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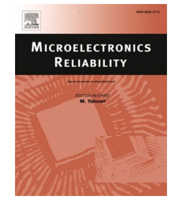

Effect of intrinsic PCB parameters on the performance of fluoropolymer coating under condensing humidity conditions

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A B S T R A C T

In this work, Fluoropolymer-based ultrathin coating is evaluated as a protective barrier for Printed Circuit Board (PCB) against corrosion failures. Constant humidity with temperature cycling was applied as external climatic conditions for performance assessment through electrochemical AC impedance and DC potentiostatic measurements. Morphology of the coating before and after test was inspected using Optical, Scanning Electron Microscopy (SEM), and Energy Dispersive Spectroscopy (EDS). Fluoropolymer coating was applied on a PCB interdigitated pattern used as test substrate. The effect of test board cleanliness, coating thickness, and orientation of the PCB placed inside a climatic chamber were investigated with subsequent corrosion morphology observations after climatic exposure. The study showed that the PCB cleanliness as a critical factor controlling performance with less reliance on the orientation of the PCB and the thickness of the coating.

1. Introduction

Today, electronic devices are part of almost every aspect of human life. Electronic devices exposed to high humidity may undergo transient condensation, resulting in the formation of a thin electrolyte layer (TEL) on a Printed Circuit Board (PCB) [1–3]. The trend of miniaturization has driven in closer spacing among electronic components, therefore different metallic points are connected easier through the TEL on an assembly (i.e. IC legs, terminals) [4–6]. If the TEL is clean on a biased PCB, it should not generate high leak current due to low conductivity [7]. Nevertheless, process related residues are introduced on the surface of PCBs during fabrication [8–12]. Humidity exposure causes dissolution of active components in the residues and subsequently, TEL obtains very good electrolytic properties for corrosion to take place [13]. Further, the active components such as weak organic acids in the flux residue have hygroscopic nature which changes the humidity boundary for TEL formation depending on the type of the activator [14–19]. As a result, enhanced leak current in TEL occurs, which leads to Surface Insulation Resistance (SIR) reduction between biased points on the PCB or with extended exposure causes Electrochemical Migration (ECM) or other corrosion failure modes [20–24]. Fluoropolymer has been utilized in major industries due to excellent properties such as insulation, flexibility, durability, and fire resistance [25–27]. However, fluoropolymer coatings are comparatively thin, compared to other coatings, and expected protective abilities are based on its hydrophobic nature [28].

Conformal coatings are well-known as a method for protecting the electronics from humidity effects. They conform on the contours of a PCB and act as a physical barrier against external harsh environments. Silicone, parylene, acrylic, polyurethane, and fluoropolymer are among some popular options of conformal coatings [29–32]. Factors related with the material type of the coating such as thickness, conformity and the cleanliness of the board affect the moisture barrier performance of all the coatings. For instance, the adhesion is determined through the interlocking and chemical bonding at the interface between a coating and a surface. The adhesion of a conformal coating on a PCB surface is highly influenced by the PCB cleanliness [33]. Additionally, the protective properties of coatings are influenced due to moisture transport through the coating, which reaches the interface, and the resulting reduced adhesion causes TEL formation leading to leak current or other corrosion phenomena [34,35].

In our previous work, wave solder no-clean flux residue under silicone and acrylic conformal coating was tested on a PCB laminate surface under various climatic conditions [13,36]. The results revealed poor performance of both silicone and acrylic conformal coating by showing blister formation when flux residue was present on the test board prior to the coating. During tests using a PCB with interdigitated pattern, both coatings offered some protection against humidity; however, extended exposure caused increased leak current when flux residue was present

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underneath of the coating.

Fluoropolymer based ultrathin coating is an organic coating with thickness in the micro- or nanoscale compared to 100–1000 times higher thickness of other conventional conformal coatings. It is known for its water repellent properties due to its low surface energy which offers protection against an external corrosive environment [37,38]. Additionally, it is characterized by low surface tension, which offers coverage of complex geometries on a PCB especially below or at the corners of components. It is considered an excellent choice for protecting PCBAs against external environments due to unique characteristics such as mechanical strength, inertness and thermal durability, resistance to chemical and biological degradation [39]. However, there is no systematic prior investigation on the fluoropolymer coating performance for PCB applications under cyclic humidity conditions.

The work in this paper focuses on the humidity performance of fluoropolymer ultra-thin coating to protect PCB under transient condensing. Investigations were carried out using an interdigitated comb pattern mimicking a PCB surface, which is coated with fluoropolymer. Effect of PCB surface cleanliness, thickness of the coating, and orientation of the PCB while placed inside the climatic chamber were tested. Exposure to transient condensing conditions was performed in a climatic chamber under constant humidity, while cycling the temperature to obtain condensation on the coated surface. Moisture uptake of the coating during humidity testing was studied initially by measuring the impedance change as a function of time using Electrochemical Impedance Spectroscopy (EIS), however subsequent DC biased condition was carried out to investigate the possible failures due to the moisture absorption. After testing, the surface of the exposed samples was analyzed using optical microscopy, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS).

2. Materials and methods

2.1. Test substrate

A test PCB (Fig. 1) with components and interdigitated patterns was used as a substrate for various investigations. Details of the test PCB can be found elsewhere [40]. Test PCB consists of as set of resistors and capacitors, and two comb SIR patterns with one of them placed under the solder mask and one outside. For the present investigation, only the open SIR pattern was used for collecting the electrochemical signals during humidity testing. The surface finish of the SIR was hot air levelled with Sn/Ag/Cu (SAC) solder alloy. The SIR pattern had a surface area of 13 × 25 mm. The conducting lines were designed with 0.3 mm width and spacing, and the SIR contained 41 interdigitated lines in total.

