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Residue-assisted water layer build-up under transient climatic conditions and failure occurrence in electronics

Kamila Piotrowska and Rajan Ambat

***Abstract*—Electronic devices are exposed to a variety of climatic conditions worldwide. The day/night temperature fluctuations between the device interior and external conditions can lead to the formation of transient conditions within the enclosure that enhance the possibility of water layer build-up on the surface of Printed Circuit Board Assembly (PCBA). This paper deals with the parametric investigation of the effects assisting the formation of water film on PCBA surfaces under transient climatic conditions, which alters the functionality of electronic devices. Investigated parameters include the external humidity level, PCBA cleanliness, temperature difference between ambient and the PCBA, and the rate of temperature/humidity change. The effect of residues commonly associated with the soldering operations – weak organic acids – on the water film formation was investigated at 25˚C/80%RH under isothermal and non-isothermal conditions. For non-isothermal conditions, the PCBA temperature was reduced to the level slightly above and below the dew point. The impact of external climate on wetting time of the contaminated PCBA was demonstrated by its exposure to day/night cyclic conditions and the overall effect on corrosion reliability of the electronic circuit was assessed. A combination of AC impedance and DC leakage current techniques was employed to determine the electrochemical changes of the PCBA surface resulting from the build-up of a conductive water film. The results show that the presence of hygroscopic flux residues increases the water vapour content above the surface leading to moisture condensation under potentially non-condensing conditions, and results in the corrosion reliability issues.**

***Index Terms*—condensation, electronic enclosure, dew point, humidity, quality, reliability of electronics, temperature**

I. INTRODUCTION

PRESENT development of electronic devices is trending towards high-density packing, component and device miniaturization, and finer pitch distances. These requirements aim to obtain the reduced weight and size of the product body, increase the thermal dissipation, lower the cost of manufacturing process, and achieve a flexible device from the design point of view [1]. However, the miniaturization tendencies may create adverse results in connection with electronics exposure to harsh climatic conditions, and together with printed circuit board assembly (PCBA) cleanliness issues and other factors enhancing the possibility for water film build-up [2][3]. Under humid conditions, potential bias, and in the presence of ionic contamination, the formation of water layer on a PCBA surface is likely to occur and lead to moisture-induced intermittent or permanent failures [4]-[8].

Electronic devices operate in a variety of geographical locations worldwide due to the use in a broad range of applications. During the day/night cycle, the electronics is exposed to changes in temperature and humidity conditions [9][10]. The critical moment for the creation of transient conditions within the enclosure occurs while the climate outside the device, especially the temperature, changes [2][11]. If the temperature of a surrounding air rapidly rises (e.g. in the morning time), the internal and PCBA surface temperatures may lag behind in reaching equilibration conditions depending on the thermal capacity of the interior parts and enclosure tightness. Due to the thermal lag, the internal conditions of the enclosure will be different from the outside conditions until the equilibrium is reached [12]. If the humidity retained inside the enclosure is high enough, depending on the temperature conditions, dewing can occur on the PCBA [13]. The dew point (DP) depends on the temperature and relative humidity (RH) levels. At high external temperature and RH conditions, the DP is high and a slight difference between the ambient and PCBA temperatures may lead to condensation. The range of temperature difference between the inside and outside of the

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device determines the thickness of the dewed water film, e.g. larger difference and longer exposure result in thicker water film. Water layer formation on the PCBA surface is also determined by the rate of temperature and humidity change depending on the climatic conditions at the geographical locations. Due to the temperature and humidity cycling process, an increased risk of the corrosion occurrence within the electronic assembly was reported [11][14]-[17] as often the transient conditions forming within the enclosure lead to the formation of thick water layer on the electronic surfaces.

The problem of water film build-up on the PCBA surface becomes more critical if other accelerating factors are present, e.g. the presence of ionic residues originating from the manufacturing process or application sites [10][18]-[25]. Moreover, the electronic enclosures often contain a number of openings for electrical connectors or drainage [10], therefore provide a path for humidity and dust ingress, which creates a risk of moisture condensation on the electronic surfaces. The risk will be increased further if the PCBA contains a heat sink, which acts as a thermal mass leading to a delay in temperature equilibration under transient conditions. The altered PCBA cleanliness, due to the presence of the contamination associated with the soldering process (WOAs – weak organic acids from no-clean flux systems) or the particulate contamination originating from the user environment [19][26]-[33], was reported to greatly accelerate the condensation and corrosion risks. Ionic residues, due to their highly hygroscopic nature [2][19] and high moisture sorption properties, facilitate the formation of an electrolyte layer even at low humidity levels. The extent of residue-assisted water film formation is determined by the chemical nature of surface contaminants [11][34] and the contamination level. Highly hygroscopic residues deliquesce at lower critical RH levels and are more water-soluble, compared to the less hygroscopic contaminants [24]. The transient climatic conditions created within the device in combination with the contaminated PCBA surface and conductive traces operating at different voltages cause an extremely high risk for the electrochemical (ECM) migration occurrence [34]-[40] and the risk of device failures [31][36][41]. Other factors influencing the formation of water film on a PCBA surface include e.g. surface finish and surface roughness, material porosities, or the component spacing [42]-[46].

This paper reports a parametric study of various factors influencing the build-up of water layer on a PCBA surface and the resulting operational performance of electronics upon the PCBA temperature reduction. The effect of various parameters was studied individually and synergistically in order to determine the contribution of these factors to an increased risk of a substantial water layer build-up. The parameters studied were the ambient humidity level, PCBA cleanliness/quality (residue effects), temperature difference between ambient and PCBA, and the rate of temperature/humidity change. Effect of the rate of surface cooling on the water film formation and its electrical property was studied on clean surfaces at various external RH levels (80%RH, 90%RH, and 95%RH) simulating the geographical variation in the rate of external temperature change. The water layer build-up on the surfaces was monitored using the AC electrochemical impedance measurements and was correlated to the gravimetric measurement of water amount. The impact of hygroscopic residues on the water film formation was studied under isothermal and non-isothermal conditions for the PCBA temperature reduction close to and below the DP. Under condensing conditions (below the DP), the AC parameters were collected for various cooling rates and residue types. The effect of ionic residues under potentially non-condensing conditions (above the DP) was assessed using the AC impedance and DC leakage current testing for various acidic activator types and reduced PCBA temperatures. The DC testing was directly related to the surface insulation resistance, and the resulting leakage current levels represented the magnitude of WOA effects. Further, the interaction between varying external conditions and the ionic contamination was assessed under the real climatic profile where the risk of occurrence of transient conditions is high.

II. MATERIALS AND METHODS

A. *Test boards*

The AC and DC electrochemical measurements under water film formation conditions were performed across the interdigitated surface insulation resistance (SIR) coupons (Fig. 1 (a)) with the Pb-free HASL (hot air solder leveling) surface finish using Sn100C solder alloy. The area between the conductor lines was bare FR4 laminate. The dimensions of the pattern were 13 mm x 25 mm and therefore the active surface area was 325 mm^2. The distance between the electrodes was 0.3 mm.

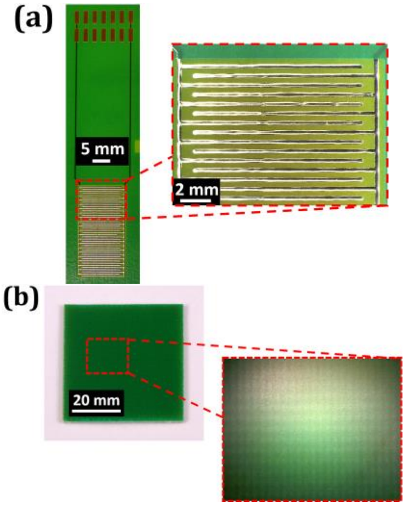

Fig. 1. The overall view on the test boards: (a) surface insulation resistance test coupon, (b) FR-4 laminate board coated with solder mask.

The thickness measurements of water layer build-up on the clean surface and the observations of changes in WOAs' morphology upon the reduction of PCB temperature at humid conditions were performed on the clean FR-4 glass-reinforced laminate substrates coated with a ~20 µm layer of solder mask (Fig. 1 (b)). The dimensions of the base material were 50 mm x 50 mm resulting in the total surface area of 2500 mm^2.

The chemistry of both FR4 and solder mask materials is different and so is their roughness level. The use of solder masked FR4 for visual testing was purely practical – it is easier to monitor the residue morphology changes through the optical microscope on the solder mask. Based on many experiments conducted prior to this, the use of different surface finishes did not cause the difference in the visual observations and electrical testing results.

Prior to each measurement, all boards were thoroughly cleaned by rinsing with deionized water, followed by cleaning with isopropyl alcohol (analytical purity of 99.8%) and drying with pressurized air. The procedure was repeated three times in order to obtain a perfectly clean surface.

B. *Ionic contaminants*

The effect of PCBA cleanliness on the water film formation and reliability were studied using the weak organic activators commonly found in the wave solder flux formulations. The contaminants were chosen based on the differences in their hygroscopic properties [24][25]: adipic acid, succinic acid, and glutaric acid. The acids were supplied by Sigma Aldrich as pure crystals of analytical grade. Required amounts of pure WOAs were dissolved in isopropyl alcohol (analytical purity of 99.8%) in order to obtain their 2.5% wt/v solutions, similar to the level of activators found in the commercial wave solder flux systems.

C. *Climatic chamber*

The experiments were carried out in the controlled environment in the climatic chamber Espec PL-3KPH. The fluctuations in the temperature and humidity levels were stated to be within the range of ±0.3°C/±2.5%RH for the conditions studied in this paper. The airflow was ~1.5 m/s.

D. *Peltier cooling stage*

The simulation of the temperature differences between the ambient air and surface of the test PCBA was carried out using a cooling Peltier stage (model CP-031, TE Technology Inc.), which comprised of a Peltier element embedded in the aluminium block. The stage was powered using a voltage supply and was connected to the TC-720 OEM (TE Technology Inc.) control unit that was further connected via USB to the computer. The test samples were pasted to the Peltier stage using a heat-transfer paste. The temperature of the test samples was monitored and controlled using the MP-3193 thermistor (TE Technology Inc.) pasted to the sample. The thermistor was connected to the TC-720 OEM control unit, which allowed for the creation of a temperature control loop between the Peltier and test samples using commercial computer software. The heat generated by the working Peltier stage was dissipated by the air flow induced by the fan attached to the cooling unit at the bottom. The fan was powered up by a separate power supply.

E. *Electrical/electrochemical measurements*

The AC electrochemical impedance and DC leakage current measurements were performed using a “BioLogic VSP” multichannel potentiostat. The impedance technique was employed in order to monitor the water film build-up on the clean and contaminated SIR surfaces under various transient conditions. The leakage current measurements were conducted in order to assess the potential for corrosion occurrence on a PCBA surface. The effect of contamination was studied on the SIR test coupons deliberately pre-contaminated with the solutions of WOAs using an automatic pipette, and the resulting residue level after solvent evaporation was ~100 $\mu g/cm^2$. The contaminated samples were stored in the desiccator box for 24h at low RH (<15% RH) prior to the exposure to desired test conditions. All electrical/electrochemical measurements were performed in the Espec climatic chamber.

The AC signal amplitude of 25 mV (Vrms = 17.68 mV) at a frequency of 10 kHz was applied. This frequency regime is governed by the capacitive character of the dry SIR electrode pattern at the humidity levels not exceeding the critical RH for deliquescence of the contamination present on the PCBA surface [32]. With an increase of RH level and the reduction of PCBA temperature, the residue deliquescence takes place, and the water layer thickness and electrolyte conductivity increase. Similarly, the water film build-up on a clean surface, for which the temperature was reduced below the DP, results in the formation of thick water layer due to the condensation. As a result, the measured impedance output decreases and a resistive character of water layer forming in between the conductors dominates. A drop of impedance to ~5-10 kΩ and the increase of phase angle towards ~-5˚ at the studied frequency indicated the residue dissolution into the water layer and the formation of a conductive electrolyte resembling a “bulk water behaviour”.

