Frequency Dependence of Impedance of Adhesive Joints

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Abstract

Electrically conductive adhesives have, in comparison with solders, significantly higher non-homogeneity of the structure, and therefore stability of electrical as well as mechanical properties of adhesive joints is lower than soldered ones. The impedance of the joints has been measured in wide frequency range (20 Hz to1 MHz and 300 MHz to 3GHz). Measurements have been carried out by two methods: impedance in the range 20 Hz to 1MHz has been measured by LCR meter HP 4284A. A special test board for assembly of 1 jumper (of the type 1206) by electrically conductive adhesive has been fabricated for this measurement. The measurements at the frequencies 300 MHz and higher have been carried out using a shielded high-Q triplate line. Specimens have been prepared on Teflon boards, a scalar analyzer Rohde Scwartz ESPI has been used for evaluation. Very low changes of impedances of the joints have been found in the range of 20 Hz to 1 MHz. Typical courses of real and imaginary components of joints impedances in the frequency range 300 MHz to 3 GHz are as follows: the real components have grown in consequence of a skin-effect and have dominated. The imaginary components have been very low. The task for the future research is to explain decrease of the resistance of the joints with growing frequency for two types of adhesives.

Introduction

Soldering processes based on Sn-Pb solders are currently under threat from the WEEE (Waste Electrical and Electronic Equipment) and RoHS (Restriction of Hazardous Substances) directives [1]. Different alternatives of these processes are investigated. There are two possible ways how to substitute environmentally dangerous soldering by the use of Sn-Pb solders: lead-free soldering or adhesive joining.

Electrically conductive adhesives (ECA) are highly promising materials. They consist of polymer binder and conductive filler. Different types of resins are used for binder, e.g. epoxy resin or silicone resin. Conductive filler consists of metal particles, usually balls with diameter of 6 – 8 microns or flakes with dimensions of 6 – 20 microns are used. Material of filler is usually silver, but other materials such as Ni, Cu covered by Ag film, Au or Pd have also been tested successfully. The practical use of some of these materials is limited by their high prices. Also polymer balls covered by thin conductive film, usually silver film, seem to be a good alternative to traditional metal particles.

Adhesives have several advantages compared to traditional soldering technologies. The use of ECAs instead of soldering is more environmentally friendly because adhesive joints are lead-free and do not require fluxes and flux cleaning. Adhesives are cured at lower temperatures than required for soldering and some types of adhesives do not require elevated temperature for curing, they are cured at the normal temperature. Therefore adhesive joining is less destructive for thermally sensitive components than soldering [2].

Basic Properties of Electrically Conductive Adhesives

Adhesive joining can also be used on non-solderable substrates and the joints with the good conductivity can be created also on the substrates, which are not perfectly cleaned [3].

Solders are always isotropically conductive materials, because solders are different types of metal alloys. Electrically conductive adhesives are of two basic types: adhesives with isotropic electrical conductivity (ICA) and adhesives with anisotropic electrical conductivity (ACA) [4]. Anisotropic adhesives have lower concentration of conductive particles and the joint creates at the higher temperature under mechanical pressure. Because the electrical conductivity of these joints is very good in the direction, which is perpendicular to the board and near to zero in other directions, these adhesive are also know as z-axis adhesives.

The use of ACA continuously grows. They are offered also as foils, which make possible joining of components with higher number of contacts with high effectiveness.

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Electrical properties of adhesive joints are, in comparison with the properties of soldered joints, worse. The contact electrical resistance is higher, and with respect to the structure of conductive adhesives and solders, noise and nonlinearity of adhesive joints are also higher [3][5][6]. The resistivity of adhesive joints to the static and dynamic mechanical loads is lower than the resistivity of soldered joints [1], [7], [8]. Adhesive joints, which has been aged at the higher temperature (e.g. 120 °C, 1000 hours), change their electrical and mechanical properties slightly only. Humidity has significant influence on the properties of the joints. The joints aged at the relative humidity near 100 % for 1000 hours have changed significantly their resistances and nonlinearity. Influence of combined climatic conditions (80 °C, 80 % RH, 1000 hours) on electrical properties of the joints is higher in comparison with the influence of the higher temperature, but significantly lower in comparison with the influence of high humidity [9].

