MEASUREMENT OF NONLINEARITY OF LEAD-FREE VAPOUR PHASE REFLOWED SOLDER JOINTS

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SUMMARY

The goal of the study is to compare quality of vapour phase reflowed solder joints soldered on different printed circuit board (PCB) surface finishes. Vapour phase reflow soldering guarantees the highest reliability, quality of processing and process safety.

The big advantage of heat transfer in vapour phase soldering (VPS) is the extremely efficient transfer of latent heat through the condensing vapour of a chemically inert liquid. The heat transfer process is about ten times faster than hot air and about eight times faster than infra red heat. The condensation mediums used are perfluorocarbon, perflouropolyeter, flouriertes phenandren or perflouramin liquids, which are clear and colourless, have no odour, no taste, are non-flammable, non-corrosive and non-ozone depleting. For lead free soldering a boiling point of 230 °C of these liquids is recommended.

The temperature of any saturated vapour cannot exceed the temperature of the boiling liquid, therefore the temperature of the PCBs and components can never be higher than that of the vapour in the machine. As the liquid boils, a layer of saturated vapour forms above the fluid creating a 100 % inert atmosphere – it allows use of less aggressive flux than in other forms of reflow. The reflow in inert gas atmosphere defines an own unique standard.

As there is no danger of overheating, there is no need to set temperature profiles. Vapour phase provides probably the best possible solder reflow conditions with only minimal temperature differences across the PCB. Vapour phase is independent of size, shape or geometry with the maximum surface area exposed and every component part seeing precisely the same temperature.

Comparison of quality of the solder joints is based on measurement of the solder joints nonlinearity of the current-voltage (C-V) characteristics.

Keywords: ***vapour phase soldering, solder joint, PCB surface finish,*** *nonlinearity, quality.*

1. INTRODUCTION

The goal of the work has been to find out if it is possible to make vapour phase reflowed solder joints of sufficient reliability and repeatability. Solder joints have been fabricated by soldering in vapour phase reflow oven. Four types of PCB surface finishes as well two types of lead-free solder pastes have been used for testing. The joints resistances have been measured by a four-point method firstly. PCB surface finishes have strong effect on quality and reliability of solder joints. Quality of solder joints is usually rated by measurement of electrical resistance, mechanical strength, X-ray diffraction and scanning electron microscope analysis. One of ways of the resistance evaluation is measuring of nonlinearity of C-V characteristics.

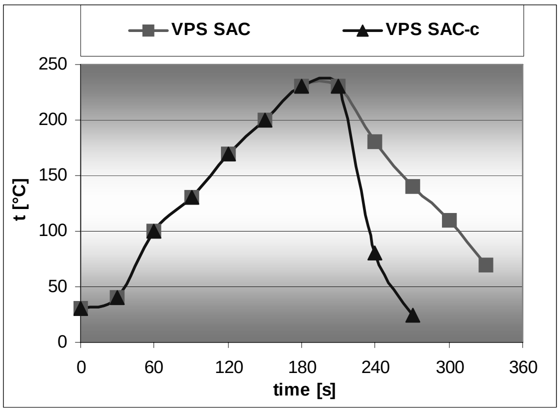
2. EXPERIMENTAL MATERIAL AND PROCESSING

Sn-Ag-Cu (SAC) alloys are leading candidates to serve as the electronics industry standard lead-free solders. Several alloys, whose compositions lie near a ternary eutectic point of approximately Sn-3.5Ag-0.9Cu are commercially available. As experimental material were used 2 different lead-free KOKI solder pastes containing: a) standard ternary alloy 96.5Sn3Ag0.5Cu – SAC (melting point 217-218°C, powder spherical particles size 20-38 μm, 11.5 % content of ROL0 flux type), b) quarternary alloy 90Sn3.5Ag0.5Bi6In – SABI (melting point 202-211°C, spherical particles size 20-38 μm, 11.5 % content of ROL1 flux type). Both compositions are known as low temperature alloys. Indium in SABI paste decreases melting point of solder, but problem of the indium type alloy is large deformation of structural shape due to heat. Both pastes were printed in the same screen printer under the same conditions.