The leakage current measurements were performed under 5 V DC potential bias. This testing allowed for the assessment of potentially corrosive effects of the contamination dissolving into the water layer. Due to the fact that the PCBA temperature reduction below the DP results in the condensation and certain corrosion occurrence, the DC technique was used only to track the residue effects upon the PCBA temperature reduction above the DP and at RH level not exceeding the deliquescence point (where the risk of corrosion occurrence potentially does not exist). The output measured during the DC testing was the surface insulation resistance, and the resulting leakage current directly reflected the interaction of residues with the water vapour. An abrupt increase of current above µA level indicates that the formation of water layer, facilitated by the residues, resulted in the occurrence of corrosion such as electrochemical migration.

F. *Water layer thickness measurements*

The measurements of water film thickness were performed on a clean laminate material (Fig. 1 (b)) using a gravimetric method. Moisture condensation on the clean PCB surfaces upon their temperature reduction below the DP resulted in the formation of water film, which, at the end of each test, was carefully collected using a fast-absorbing filter paper. Subsequently, the weight of a wet paper was measured and from the weight gain the averaged thickness of the water film was calculated. Each experiment was repeated 3-5 times in order to obtain good statistics. The measurement carried a risk that the water layer formed upon the condensation may not be fully

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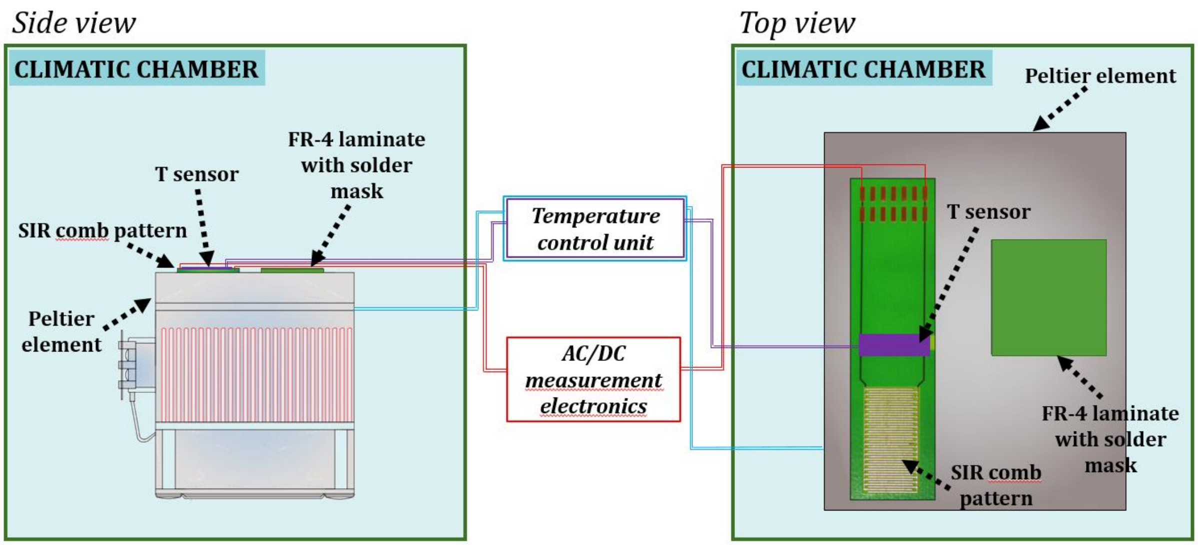

Fig. 2. 2D schematics of a test setup used for water film formation testing.

collected from the surface due to the technique employed. However, a control experiment where the laminate is dipped into water followed by removing the water using a filter paper and repeated weighing showed that the error due to remaining water on the surface is about 5-10%.

G. *Water film formation on the clean PCBA surface*

The studies of water film formation characteristics on the clean PCBA surface were performed under non-isothermal conditions with the PCBA temperature reduction below the dew point in order to provoke the build-up of water layer. The effects of ambient humidity level and the PCBA cooling rates were studied.

The test setup used for the investigations of the water film formation on the PCBA surface is shown in Fig. 2. The SIR pattern and FR-4 laminate were pasted to the Peltier cooling element and the setup was placed in the Espec climatic chamber. The water film formation was evaluated electrically (SIR board) and quantified using a gravimetric method (solder masked FR-4 laminate board).

The SIR and FR-4 laminate specimens were subjected for water layer build-up at 25˚C and various RH levels (Fig. 3 (a)), namely 80%RH, 90%RH, and 95%RH. The DP at each test condition was calculated according to the formula given in [47]: 21.3˚C (at 80%RH), 23.2˚C (at 90%RH), and 24.1˚C (at 95%RH). Prior to the measurements, the samples were kept in the climatic chamber at 25˚C/30%RH for 30 min, then the humidity was raised from 30%RH to the desired humidity level (80%RH, 90%RH, or 95%RH) within 1h at constant temperature, and maintained thereafter. The PCBA and chamber conditions were monitored throughout the process using a set of temperature and RH sensors.

In order to provoke condensation on the clean surfaces, after reaching a steady humidity level in the PCBA surroundings, the PCBA temperatures were reduced from 25˚C to the set temperatures below the DP (Fig. 3 (b)), accordingly to the ambient RH level. The time of cooling was set to 12 minutes, which implied that different PCBA set temperatures constitute individual cooling rates. The water vapour density on the PCBA surface and the resulting water layer formation were therefore the effect of ambient RH level and the cooling rate. Throughout

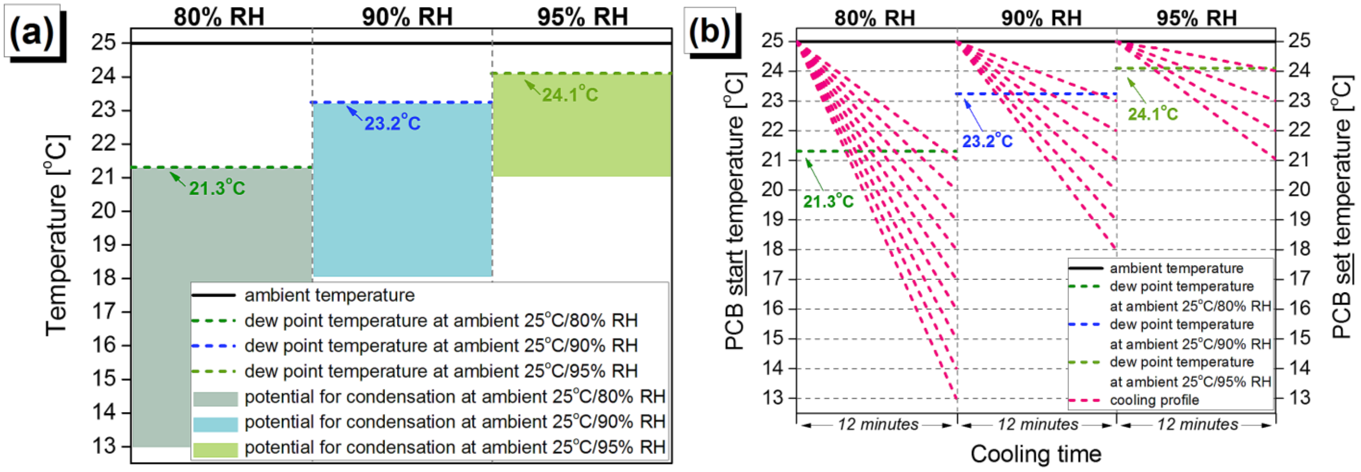

Fig. 3. (a) conditions for investigations of the water film formation on a clean PCBA surface, (b) cooling profiles for various test conditions.

the cooling period, the impedance and phase angle outputs were monitored, and each experiment required the use of new SIR pattern. At the end of each test, the water film formed upon moisture condensation on the laminate surface was carefully collected with the filter paper and weighted in order to evaluate the average water layer thickness, which was then correlated with the AC data.

The observations of SIR pattern appearance during the condensation were conducted *in-situ* using AD7013MZT Dino-Lite digital microscope.

H. *Water film formation on the contaminated PCBA surface*

The presence of residues on a PCBA surface changes its properties when interacting with water vapour under humid conditions. In our study, the effect of altered PCBA cleanliness on the water layer build-up was studied only at 25˚C/80%RH (contrary to the studies performed on the clean PCBA) due to the fact that at these climatic conditions no corrosion induced by either of the tested ionic contaminants can be expected to occur unless transient condensing conditions develop [24].

The residue effects were studied under: (i) isothermal conditions, (ii) non-isothermal conditions with the PCBA temperature reduction above the DP, (iii) non-isothermal conditions with the PCBA temperature reduction below the DP, and (iv) transient climatic conditions of a geographical location.

The test setup used for the investigations of the residue-assisted water film formation on the PCBA surface is shown in Fig. 2. The formation of water film was investigated electrically (SIR board), whereas the morphology of the residue subjected to isothermal and non-isothermal conditions was visualized on the FR-4 laminate. Additionally, the appearance of SIR pattern during the moisture condensation on a contaminated surface were conducted *in-situ* using AD7013MZT Dino-Lite digital microscope.

1) *Isothermal conditions*

Firstly, the residue interaction with water vapour was assessed at constant 25˚C/80%RH ambient conditions and PCBA surface temperature equal to 25˚C. Both AC and DC data were recorded separately for the contaminated SIR specimens. The electrical properties of the SIR samples were then monitored for the total of ~20h.

The interaction between ionic contaminant and water vapour may result in moisture adsorption to its surface or deliquescence, depending on the residue type and ambient humidity level. As a result, the morphology of residues remaining on the PCBA surface changes due to e.g. dissolution into the water layer and subsequent crystallization. Under isothermal conditions, the morphology changes of the residues were investigated on the FR-4 laminates coated with solder mask (Fig. 2). The solutions of activators were applied on the PCB material using an automatic pipette, which resulted in a residue level of ~40 µg/mm^2. The temperature sensor was pasted onto the FR-4 substrate next to the contamination area, which allowed for the temperature control of the PCB in order to maintain constant at 25˚C. Subsequently, the pre-contaminated samples were placed in the Espec climatic chamber and after the ~20h exposure, the FR-4 samples were stored in the desiccator box for 72-168h at low RH (<15% RH). Pictures of the residue before and after the test were taken with the use of Alicona InfiniteFocus.

2) *Non-isothermal conditions (reduction of PCBA temperature above the DP)*

The effect of process-related residues on the water layer build-up was then evaluated under non-isothermal conditions with the PCBA temperature reduction above the DP, which implied that any potential condensation occurrence is a result of ionic nature of the contamination. The testing was performed at constant 25˚C/80%RH chamber conditions, which settled the DP temperature at 21.3˚C.

The samples were kept in the climatic chamber where the conditions were set at 25˚C/80%RH as described before, and with the constant PCBA temperature of 25˚C. After the stabilization of chamber conditions, the PCBA temperatures were decreased from 25˚C, while remaining in the non-condensing region above the DP (Fig. 4).

The PCBA set temperatures were reached by a decrease from ambient 25˚C to the final 24.5˚C, 24˚C, 23.5˚C, 23˚C, 22.5˚C,

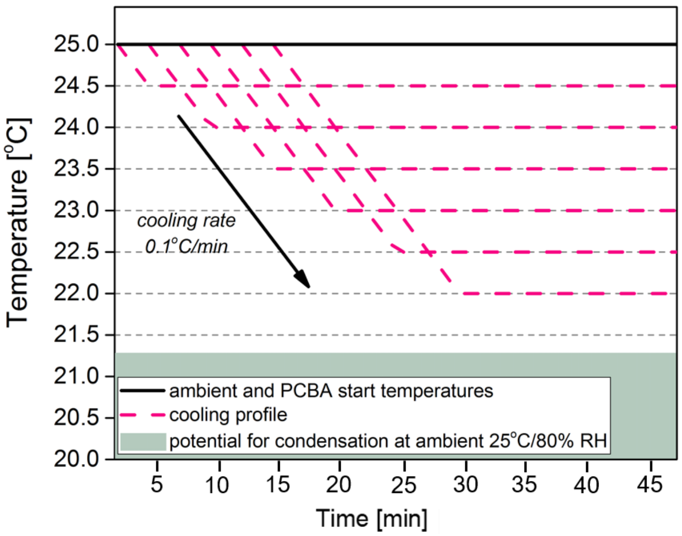

Fig. 4. Cooling profiles used for testing under non-isothermal conditions with the PCBA temperature reduction above the DP.

