Resistance and Nonlinearity of Current-Voltage Characteristic of Conductive Adhesive Joints with Isotropic Conductivity: Tunnel Theory

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Abstract:
Electrical conductivity of electrically conductive adhesives is the most significant parameter these environmental friendly materials for adhesive assembly in electronics. Electrical conductivity of influenced by two types of resistances: by the constriction resistance and by the tunnel one. If adhesives with isotropic electrical conductivity are used for assembly, the tunnel resistance dominates in the total value of the resistance of an adhesive joint. Therefore, the adhesion joint is seen as an aggregate tunnel junction. The theory of conductivity of this junction emerges from the theoretical description of the tunnel phenomenon. Dependence of the tunnel junction resistance on the thickness of the insulating barrier is presented. Measurement of nonlinearity of the I-V characteristic of the tunnel junction is described as well. The results of this measurement make it possible to find the constant needed in the formula for calculating the joint resistance

INTRODUCTION

Electrically conductive adhesives are composite materials used in wide spectrum of applications in electronic and electrical industry [1]. These materials are mainly used for the assembly of electronic components of such types that do not allow the use of soldering. This applies, for example, to components that can be destroyed by the soldering temperature.

There are many properties of these materials that have to be tracked for their optimal use. These include, in particular, the electrical and mechanical properties, the climate resistance, the life time, the shelf time, and many others. Regarding the electrical properties of the adhesive joints, their resistance is most often observed. In addition to this parameter, however, the non-linearity of voltage-current characteristic of these materials is also inspected, because this parameter can limit using of adhesive assembly in some applications.

The total resistance of an adhesive joint consists of two components: the contact resistance and the resistance of the material of flakes. The total contact resistance consists of three components: the resistance of the contacts formed between the filler particles, the contact resistance between the filler particles and the outlet of the assembled component, and the contact resistance between the filler particles and the pad.

The resistance of every of these contacts can be of the type metal-metal or constriction resistance or tunnel one. The metal-metal resistance is neglected usually because it is very low. Therefore the total resistance of an adhesive joint is usually presented as the sum of the constriction resistance and the tunnel resistance [2], [3]. Which of these resistances dominates depends mainly on the type of the filler. For adhesives with anisotropic conductivity filled with the balls and adhesives with isotropic conductivity filed with particles of small dimensions the constriction resistance prevails, for isotropic adhesives filled with flakes the tunnel resistance dominates [4], [5]. The dominance of the tunnel resistance has also been confirmed by measurement of the Cu/Cu2O/Cu contact presented in [2]. Our work is focused on this type adhesives.

STRUCTURE OF ADHESIVE JOINT

An adhesive joint is formed by application of adhesive on a pad and placing of a lead of a component on this pad. The resistance of the joint consists of three parts (Fig. 1). The first one is the resistance between the component lead and adhesive

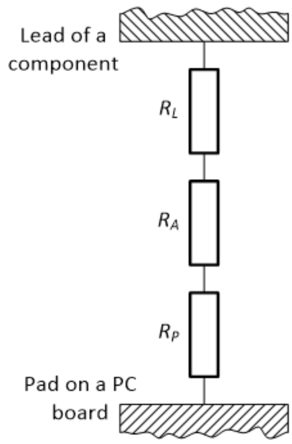

Fig. 1: Structure of adhesive joint

(R_L), the second part is the resistance of the conductive adhesive itself (R_A) and the third one is the resistance between the adhesive and the pad (R_P). The total resistance of the joint is:

$$R_{TOTAL} = R_L + R_A + R_P \qquad (1)$$

Isotropic conductive adhesives are usually filled with silver flakes. Silver is the most often used material of filler in general, because it has very high electrical conductivity. It was already mentioned that the concentration of these particles must be higher than a percolation threshold. Therefore, the filler concentration is high; it is in the range of 55 – 80 % b.w. usually. A conductive network formed of particles of filler provides electrical conduction.
Filler particles and the lead of a component form the contact RC. Following parameters influence quality of all contacts:

- Material of joined parts.
- Surface finish of joined parts.
- Oxidation and other types of chemical layers that cover surface of joined parts [1].