It has been also found that adhesive joints can change their properties if they are loaded by DC current of higher intensity or by current pulses [10]. It is assumed that the current can cause migration of silver ions among conductive particles. Due to this migration some properties of the barriers can be changed. Migration of silver ions out of the joints to create a bridge between neighboring joints separated by a very narrow gaps has not been observed.

Description of a conductivity of a heterogeneous system is complicated by effects on surfaces of heterogeneities, which influence transmission and movement of carriers. Surface of a conductive particle is an area, where traps for carriers exist. Crossing of an electron from one conductive particle to another is influenced by an output work of the material of the matrix. Crossing is possible by different types of mechanisms, e. g. by thermoemission. In this case the level of the current, which passes through the barrier, is described by a Dushman-Richardson equation:

$$I = A(l - r)T^2 \exp(-\frac{\phi}{kT}) \qquad (1)$$

Where

$$A = 4\pi emk^2 / h^3 \qquad (2)$$

Here r – coefficient of reflection, ϕ - output work, T – temperature, k – Boltzman constant, e – charge of electron, m – mass of electron, h – Planck constant.

If the intensity of the electrical field is sufficiently high and the barriers among conductive particles very thin, tunneling of electron between neighboring particles can appear. Probability of tunneling of electrons through a barrier with the electrical potential V_0 and width a is given by the equation

$$T = \frac{1}{1 + \frac{V_0^2 \sinh^2 \alpha . a}{4E(eV_0 - E)}} \qquad \text{for } E < eV_0 \qquad (3)$$

Where

$$\alpha = \left[\frac{2m(eV_0 - E)}{\hbar^2} \right]^{1/2} \qquad (4)$$

T … coefficient of transmission of a particle with the energy E through the potential barrier. It follows from the equation (3) that the tunneling current does not depend on the temperature. However, the experiment in real conditions will be influenced by thermal dilatation of the binder and filler.

It can be found from equations (1) and (3) that the conductivity of electrically conductive adhesives will be nonlinear in principle.

Methods for the Measurement of the Impedance of the Joints

The measurement of impedances of adhesive joints is limited on the measurement of their resistances usually, because imaginary parts of impedances are very low in comparison with the real one. Value of the impedance of an adhesive joint is usually 5 to 15 mΩ for a contact of a 1206 resistor at the low frequency.

If the resistance of an adhesive joint is measured in at low frequencies, a four point method must be used to avoid errors caused by contact resistances.

The measurement of impedance at lower frequency range, 20 Hz to 1 MHz, is very simple. It has been carried out using an RLC meter HP 4284A. The specimen consists of the resistor with “zero” resistance (jumper) mounted on proper pads using electrically conductive adhesive. To minimize errors caused by conductive connections between the specimen and measuring equipment, these connections must be as short as possible. Therefore a special fixture with one jumper and two adhesive joints has been made. It has been clapped directly on connectors of the RLC meter.

The measurement of impedances of the joints at the high frequency range, 200 MHz to 3 GHz, is more difficult. The “high-Q” triplate stripline has been used for this measurement [11]. The cross section of this type of the resonator is shown in Fig. 1.