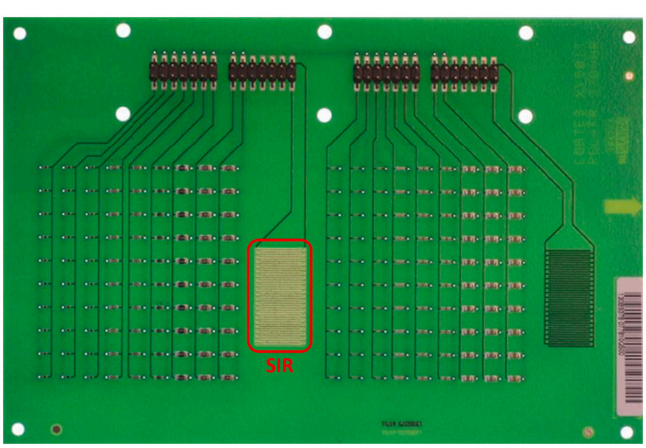

Fig. 1. Test PCB substrate used for testing (SIR pattern used for collecting electrochemical signal is shown in red box). (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this chapter.)

2.2. Surface condition of test PCB for coating and testing

In this work, the effect of PCB surface cleanliness on the fluoropolymer performance was evaluated using a clean and contaminated test PCB. The process cleanliness effect was simulated using the test PCB contaminated with commercial flux system. For clean PCB, prior to coating, the surface was cleaned using isopropanol followed by rinsing with milli-Q water and drying with pressurized air. For flux contaminated PCBs, after cleaning, 30 μL flux solution was poured on the SIR area (325 mm^2) prior to coating, yielding a contamination level of 420.37 $\mu g/cm^2$. A water-based flux (95% *w*/w content) with adipic and glutaric acid activators was used as a contamination (Cobar 396-DRM). The acid number of the flux was 36.85 mg KOH equivalent. The flux had a moderate activation system (ORM0) according to the IPC J-STD-004 classification.

2.3. Ultra-thin coating of the test PCBs

Ultrathin fluorinated acrylate polymer coating was used on the test PCBs. The coating consisted of fluorocarbons and hydrofluoroether solvent carrier. The polymer percentage content was varied at 2% and 10% resulting a thickness of approximately 0.15 μm (named as LOW) and 1 μm (HIGH), respectively. The coating was applied on the test boards by dipping in a coating bath for 30 s. Subsequently, it dried for 1 min and 5 min for lower and higher polymer content, respectively. Immersion and drying took place at room temperature.

2.4. Notation used for PCB samples for testing

Table 1 shows the notation used for various test PCB samples according to various parameters used for testing. All tests were repeated three times ($N = 3$) for all combinations of orientation, contamination, and thickness.

2.5. Testing configurations inside climatic chamber

During humidity testing, slight condensation can occur on the top of the coated PCBs due to the thermal cycling, while keeping constant relative humidity (RH). The retained water from the humidity and thermal cycling depends on the placement of the PCB as the gravitational flow can be inhibited depending on whether it is placed horizontal (H) or vertical (V). Therefore, both orientation were tested. For horizontal orientation, the PCBs were placed on a metal grid of inside the climatic chamber, while for vertical orientation, the test substrates were hanged with metal wires beneath the grid. The positions of the wires were chosen at the corners of the PCB to avoid drops of water dripping down to the SIR pattern in case of condensation.

2.6. Humidity test profile used for testing

The test PCBs were exposed under temperature and humidity

Table 1
Notation of all investigated cases in this work and number of repetitions.

Orientation	Contamination	Thickness	Notation	N
PCB with horizontal placement during humidity testing	No	High	H_NF_HIGH	3
		Low	H_NF_LOW	
	Yes	High	H_F_HIGH	
		Low	H_F_LOW	
PCB with vertical placement during humidity testing	No	High	V_NF_HIGH	
		Low	V_NF_LOW	
	Yes	High	V_F_HIGH	
		Low	V_F_LOW	

conditions in a climatic chamber (Espec PL-3KPH) with accuracy ±0.3°C and 2.5% RH. The exposure profile included constant 93% RH during all experiment, while the temperature was cycled. For the temperature cycling, test PCBs were exposed at 40°C for 2 h and ramped up to 65°C within 1 h. Subsequently, temperature was kept at 65°C for 2 h and ramped down to 40°C within 1 h, all at constant 93% RH. Therefore, the total period of one cycle was 6 h (Fig. 2) and it was repeated 48 times (total time of experiment was 12 days). The temperature ramping aimed to create transient condensation on the coated surface due to transients between high and low water content regimes due to change in absolute humidity when the temperature changes.

2.7. Electrochemical impedance spectroscopy (EIS)

During climatic exposure, the interdigitated SIR was connected to a potentiostat (BioLogic-VSP, Bio-logic Instruments) for electrochemical data collection (EC-Lab software). Intermittent electrochemical impedance spectroscopy (EIS) was performed using an AC signal with amplitude 25 mV (V_{rms} = 17.68 mV) for the first 5 days to monitor the impedance characteristics through changes in moisture transport. The frequency range was 100 kHz to 100 mHz and 5 measurements per frequency were recorded. The recorded EIS signal was the impedance among the interdigitated lines of the SIR pattern, which changes due to moisture absorption by the coating.

2.8. Leakage current measurements

At the end of the EIS measurements (after 5 days) when moisture was penetrated enough into the coating, the coated PCB was subjected to a DC bias to understand whether the water absorption leads to adhesion loss and failure. During the DC bias, leak current was measured for additional 7 days by applying 5 V voltage difference. The level of leak current shows the damage to the coating, while intermittent high current spike shows the dendrite formation due to electrochemical migration (ECM).

2.9. Optical microscopy and SEM-EDX inspection

Initial inspection of the exposed samples was carried out using optical 3D digital microscope (KEYENCE, VHX-6000 Series). Scanning Electron Microscopy (Quanta FEG 250 Analytical ESEM) was used to investigate the corrosion morphology after the climatic exposure. In SEM, the acceleration voltage was 5 V and the working distance was set at 10 mm. Energy-Dispersive X-Ray Spectroscopy (EDX) connected to the SEM was used for chemical analysis.