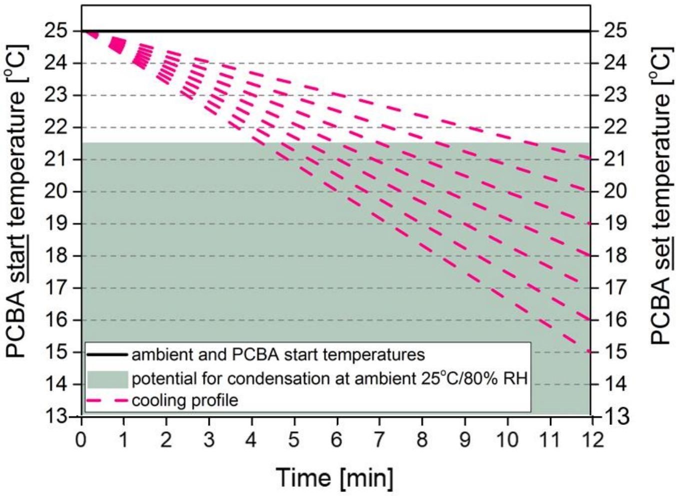

Fig. 5. Cooling profiles used for testing under non-isothermal conditions with the PCBA temperature reduction below DP.

and 22˚C, with the cooling rate of 0.1˚C/min (Fig. 4). After the set temperatures were reached, they were maintained for 3-7 days, and the deviation of ±0.01-0.03˚C from the final set temperatures was recorded throughout this time period for all the experiments. During the cooling step and thereafter, the impedance, phase angle, and leakage current signals were monitored. Each set of PCBA temperature testing comprised of a separate experiment and required the use of new SIR pattern. Both AC and DC measurements were performed using the above procedure, but on separate SIR substrates.

The visualization of residue morphology changes upon the interaction with water vapour was carried out on the FR-4 laminates (Fig. 2) using a procedure described for the isothermal testing. The desired PCB set temperatures were reached according to the profiles shown in Fig. 4.

3) *Non-isothermal conditions (reduction of PCBA temperature below the DP)*

The effect of residues presence on the water film build-up was further studied under non-isothermal conditions with the PCBA temperature reduction below the DP (21.3˚C), which implied that the extent of water layer formation was a result of both ionic contamination presence (enhanced absorption of moisture to the surface) and the condensation.

The samples were kept in the climatic chamber where the conditions settled at 25˚C/80%RH as described previously, and with the constant PCBA temperature of 25˚C. Subsequently, the PCBA temperatures were decreased from 25˚C to the final temperatures (Fig. 5 (a)) within 12 minutes (Fig. 5 (b)). The time of cooling was set to 12 minutes in order to exclude the time factor from the observations. The constant cooling time implied different temperature reduction rates depending on the final PCBA temperature. The water vapour density above the PCBA surface and the resulting water layer formation were therefore a function of the residue type and the cooling rate. Throughout the cooling period, the impedance and phase angle were monitored. Each PCBA set temperature testing comprised of a separate experiment and required the use of new SIR pattern.

The *in-situ* observation of the SIR pattern appearance during the reduction of PCBA surface temperature below the DP was carried out with the use of AD7013MZT Dino-Lite digital microscope.

4) *Transient climatic conditions in a geographical location*

The effect of WOA residues on the water layer build-up under transient climatic conditions was further investigated under varying temperature and humidity conditions for the PCBA placed inside a model electronic enclosure. The enclosure used for investigations was made of aluminium with dimensions of 260 mm x 160 mm x 90 mm. The IP rating [48] for this enclosure type is 66 which indicates a “dust tight” casing capable to withstand water projected from powerful jets for a given amount of time. The through-holes of 1 or 3 mm diameter size were drilled in the casing material (one side) in order to simulate a leakage path for humidity due to the opening (usually arising from cable feedthrough, sealing imperfections, or drain hole presence). On the opposite side of the drilled through-hole, an opening for the cables was provided and the

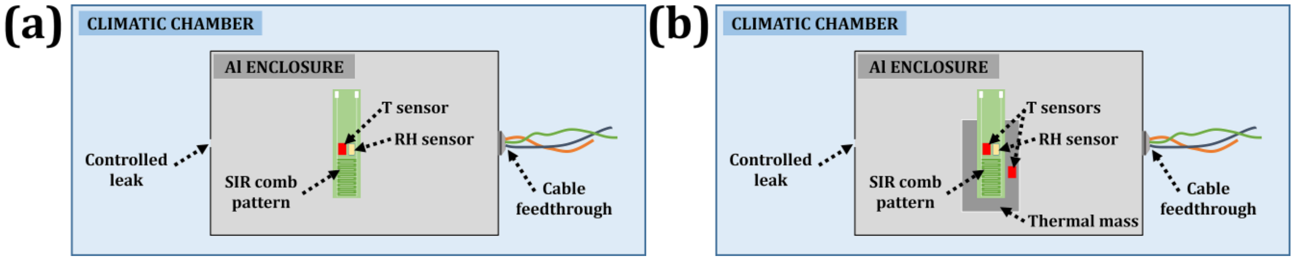

Fig. 6. Top view of 2D schematics of the PCBA/enclosure configurations used for testing of the water layer build-up on the PCBA surfaces under transient climatic conditions: (a) PCBA in Al enclosure, (b) PCBA on thermal mass in Al enclosure.

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gasket for cable sealing. The overall geometry of the casings is shown in Fig. 6.

The calibrated sensors Pt1000 (temperature) and HIH4021 (humidity) were placed inside the aluminium enclosures, attached to the PCBA surfaces and aluminium thermal mass (Fig. 6 (b)), and connected to a data logging system (model 2700 Multimeter, Keithley Instruments). The thermal mass was introduced for the investigations in order to simulate the behaviour of actual PCBA containing large thermal components attached to it (e.g. heat sink) that delay the PCBA temperature equilibration with the external conditions. An additional set of sensors was used to monitor the humidity and temperature conditions inside the enclosures.

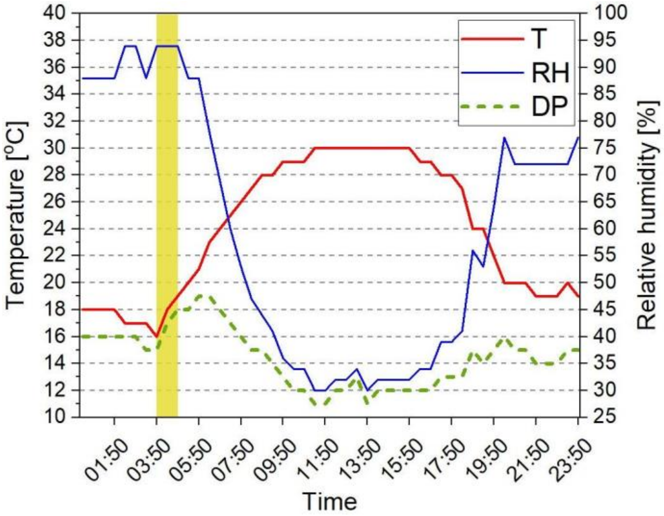

Fig. 7. Climatic profile in Copenhagen, Denmark (July 28, 2008). Data of ambient temperature (T), relative humidity (RH), and dew point (DP). The period of transient conditions with high risk of condensation is highlighted in yellow.

The contaminated SIR patterns were placed at the center of the enclosure and attached to the thermal mass of a defined 40m^3 volume. The enclosures containing test SIR specimens were sealed and subsequently placed in the Espec climatic chamber in which the day climate of Copenhagen (Denmark) was simulated as an example of a geographical location. According to the hourly data generated in global humidity index [49], the 24h climate measured on 28.07.2008 was used for the housing exposure (Fig. 7).

The chosen climatic conditions represent the critical T and RH changes in the morning time (~03:50-04:50, highlighted in pink) that commonly pose a threat for the PCBA reliability when the outside temperature rapidly increases and the DP temperature is only 1˚C lower than the ambient. If the temperature of the device placed in a humid area lags behind an outdoor climate due to the casing barrier and presence of thermal mass, the risk of condensation can occur. Throughout the 24h exposure, the impedance and phase angle data were collected for different ionic contaminants present on the SIR surfaces.

III. RESULTS

A. *Isothermal conditions*

The results from electrochemical testing of the residue effect

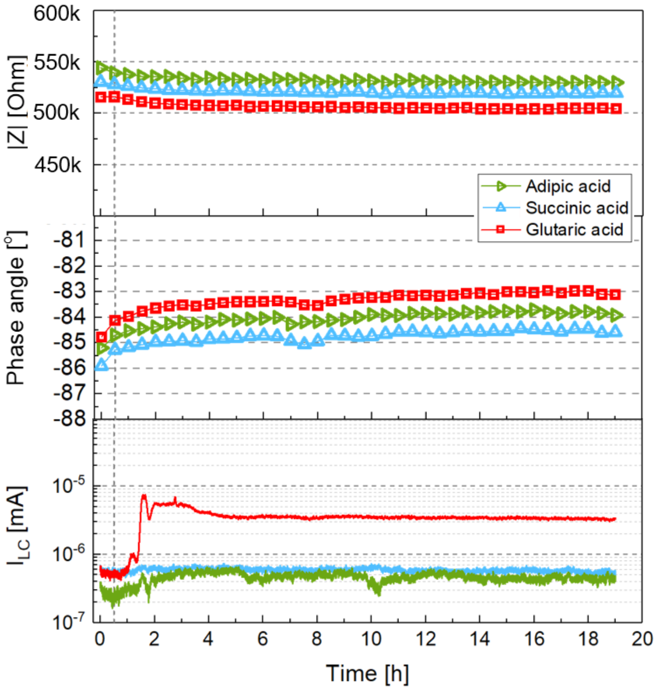

Fig. 8. Impedance, phase angle, and leakage current data obtained under isothermal (non-condensing conditions) at ambient 25˚C/80%RH for SIR-patterns pre-contaminated with 100 μg/cm^2 of WOAs: adipic acid, succinic acid, and glutaric acid. The grey dashed line indicates the transition from initial 30%RH to the final 80%RH.

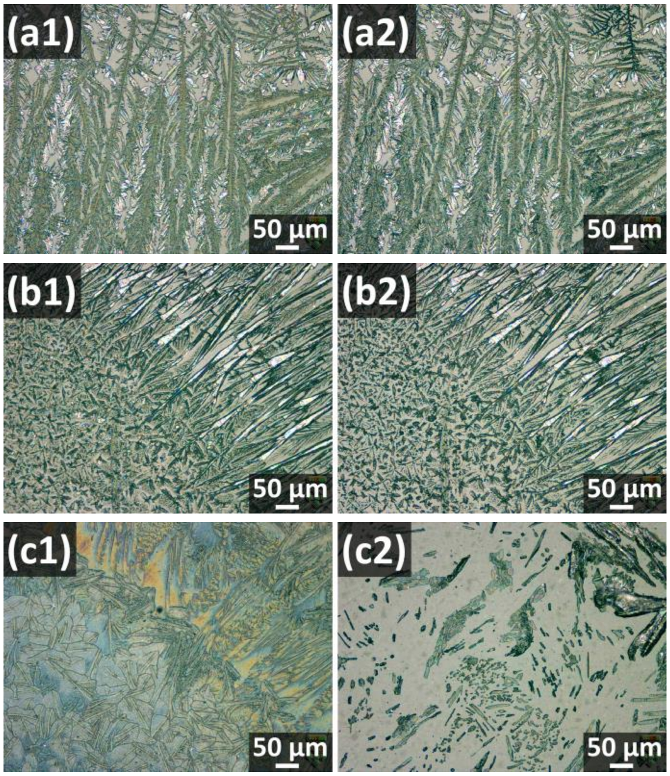

Fig. 9. The overview on WOAs' morphology (1) before and (2) after the residue exposure to 25˚C/80%RH: (a) adipic acid, (b) succinic acid, (c) glutaric acid.