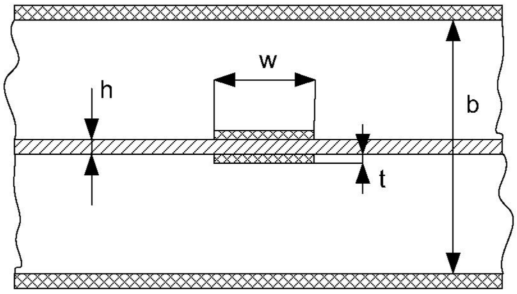

Fig. 1 Structure of a High-Q triplate stripline

The methodology of the measurement is based on utilization of a resonator with the stripline of the type TEM for the measurement of small impedances. The resonator is designed as at the ends opened resonator of the length (2n – 1)λ/2 with non-symmetrical stripline. In the middle of the stripline, where it is located the maximum of the resonant current, is a live conductor interrupted and the gap is bridged by the measured impedance. This bridge is joined with the line using electrically conductive adhesive. The electrical contact resistance is evaluated as the real part of impedance by the use of a following way: the Q-factor of the resonator with the adhesive joints and of the Q-factor of the resonator with the joints carried out by soldering (it has been found that the soldered joints have 10x to 100x lower resistance in comparison with the adhesive ones) are mutually compared.

Analysis of a measuring method

A symmetrical resonator with the length of nλ/2 (see Fig. 2a)

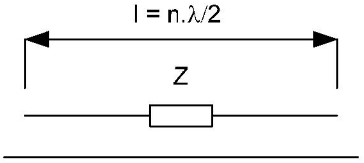

Fig. 2a Symmetrical resonator

has been simplified for following analysis on its one half as a λ/4 opened resonator of the length (2n-1). λ/4 with defined impedance of a shorted link (Z/2) - see Fig. 2b.

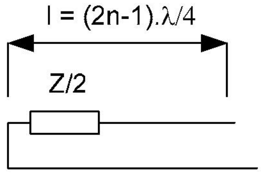

Fig. 2b Simplification for following analysis

The Q-factor of the resonator can be expressed by the use of generalized definition of the Q-factor on the basis of the ratio of total energy accumulated in the electromagnetic field of the resonator and the power losses in the resonator [11]:

$$Q = \frac{\omega W_a}{P} \tag{5}$$

It can be written for the power losses if Q-factor of the resonator with the minimum resistance is Q_0 and the resonator with the measured resistance has the Q-factor Q_M, and if the frequency would be changed slightly only:

$$\frac{1}{Q_0} = \frac{P_0}{\omega W_a} \tag{6}$$

$$\frac{1}{Q_M} = \frac{P_0 + P_M}{\omega W_a} \tag{7}$$

Where P_0 is the power lost in the resonator out of the specimen, P_M is the power lost in the specimen.

The power lost in the specimen can be expressed using the formula:

$$\frac{1}{Q_M} - \frac{1}{Q_0} = \frac{P_M}{\omega W_a} \tag{8}$$

The power lost in the real part R_1 of the impedance Z/2 can be written in dependence on the maximum voltage U_{max} in the resonator and the characteristic impedance Z_0 of the stripline:

$$P_M = \frac{R_1}{2Z_0} U_{MAX}^2 \tag{9}$$

Energy of the electromagnetic field in the resonator at the resonance can be expressed using the equation:

$$W_A = \frac{1}{4} \frac{l_1}{v} \frac{U_{MAX}^2}{Z_0} \tag{10}$$

Where l_1 is the length of the resonator (2n-1).λ/4,

v is the phase velocity in the resonator.

After substitution of (9) and (10) into (8) it will be found:

$$\frac{1}{Q_M}-\frac{1}{Q_0}=\frac{R_1}{Z_0}\frac{v}{\pi l_1 f} \tag{11}$$

The resistance of the shorted link in the λ/4 resonator can be calculated as follows:

$$R_1=\left(\frac{1}{Q_M}-\frac{1}{Q_0}\right)\frac{Z_0 \pi l_1}{\lambda} \tag{12}$$

After re-calculation for the resonator of doubled length the final formula for the calculation of the resistance R = $2R_1$ of the specimen is found:

$$R=\left(\frac{1}{Q_M}-\frac{1}{Q_0}\right)\frac{Z_0 \pi m}{2} \tag{13}$$

Where m is the length of the resonator:

$$l=m.\frac{\lambda}{2} \tag{14}$$

Measuring equipment

The measuring fixture has been made with stripline Shielded high-Q triplate line with the impedance Z0 = 50 Ω [12]. The inner conductor has been made on a PTFE (Taconic TLY 5A-C1) of the thickness 0,78 mm with Cu cladding 35 µm, the external conductor has been, with respect to the maximum mechanical stability of the fixture, milled of Cu bands.