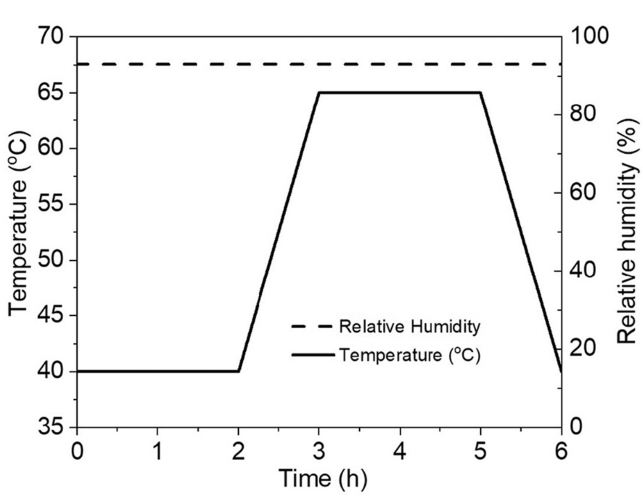

Fig. 2. One cycle of temperature and humidity profile used for testing fluoropolymer on the test PCBs.

2.10. Residue RAT inspection for residue bleeding for contaminated PCBs

Investigation of the flux residue release through the coating was tested using a patented gel product (Residue RAT™, EC-RAT) and subsequent visual observation. This method utilized pH changes and reactions between the gel indicator and the acidic nature of the residue [41]. The gel was heated for 3 min at 80°C, applied on the surface of the coating and left to be dried for 2 min. Subsequently, the color variations of the gel were evaluated to understand the residue bleeding through the coating.

3. Results

3.1. Impedance spectroscopy analyses

Fig. 3 shows the overall impedance spectra and the phase angle for various cases in the first and second column, respectively. The investigated frequency range was 100 mHz to 100 kHz. Fig. 3a and Fig. 3c shows the results for clean PCBs, while the results for contaminated PCBs are shown in Fig. 3b and Fig. 3d. On the other hand, Fig. 3a and Fig. 3b gives the results for horizontal placement, while Fig. 3c and Fig. 3d shows for vertical arrangement of the PCB in the climatic chamber. The plots presented in Fig. 3 shows spectra obtained between the time range t_1 = 6 h and t_2 = 9 h of the exposure profile (Fig. 2) for low and high thickness of fluoropolymer. The time interval represents the beginning of the step with temperature T_1 = 40°C and T_2 = 65°C in the second cycle of the exposure profile. The times t_1 and t_2 were chosen in order to record impedance values after the measurement was stabilized in the first cycle of exposure. Each point in the plots is an average of three repetitions (N = 3).

Impedance spectra show that for non-contaminated boards, the coating showed similar behavior irrespective of the coating thickness or orientation during testing (Fig. 3a.1 and Fig. 3c.1). High frequency side of the spectra showing almost purely capacitive character of the coating and they did not present significant differences. This capacitive behavior was observed in the phase angle, which obtained values higher than 85 degrees in the frequency range 1–100 kHz (Fig. 3a.2 and Fig. 3c.2). At lower frequencies, the impedance characterizes the surface resistance among the conducting SIR lines under the coating. Although some differences were observed between different coatings, however high scattering in the data for both impedance and phase angle values showed that the difference was not significant.

Compared to the clean boards, PCBs with contamination under the coating showed impedance values below 100 kHz for f = 0.1 Hz (Fig. 3b.1 and Fig. 3d.1) which was 100 times less than the smallest value for clean boards (Fig. 3a.1 and Fig. 3c.1). Comparing different parameters, thickness differences did not show significant effect, while different from clean PCBs, spectra corresponding to t_1 and t_2 showed a difference showing the moisture absorption and release depending on the moment in the climatic exposure profile. Difference was seen at both low and high frequency side showing that both resistive and capacitive character was affected, which was also observed for the phase angle.

3.2. Analysis of Impedance data

In order to differentiate the effect of various types of coatings, all impedance data were analyzed over time for a specific frequency. Fig. 4 shows the impedance value at f = 120 mHz at a time which corresponds in the middle of the period with temperature of 40°C (i.e. t = 4 h for the first cycle). For subsequent number of cycles (n = 1, 2, 3…), data corresponded to the measurements at t = 4 + n6 (unit in h), meaning that the impedance was recorded every 6 h after the first 4 h until total time of testing of impedance testing 120 h. The data presented in Fig. 4 show the average of three repetitions together with SD and Fig. 4a displays the

