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Usability of Electrically Conductive Adhesives for Power Components Assembly

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Abstract—**Sensitivity of the resistance of adhesive joints formed of frequently used electrically conductive adhesives with isotropic electrical conductivity (ICAs) to loading with short current pulses of high amplitude has been examined. It has been found that the resistance increases with the increase of pulses amplitude and with the temperature at which experiments are carried out. It is assumed that the increase is caused by the increase of the thickness of insulating barriers between particles caused with chemical products originated by temperature degradation of resin is surroundings of contacts between particles. Heating of contacts is caused with the passing current.**

Keywords-electrically conductive adhesives; adhesive joint; joint resistance

I. INTRODUCTION

Electrically conductive adhesives are environmental friendly joining materials used in electronics assembly for many years. With respect to their price, which is comparable with the price of silver very often, these materials are used for special applications such as assembly of temperature sensitive components or assembly of components with fine pitch and ultra-fine pitch packages.

Mechanical as well as electrical properties of adhesives are mostly worst in comparison with properties of lead-free solders. Price of these materials is higher than price of solders. Different types of thermoplastic and thermosetting resins are used as insulating matrix of electrically conductive adhesives. Used resins are of two types, one-component or two component ones. The most used type of resin is epoxy resin, but silicon, polyimide and other types are also used.

Conductive component of electrically conductive adhesives is formed by electrically conductive particles, which are uniformly disseminated in adhesive. The mostly used particles are silver ones, but other metals, such as gold, nickel, palladium or copper covered with silver film is also used. Some adhesives are filled with particles fabricated of plastic materials covered with a conductive metal film. Main advantage joined with application of these materials is a possibility to use plastic materials with such mechanical properties, which make elastic deformation after curing of adhesive possible. This deformation causes the permanent mutual pressure between neighbouring particles and improves quality of contacts between them.

Conductive particles added into conductive adhesives are micro particles. Their dimensions are 5 μm to 15 μm usually. Two basic shapes of particles are used: flakes for adhesives with isotropic electrical conductivity and balls for adhesives with anisotropic electrical conductivity. Instead flakes and balls other shapes of particles have also been tested. Adhesives filled with carbon nanotubes have been formed, adhesives filled with mixture of micro and nanoparticles of different types like balls, wires or tubes have also been tested. It has been found that electrical properties of adhesives filled with a mixture micro and nanoparticles are worst in comparison with adhesives filled with microparticles only, if content of silver in adhesives is the same. The reason is that the number of contacts between particles, whose resistance represents a significant part of the total resistance of an adhesive, has been increased this way.

Very good electrical properties have been found for adhesives filled with particles or alloys with low melting point after such temperature processing, which has caused sintering of particles [1]. Sintering of conductive particles in adhesive is a basic condition for achievement of electrical properties comparable with electrical properties of solders. However, the sintering temperature must be low to avoid to temperature damage of resin or joined components or substrates, on which components are assembled.

The curing temperature of adhesives of an epoxy type is between 120 ^{o}C to 180 ^{o}C, the curing time between 5 minutes to 20 minutes. Curing of adhesives can be carried out using hot air, or in an oven. If such the curing temperature is too high, adhesives cured at the standard temperature (24 ^{o}C) with the curing time 24 hours or 48 hours can be used.

Adhesive assembly is mostly used for mounting of low power components. There are no experiences with adhesive assembly of power components. These components are loaded with the high current intensity or with the high current pulses.

It is not assumed that adhesive assembly would substitute classical soldering of power components in power electronics assembly. Possible applications are joined with repairs on boards, whose dismounting is troublesome and where it is not possible to use soldering without dismounting of a board. The use of adhesive cured with hot air can decrease the repair time significantly.

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The resistance of an adhesive joint depends on quality of an insulating barrier between filler particles significantly [2], [3]. Thickness of this barrier can be changed by diffusion of silver ions caused with current pulses. The goal of the work has been to find how the resistance of adhesive joints, formed of frequently used electrically conductive adhesives with isotropic electrical conductivity (ICAs), is sensitive to loading with short current pulses of high amplitude. High sensitivity of the joints resistance to the loading with the current pulses would suspend the use of this type of assembly for power electronic devices.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Samples Preparation

Three types of ICAs based on bis-phenol epoxy matrix filled with silver flakes have been used for experiments. Basic parameters of adhesives have been as follows:

- Formulation A: Silver concentration 60 % b.w., curing schedule 180 °C/6–10 min, 200 °C/3-4 min, electrical resistivity (4-5,5).10^{-4} Ωcm.

