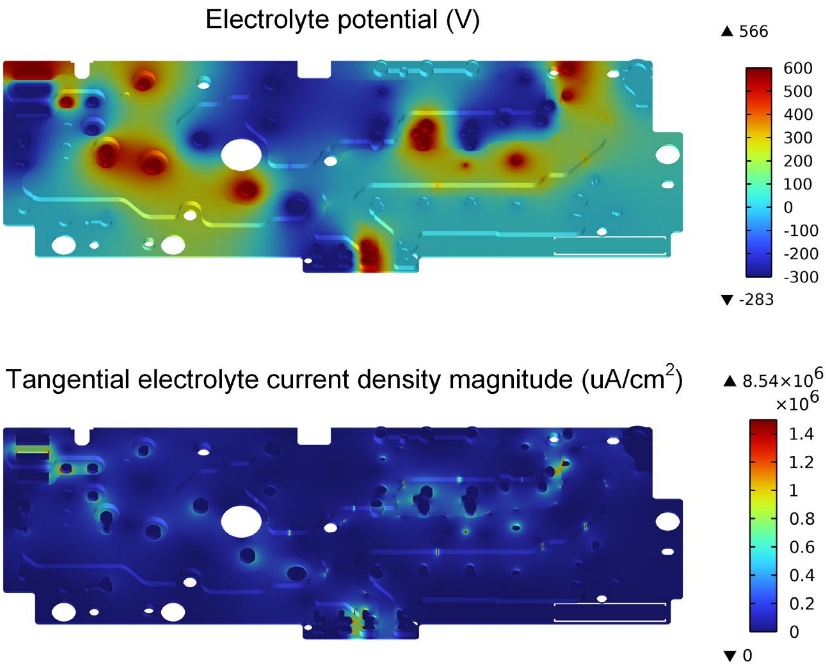

Fig. 12. Electrolyte potential and current density distributions on the PCB surface (with pinholes).

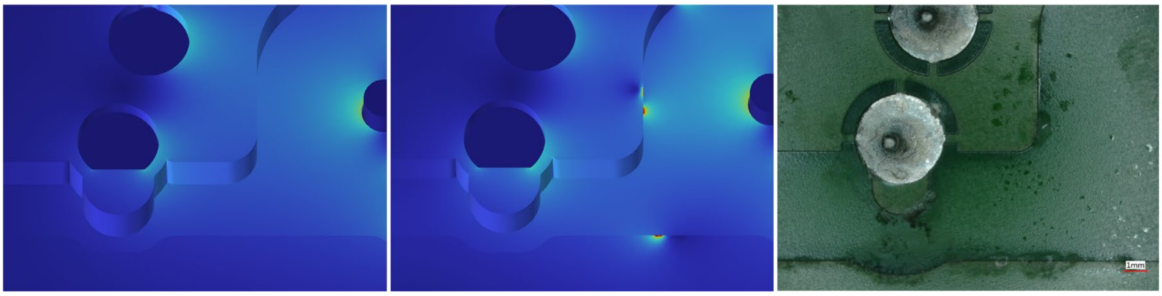

Fig. 13. Simulated current density (without and with pinholes) and optical microscopy picture in region C1.

possible. The simulated current density results without and with pinholes in Fig. 13 effetely verified the pinhole's impact on the LC level and path, and how it can influence the PCBA's humidity resistance capability.

5. Conclusions

This paper introduced a numerical approach for assessing the influence of solder mask defects on the surface leakage current of PCBA when subjected to humid conditions. Using a commercial PCBA as a practical example, a realistic model of the test board incorporating the solder mask layer was constructed using COMSOL software. Both scenarios, with and without pinholes, were comprehensively investigated. Electrochemical reaction simulations were conducted under critical electrical conditions for both cases. The simulation outcomes were validated against experimental findings, effectively identifying regions with high LC levels. Notably, the results highlighted the role of pinholes in intensifying LC and altering its pathways.

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References

[1] E. Wolfgang "Examples for failures in power electronics systems," presented at ECPE Tutorial 'Rel. Power Electron. Syst.', Nuremberg, Germany, Apr. 2007.

[2] M. Tencer, "Conductive aqueous layer formation at the gel-substrate interface in equilibrium with 100% RH environment," in IEEE Transactions on Components and Packaging Technologies, vol. 23, no. 4, pp. 693-699, Dec. 2000.

[3] K. Piotrowska, R. U. Din, M. S. Jellesen and R. Ambat, "Effect of Solder Mask Surface Chemistry and Morphology on the Water Layer Formation Under Humid Conditions," in IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 8, no. 10, pp. 1756-1768, Oct. 2018.

[4] S. Bahrebar and R. Ambat, "Investigation of critical factors effect to predict leakage current and time to failure due to ECM on PCB under humidity," Microelectronics Reliability, vol. 127, 2021.

[5] F. Riley, The Electronics Assembly, Springer Berlin Heidelberg, 1988, https://doi.org/10.1007/978-3-662-13161-9.

[6] M.R. Sculpher, Advanced solder masks, Circ. World 12 (3) (1986) 9-11, https://doi.org/10.1108/eb043813.

[7] R .Dias, et al., "Challenges and Approaches to Developing Automotive Grade 1/0 FCBGA Package Capability," 2019 IEEE 69th Electronic Components and Technology Conference (ECTC), Las Vegas, NV, USA, 2019.

[8] C. Ueta, K. Okada, T. Shiina, T. Hanada and N. Ito, "Development of Solder Resist with Improved Adhesion at HTSL (175 deg C for 3000 Hours) and Crack Resistance at TST for Automotive IC Package," 2017 IEEE 67th Electronic Components and Technology Conference (ECTC), Orlando, FL, USA, 2017.

[9] TechnoLab GmbH, Defective resist, Berlin, Germany, https://solderdict.technolab.de/pcb/defective-resist.php.

[10] X. Peng, A. S. Bahman, F. Iannuzzo, H. C. Gudla, A. R. Lakkaraju, and R. Ambat, "Prediction of the electrochemical migration induced failure on power PCBs under humidity condition — A case study," Microelectronics Reliability, vol. 139, 2022.

[11] K. Piotrowska, R. Ud Din, F.B. Grumsen, M.S. Jellesen, R. Ambat, Parametric study of solder flux hygroscopicity: Impact of weak organic acids on water layer formation and corrosion of electronics, J. Electron. Mater. 47 (7) (2018) 4190–4207.

[12] V. Verdingovas, M.S. Jellesen, R. Ambat, Relative effect of solder flux chemistry on the humidity related failures in electronics, Solder. Surf. Mount Technol (2015).

[13] V. Verdingovas, M.S. Jellesen, R. Ambat, Solder flux residues and humidityrelated failures in electronics: Relative effects of weak organic acids used in no-clean flux systems, J. Electron. Mater. 44 (4) (2015) 1116–1127.