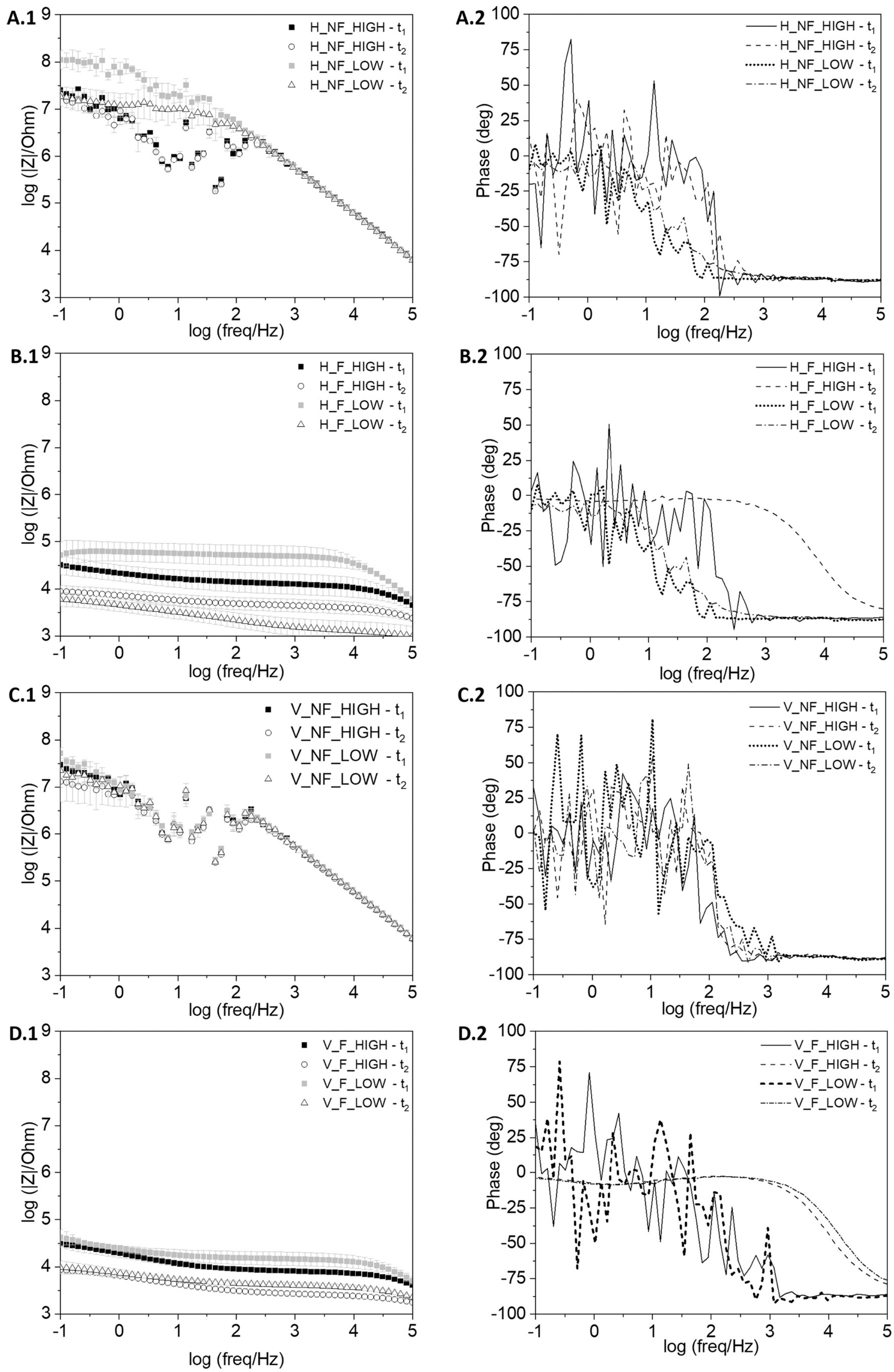

Fig. 3. Impedance as a function of frequency between 100 mHz to 100 kHz at $t_1 = 6$ h and $t_2 = 9$ h of the climatic exposure profile for (A) H_NF_HIGH/LOW, (B) H_F_HIGH/LOW, (C) V_NF_HIGH/LOW and (D) V_F_HIGH/LOW, ($N = 3$).

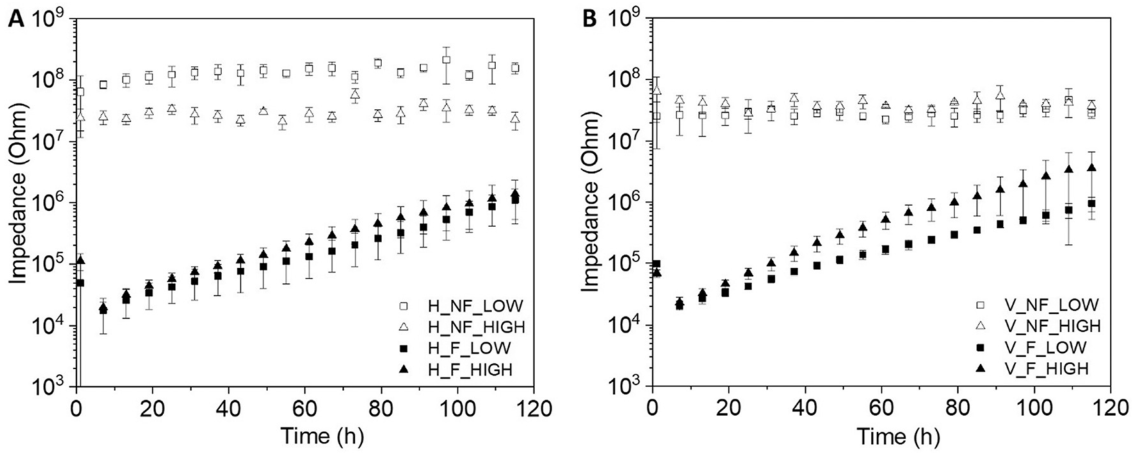

Fig. 4. Impedance recordings over time during the overall exposure profile of 120 h at f = 126,502 mHz in (A) horizontal and (B) vertical orientation (N = 3). The impedance data are presented for clean and contaminated PCBs with low and high thickness of Fluoropolymer-based ultrathin coating.

results for horizontal orientation, while Fig. 4b for vertical.

In Fig. 4a-b, boards with contamination (H_F_HIGH, H_F_LOW, V_F_HIGH and V_F_LOW) have an average impedance value in the range of 10^4 Ohm at the beginning of the test. For these cases, the impedance increased and reached an average in the range of 10^6 Ohm at 120 h. On the contrary, non-contaminated PCBs (H_NF_HIGH, H_NF_LOW, V_NF_HIGH and V_NF_LOW) had impedance values on the same level during all exposure (10^7–10^8 Ohm). Considering the standard deviation for all measurements, no significant difference was observed between fluoropolymer with low and high thickness or PCBs placed in horizontal and vertical orientation.