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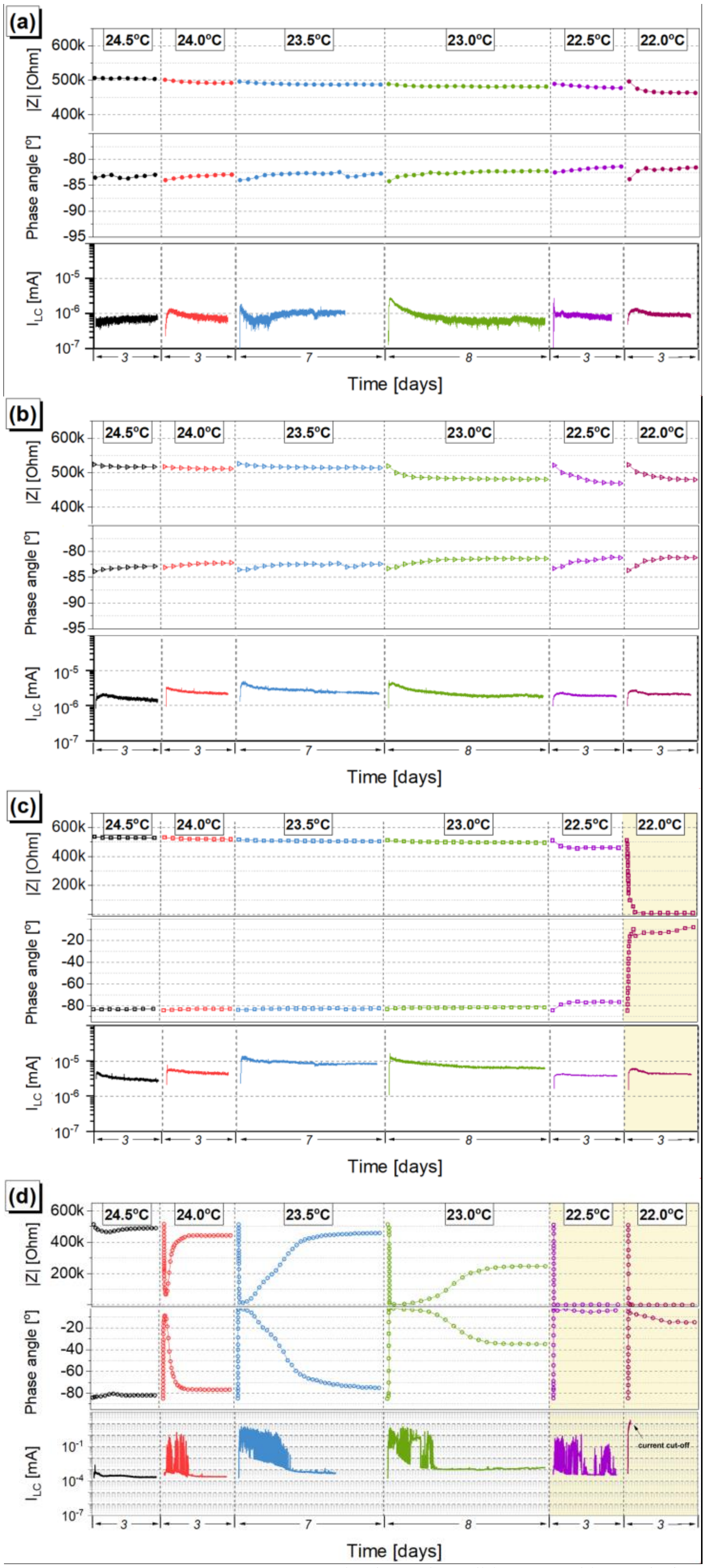

Fig. 10. Impedance, phase angle, and leakage current data obtained under non-isothermal conditions at ambient 25˚C/80%RH and PCBA temperature reduction above the DP for clean SIR pattern (a), and SIR-patterns pre-contaminated with 100 μg/cm^2 of WOAs: (b) adipic acid, (c) succinic acid, (d) glutaric acid. The final PCBA temperatures after cooling are indicated, and the “bulk-water behaviour” for the SIR patterns indicated by the AC results is highlighted in yellow.

on the water film formation performed under isothermal conditions at 25˚C/80%RH (without PCBA temperature reduction) are presented in Fig. 8. A slight decrease of impedance values and increase of phase angle values were recorded for all the investigated contamination types throughout the measurement. The leak current values for the succinic and adipic acid contaminated patterns remained below nA level, and slightly higher current level (1-10 nA) was

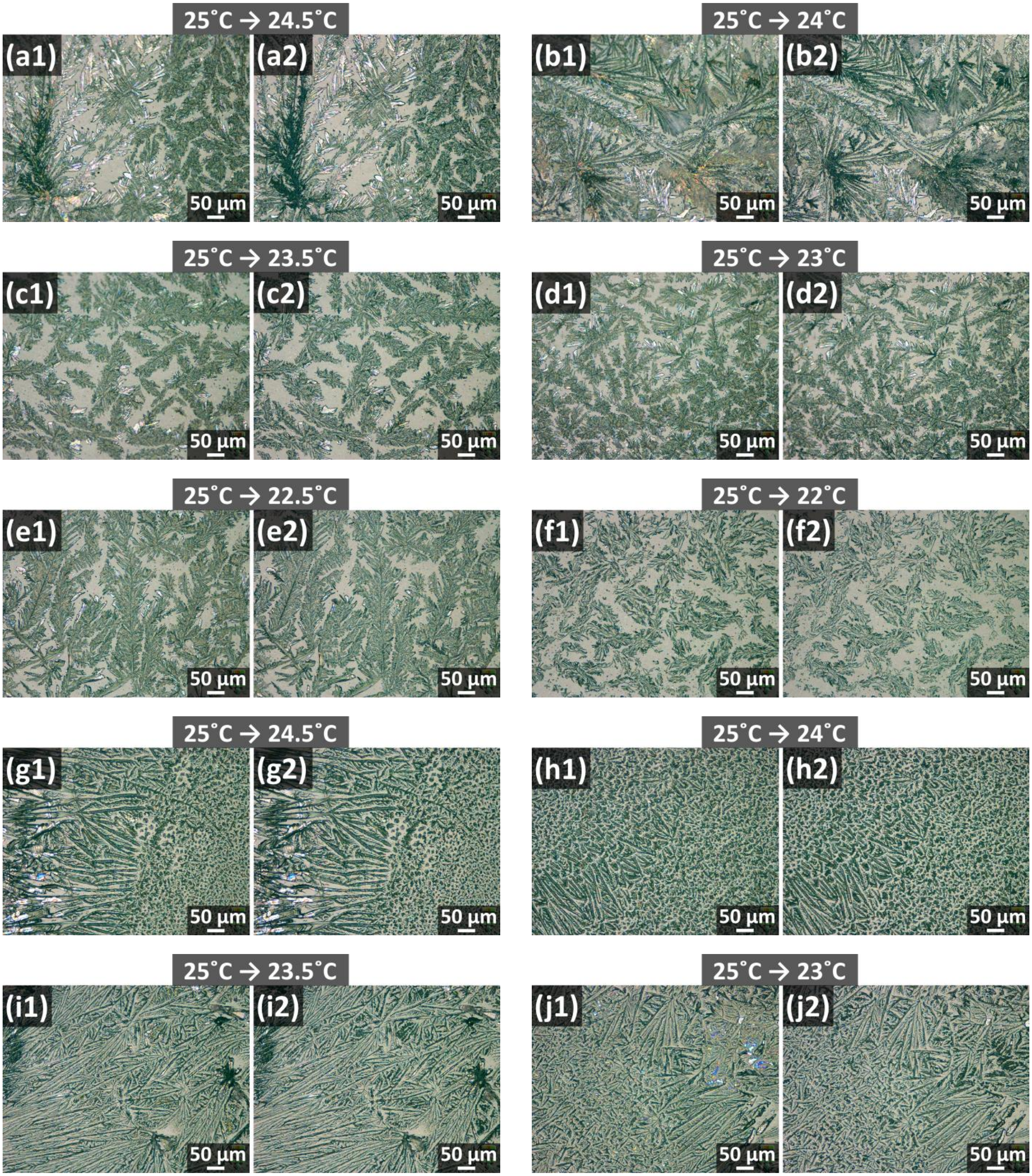

Fig. 11. The overview on WOAs' morphology (1) before and (2) after temperature decrease from 25˚C to temperatures above DP: (a)-(f) adipic acid, (g)-(l) succinic acid, (m)-(r) glutaric acid. The final PCB temperatures after cooling are indicated.

observed for the SIR pattern containing glutaric acid. However, no corrosion (under DC conditions) or significant decrease of impedance signal (under AC conditions) were observed when the ambient humidity level remained at 80%.

Changes in WOAs morphology associated with the interaction between the residue and humidity are shown in Fig. 9 as representative optical micrographs taken before and after the exposure of the contaminated laminate surfaces to

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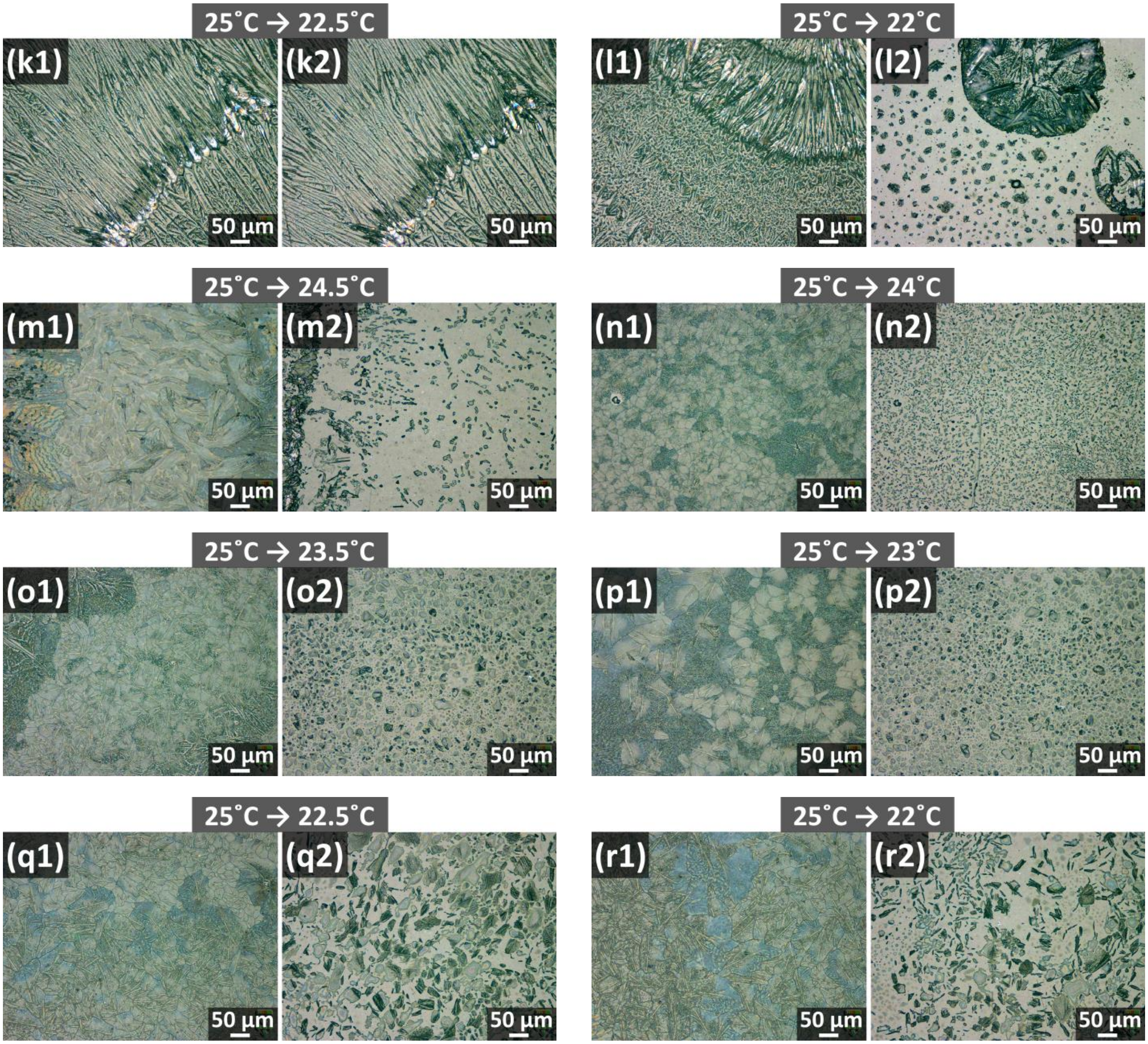

Fig. 11. (cont.) The overview on WOAs' morphology (1) before and (2) after temperature decrease from 25˚C to temperatures above DP: (a)-(f) adipic acid, (g)-(l) succinic acid, (m)-(r) glutaric acid. The final PCB temperatures after cooling are indicated.

