INFLUENCE OF MULTIPLE REFLOWS AND SURFACE FINISHES ON SOLDER JOINT RESISTIVITY

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ABSTRACT

The main purpose of this paper is the analysis of the electrical resistivity of solder joints depending on various surface finishes and on the number of reflow processes. The electrical resistivity was determined after 1, 2, 3, 5 and 6 reflow cycles as a replacement for the basic accelerated aging test. In this article, various surface finishes are compared by measuring electrical resistivity of solder joints between two soldering pads. The influence of standard surface finishes (ENIG, Lead HASL, Lead-free HASL, Cu, ImSn) with the new developed surface finish based on SnAg7 is also compared. Measurements show that the electrical resistivity is dependent on surface finish type and the thickness of the solder joint. The results prove that the new developed surface finish based on SnAg7 is stable against multiple reflows and comparable to the surface finish based on Au. The new developed surface finish based on SnAg7 can be recommended as a replacement for other conventional surface finishes.

Keywords: *surface finish, electrical resistivity, multiple reflows*

1. INTRODUCTION

Nowadays, surface finish is one of the standard processes that are used for the protection of the underlying copper from oxidation, for provision a barrier for copper dissolution and for provision a solderable coating for creation of a functional interface. The use of lead-free solder requires a higher assembly temperature in a reflow process and developing new compatible lead-free surface finishes. Actual studies compare the quality of the solder joint depending on the type of lead-free solder, most often based on SnAgCu. However, none of these works point to the influence of quality of the PCB´s (Printed Circuit Board) surface finish in relation to the quality of the solder joint, specifically to its resistivity [1-4].

The reflow is process, in which solder joints are formed during melting of a solder between component and solder pad. With the increasing complexity of electronic circuits, it is impossible to form all the solder joints within one reflow. Besides that, it happens very often that the technological process of the PCB fabrication requires multiple reflows that PCB must resist. This process is linked with the change of microstructure of the solder joint and it´s electrical resistivity. The use of lead-free solders causes reliability problems between the solder and the substrate, due to exposure of high temperature in the reflow furnace [5-8].

Testing of the surface finishes is aimed for the evaluation of long-term reliability, resistance against multiple reflows and of the ageing process. The thickness of IMC (InterMetallic Compounds) is the most noticeable parameter for evaluation of long-term reliability, as well as multiple reflows and ageing process. Studies have shown that the electrical resistivity of the solder joint is changing with number of reflows as we can see in changes of microstructure and especially in grow of the IMCs´ layers. Grow of IMCs is related to changes in the electrical resistance of the solder joint [9-12].

The primary function of the solder joint is to ensure the electrical and mechanical connection between the substrate and component. Thus, electrical resistance is a very important parameter that causes losses during the signal transmission for more complex electronic circuits. Electrical resistance´s values of the solder joints are generally small, and they have little effect to work of the basic electronic circuit and it´s quality. However, in this article Kelvin´s 4-wire method for measuring of the electrical resistance is used. This method is valuable and proper for measuring of a very small electrical resistances in the order of micro-ohms. Values of the measured electrical resistance correlates with the evaluation of the microstructure of the solder joint. Problem that we aimed within this context was measuring very small changes of resistivity linked with change of the solder joint´s microstructure after multiple reflows. Temperature cycling of the solder joint causes cracks to form at the interface between the solder and soldered surface. Also, this type of experiment can be applied as a non-destructive technique for prediction of the solder joint´s end-of-life. Besides that, change of electrical resistivity of the solder joint on different surfaces is also studied in this work [13-17].

Although the relative values of solder joints´ resistance are very small, a measuring of the resistance can be considered a very suitable method for assessing their quality without the need to perform complex microstructural analyses. This measurement is attended by repeated thermal cycling to assess the quality and stability of the surface finish and, consequently, the long-term stability of solder joints. In our article, we also analyse the quality of a solder joint created on 5 types of conventional surface finishes. We compare the results of these measurements with the results of the newly created surface, which is not yet applied in electronics, and which is based on the SnAg alloy [18-21].

2. PRINCIPLE OF ELECTRICAL RESISTIVITY MEASUREMENT

The purpose of the article is to show the influence of multiple reflows on the change of electrical resistivity in correlation with the solder joints´ microstructure. 4-wire Kelvin´s method measurement of the electrical resistance was used for sensitive investigation of the changes of electrical resistivity. This method is based on Ohm´s law. In Kelvin´s method, a constant current flow through the resistor and a voltage drop is measured and allows to measure the resistivity of the entire joint volume, which consists of a mixture of materials, or more precisely layers (Fig. 1). The method is a suitable indicator of the quality of the joint, even without the need to analyse its microstructure. The electrical resistance R can be counted by formula:

$$R = \frac{U}{I}\,[\Omega], \tag{1}$$

where: U – measured voltage drop and I – constant current (in the case of our experiments 20 mA).