There were also used four different PCB surface finishes (conductive PCB layer was Cu foil): electroless nickel/immersion gold (ENIG), hot air solder levelling (HASL), tin (Sn) and copper (Cu) finish. ENIG is known as widespread surface coating, which has these main properties: co-planar finish, lead free compatibility, wire bondable, nickel barrier mitigates copper dissolution, excellent wear resistance, shelf life (1 year), Sn-Ni intermetallic joint integrity, but there is also „black pad” interfacial fracture, which causes mechanical stress and corrosion. HASL has excellent wettability, good shelf-life, re-workable, good process window and adhesion, excellent solder joints, process control, but also poor coplanarity, surface oxidation and dark solder joints. Sn is well-known lead-free surface finish with these properties: good wetability and co planarity, possibility of repeated reflow, good process control, good adhesion, but problem is surface oxidation and creation of whiskers and dendrites. Cu finish is bare copper, if soldered in air atmosphere, it results to extensive oxidation of the finish.

Pattern of the PCB circuit (PCB substrate is conventional fiberglass laminate FR4) was designed to measure electrical and mechanical properties. For measurement of electrical properties were used 1206 zero resistance SMDs (jumpers, Sn surface finish) placed by Philips Topaz XII pick and place machine.

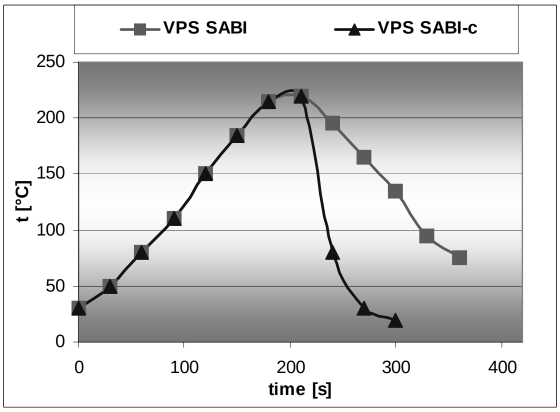
Reflow soldering was realized in experimental VPS oven that was developed at the Department of Technologies in Electronics [5]. Temperature distribution was measured by set of thermocouples spread out all over the top of PCB surface. Measurement of the temperature distribution is one from the most important items that determines quality of solder paste thermal treatment during reflow process. Vapour phase provides the best possible solder reflow conditions with only minimal temperature differences across the PCB (ΔT – is always close to zero as it is possible, but whatever the configuration of the PCB, always under 5ºC). Vapour phase is independent of size, shape or geometry with the maximum surface area exposed and every component part seeing precisely the same temperature. The cooling rate during the reflow of SAC alloys was found to be a critical factor in controlling the formation of large intermetallic compounds (Ag_3Sn plates) in SAC joints. At a high cooling rate, such as 1.5°C/s or higher, the formation of large Ag_3Sn plates can be kinetically suppressed during a reflow process. Providing a high cooling rate is often practical, especially in the case of vapour phase soldering. It was found that large Ag_3Sn plate formation was substantially reduced in controlled cooling rate during reflow that reported to possibility to control the growth of large Ag_3Sn plates during solidification of Sn [7]. This can be achieved by structure analyse based on X-ray diffraction and scanning electron microscope analysis [5].



Graph 1 Reflow profile of SAC paste.

Experimental VPS oven was developed because VPS soldering is currently the most flexible, simplest and most reliable method of soldering. It is ideally suited for all types of SMD components and base materials. It allows processing of all components without need of any complicated calculations or necessity to maintain temperature profiles, cooling rate can change from 0.5 to 10°C/s. The PCB moves because of the temperature gradient in the chamber. In this way is achieved temperature profile of solder paste. Reflow profiles of solder pastes are in Graph 1 (SAC paste) and Graph 2 (SABI paste), both with 2 cooling rates – 1.8˚C/s (VPS SAC, VPS SABI) and 5˚C/s (VPS SAC-c, VPS SABI-c).

Our results show on possibility of optional fast cooling system for minimising the growth of intermetallic phases [5]. PCBs were cooled up to 5°C/s. Fast cooling of solder joints is necessary due to the finer microstructure formation that results in improved mechanical and electrical properties.



Graph 2 Reflow profile of SABI paste.

3. MEASUREMENT OF NONLINEARITY OF THE CURRENT-VOLTAGE CHARACTERISTICS

3.1. Principle of measurement of nonlinearity of the C-V characteristics

Measurement of nonlinearity of the C-V characteristics lies in evaluation of intermodulation distortion (IMD). IMD is a common problem in a variety of areas of electronics and is caused by nonlinear behaviour of the signal processing being used. It is a popular measure of the linearity (nonlinearity) of amplifiers, gain blocks, mixers, and other components.