TUNNEL AND CONSTRICTION RESISTANCE

Contacts between connected parts may be of the following types:

- A contact metal-metal. This case occurs when e.g. two metal surfaces that are not oxidized and completely clean are pressed together.
- A contact of a constriction type (Fig. 2). Such the contact occurs if the conducting spot is substantially smaller than the cross-section of the connected parts (Fig. 3). The basic electrical parameter of this contact is the constriction resistance R_C that appears because of a constriction of the current flow through the circle contact spot with the diameter $2a$ (see Fig. 3). A typical example is when a spherical particle forms the contact with a planar surface.
- A contact of a tunnel type. This contact is formed between the connected parts separated by a very thin insulating barrier, e.g. by an oxide barrier. The basic electrical parameter of this contact is the tunnel resistance R_T.

The resistors R_L R_A and R_T in Fig. 1 are composed of the contacts of these three types. The contacts of the type metal-metal are very low and therefore they may be neglected in the overall balance of the joint resistance.

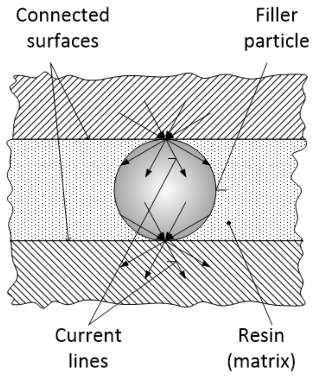

Fig. 2: Example of formation of constriction resistance

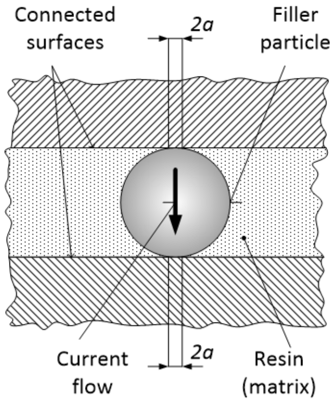

Fig. 3: Conducting spot having diameter *2a* caused by deformation of the ball and connected surfaces

Calculation of the constriction and the tunnel resistance is carried out in [2]. When two semi-infinite contact parts made of the material with the resistivity ρ are mutually connected by a small circular contact area with the diameter $2a$ (see Fig. 2) and the contact spot is substantially lower than the dimensions of these parts, the constriction resistance R_C occurs. The value of this resistance can be calculated using the formula:

$$R_C = \rho/2a \qquad (2)$$

The constriction resistance is applied especially for adhesives with anisotropic electrical conductivity, which are filled with conductive spherical particles.
The tunnel resistance is due to the tunneling between the conductive particles separated by the thin insulating layer. The tunneling occurs when the thickness of the insulating film is lower than 5 nm, mostly is the thickness of the insulating films in tunnel junctions lower than 2-3 nm. Tunnel resistance depends strongly on the thickness of the insulating film. Resistance of the tunnel junction RT can be calculated as:

$$R_T = \sigma/\pi a^2 \qquad (3)$$

Where σ … tunnel resistivity, a … radius of a circular tunnel contact.

THEORY OF CONDUCTIVITY OF AGGREGATED TUNNEL JUNCTION

The opinions on dominant mechanism that influences the total resistance of an adhesive joint differ.

In our opinion, the constriction resistance will dominate with adhesives having the anisotropic electrical conductivity. The filler particles are mostly metal balls or metalized balls made from plastic material. The area of contacts is formed by the pressure used during curing of adhesive and depends on the deformation of the filler particles and the surface of the pad or the component lead. It is low.

As for the adhesives with isotropic conductivity they are mostly filled with flakes that are substantially larger, in terms of area, than the particles used as filler for anisotropically conductive adhesives. The flakes are, unlike the balls used, other type of the particles. They are more or less two-dimensional with a larger area than the cross section of the balls, whereas the balls are three-dimensional particles. Therefore it is a higher number of contacts between them than between the balls and the contacts do not have the character of point contacts. Therefore, it is possible to consider that the tunnel resistance dominates here.