Finding out the electrical resistivity consists of measuring the electrical resistance with Agilent 4338B miliohmmeter and counting values of the electrical resistivity ρ by formula:

$$\rho = R\frac{S}{l}\,[\Omega.m], \tag{2}$$

where: R – measured electrical resistance, S – area of a copper pad, l – thickness of copper pads on both opposite parts of samples (Fig. 2), thickness of surface finishes and thickness of reflowed solder between both opposite parts of samples.

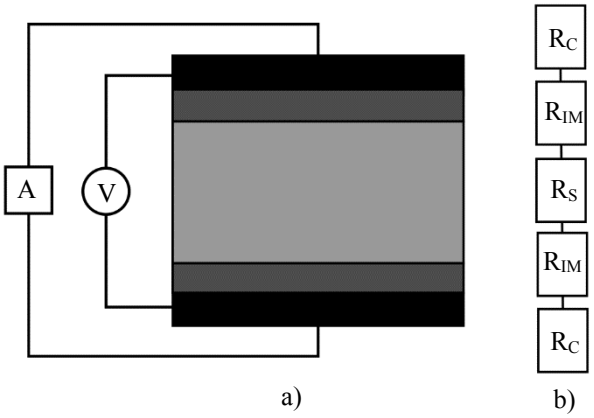


Fig. 1 Principle of measurement of the solder joint´s electrical resistance a) and it´s alternative resistor model b)

The equivalent resistor values and measurement´s principle of the solder joints are shown in the Fig. 1. Transient resistance between each layer is not shown, but we consider that it causes the changes. For the measurement, current probes were connected through two pins on opposite sides of the PCB and electrical current flows through the sample (Fig. 2). Voltage was measured using a detached two-pin probe that was relocated after every measured value.

Measured resistance is a combination of 5 layers connected in series, which are involved in creating the solder joint as shown in Fig. 1:

$$R = R_C + R_{IM} + R_S + R_{IM} + R_C\,[\Omega], \tag{3}$$

where: R_C – copper´s layer resistance, R_{IM} – intermetallic compound´s layer resistance, R_S – solder´s layer resistance.

3. SAMPLES PREPARATION

Five types of conventional surface finishes were used for the measurement of solder joints' electrical resistance, whereas the most used surface finishes like Cu, ENIG (Electroless Nickel Immersion Gold), lead-free HASL (Hot Air Solder Levelling), lead HASL and ImSn (Immersion Tin) were selected, as well as new developed surface finish based on SnAg7. Every sample was degreased by isopropyl alcohol. Besides that, surface finishes based on Cu and SnAg7 were micro etched by 5% hydrochloric acid for one minute and then cleaned with deionised water and with isopropyl alcohol to ensure clean surfaces without any amounts of oxides.

3.1. Designing for the measurement

The design for the tested samples using the Kelvin´s 4-wire method was developed and used for all types of surface finishes. The conductive pattern was applied in fabrication process of PCBs with different surface finishes. Design of the circuit had to be developed for the accurate and fast measuring of electrical resistance where IMCs are contained. Conductive pattern was optimized for Kelvin´s 4-wire method. Test pattern of the bottom PCB is in Fig. 2. The voltage drop is measured between the top and the bottom of the solder joint.

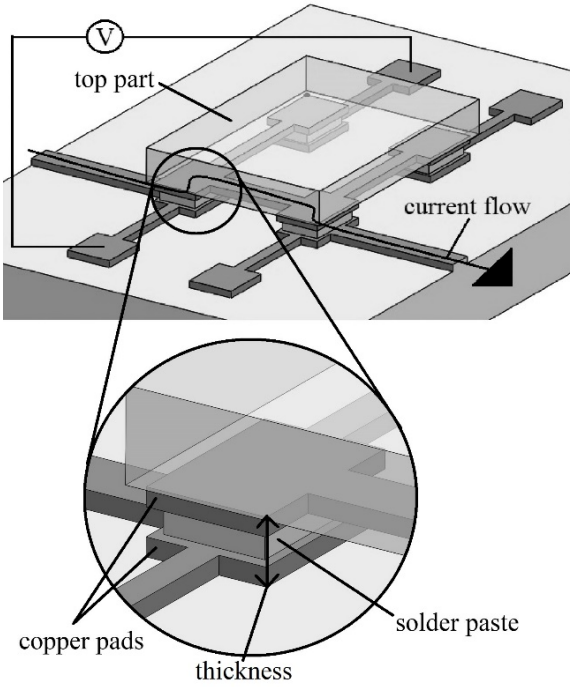


Fig. 2 Pattern of the sample (up) and the detail of the soldered top part (down)