25˚C/80%RH. Among the tested contamination types, the changes in residue appearance occurred only in the case of glutaric acid (Fig. 9 (c)).

B. *Non-isothermal conditions (reduction of PCBA temperature above the DP)*

The results of AC and DC testing performed at ambient 25˚C/80%RH for the contaminated SIR samples for which the temperatures were gradually reduced from 25˚C to the set temperatures above the DP (non-condensing region) are shown in Fig. 10. For a reference, the data recorded for a clean SIR pattern is shown in Fig. 10 (a).

1) *Clean PCBA surface*

No significant changes in the impedance, phase angle, and leak current data were observed for the clean SIR patterns at the PCBA temperature range 24.5˚C-22˚C (Fig. 10 (a)). The impedance decreased and phase angle values progressively increased for the conditions where the larger temperature difference occurred between PCBA and ambient temperature, however, the changes were not significant.

2) *Contaminated PCBA surface*

No significant changes in the impedance, phase angle, and leak current data were observed for the adipic acid contaminated SIR patterns at the PCBA temperature range 24.5˚C-22˚C (Fig. 10 (b)). The leakage current recorded for adipic acid containing system was slightly higher compared to

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the clean SIR surface, however it remained at the nA level. The effect of succinic acid (Fig. 10 (c)) tested under the AC conditions showed a similar trend as in the case of clean SIR and adipic acid containing system. However, the impedance reached low values upon the PCBA temperature reduction to 22˚C, which indicated the advanced water layer formation and "bulk water behaviour". The leakage current measured for succinic acid at the surface temperature of 22˚C did not show signs of ECM.

On the contrary, the results for glutaric acid testing (Fig. 10 (d)) showed significant changes in the AC and DC signals occurring for every PCBA surface temperature tested, indicating the dissolution of the acid into the formed water film. The decrease in impedance values and increase in phase angle were more pronounced and lasted for a longer period of time in cases where larger temperature differences between the PCBA surface and ambient air occurred. The DC signal followed the trend of AC output, increasing initially to the mA levels sufficient for the occurrence of ECM. After a certain time interval, the impedance, phase angle, and leak current values returned to the original values for the PCBA temperatures 24.5˚C-23˚C. At the PCBA temperatures below 23˚C, the "bulk water behaviour" occurred, which was evident from the very low impedance and high phase angle values maintained throughout the time of testing.

The changes in WOA morphology induced by the PCB temperature reduction above the DP are shown in the Fig. 11. No significant changes in the residue appearance occurred for adipic acid within the test temperature range (24.5˚C-22˚C) (Fig. 11 (a)-(f)). Succinic acid did not undergo a noticeable change in appearance within the temperature range of 24.5˚C-22.5˚C (Fig. 11 (g)-(k)), however the residue was dissolution into the water film at 22˚C (Fig. 11 (l)) and subsequent recrystallization showed different morphology. On the contrary, for the glutaric acid, every PCB temperature decrease has caused morphology changes (Fig. 11 (m)-(r)), and the recrystallized islands of residue were of a small size and densely concentrated.

C. *Non-isothermal conditions (reduction of PCBA temperature below the DP)*

1) *Clean PCBA surface*

The results of AC testing of the water film formation associated with a clean PCBA surface under non-isothermal conditions and PCBA temperature reduction below the DP (21.3˚C) are presented in Fig. 12. The time of cooling was kept constant, while the factors such as the cooling rate and ambient humidity levels were investigated during testing. The final impedance (Fig. 12 (a)) and phase angle (Fig. 12 (b)) values obtained at the end of the 12 minute cooling experiments were plotted against the averaged water film thicknesses obtained via the gravimetric measurement of water loading on the FR-4 laminate for the respective cooling experiments. The impedance and phase angle values for dry clean surfaces at all ambient humidity levels were in the range of ~480-520 kΩ and -86˚ (±2), respectively, before the condensation occurred. Each point on the graph represents the results obtained for different final PCBA temperatures after cooling (different cooling rates). Changes in impedance and phase angle values, and the related substantial water coverage, occurred at PCBA temperatures of 21˚C, 23˚C, and 24˚C respectively for 80%RH, 90%RH, and 95%RH humidity levels.

The decrease of impedance progressed gradually and was linear for the ambient conditions of 80%RH and 90%RH until the low values were reached, contrary to 95%RH where the PCBA temperature decrease led to low impedance values regardless the cooling rate. The phase angle data followed the same trend with a shift towards less negative values. The "bulk water behaviour" (impedance reaching ~5-10 kΩ and phase angle values shifting to ~-5˚) was observed for a large range of thickness values (6-40 µm).

The photographs in Fig. 13 show the appearance of water droplets formed on the SIR surface upon the moisture condensation and PCBA surface temperature reduction from 25˚C to 21˚C (after 12 minutes of cooling) under the ambient humidity level kept at 80%RH, 90%RH, and 95%RH. The appearance of water film formation corresponds to the respective impedance and phase angle values shown with black arrows in the Fig. 12 (a) and (b). For the lowest RH level, the

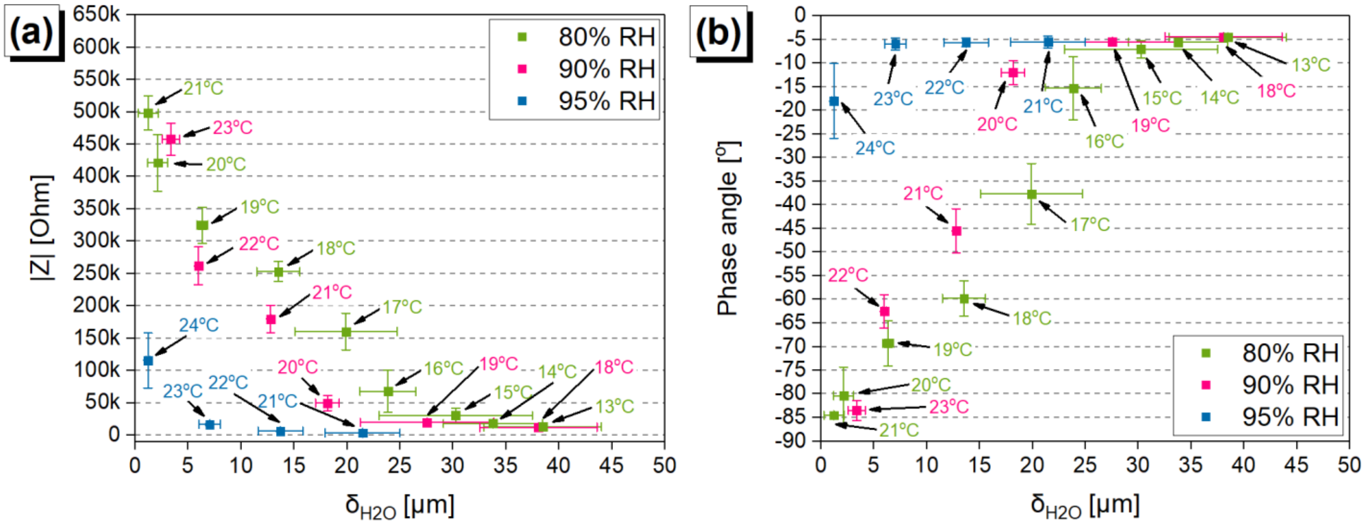

Fig. 12. Impedance (a) and phase angle (b) data characterizing the water layer build-up on a clean SIR surface at 25°C/80%RH and PCBA temperature reduction below the DP. Each point represents an average with the deviation bar given for 3-5 measurements and represents the final temperature after cooling.

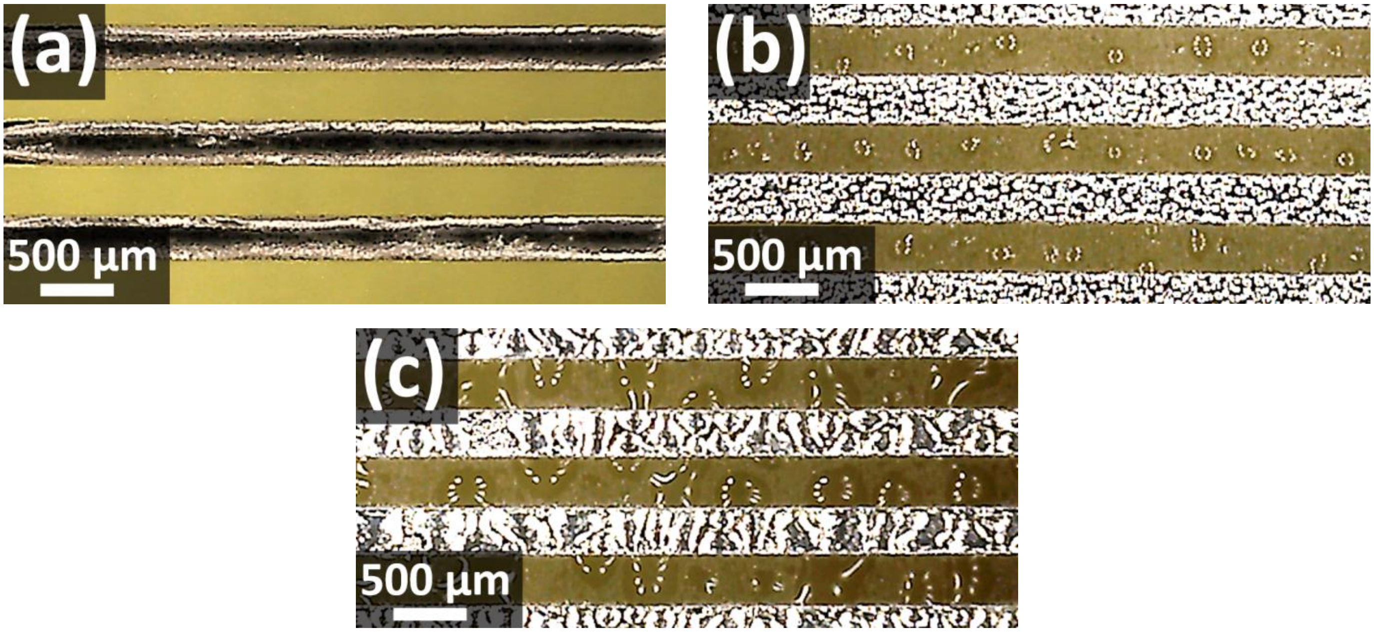

Fig. 13. Optical images with an overview on the clean SIR surfaces upon the moisture condensation and PCBA temperature reduction from 25˚C to 21˚C at: (a) 80%RH, (b) 90%RH, and (c) 95%RH.

formation of water droplets was not observed at the end of experiment (Fig. 13 (a)). At higher humidity levels, the visible water layer was built up in the course of condensation, however significantly higher amount of water vapour condensed at 95%RH (Fig. 13 (c)) leading to a more pronounced conductor bridging, compared to 90%RH (Fig. 13 (b)).

2) *Contaminated PCBA surface*

Fig. 14 shows the results of AC impedance testing for moisture condensation on the contaminated SIR patterns at ambient 25˚C/80%RH with the PCBA temperature reduction below DP (13-21˚C). For reference, the results obtained for the clean SIR surface at 80%RH were shown together (data from Fig. 12). Based on the AC impedance results, significant decrease of impedance (Fig. 14 (a)) and increase of phase angle values (Fig. 14 (b)) were observed upon the PCBA surface temperature reduction below the DP (21.3˚C) for all the acids. Between the tested activators, glutaric and succinic acids contributed significantly to low impedance and high phase angle values, and, therefore, a "bulk water behaviour", compared to adipic acid. Compared to the impedance results obtained under condensing conditions for the clean PCBA surface at 80%RH, the values obtained for WOAs were significantly lower considering the corresponding PCBA set temperatures.