IMD is the result of two or more signals interacting in a nonlinear device to produce additional unwanted signals. These additional signals (intermodulation products, Tab. 1) occur mainly in devices such as amplifiers and mixers, but to a lesser extent they also occur in passive devices such as those found in many transmission systems. Two interacting signals will produce intermodulation products at the sum and difference of integer multiples of the original frequencies. For two input signals, the output frequency components can be expressed as: $n.f_1 \pm m.f_2$. The order of the intermodulation product is the sum of the integers $m + n$. The two tone (f_1, f_2) third order components

($2.f_1 - f_2, 2.f_2 - f_1, 2.f_1 + f_2$ and $2.f_2 + f_1$) are particularly important because unlike second order distortion, i.e. harmonic distortion at $2.f_1$ or $2.f_2$, they can occur at frequencies close to the desired/interfering signals and so cannot be easily filtered. Higher order intermodulation products are generally less important because they have lower amplitudes and are more widelyspaced. The magnitude of intermodulation products cannot be predicted easily but it is known that their amplitude diminishes with order.

1st order	f_1	f_2
2nd order	$f_1 + f_2$	$f_1 - f_2, f_2 - f_1$
3rd order	$2.f_1 - f_2$	$2.f_2 - f_1$
	$2.f_1 + f_2$	$2.f_2 + f_1$
	$3.f_1$	$3.f_2$
Etc.		

Tab. 1 Intermodulation products.

3.2. Measurement of nonlinearity of the C-V characteristics

Contact resistance should be measured by classic 4-wire Kelvin method. The principle of the method lies in elimination of voltmeter wires resistance, what results in exact values of measured voltage. On the other way, measurement of nonlinearity of the C-V characteristics (Fig. 1) is in electronics often used for quality and reliability prediction of solder joints.

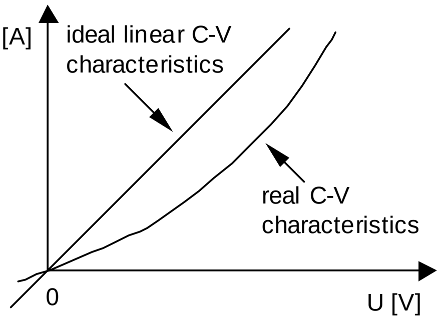


Fig. 1 C-V characteristics of resistance.

The general assumption for C-V measurement is that two tones are applied to a device under test – solder joint at frequencies of f_1 and f_2 (IN1, IN2). The difference in frequency between the two tones, termed the offset, is often between a few hundred kHz and a few MHz, although other values are possible. The nonlinear characteristics of the solder joint generates intermodulation products, among them is signal at $f_1 + 2.f_2$, which will be very close to the original tone f_1 and represent potential adjacent channel spurious signals.

The applied approach was method of evaluation of the IMD (Fig. 2). The distortion was evaluated with spectral analyzer unit HP 8560E. In principle, the intermodulation products are described by following equation:

$$f = n.f_1 + m.f_2 \qquad (1)$$

The frequencies: $f_1 = 4106\,\text{MHz}, n = 1$,

$f_2 = 150\,\text{kHz}, m = 2$.

Then the final measured frequency is:

$$f = 4406\,\text{MHz}.$$

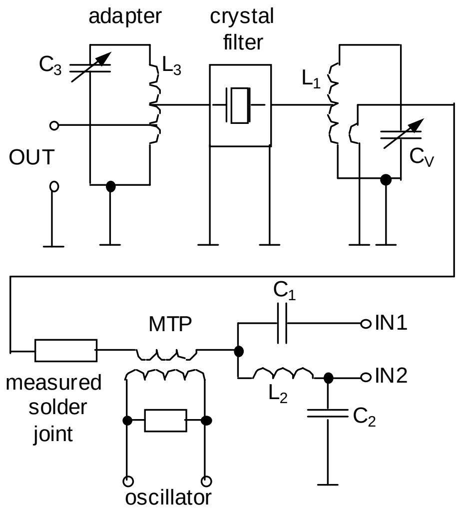


Fig. 2 Measuring tool of nonlinearity of the C-V characteristics.