It was also observed alignment of filler particles in isotropic adhesives after mounting of the component lead. Whereas the particles are oriented randomly in the adhesive, after mounting of a component lead they alignment on the surface of the lead and pad and likewise the particles in all the layers between the pad and the component lead are also oriented.

Examination of influence of this alignment effects on the adhesive joint resistance was examined in [3]. It was found using a simulation that the resistivity increases after flakes orientation in one layer on the bottom and on the top planes, then slowly growths and saturates approximately for the three layer of the flakes. Method of application of adhesive can also influence alignment of filler flakes. In our experience, the highest influence on alignment of filler particles has stencil printing.

This fact simplifies the simulation of the resistance of the adhesive joint significantly. If it will be assumed that the flakes are approximately oriented in parallel with the pad and lead surface, they are connected in 3D net in parallel and serial combinations only. It is assumed that the tunnel conductivity dominates in all contacts, in means in the contacts between the flakes mutually and between the flakes and the lead of the component and the pad. Then it is possible to replace the network formed by the series-parallel combinations of tunnel junctions with one aggregate conductive joint (ACJ) having the VA characteristics of a tunnel junction. Properties of such the component are interesting for a user and on examination of these properties focuses our theory. Such an approach to describing conductivity of the adhesive conductive joints made of the adhesive with isotropic conductivity is entirely new.

The investigation of properties of ACJ is based on general description of properties of a tunnel junction formed between similar electrodes. For intermediate level of the voltage V between the electrodes, it means for the voltage $0<V<\phi_0$, where ϕ_0 is the work function of the metal, the current density J flowing through the junction was derived by Simmons [6] and further elaborated by Takano [7]. According to the [6] this current density J can be calculated using a formula:

$$J = J_0\{(\phi_0 - eV/2).\exp[-A(\phi_0 - eV/2)^{1/2}] - (\phi_0 + eV/2).\exp[-A(\phi_0 + eV/2)^{1/2}]\} \quad (4)$$

Where $J_0 = e/2\pi hs^2$, e … electron charge, h … Planck's constant, s … thickness of the tunnel barrier, $A = (4\pi s/h).(2m)^{1/2}$, m … electron mass (effective), ϕ_0 … work function of the metal, V … voltage across the film.

Formula (7) was simplified by Takano [7] as follows: Provided that the voltage $V \leq 0.1$ V and $eV << \phi_0$, the first term in parenthesis { } of the equation (4) was simplified:

$$\phi_0 (1-\nu/2).\exp[-k(1-\nu/4-\nu^2/32)] \quad (5)$$

Where

$$\nu = eV/\phi_0 \quad (6)$$

$$k = A.(\phi_0)^{1/2} \quad (7)$$

Condition $eV << \phi_0$ is satisfied because for the voltage $V \leq 0.1$ V the value of eV is 0.1 eV and the work function ϕ_0 of Ag is 4.64 eV, of Au 5.31 and Cu 4.48 eV.

In the same way, the second term in parenthesis { } of the equation (4) was simplified.

Then, under assumptions that the thickness of the tunnel barrier s is in the range of 0.4-2.0 nm, $k\nu/4 < 1$ and $k\nu^2/32 << 1$, the exponential part of the equation (5) was expanded in Taylor series to ν. After neglecting terms ν^4 and higher, the equation (4) is changed as follows:

$$J^* = J_0\phi_0\{(k/2-1)\nu + 1/32(k^3/6-k^2/2-k)\nu^3\}.\exp(-k) \quad (8)$$

Conditions for this simplifying are satisfied, the value $k\nu/4$ is in the range of 0.0095-0.14 and $k\nu^2/32$ in the range of $2.56 \cdot 10^{-5}$-$3.84 \cdot 10^{-4}$ for Ag and similar values were also calculated for Au and Cu.

The formula (8) describes the current density that flows through the tunnel junction in dependence on the work function of the metal, the voltage between the electrodes of the tunnel junction and the thickness of the tunnel barrier. It is assumed that the value of the voltage is lower or equal 0.1 V and that it is the DC voltage.