An *in-situ* overview of the SIR patterns appearance upon the moisture condensation on clean and contaminated SIR surfaces is shown in Fig. 15 for the PCBA temperature reduction from 25˚C to 20˚C within 12 minutes. In case of the clean PCBA surface (Fig. 15 (a)), small water droplets were formed upon

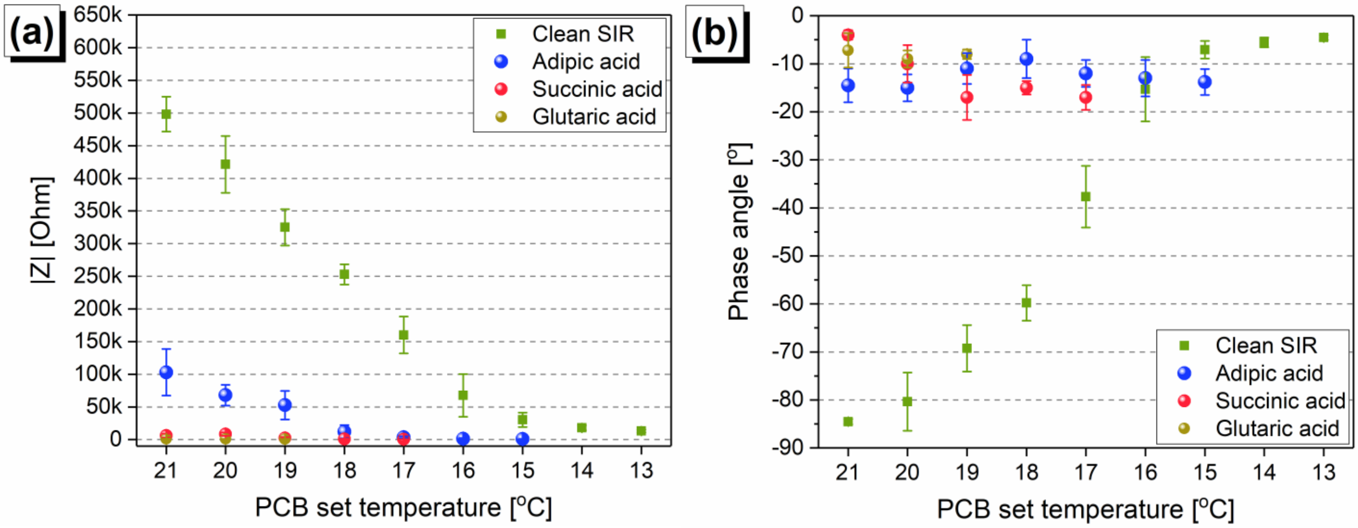

Fig. 14. Impedance (a) and phase angle (b) data characterizing the water layer build-up on the clean and contaminated SIR surfaces at 25˚C/80%RH and PCBA temperature reduction below the DP. Each point represents an average with the deviation bar given for 3-5 measurements.

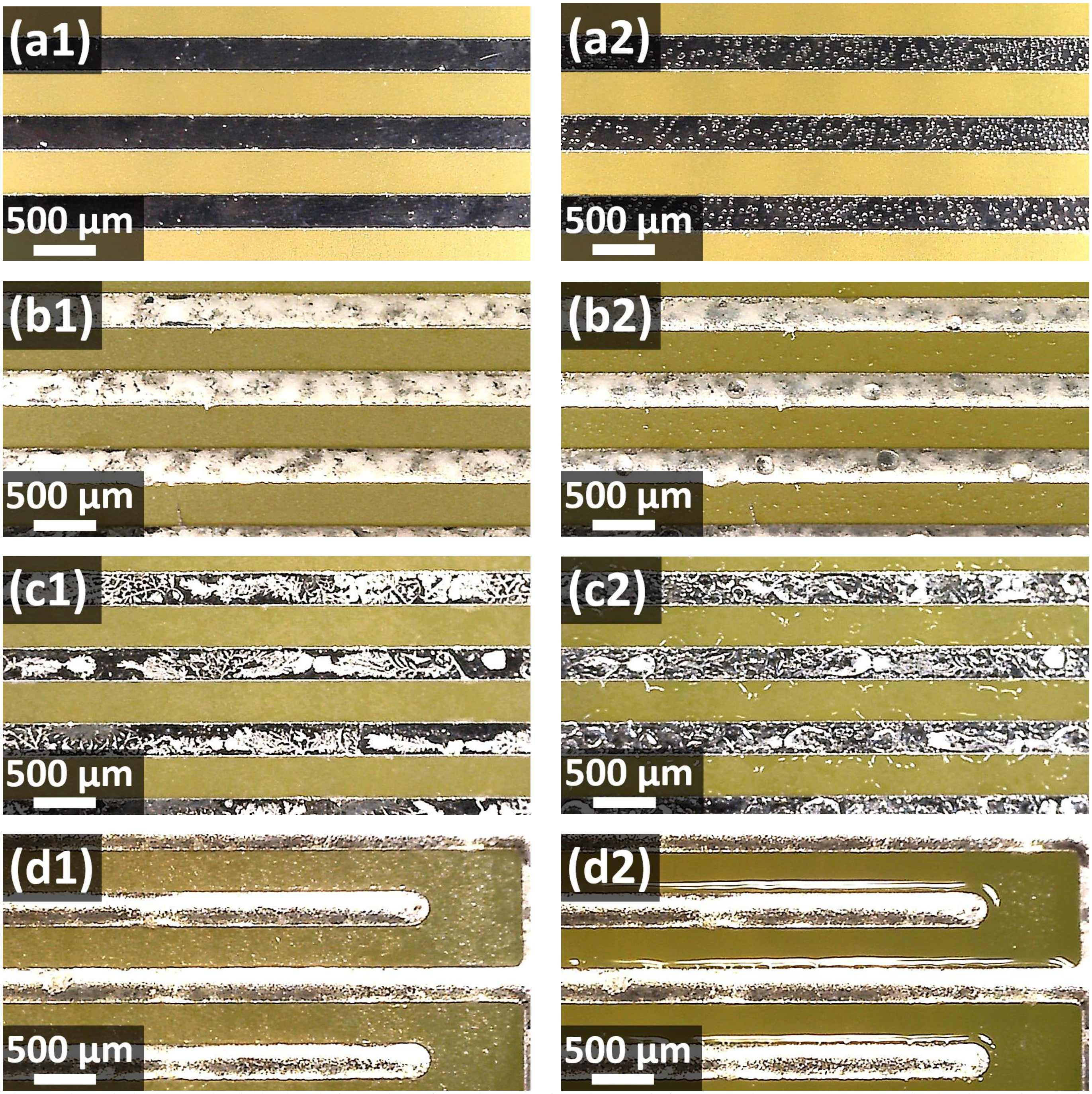

Fig. 15. The optical micrographs obtained (1) before and (2) after moisture condensation at 25˚C/80%RH and PCBA temperature reduction from 25˚C to 20˚C for: (a) clean SIR pattern, and SIR specimens pre-contaminated with 100 µg/cm^2 of (b) adipic acid, (c) succinic acid, (d) glutaric acid.

cooling. Compared to the clean surface, more significant amount of water droplets was formed on the contaminated specimens (Fig. 15 (b), (c), and (d)), with the large droplet islands formed for succinic acid and thick continuous water film built up on the glutaric acid containing SIR comb pattern.

D. *Transient climatic conditions*

Contrary to the tests in sections A, B, and C, which relied on the exposure to the controlled and constant climatic conditions, and the PCBA temperatures control by a Peltier element, the experiments described in this section relied on hourly varying climate and lack of temperature control of PCBA. The investigations focusing on the interaction between the residues remaining on the PCBA surface and water vapour above it, which content varied depending on the hourly varying external changes in temperature and humidity levels, were carried out using a model electronic housing (Fig. 5).

The contaminated PCBAs were placed inside the enclosures, which were then subjected to the climatic profile of Copenhagen (Denmark). The chosen 24h profile of Copenhagen (Fig. 6) represents the critical temperature and humidity changes that can occur in the morning time (~03:50-04:50, highlighted in pink in Fig. 16) when the transient

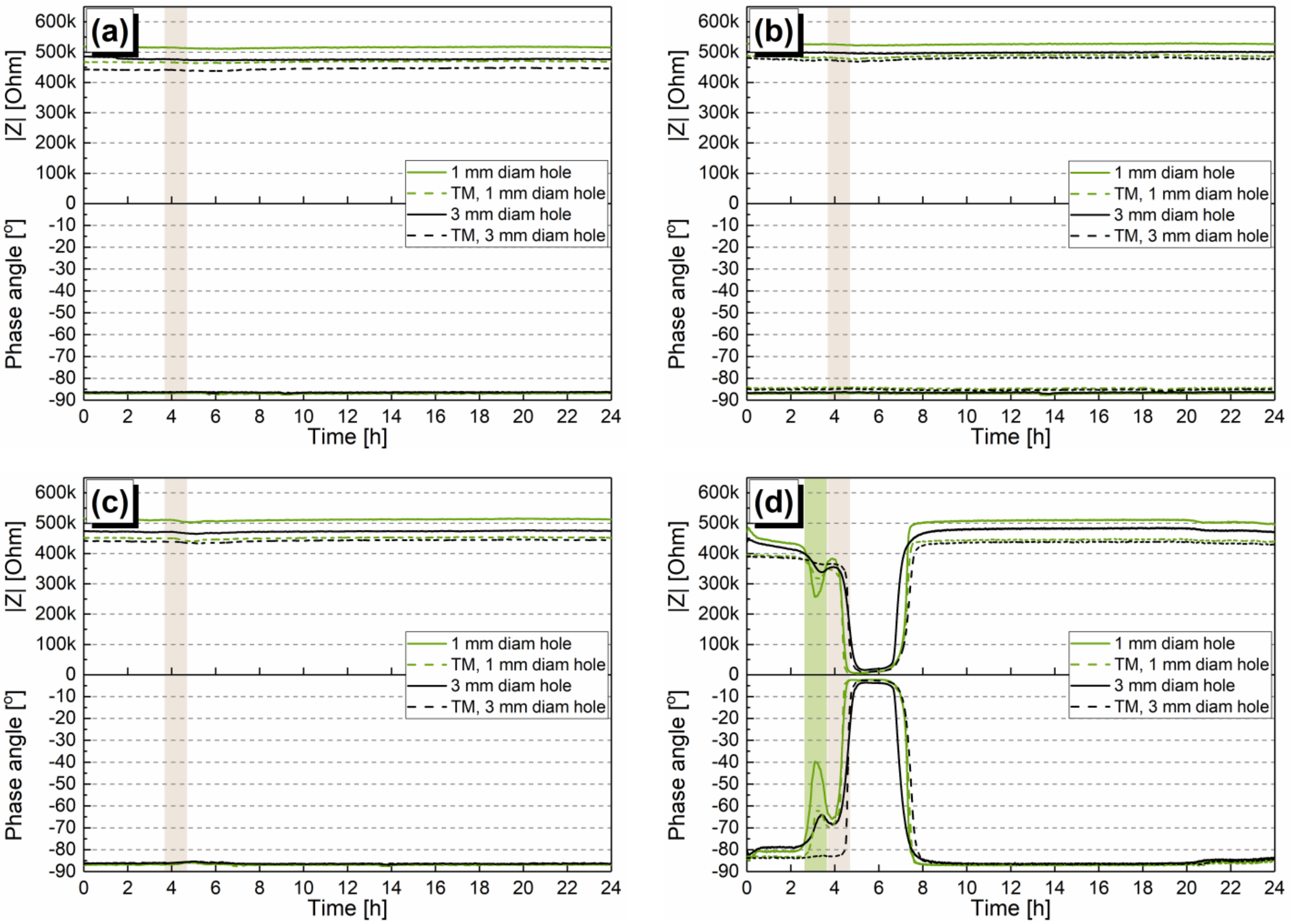

Fig. 16. Impedance and phase angle data as a function of contamination type and thermal mass (TM) presence obtained under exposure of PCBA in aluminium enclosure with 1 mm and 3mm leak size to climate profile in Copenhagen: (a) clean SIR pattern, and SIR-patterns pre-contaminated with 100 µg/cm^2 of WOAs: (b) adipic acid, (c) succinic acid, (d) glutaric acid. The time period for the occurrence of transient conditions, extracted from the climatic profile in Fig. 6, is highlighted in pink.

condensing conditions may develop inside an electronic enclosure if the external temperature rapidly increases, and the enclosure and PCBA temperatures lag with the temperature equilibration (Fig. 17). The transient condensing conditions will force the condensation on enclosure and PCBA surfaces. The electrical response from the system does not directly reflect the temperature and humidity conditions within the enclosure but is dependent on the conditions existing on the PCBA surface at the time of measurement. If the surface temperature of PCBA lags behind the changing temperature conditions around it (inside the enclosure that lags behind the environment), and if that potential condensation scenario is enhanced by a presence of a hygroscopic contamination, this is reflected in the electrical response from the system.