In the measurement was used power measurement relative to 1 milliwatt – evaluation of nonlinearity in dBm. For evaluation of third order harmonics ($n + m = 3$) $U_c = U_3$ can be used equation (2) or evaluation with noise index NI (3):

$$U_C = 224.1000.10^{NI/20} \quad [\mu V] \qquad (2)$$

$$NI = 20.\log\frac{U_C}{U_1} \quad [\text{dBm}] \qquad (3)$$

Based on previous measurements of contact resistance by 4-wire Kelvin method (fast cooled solder joints exhibit lower resistance), nonlinearity measurements have been performed over fast cooled joints (specifically 4 solder joints and 2 SMD jumpers - because of sensitivity of the measuring tool). For every type of PCB surface finish and solder paste were measured 5 couples of SMD jumpers.

	NI [dBm]					
Surface finish	**1**	**2**	**3**	**4**	**5**	**Mean**
Cu	-137	-138	-135	-138	-137	**-137**
Sn	-138	-139	-137	-137	-138	**-137.8**
HASL	-137	-137	-136	-137	-138	**-137**
ENIG	-144	-145	-143	-143	-145	**-144**

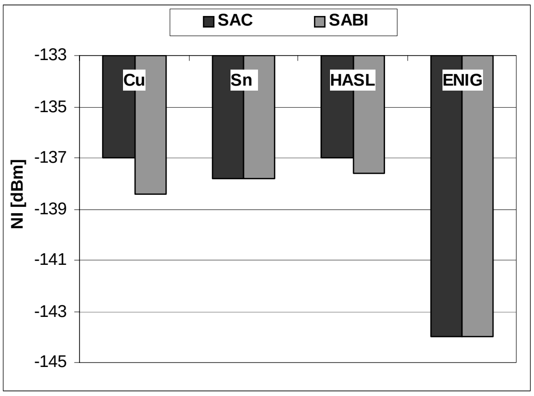
Tab. 2 Effect of surface finish on nonlinearity of C-V characteristics of fast cooled SAC solder.

From the measurement it is significant that nonlinearity measurement as a quality determination of solder joints is very hard to be acceptable for all types of surface finishes – see Tab. 2 and Tab 3.

All measured values of NI are on limit of the measuring tool. So the final mean results (Graph 3) show only differences between ENIG and other types of PCB surface finishes. Higher nonlinearity of Cu, Sn and HASL surface finishes was measured. For ENIG surface finish the nonlinearity of solder joint is insignificant (conductive path: $\mathrm{NI} \cong 145\,\mathrm{dBm}$). It means that the lowest nonlinearity was measured for ENIG finish.

	NI [dBm]					
Surface finish	**1**	**2**	**3**		**5**	**Mean**
Cu	-138	-138	-139	-139	-138	**-138.4**
Sn	-138	-139	-137	-137	-138	**-137.8**
HASL	-138	-138	-137	-138	-137	**-137.6**
ENIG	-143	-144	-145	-143	-145	**-144**

Tab. 3 Effect of surface finish on nonlinearity of C-V characteristics of fast cooled SABI solder.



Graph 3 Evaluation of nonlinearity of the C-V characteristics of surface finishes.

4. CONCLUSION

Measurement of nonlinearity of C-V characteristics is one of many methods of quality and reliability evaluation of solder joints. Ideal solder joint has linear dependency of current vs. voltage, but real relation is always nonlinear. The closer is the C-V characteristics of solder joint to the ideal linear C-V characteristics, the better. In our measurement ENIG surface finish has better C-V characteristics compared to other surface finishes, because NI of ENIG has the lowest value compared to NI of other tested surface finishes.

Acknowledgement

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BIOGRAPHIES

Alena Pietriková (Prof., PhD.) received PhD degree in Material Engineering from the Technical University of Košice in 1986. Since 2007 she has been professor at FEI TU of Košice in the branch of Electrotechnology and Materials. Her research interests include thick film technology and materials for electronics like ceramics, lead free solders and other materials for electronics.

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Juraj Ďurišin was born on 30.9.1982 in Košice. In 2006 he graduated (Ing.) at the Department of Technologies in Electronics of the Faculty of Electrical Engineering and Informatics at Technical University in Košice. Since 2006 he is working on his PhD degree at the Department of Technologies in Electronics FEI TU of Kosice, Slovakia. His scientific research is focusing on the vapour phase lead-free soldering.