The resonator has been as a two-port network connected to a scalar analyzer Rohde-Schwartz ESPI (see Fig. 3). Couplings on output striplines have been chosen very weak, transmission of the resonator in resonance has been about minus 40 dB. The Q-factor of the resonator without the specimen has been approximately 300 at the frequency of 300 MHz and approximately 600 for the frequency of 3 GHz. Resolution of this equipment for the measurement of the impedance has been about 2 mΩ. The impedances have been measured in the frequency range 300 MHz to 3 GHz.

Results of the measurement

Seven types of adhesives of the company Amepox have been tested: 55MN, 55MNa, AX70N, ER48, ER48a, AX20, AX20a. All these adhesives are one-part adhesives with isotropic electrical conductivity and with epoxy matrix and silver filler.

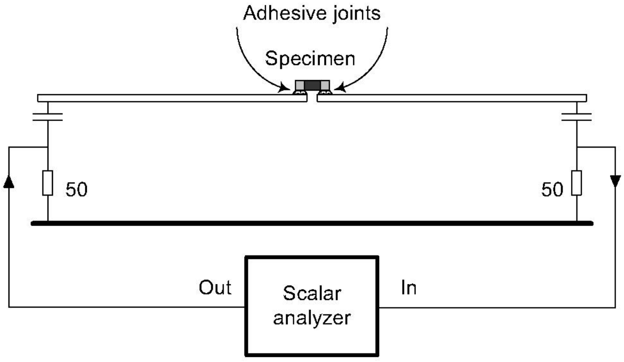

Fig. 3 Arrangement of the measurement

Typical courses of the impedances of adhesive joints in the frequency range 20 Hz to 1 MHz are shown in Fig. 4.

It has been found that the changes of the impedances of the joints are very low in this frequency range, imaginary parts of the impedances are negligible in comparison with the resistances of the joints, and therefore the impedances are approximately equal to the resistances of the joints (there are shown courses of the impedances of the joints fabricated of 5 types of adhesives in Fig. 4. Total number of types of adhesives under test has been 7. The courses of the impedances fabricated of adhesives of 2 types, which are not presented, have been of the same type. They are not drawn in the figure to improve its readability).

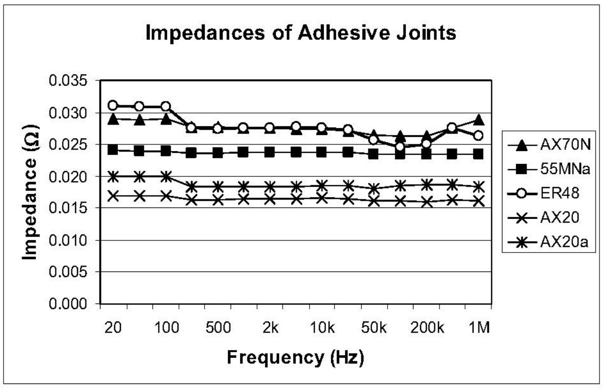

Fig. 4 Impedances of adhesive joints in the frequency range 20 Hz to 1 MHz

The measurements in the frequency range of 300 MHz to 3 GHz have been carried out using the high-Q triplate stripline. The impedances of the joints have been calculated as follows:

- The standard specimen has been fabricated at first. The standard has been carried out by mounting of the jumper of the same type on the test board using soldering. Considering the fact that the soldered joints have substantially lower impedances in comparison with adhesive ones, the impedance of the soldered jumper has been taken as a standard.
- The impedance of the jumper mounted using electrically conductive adhesive has been measured at different frequencies and at the same frequencies the impedance of the standard has been measured. The impedances of the adhesive joints have been calculated as follows:

$$Z_1 = \frac{Z_{TOT} - Z_{ST}}{2} \qquad (15)$$

WhereZ_1 … impedance of an adhesive joint, Z_{TOT} … impedance of the jumper mounted by adhesive (impedance of the jumper + 2 x impedance of the adhesive joint), Z_{SR} … impedance of the standard. It has been found that the imaginary part of the impedance is very low and therefore it can be neglected. Therefore it is possible to write:

$$Z_1 \approx R_1 \qquad (16)$$

The process of ascertaining of the joint impedance is shown in Fig. 5.

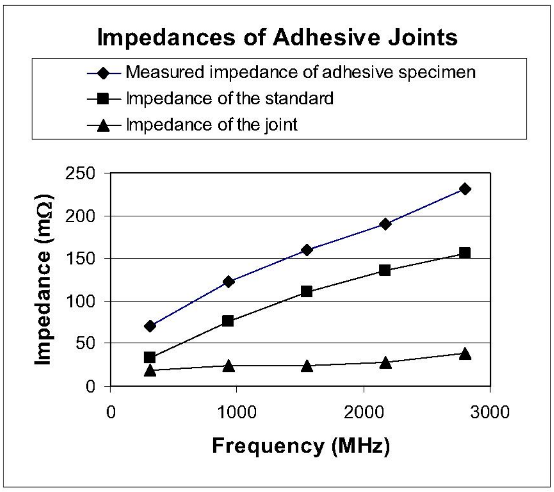

Fig. 5 Principle of calculation of the joints impedances

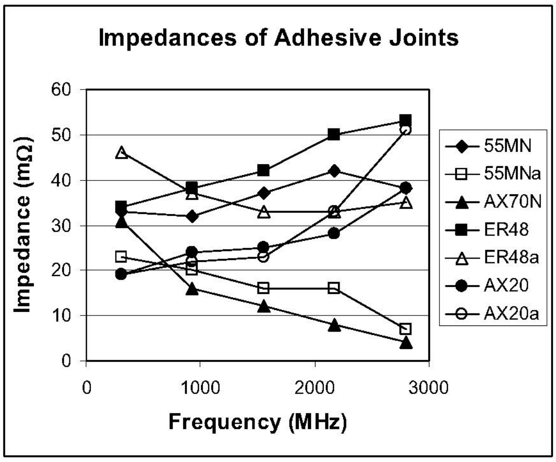

Fig. 6 Impedances of adhesive joints made of different types of electrically conductive adhesives

The frequency dependences of the impedances of the joints made of different types of adhesives are shown in Fig. 6.

Discussion of Results

It has been found that the frequency dependence of the adhesive joints is weak. With respect to the very low imaginary part of the impedance it is assumed that the growth of the impedances with growing frequency is caused by the skin-effect. The decrease of the impedance with the growing frequency for adhesives AX70N and 55MNa is unexpected. It could be caused by micro-cracks in adhesive joints, by other inhomogeneities, or by other reasons. Explanation of this decrease will be the goal of our future work in this field.

Conclusions

The frequency dependence of impedances of adhesive joints has been investigated in two frequency ranges: 20 Hz to 1 MHz and 300 MHz to 3 GHz. The imaginary parts of the impedances of the joints are very low in comparison with their real parts. Therefore the values of the impedances are approximately of the same value like the values of the resistances of the joints. It has been also found that the impedances of the joints do not change in the frequency range 20 Hz to 1 MHz. In the frequency range 300 MHz to 1 GHz the impedances mostly grow. The increase of the values of the impedances is caused by the skin-effect. It has also been found that the impedances of the joints made of two types of adhesives have decreased with growing frequency. It is assumed that the reason of such the course could be inhomogeneities in the material, but this assumption must be attested by following experiments.

It has been also found that the high-Q triplate stripline can be used for such the measurement, because it has sufficient sensitivity.

Acknowledgments

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