NONLINEARITY OF AGGREGATED TUNNEL JUNCTION

Let us now study the situation that the tunnel junction will be powered by the sinewave voltage $V = V_0 \sin\omega t$. The parameter ν will be now calculated according to the formula:

$$\nu = (eV_0 \sin\omega t)/\phi_0 = (eV_0/\phi_0).\sin\omega t = \nu_0.\ \sin\omega t \qquad (9)$$

Where

$$\nu_0 = eV_0/\phi_0 \qquad (10)$$

After Fourier transform of (8) derived Takano [7] approximate formula for the current density J^*:

$$J^* = J_0\phi_0\,[\{(k/2-1)\,\nu_0 + 3/128(k^3/6-k^2/2-k)\,\nu_0^3\}.\sin\omega t - 1/128(k^3/6-k^2/2-k)\,\nu_0^3.\ \sin 3\omega t].\exp(-k) \qquad (11)$$

In equation (11):

$$(k/2-1)\,\nu_0 \gg 3/128(k^3/6-k^2/2-k)\,\nu_0^3 \qquad (12)$$

Then it is possible to neglect the term $3/128(k^3/6-k^2/2-k)\,\nu_0^3$ and to calculate the third harmonic distortion *THD* obtained by dividing the third harmonics by the first harmonics value:

$$THD = \nu_0^2\,(k^3/6 - k^2/2 - k)/(128\,(k/2 - 1)) \qquad (13)$$

After fitting for ν_0 and k the folowing equation will be obtained:

$$THD = e^2V_0^2/(128\ \phi_0^2).(K^2s^2/3 - Ks/3 - 8/3 - 16/(3Ks - 6)) \qquad (14)$$

Where

$$K = (8\pi/h).m^{1/2}\phi_0^{1/2} \qquad (15)$$

The dependence of the *THD* on the thickness s of the tunnel barrier is presented in Fig. 4. Sometimes the third harmonic distortion is expressed in dB as the third harmonic index *THI*:

$$THI = 20.\log THD \qquad (16)$$

The dependence of the *THI* on the thickness s of the tunnel barrier is presented in Fig. 5.

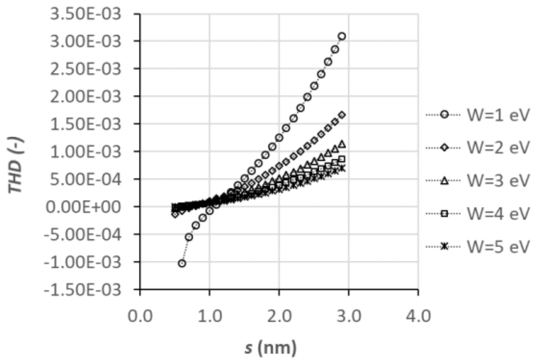

Fig. 4: Dependence of *THD* on thickness of the tunnel barrier for different work functions.

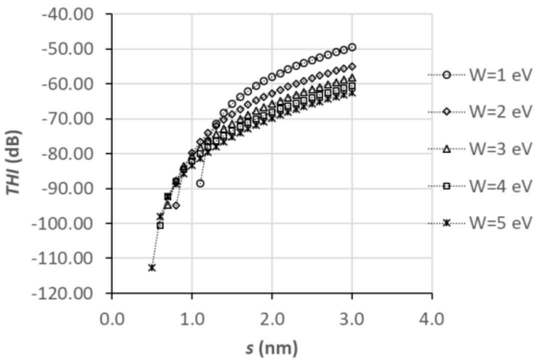

Fig. 5: Dependence of *THI* on thickness of the tunnel barrier for different work functions.

RESISTANCE OF AGGREGATED TUNNEL JUNCTION

The resistance of the tunnel junction R_T is exponentially dependent on the thickness of the tunnel barrier [7]:

$$R_T = \beta.\exp\,(s/b) \qquad (17)$$

Where β, b … constants, s … thickness of the tunnel barrier.