The impedance and phase angle data obtained for a clean SIR (Fig. 16 (a)), shown here for a reference, showed no significant change in the output upon the PCBA exposure to varying temperature and humidity conditions. The SIR samples contaminated with adipic (Fig. 16 (b)) and succinic acids (Fig. 16 (c)) showed distinct changes in the AC data between 4-6h of the 24h profile, which corresponds to the rapid change of external conditions in the morning time (conditions around PCBA).

On the contrary, the presence of glutaric acid on the SIR pattern significantly decreased the impedance values (Fig. 16 (d)), indicating the residue dissolution into the formed water film, in the time period associated with the development of potentially transient conditions within the enclosure and around the PCBA (highlighted in pink). The phase angle followed the trend and reached levels close to 0˚. Considering this, according to the climatic profile given in Fig. 6 where the transient conditions lasted for 1h (~03:50-04:50), the water layer formed on the SIR surface contaminated with glutaric acid remained present for ~3.5-4h, even though the transient period for condensation has theoretically passed for the enclosure and PCBA. Moreover, prior to the dissolution of residue related to the occurrence of transient conditions at ~03:50-04:50, additional decrease in AC impedance values occurred at ~02:40-03:50 (highlighted in green in Fig. 16 (d)), corresponding to the time period in the climatic profile where the high external humidity conditions were present (Fig. 6).

Considering different through-hole sizes, the critical period of time when the impedance values remained low occurred ~30 min earlier and lasted ~10 min longer for the 1 mm diameter opening, compared to the 3 mm diameter hole. In the presence of thermal mass attached to the PCBA, the wetting period began

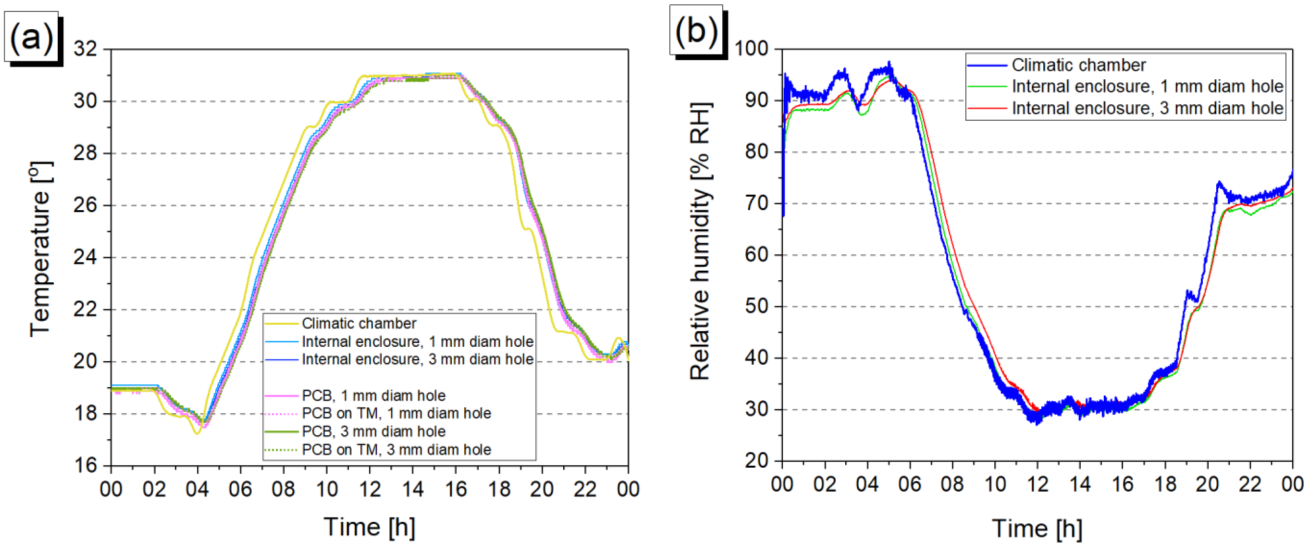

Fig. 17. (a) Temperature and (b) humidity conditions recorded inside the climatic chamber, inside electronic enclosures, and on PCBA surface used in the testing.

~7-9 min earlier than wetting of the PCBA with no thermal mass. Upon the moisture desorption from the PCBA surface, the presence of thermal mass increased the time of water layer presence on the SIR of ~15 min in case of the casing with 3 mm opening hole. For the enclosure with 1 mm diameter through-hole, the differences in wetting time of the SIR with and without the thermal mass were negligible.

IV. Discussion

Investigations presented in this paper focused on studying the effect of various parameters determining the characteristics and extent of water layer build-up on the PCBA surface under exposure to detrimental climate conditions. The four parameters investigated were external humidity level, PCBA cleanliness (residue effects), temperature difference between ambient and PCBA, and the rate of temperature/humidity change. The effect of these parameters was studied individually and combinedly in order to pin-point which of the factors contributes majorly to an increased risk of a substantial water layer build-up. The study shows that synergistic effects of various parameters significantly change the moisture interaction with PCBA surface and alter reliability. The results clearly demonstrate that the PCBA DP temperature depends on the PCBA cleanliness [11], and the resulting extent of water layer build-up is related to the ionic nature of the residues [50]. Under transient conditions, when the risk of condensation occurrence is high due to the small difference between ambient and DP temperatures (e.g. $\delta=1^\circ$C as shown in our study), the altered DP of the contaminated PCBA surface could significantly change its humidity robustness due to the water film existing on the PCBA for an extended period of time.

Under the applied AC voltage for the impedance testing, when the conditions are dry and non-condensing, the clean SIR system follows the simple RC circuit behaviour [27] and at high frequency (e.g. 10^4 Hz used in this study) acts as a capacitor [32]. The capacitive nature is related to the geometry of the comb pattern and permittivity of the laminate embedded between the electrodes of the pattern. The impedance values under these conditions are high and the phase angle values oscillate around -90˚, which indicates a capacitive behaviour. Upon adsorption of moisture to the PCBA surface resulting from RH increase or change in PCBA temperature (moisture condensation), the water layer is formed, which changes the electrical properties of the system. The water film acts as a conductive electrolyte and provides a pathway for the current flow, reducing the capacitive nature of the bulk SIR system and enhancing the resistive conduction behaviour. Upon the continuous water layer growth, the pathway becomes more conductive and the charge can be transferred between the electrodes [51]. Therefore, throughout the results presented in this study, the impedance and phase angle values associated with a "dry" PCBA at 25˚C/80%RH (water layer formation not induced by the PCBA temperature reduction, Fig. 8) complied with the expected behaviour of a capacitive SIR nature (phase shift ~-85˚ and high impedance value). Upon the moisture adsorption to the SIR specimens and the water layer build-up (increased conductivity between the conductors), the impedance values decreased and phase angle values raised towards less negative values, which reflects the change in electrical properties from capacitive-dominated mode to the resistive character of the system [51]-[54]. This change also coincides with the higher leak current possibilities and electrochemical migration. With the significant increase of film thickness, the conductivity of a water film increased, which was reflected in the results by a pronounced impedance reduction to a value of 5-10 kΩ and phase angle values approaching ~0˚ ("bulk water behaviour").

The investigations in this paper included two types of non-condensing conditions in order to elucidate the effect of hygroscopic residues remaining on the PCBA surface namely (i) isothermal conditions, and (ii) non-isothermal conditions with the PCBA temperature reduced until close, but above the DP. In the case of isothermal conditions, the interaction between the residue and water vapour depends on the critical RH of the residue deliquescence [24], which defines the DP of the SIR surface. In case of non-isothermal conditions, the hygroscopicity effect of the residues was found to be reducing

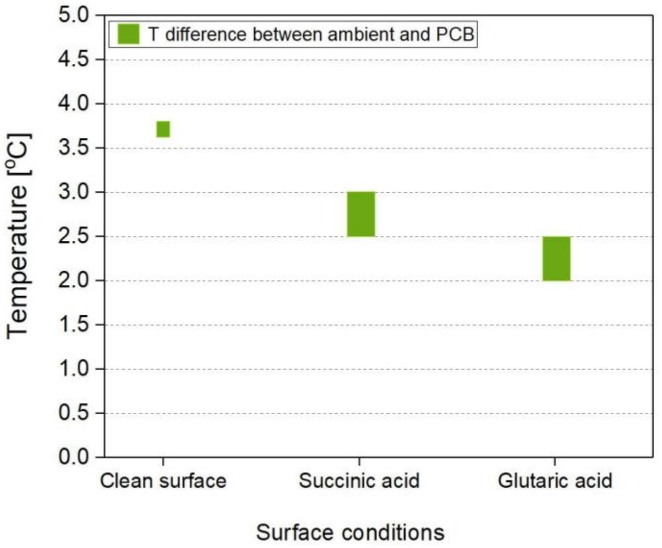

Fig. 18. The required temperature difference between the climate and PCB temperature for condensation occurrence under potentially non-condensing conditions as a function of PCBA cleanliness. Results derived from Fig. 10. The values are only correct for a PCBA exposed to ambient 25°C/80%RH.

the required gap between the actual temperature and DP, which results in the accelerated moisture condensation under hygroscopic residue conditions. As a result, the boundary for humidity robustness of the PCBA under transient conditions will be different depending on the type of contamination present on the surface. This is experimentally demonstrated e.g. in the investigation carried out using a model device (Fig. 5) and Copenhagen climatic profile (Fig. 6) when the transient effect of the humidity and temperature change was enhanced and dependent on the type of hygroscopic residues on the PCBA surface (Fig. 16). In this case presence of glutaric acid not only caused the water layer build-up and large impedance drop even though the PCBA temperature remained above the DP, but also the residue kept the water film for an extended period of time even though the transient conditions have theoretically passed.

If the PCBA temperature drops below the DP (investigations conducted under the non-isothermal conditions where the PCBA temperature was reduced below the DP) the presence of residue largely influences the extent of water film build-up.

A. Residue effects under isothermal conditions

At 25˚C/80%RH, when the temperature of PCBA and chamber are similar (25˚C), no significant changes in the AC and DC data were observed for adipic and succinic acids contaminant (Fig. 8), which implies no dissolution into the water film occurred. On the contrary, the morphology visualization (Fig. 9) showed that glutaric acid clearly exhibited a stronger interaction with the surrounding moisture, compared to the other acids; however, the results of electrochemical testing suggest that the dissolution into the water film was insufficient to lead to corrosion or significant decrease of impedance signal. Under isothermal conditions tested in this study, the ionic nature of the WOA residues was not sufficient to induce a pronounced formation of water layer. Among the investigated WOA types, glutaric acid is the most hygroscopic and soluble in water [24][27][55], and interacts with water vapour easily, which can explain its clear morphology changes when exposed to 80%RH.

Additionally, a lack of more pronounced electrical response can be related to the distance between the conductors (300 µm) that were not bridged by the low amount of forming water film, therefore did not react as significantly to the low amount of forming water film as visual observations could suggest.

B. Non-isothermal conditions with the PCBA temperature reduction above the DP

The results shown in Fig. 10 and Fig. 11 show that the synergistic effects of residue and temperature difference between ambient and PCBA led to thicker water film build-up and significant electrical effects (AC/DC measurements), although the PCBA temperature did not fall below the DP.

No changes in the electrical properties and residue morphology were observed for adipic acid at any tested PCBA temperatures, and the results of electrochemical testing were comparable to those of a clean PCBA surface. Succinic acid showed the significant SIR reduction and dissolution into the water layer only upon the PCBA temperature decrease to 22˚C, where the "bulk water behaviour" (low impedance and high phase angle values) was maintained throughout the 3 days of testing. On the contrary, the SIR patterns containing glutaric acid showed a pronounced decrease of impedance values, increase in phase angle, and the corresponding ECM occurrence at the PCBA temperatures 24.5-23˚C, however the values returned to the initial levels within ~2.5 days. In case of larger temperature differences between ambient and PCBA (22.5˚C, 22˚C), glutaric acid residues dissolved into the water layer and exhibited "bulk water behaviour" throughout the whole test time (3 days). The temperature levels at which condensation of a substantial amount of moisture occurred depending on the PCBA cleanliness were derived from Fig. 10 and are plotted together in Fig. 18. As shown, the temperature required for a condensation decreases if a highly hygroscopic residue is present on a PCBA surface, compared to the clean PCBA. This means that the build-up of thick water layer occurs easily (e.g. at 22.5˚C) if glutaric acid remains on the surface, and the PCBA temperature does not necessarily has to fall below the DP (21.3°C) for that manner. This information has a significant importance as even under humid but non-condensing conditions (e.g. in humid locations worldwide) the residues remaining on the PCBA surface after manufacturing process may still decrease the temperature gap for condensation and lead to the build-up of thick water film.