One test board consists of 21 samples and 42 solder joints, where the electrical resistance can be measured. One sample consists of 4 solder joints, which were formed by soldering the top part on the bottom PCB as shown in Fig. 2. ENIG was selected as a top part´s surface finish because it is known that the ENIG is stable due to multiple reflows as well as it is reliable. Dimension of one copper pad is 1.6 mm x 0.9 mm. Thickness of the solder joint is various because every surface finish has different thickness that is linked to the fabrication process of each surface finish. The thickness of the whole measured solder joint is approximately 110 – 140 μm.

3.2. Material Selection

Cu surface finish was made by electrodeposited copper on standard PCB. This process is basically used, when drilled holes on the PCB need to be galvanically plated by copper. ENIG is a double layer metallic coating, where nickel is acting like diffusion barrier for copper and a surface to which components are soldered. Layer of gold (0.05 – 0.2 μm) is on the top of a nickel coating (3 – 5 μm) for protecting nickel against oxidation. ENIG is one of the best lead-free surface finishes, because it is stable against multiple reflows and has a long term reliability [22].

For the comparison of lead and lead-free surface finishes, HASL surface finish was fabricated in two ways: with the use of alloy based on SnPb and second alloy based on SnAgCu. Lead HASL surface finish is a layer of the SnPb solder alloy on PCB. It was applied by dipping of the PCB to molten SnPb solder alloy. For decades it was one of the most popular surface finishes. But with coming to the lead-free era, lead became a restricted substation. SnPb solder alloy was replaced by the SnAgCu solder alloy. The lead-free HASL is also a layer of metal on copper but made of the SnAgCu solder alloy. Application of lead-free HASL is the same as the lead HASL. The thickness of the average HASL surface finish is 1.5 – 45 μm.

Another tin-based surface finish that was selected for our comparison is ImSn. This surface finish is relatively cheap, it has lower thickness (0.6 – 1.2 μm) in comparison to HASL surface finishes and it is planar. ImSn surface finish is made using the chemical reaction of copper in solution based on tin and sulfuric acid.

The most important surface finish is SnAg7 that was not published or reviewed anywhere. This surface finish consists of two layers: Ni layer and SnAg7 layer. Ni layer is deposited chemically as Ni layer in the ENIG surface finish. SnAg7 alloy applied on PCB was obtained electrochemically in non-aqueous electrolyte. Its thickness is 0.5 μm.

Nowadays, ENIG and HASL surface finishes are the most used surface finishes, because they are robust and have very good long-term reliability. However, ENIG surface finish is relatively more expensive than other surface finishes based on tin. HASL surface finish is relatively cheap, but it is not planar. ImSn surface finish is planar and relatively cheap, but a manufacturing process of the Sn layer is very complicated due to the use of hazardous substances and problems during storage. For this reasons, SnAg7 surface finish could be the best option for the average customer that wants electrically stable and planar surface finish for a lower price.

3.3. Joining (reflow) process

For soldering, Heraeus SAC305 (96,5 % Sn/3 % Ag/0,5 % Cu) solder paste was selected. It is a lead-free no-clean solder paste with REL0 solder flux optimized for SAC solders.

Stencil printing technology was applied for solder paste application onto copper (or another type of surface finish) pads. The thickness of the stainless-steel mask stencil used was 127 μm. Since the holes in the stencil mask were created by a laser, there is sufficient guarantee that the thickness of the applied solder paste was uniform in all tested samples.

Fully programmable IR furnace was used for the reflow process to ensure constant conditions for the thermal stress. Maximum temperature of the reflow process was 245 °C. Reflow profile was measured and optimized for SAC305 solder paste, and it was the same for every sample and for every additional reflow within accelerated ageing (Fig.3.). The thickness of solder joints was measured after every reflow. Almost no changes in thickness were measured. It was possible to maintain the repeatability of the reflow temperature cycling by setting the parameters in this furnace.