3.3. Leakage Current analyses under DC condition

Fig. 5 shows the leak current recorded during the last 7 days testing with DC bias after the impedance analysis for 5 days. Fig. 5a-b shows the results for PCBs with horizontal and vertical orientation, respectively. The applied potential bias was equal to 5 V and the measurement lasted for 168 h and started immediately after the 5 days period of EIS measurement.

The coated PCBs without contamination exhibited leakage current values below 10^{-4} mA, which is significantly lower than the contaminated PCBs. All contaminated PCBs shows about 3-magnitude higher leak current levels compared to the clean PCBs, while some of them shows increasing leak current over time as well as high current initially followed by a sudden drop due to corrosion (such as electrochemical migration) and damage of the SIR pattern. Particularly, spikes observed for H_F_HIGH and V_F_HIGH for the first 20 h of the experiment, while H_F_LOW showed multiple spikes for all the duration of the DC measurement.

The electrochemical performance of fluoropolymer was evaluated according to the level of the leakage current. The PCBs were considered as failed when the current was above the limit of 10^{-3} mA or showing spikes due to dendrite shorting. In Table 2, the failure time was recorded for all investigated cases in Fig. 5 for three repetitions (N = 3). In addition, the failure rate was calculated as the number of failed over the total number of investigated PCBs. All PCBs with contamination failed instantly (H_F_HIGH, H_F_LOW, V_F_HIGH and V_F_LOW) and without flux presented no failure (NA). The failure analyses showed no influence

Table 2
Failure rate and time for all investigated cases (N = 3).

Orientation	Flux	Thickness	Failure rate (%)	Time to fail (h)
Horizontal	No	Low	0	NA
		High	0	NA
	Yes	Low	100	Instantly
		High	100	Instantly
Vertical	No	Low	0	NA
		High	0	NA
	Yes	Low	100	Instantly
		High	100	Instantly

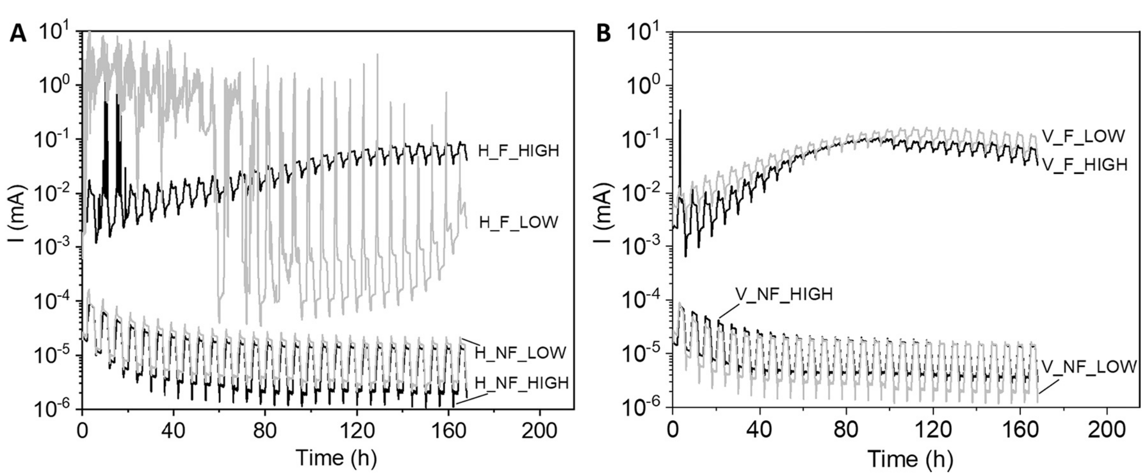

Fig. 5. Leakage current measurements for all investigated cases of PCBs with (A) horizontal and (B) vertical orientation.

of the PCB orientation or thickness of fluoropolymer on the electronic reliability.

3.4. Optical microscopy and Residue Rat analyses

Residue RAT analysis was carried out on the test PCBs before and after exposure to understand the presence of the flux residues, which were placed on the SIR pattern before coating. This is an important aspect in connection with performance of the coating under humidity conditions. Fig. 6 shows the appearance of the coated PCB under optical microscope together with picture after applying residue RAT both before and after exposure to humidity. Comparison of Fig. 6a.1 and Fig. 6a.2 with Fig. 6b.1 and Fig. 6b.2 shows intense red color for low thickness coating compared to high thickness. These results showed the interaction of the flux residue with residue RAT due to the porosity in the coating, even if the flux residue was placed between the coating and PCB surface. After exposure, the comparison of Fig. 6c.2 and Fig. 6d.2 shows that for high thickness coating, the coloration of residue RAT was less compared to low thickness coating. Additionally, the coloration in Fig. 6d.2 (orange hue) was less compared to the original level in Fig. 6b.2 (dark red), indicating that the flux residue was washed away during testing.

3.5. SEM-EDX analyses of the coated PCBs before and after exposure

Fig. 7 shows the SEM pictures of the coated PCB surfaces before and after exposure to humidity. Before exposure, SEM pictures of H_NF_LOW presented several regions with defects (Fig. 7a.1) which became larger after exposure indicating the influence of the climatic conditions (Fig. 7a.2). Conversely, H_NF_HIGH showed smooth surface before exposure (Fig. 7c.1), which maintained also after exposure (Fig. 7c.2). In Fig. 7b.1, flux residues were found on the surface of H_F_LOW before exposure, which caused the delamination of the coating after exposure (Fig. 7b.2). Similar effect can be seen for H_F_HIGH in Fig. 7d.2, however to less extent.