The discrepancy in facilitation of the water layer build-up exhibited by the three contaminants originates from their hygroscopicity [24][27]: at ambient 25˚C adipic acid deliquesces only at very high humidity levels and dissolves into the water film to a small extent. Slightly higher hygroscopicity is exhibited by succinic acid, however, glutaric acid significantly differs from the other two residue types due the high polarity of its molecules and high solubility in water. The presence of highly hygroscopic glutaric acid changed the humidity boundary of the PCBA surface and led to the accelerated formation of a water film upon the PCBA temperature reduction.

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According to the Mollier diagram, the moisture content expressed as an absolute humidity (AH) was 18.3 g/m^3 for the ambient conditions of 25˚C/80%RH applied in this study (Fig. 19). Upon the PCBA temperature reduction, the same amount of water vapour was contained within the air surrounding the sample, therefore, in order to equilibrate and compensate for the surface temperature decrease, the relative water vapour content (RH) above the contamination has increased [56]. As a consequence, when the PCBA temperature reached, e.g. 24.5˚C, the RH level above the contaminated sample increased to 82.5%RH, which strengthened the interaction between the water vapour and glutaric acid, and the potential for moisture condensation on the SIR surface raised. In case of PCBA temperature decrease from 25˚C to 24.5-23˚C, the initial impedance decrease due to the water film formation and subsequent return to the higher values is believed to be the results of RH equilibration with the chamber conditions after ~2.5 days (due to e.g. strong air flow). In case of the PCBA temperature reduction from 25˚C to 22.5˚C and 22˚C, the formed electrolyte layer resembled the “bulk water behaviour” as the actual RH levels above the SIR surface reached 92%RH and 95%RH (Fig. 19). At such high humidity level of 95%RH, the amount of water vapour sorbed by glutaric acid rises significantly to 100 wt% (compared to 0.05 and 0.1 wt% for adipic and succinic acids, respectively) [24] which is sufficient for a formation of a continuous liquid film and occurrence of “bulk water behaviour”, critical from the electronics reliability point of view. The results show that highly hygroscopic contamination types can reduce the critical RH level of the SIR surface and increase the water vapour content above it. Even under potentially non-condensing conditions, if the temperature of the contaminated PCBA is reduced of only few degrees, the risk of water layer formation and corrosion occurrence is high. In actual practice, this shows that for an electronic device with the PCBA soldered using glutaric acid containing flux system, the condensed water film can be created on the surface of electronic unit at low transient temperature reduction conditions, compared to the flux systems with adipic or succinic acids.

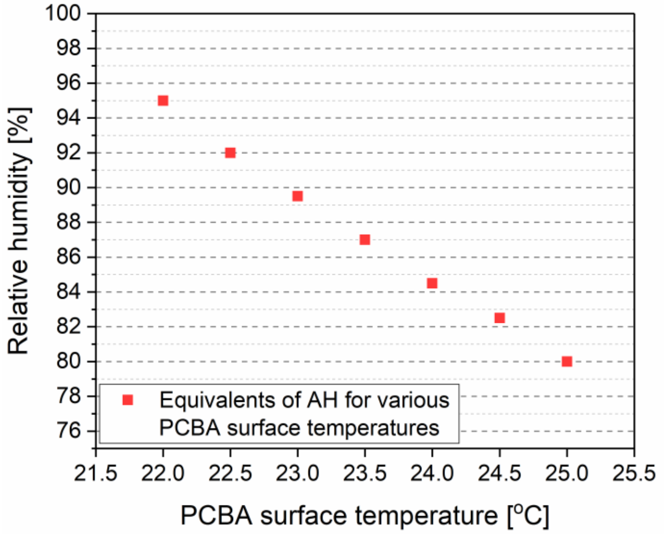

Fig. 19. The related RH values for constant absolute humidity (AH) (AH= 18.3 g/m^3 for 25˚C/80%RH ambient conditions) for the PCBA temperatures tested in this study.

C. Non-isothermal conditions with the PCBA temperature reduction below the DP

The thickness of water layer was calculated through the gravimetric measurements assuming that the water layer was formed uniformly on the laminate surface. However, various parameters affecting the surface (e.g. surface chemistry, surface roughness [42]) cause the forming water layer not to be uniform but rather form in the form of droplets as shown in Fig. 15.

In case of clean surfaces (Fig. 12), no correlation between the impedance or phase angle change and the averaged water layer thickness can be done - the “bulk water behaviour” (low impedance and high phase angle) was observed for the large range of thickness values (6-40 µm) which is directly associated with the ambient RH level. These results show the “averaged water layer thickness” cannot be used as a mean for failure prediction. It appears that the failure of electronic circuit will depend not only on the amount of a formed water but also on the surface features of the substrate, on which that water layer forms. Surface features like hydrophilicity and roughness will influence the geometry of the water droplets (size) [42] directly impacting the risk of droplet bridging the conductor lines.

The amount of water vapour available to be adsorbed to the PCBA surface upon condensation is proportional to the RH at constant temperature. For the tested humidity conditions at 25˚C, the moisture content expressed as an absolute humidity (AH) [57] was 18.3 g/m^3, 20.6 g/m^3, and 21.7 g/m^3 according to the Mollier diagram, for 80%RH, 90%RH, and 95%RH, respectively. Considering the same cooling rate (e.g. 25˚C->21˚C) and cooling time (12 minutes) applied at the tested RH levels for a clean SIR, the resulting impedance, phase angle, and averaged water film thickness values differed (Fig. 12, shown with black arrows). A continuous water layer was formed at 95%RH (Fig. 13 (c)) which resulted in the “bulk water behaviour” as inferred from the impedance data, compared to the data obtained at 80%RH and 90%RH. The observations are related to the characteristics of water film formation between the electrodes where the high moisture content at 95%RH allowed for advanced conductor bridging [3]. The water vapour density on the PCBA surface, and the resulting impedance and phase angle responses for the clean surface, were therefore a function of the absolute humidity level which defined the tendencies of the water film to bridge the electrode pattern (Fig. 13). Moreover, the considered PCBA temperature reduction (25˚C->21˚C) indicated that the DP was exceeded of 0.3˚C, 2.2˚C, and 3.1˚C for 80%RH, 90%RH, and 95%RH, respectively, and that largest temperature difference between the PCBA and surrounding air (3.1˚C) additionally contributed to the enhanced condensation and the observed impedance decrease.

The conductor bridging primarily depends on the surface roughness, type of the insulation material, and thermal conductivity of the materials [42][58]. Similarly as shown for the clean surfaces, where the increase of ambient RH (AH) resulted in the increase of moisture condensation and electrode bridging characteristics, the presence of ionic residues (Fig. 14) changed the critical RH of the surface, increased the water vapour content above the surface, and lead to the electrolyte formation and conductor bridging [3][50]. In a thick water film, the charge transfer occurs easily and a system exhibits low resistance against it [51]. Between the tested activators, glutaric and succinic acids led to a significant impedance reduction and phase angle increase, similarly as in the case of moisture condensation on a clean PCBA at 95%RH (Fig. 12). As discussed by Tencer [50], both parameters of deliquescence and surface coverage by the residue are vital for the formation of a conductive layer and electrode bridging. The contamination effect was visualized in Fig. 15 where the reported photographs showed the advanced water film formation in case of succinic and glutaric acids, compared to the clean and adipic acid contaminated surfaces where only few water droplets can be observed under the same cooling conditions. The results show that highly hygroscopic contamination further enhances the existing condensing conditions, leading to the accelerated water film formation and advanced conductor bridging.

D. *Transient climatic conditions*

The extent of water film formation on the SIR surfaces subjected to transient climatic conditions (Fig. 16) was influenced by the PCBA surface conditions and contamination type. Under the 24h climatic profile of Copenhagen (Fig. 6), the transient conditions can be expected to occur in the enclosure for the ~1h period in the morning time (~03:50-04:50) due to the high humidity level and rapid increase of external temperature. During that critical period, the DP raised to critically high levels and the difference of only 1˚C was noted compared to the ambient temperature. In case of clean surface (Fig. 16), the tested climatic profile did not result in a significant build-up of the water film. For the adipic and succinic acids, the effect was less significant. The residue contribution to the formation of water layer during the critical period of temperature change was observed only in the case of highly hygroscopic glutaric acid under a given climatic profile. The results are vital from the electronics application point of view: the effect of a temperature lag between outdoor, enclosure, and PCBA, almost unavoidable in a real life and primarily leading to a water film formation, is enhanced by the presence of hygroscopic ionic contamination [10].

The critical transient conditions, enhanced by the presence of glutaric acid on the PCBA surface, lasted for a shorter time period in the case of enclosure with larger through-hole (3 mm diameter) compared to the smaller leak size (1 mm diameter). As a result of natural convection occurring upon the temperature difference development between the chamber and internal enclosure conditions [10], a larger opening allowed for a less disturbed airflow and the PCBA could equilibrate with the external conditions faster. The presence of thermal mass increased the PCBA wetting time of ~15 min in case of enclosure with 3 mm diameter hole, however no effect of thermal mass was noted for the profiles obtained for casing with 1 mm diameter opening. The internal thermal mass attached at the bottom of test PCBA created an additional thermal gradient between the PCBA, external conditions, and enclosure conditions [59] prolonging the wetting time of SIR pattern.

It is rather unusual to encounter bare copper in the electronics applications – typically it is protected by a layer of solder mask (Cu traces on the PCBA) or by a polymeric insulation (cables). Even though the protective measures exist, copper can oxidize under specifically harsh conditions. In practice and many applications, the conductor traces are covered by a protective layer of solder mask that will not respond to changed of temperature or humidity (or undergo corrosion) as rapidly as the bare electrodes. Solder mask blocks the access to bare metal, delaying or, potentially, removing the risk of corrosion occurrence. However, it is also known that solder mask as a polymer is transparent to water vapour, so eventually the moisture will diffuse through it and reach the metal surface leading to its oxidation. However, the protective effects of solder mask require a deep study.

Overall, the results show the dependency of the water layer build-up on various parameters, which synergistically alter the extent of moisture adsorption and the electrical properties of the formed water film. The local RH increase due to the temperature difference between PCBA and ambient [11], ambient RH level, PCBA cleanliness, rate of temperature/humidity change, and the enclosure characteristics defy the robustness of the system by contributing to the tendency of a conductor bridging and subsequent risk of failure occurrence. Even potentially non-condensing conditions may be detrimental for the device if harsh process-related contamination is present on a PCBA surface. Maintaining the PCBA cleanliness and a control of internal climate of the device (e.g. towards less abrupt temperature changes) could influence the response of the device interior conditions to external climate fluctuation and condensation risk, delaying the potential deterioration in electronics performance.

V. CONCLUSIONS

1) Water vapour condensation on the clean PCBA surface and the resulting electrical properties of the water film are dependent on the ambient RH level and the rate of temperature change, which define the characteristics of conductor bridging. At constant ambient temperature, higher amount of water vapour exists at 95%RH than at 80%RH, which, at the same cooling rate, leads to the formation of a continuous water film and easy conductor bridging.

2) The altered PCBA cleanliness decreases the critical RH level of the surface and increases PCBA temperature required for condensation, increasing the water vapour content above it, and its extent is dictated by the ionic nature of residues. Under non-isothermal conditions and PCBA temperature reduction above the DP (non-condensing conditions), high affinity to water and solubility of glutaric acid are sufficient to provoke the condensation of water vapour and subsequent corrosion issues for ~2.5 days if the PCBA temperature drops of 0.5-2˚C from ambient 25˚C.

3) Under non-isothermal conditions when the PCBA temperature decreases below the DP, the presence of succinic and glutaric acids accelerate the formation of a continuous water layer and conductor bridging.

4) Under transient conditions generated for ~1h within an electronic enclosure, the presence of highly hygroscopic glutaric acid prolonged the duration of PCBA surface wetting to ~4h. The presence of a thermal mass attached to the PCBA

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further extended the time for water layer existence of ~15min, increasing the extent of failure.

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