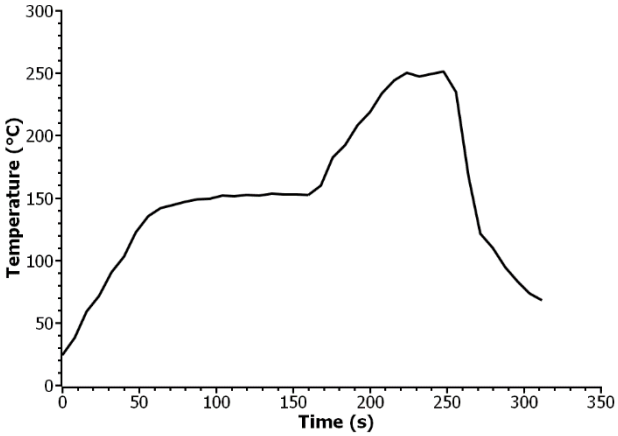


Fig. 3 SAC solder paste reflow profile applied for tested samples

4. RESULTS AND DISCUSSION

In Fig. 4, the results show the influence of the number of reflows on the electrical resistivity´s mean value of solder joints depending on the type of surface finish. The results show that the lowest electrical resistivity´s values as well as the highest stability have the gold-based surface (ENIG) and the silver-based surface (SnAg7).

After 2 reflows, the electrical resistivity of all solder joints decreases due to further formation of the solder joint. Our reason grounds in a theoretical analysis of the creation of IMC [3, 18]. It is true that IMC, which forms at the interfacial interface between the solder and the PCB surface, contributes to the deterioration of resistivity of the solder joint. However, in initial stages of solder joint formation, IMC formation ensures perfect adhesion, thus having a positive effect on the solder joint quality. As the number of reflow processes increases, the thickness of IMC increases too.

The repeated number of reflow processes contributes to the increase in IMC thickness and thus to the increase in resistivity of solder joints [5]. After the third, fifth and sixth reflow, the electrical resistivity grows for all samples. The results also show that the electrical resistivity of solder joints is influenced by the type of surface finish. The electrical resistivity of the new developed surface finish based on SnAg7 is the lowest even after accelerated aging – after 6 reflows. For the ENIG and the Cu surface finish, the change of electrical resistivity is minimal. The main difference occurred after 6th reflow when oxidation of copper increased. Lead and lead-free HASL surface finishes have the highest values of electrical resistivity. Electrical resistivity of the ImSn surface finish is higher than the electrical resistivity of copper, but lower than the HASL surface finishes.

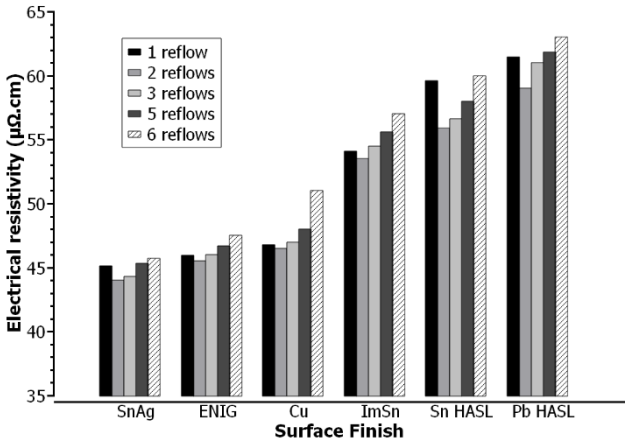


Fig. 4 Influence of surface finish on the electrical resistivity of the solder joint

Our investigation of solder joints´ resistivity leads to interesting knowledge, which indicates the behaviour of SAC-based solder paste as well as the formation of interfacial reactions between solders and surface finishes. In our experiment, 6 surface finishes were compared. A comparison of surface finishes´ materials electrical resistivities applied on PCB surface, as well as IMC electrical resistivities, the formation of which we assume at the interfacial interface of the soldered joint, are shown in the Tab. 1. The value of the total resistivity of the measured solder joint consists of these individual layers, as shown in Fig. 5.