Fig. 8 shows the results of the EDX mapping from SEM. Fluorine signal was particularly analyzed as this can be used as finger print for the coated region due to the presence of fluorine in the coating. Only results for the horizontal placement is shown as the results for vertical placement is similar. Compared with the SEM picture, the EDS mapping result for fluorine after climatic exposure shows good coverage of coating for PCBs without flux residue. However, for the PCBs with flux residue, the SEM picture shows rough areas of the coating due to flux residue and correspondingly, the EDX shows dark regions. These dark regions are opening in the coating because the coating is not formed over the areas with flux residues. This behavior was observed both for coatings with low and high thickness.

4. Discussion

Overall results show that fluoropolymer coating can be used as a barrier for protecting PCBs from humidity and transient condensing conditions if one can assure that the PCB surface is clean before the coating is applied. The performance of fluoropolymer was reduced when flux residues were present prior to the application of the coating and PCB was exposed to cyclic humidity conditions. The transient changes in temperature resulted in condensation of moisture on the surface of the coating due to sudden changes in absolute humidity and differential temperature between the PCB and the test chamber. Subsequently, the water molecules permeated through the coating or directly interacted with the electrode surface/contamination through the openings in the coating. When the electrodes were connected due to the formation of a thin electrolyte layer with increased conductivity due to the flux residue, resulting leak current finally led to the formation of ECM. Additionally, stresses generated at the interface with the substrate resulted in delamination of the coating.

Organic coatings are widely used to protect metallic substrates. They are a popular choice due to cost saving and their effectiveness to protect against the corrosive environments. Fluoropolymer can be applied on a substrate with various ways with the most popular to be partial vacuum deposition and direct immersion. Direct immersion technique was used for this investigation, and by varying the polymer content, two different

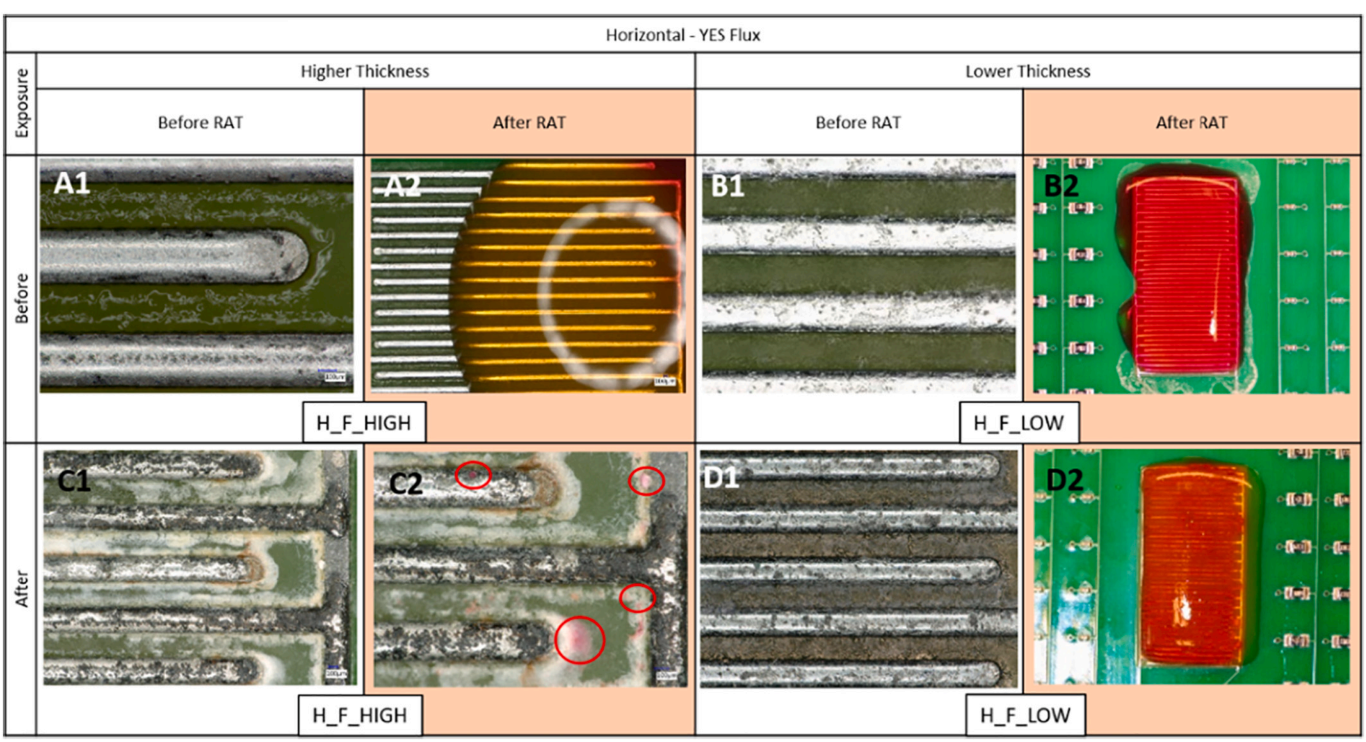

Fig. 6. Optical images for coated PCBs together with photo after application of residue RAT: (A) and (B) before exposure and (C) and (D) after exposure.