When the thickness of the tunnel barrier of the junction having the resistance R_1 is s_1 and the junction with the resistance R_2 will have the thickness of the tunnel barrier s_2, the ratio of the resistances R_1 and R_2 will be:

$$R_{T1}/R_{T2} = \exp\,((s_2-s_1)/b) \qquad (18)$$

When the *THD*1 and *THD*2 will be measured for the junctions 1 and 2, then it is possible to calculate the thickness of the tunnel barrier s_1 and s_2, using (17) and (18), and the difference $(s_2 - s_1)$. Then it is possible to calculate the constant b as follows:

$$b = (s_2-s_1) / \ln(R_1/R_2) \qquad (19)$$

Using this constant it is possible to calculate the constant β in equation (17).

In summary, to describe the basic parameters of the adhesive joint, it means of the aggregated tunnel junction in this theory, it is first necessary to measure the resistance R_T and *THD* (*THI*) of the joint before aging and after aging. Aging can be, for example, in increased humidity. The thickness of the tunnel barrier is calculated of the *THD* (*THI*). Then, using the equation (18) is calculated value of the constant *b*. When the constant is known, it is possible to use the relation (17) to calculate the constant β. This relationship can then be used to study variations of the adhesive joint resistance, depending on the changes in the thickness of the tunnel barrier.

CONCLUSION

A new theory of conductivity of adhesive joints based on the assumption that the tunnel resistance in adhesives with isotropic electrical conductivity dominates was presented. It was shown that an adhesive joint formed of this type of adhesive has nonlinear VA characteristics. Due to the alignment of the filler particles in parallel with the plane of the pad and the contact of the component an adhesive joint can be considered as a component with a tunnel characteristic. Such the component was named aggregated tunnel junction (*ATJ*). Parameters of this junction are investigated.

Analysis of the current density flowing through the junction when it is powered by the voltage V is provided. The measurement of *ATJ* nonlinearity can be performed by feeding the joint by a sinusoidal voltage and by measuring the third harmonics voltage generated at the joint. The measurement of nonlinearity informs about thickness of the tunnel barrier and makes possible calculation of the joint resistance in dependence on the thickness of the tunnel barrier of the *ATJ*. Such the knowledge can be used for analysis of reasons of changes of the joint resistance e.g. during climatic treatment.

REFERENCES

[1] Yim, M. J.: Review of Electrically Conductive Adhesive Technologies for Electronic Packaging, Electronic Materials Letters, Vol. 2 No. 3 (2006), pp. 183-194Eric C. Le Ru and Pablo G. Etchegoin: Principles of Surface-Enhanced Raman Spectroscopy, Elsevier B.V., 2009.

[2] Bin, Su: Electrical, Thermomechanical and Reliability Modeling of Electrically Conductive Adhesives, Doctoral thesis, Georgia Institute of Technology, pp. 24-26, 2006.

[3] Li, L., Morris J. E.: Electrical Conduction Models for Isotropically Conductive Adhesive Joints, IEEE Trans. on Electronics Packaging Manufacturing, Vol. 22, (1997), pp.3-8.

[4] Yim, M. J., Li, Y., Moon, K., Paik, K. W. Wong. C. P.:Review of Recent Advances in Electrically Conductive Adhesive Materials and Technologies in Electronic Packaging, Journal of Adhesion Science and Technology, Vol. 24, No. 14, pp. 1593-1630.

[5] Daoqiang, Lu, Quinn K. Tong, Wong, C. P.: Conductivity Mechanism of Isotropic Conductive Adhesives (ICA‘s), IEEE Trans. on Electronics Packaging Manufacturing, Vol. 22, No. 3 (1999), pp.223-227.

[6] Simmons, J. G.: Generalized Formula for the Electric Tunnel Effect between Similar Electrodes Separated by a Thin Insulating Film, Journal of Applied Physics, Vol. 34, No. 6, (1963), pp. 1793-1803.

[7] Takano, E.: Contact Current Distortion Due to the Tunnel Effect, Proc. 46th Holm conference on electrical contacts, Chicago, USA, 25-27 Sept. 2000, pp. 169-175.

[8] Holm, R.: Electric contacts, theory and application. 4th ed., 1967, New York, Springer Verlag.

[9] Hansma, P. K.: Inelastic Electron Tunneling, Physics Letters (Section C), Vol. 30C, No. 2, 1977, p. 163.