Tab. 1 Electrical resistivity of selected metals, alloys and IMC occurring in solder joints [23, 24]

Material	Electrical resistivity (μΩ.cm)
Cu	1.7
Sn	11.5
Ni	7.8
SAC305	12.9
SnPb	14.5
Cu_6Sn_5	17.5
Cu_3Sn	8.93
Ni_3Sn_4	28.5

Ni_3Sn_4 IMC is obtained in every single sample due to the ENIG surface finish of the top part of our experimental sample (top part in the Fig. 2). This type of IMC has higher resistivity than Cu_6Sn_5. However, it is known that Cu_6Sn_5 IMC grows much faster than Ni_3Sn_4 IMC [19, 20]. The solder joints of samples without nickel layer consist of 4 layers (Fig. 5). The electrical resistance depends on metals used for soldering and on formed alloys. Solder joints formed on nickel layer consist of 4 layers too, but in this case, only one layer of IMC is formed by interfacial reactions.

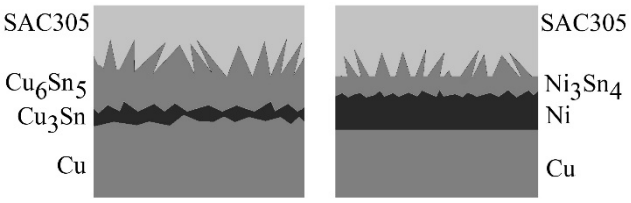


Fig. 5 Assumed composition at the solder joint interface for Cu-Sn IMC (left) and for Ni-Sn IMC (right)

Results show that the surface finish based on SnAg7 is stable even after 6 reflow cycles and comparable to much more expensive ENIG surface finish. The worst results in terms of electrical properties were, as expected, for lead-free HASL and lead HASL. However, from the point of view of stability and aging resistance, the most significant increase in resistivity was spotted for the Cu surface and for ImSn.

5. CONCLUSIONS

The paper describes the influence of multiple reflows and surface finishes on the electrical resistivity of solder joins. According to our study, the electrical resistivity changes with the growth of the IMC layer. The repeated reflow process initially leads to improved adhesion for all types of surfaces and thus to a slight decrease in electrical resistivity. Further (3rd, 5th, 6th) reflow processes increase the resistivity, the rate of increase significantly depends on the type of surface treatment. Every additional reflow leads to aging of the joint and to the expected increase in IMC thickness at the solder-surface finish interface. The smallest increase in resistivity values and greater stability of the measured values were recorded in case of the gold-based surface and in case of the newly developed type of SnAg7-based surface finish. Based on evaluation of electrical resistance of solder joints we can recommend the new developed surface finish based on SnAg7 as proper and cheap type of surface finish for application in electronics. Further reliability tests, microstructure analysis and test for wettability will be required as well.

Our experiments showed that Kelvin´s 4-wire method is proper for measuring the solder joint´s electrical resistance and for further evaluation of solder joint´s electrical resistivity as a replacement for the testing of quality without the need to perform complex microstructural analyses.

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BIOGRAPHIES

Daniel Dzivy was born in 1995. In 2019 he graduated (MSc) at the Department of Technologies in Electronics of the Faculty of Electrical Engineering and Informatics at Technical University of Kosice. Now, he is a PhD. student at the same department. His scientific research is aimed on technologies of surface finishes and their application in electronics.

Alena Pietrikova obtained M.Sc. in material science in 1980 and Ph.D. in 1986 at Technical University of Kosice, Slovakia. Currently she is professor of electro-technology and materials at the Department of Technologies in Electronics of the Faculty of Electrical Engineering and Informatics at Technical University of Kosice. She is co-author of more than 300 scientific publications, 8 patents and 7 books. The most of her research works is focused on study of materials and technologies in electronics.

Olga Vrublevskaya obtained Ph.D in chemistry in 2003 at Belarusian State University. Currently she is docent of Inorganic Chemistry Chair, Faculty of Chemistry, Belarusian State University, and vice director for scientific work. Her current research is aimed on Electroless and electrochemical deposition of metals, alloys and composite coatings from the aqueous and non-aqueous solutions on the substrates of different nature, elaboration of new ways of electrochemical and chemical synthesis of the coatings (or powders) from the alloys on the base of tin (Sn-Cu, Sn-Ag, Sn-Bi, Sn-Au and etc) which can be used as the solders in the processes of electronic devices assembly, synthesis and investigation of physico-chemical metal sols, the elaboration of the test systems for the exposure of causative agent.

Marina Shikun obtained M.Sc. in chemistry in 2019 at Belarusian State University. Currently she is a PhD student at the Department of Inorganic Chemistry of Belarusian State University and a researcher of the Research Institute for Physical Chemical Problems of Belarusian State University. Her current research is aimed on electrochemical synthesis of Sn-Ag alloy coatings in aqueous and non-aqueous solutions and electroless synthesis of Sn-Ag powders applicable as a solder in the electronic devices production.