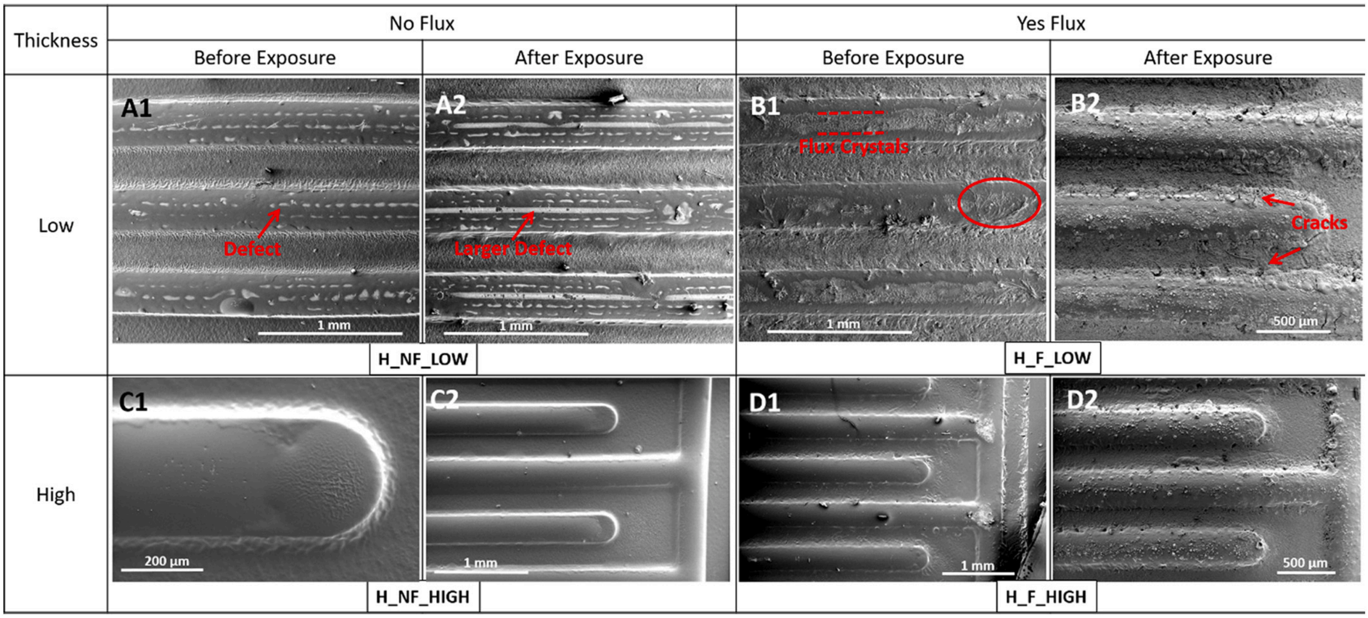

Fig. 7. SEM images of the coated PCBs before and after exposure to humidity: (A1-A2) and (C1-C2) without flux and (B1-B2) and (D1-D2) with flux residue.

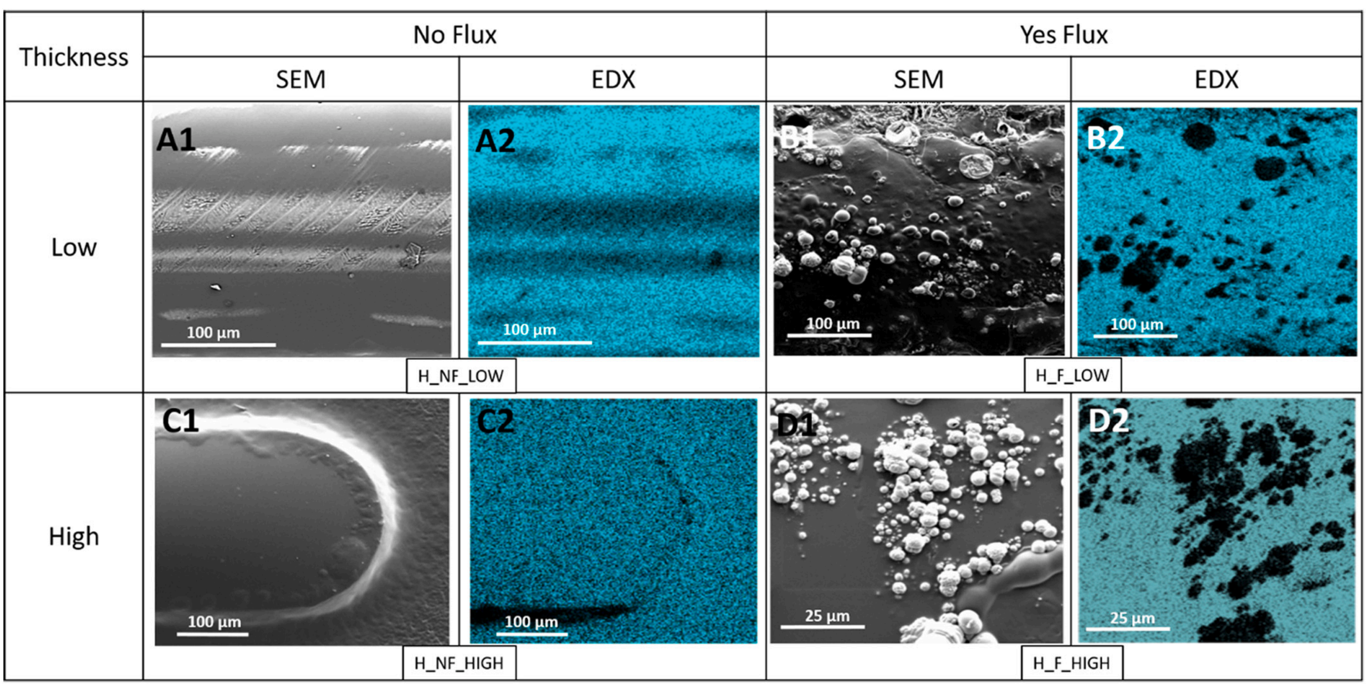

Fig. 8. Inspection of (A) H_NF_LOW, (B) H_F_LOW, (C) H_NF_HIGH and (D) H_F_HIGH, presented after climatic exposure in (1) SEM and (2) EDX images.

values of coating thickness were achieved. Organic coatings characterized by low permeability are considered having good performance as a physical barrier protecting electronic systems against external harsh environments. However, there is no ideal case where reactants in a corrosion process such as water do not pass through the coating as all polymer coatings are permeable to moisture. On the other hand, Fluoropolymer coating usually results in a thin coating on the PCBA surface, and the protection which they offer is expected to be more effective due to the hydrophobicity resulted by the carbon-fluorine bonds.

Impedance and leak current results for the present investigation showed good performance for the fluoropolymer coating when the test PCB surface was clean. Under this condition, none of the tested systems failed and impedance values remained close to 10^7–10^8 Ohm throughout the test period. However, presence of flux residues on the surface reduced the impedance level significantly from the beginning of the test to a value of 10^4 Ohm. The impedance values presented in Fig. 4 over the exposure time showed a subsequent increase with time, which might be attributed to the removal (wash out) of the flux residue from the surface during the repeated transient condensing cycles [42]. This is evident in the Residue Rat picture for H_F_LOW before (Fig. 6b.2) and after exposure (Fig. 6d.2), which shows reduction in red color after humidity exposure, indicating removal of flux residue during exposure. Microscopic observations and Residue Rat (Figs. 6, 7 and 8) analysis showed openings in the coating, which allow flux residue to interact freely with condensed water, allowing the possibility for displacement of some residue with time. There are numerous investigations in the literature showing the effect of flux residues on humidity related reliability issues of electronics as well as on conformal coating performance when they are present at the interface between coating and PCB [43–45]. Hygroscopic nature of the flux residue is reported to be one of key factor determining its effect on corrosion under humid conditions [46–48]. Therefore, the type of flux chemistry is important in determining the humidity boundary for failure [49–51]. Optical and SEM analysis of the coated test PCBs (Figs. 6, 7 and 8) after humidity exposure showed signs of corrosion and ECM for the flux contaminated samples, which is in agreement with previous observation regarding the performance of conformal coatings. Particularly, water and solvent based acrylic, epoxy and polyurethane/alkyd coatings offered protection to some extent but loss of coatings' adhesion and blister formation observed and attributed on the corrosion underlying the coatings during extended exposure when the interface between the coatings and substrate was contaminated with flux residues [13,36,52]. These results are in agreement with the current work, which highlighted the cleanliness of the PCBs as an important factor for the performance of fluoropolymer based ultra-thin coating.

Therefore, the lower impedance for PCBs with contamination under fluoropolymer (Fig. 3b and Fig. 3d) was attributed on the water absorption due to the hygroscopic character of the flux [53,54]. Particularly, the presence of contamination lowers the deliquescence point of relative humidity (RH) as reported for various flux systems with different type of weak organic acids as activators [55,56]. As a result, thicker water layer is formed on the coating surface compared to the clean-coated PCB under same cyclic humidity conditions. Additionally, once the water film forms, presence of contamination will increase the conductivity of the TEL, which leads to reduction in impedance and increase in leak current [40].

The thickness of fluoropolymer coating showed some influence on the performance. Fluoropolymer with lower thickness was unable to cover completely the SIR pattern, therefore showed less uniformity (Fig. 7) on the clean SIR PCB. However, for the samples with flux residue, both low and high thickness showed similar levels of defects (Fig. 8), although the SEM pictures in Fig. 7 showed more smooth morphology for the higher thickness. The inability of lower thickness fluoropolymer to shield the SIR was also evident in relation with the flux release during testing (Fig. 7a.1). Particularly, the openings allowed the flux to wash out (Fig. 7b.1) compared with higher thickness. The latter one did not show these defects before exposure (Fig. 7c.1) and any visible flux crystals in the case of contaminated boards (Fig. 7d.1).

Orientation of the test PCB during testing did not significantly influence the performance of the fluoropolymer coating. When the PCB was placed in horizontal orientation, condensed water can be collected, while the vertical orientation caused removal of water due to gravity. For fluoropolymer, this effect was expected to be higher due to the hydrophobic nature of the coating. However, the results from the present investigation did not show this difference, which might be due to the non-coverage of the coating, which resulted in hydrophobic interaction of water molecules. This is especially true for flux contaminated surface as the hygroscopic nature of the residue can retain water irrespective of whether the PCB is oriented horizontal or vertical [57]. Even if fluoropolymer is a hydrophobic material, the pores through which the flux passed on the surface became hydrophilic and as a result, humidity was absorbed due to the hydroscopic character of the flux [58,59].

5. Conclusion

- EIS showed stable impedance values in the range of 10^7–10^8 Ohm for fluoropolymer on clean PCBs, while the ones with contaminated presented 3 to 4 magnitudes lower values at the beginning of the experiment attributed on the hygroscopic character of the flux residues. The contaminated PCBs showed a 2-fold increase of impedance at the end of the test due to the flux wash out phenomenon during exposure.
- Leak current measurement with DC bias showed poor performance of fluoropolymer coating for contaminated PCBs exhibiting 3-fold higher values compared to the clean test boards, which showed current below 10^{-4} mA. The occurrence of corrosion for contaminated boards was indicated by increasing values over time, sudden drops and spikes in the leak current.
- Thickness of the Fluoropolymer coating did not alter the coating defect in the case of contaminated boards, and coating was unable to cover the contaminated area. In contrast, clean PCBs with higher thickness of fluoropolymer showed smooth morphology of the surface before and after exposure.
- Horizontal or vertical orientation of the PCBs did not influence the performance of fluoropolymer. Even if the coating is considered hydrophobic, the inability to cover the surface or exposure of the flux residue through the pores of the coating resulted in interaction of water molecules.
- Residue Rat analysis revealed large amounts of flux residues on the surface of fluoropolymer with lower thickness compared to the ones with higher, validating the no full coverage of the substrate, together with washing out of the contamination as the observed coloration was more intense before exposure.

CRediT authorship contribution statement

Ioannis Mantis: Visualization, Writing – original draft, Writing – review editing, Formal analysis, Investigation, Validation. **Feng Li:** Resources, Investigation. **Morten Jellesen:** Conceptualization, Methodology, Project administration, Supervision. **Rajan Ambat:** Conceptualization, Methodology, Funding acquisition, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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