- Formulation B: Silver concentration 75 % b.w., curing schedule 140 °C/30 min, 170 °C/5 min, electrical resistivity (2-5).10^{-4} Ωcm.

- Formulation C: Silver concentration 66 %, curing schedule 150 °C/120 min, 180 °C/15 min, 200 °C/5 min, electrical resistivity (6-30).10^{-4} Ωcm.

Jumpers - resistors with the “zero” resistance (measured resistance of these resistors has been 14 mΩ) of the type 1206 with Pd surface finish have been mounted on test PCBs. ENIC surface finish has been used for pads. Adhesive assembly has been carried out using a semi-automatic assembly machine SMT M01A. Adhesives have been applied by dispensing.

B. Powering with Current Pulses

Rectangular current pulses with amplitudes of 5 A or 10 A, with the frequency of 100 Hz and the width of 100 μs have been used for loading. RMS current has been 0,5 A or 1,0 A, respectively. Total power loss on an adhesive joint depends on the joint resistance. For the joint resistance between 15 to 75 mΩ it has been 3,75 to 18,75 mW for the pulses with the amplitude 5 A or 15 to 75 mW for the pulses with the amplitude 10 A.

Warming-up of the joints has been measured, when pulses have been applied, using Cu-constantan thermocouples. It has been found that the warming-up is low; it has not been higher than 10 °C. With respect to the curing temperature of adhesives it is possible to assume that changes caused with this warming up are insignificant for changes of properties of adhesive joints.

C. Climatic Conditions of the test

It has been assumed that current pulses will support migration of silver ions, which can change quality of contacts between silver particles, and this way will modify electrical properties of these contacts. With respect to very small area of these contacts and the high amplitude of the current pulses, the current density in the contacts is very high during the current pulses [4]. Therefore it is possible to assume that some particles will be sintered. Therefore values of electrical parameters of adhesive joints such as the joint resistance, nonlinearity of the joint current vs. voltage characteristic and joint noise should decrease.

On the other hand, if the temperature of contacts between conductive particles inside adhesive, caused with the loading of the joints with current pulses, would be too high and would influence matrix resin for the longer time, resin will be damaged and the decomposition product could decrease contact quality and make worse its electrical properties.

Many electrical apparatuses are used at the higher temperature. Therefore the current pulses have been applied at the ambient temperature and at the temperature of 125 °C. Powering at the higher temperature has been carried out in a climatic chamber WTB Binder.

D. Time of Loading with Current Pulses

A significant parameter, which influences changes of properties of adhesive joints caused with current pulses, is the time of loading. The joints have been loaded for 45 minutes and for 90 minutes. Energy supported to adhesive joints for different conditions of loading are shown in Tab. 1.

TABLE I.

Time of loading (min)	**Pulse amplitude (A)**	**Joint resistance (mΩ)**	**Supported energy (J)**
45	5	15	10,1
45	5	75	50,7
90	5	15	20,3
90	5	75	101,4
45	10	15	40,5
45	10	75	202,5
90	10	15	81,0
90	10	75	405,0

It is necessary to complete that the resistance of the joints has changed during loading with the current pulses. The supported energy presented in Table I. is energy calculated for the starting values of the joints resistances. Real energy has been mostly higher.

E. Measurement of Resistance of Adhesive Joints

The resistance of adhesive joints has been in the range of 15 to 75 mΩ. Therefore the measurements have been carried out using a four-terminal probe.

A Precision LCR meter HP 4284A has been used for the measurement of the resistance. The measuring frequency has been 1 kHz to avoid problems with possible thermochemical voltage generated on the contacts.

Every presented value has been calculated of 21 measured values. Mathematical smoothing of measured values has been carried out as follows: at first two highest and two lowest measured resistances have been deleted and at second the

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average of remaining values has been calculated. All measurements have been carried out after cooling of measured samples to the standard temperature.

F. Experimental Results

Experimental results are presented in following figures.

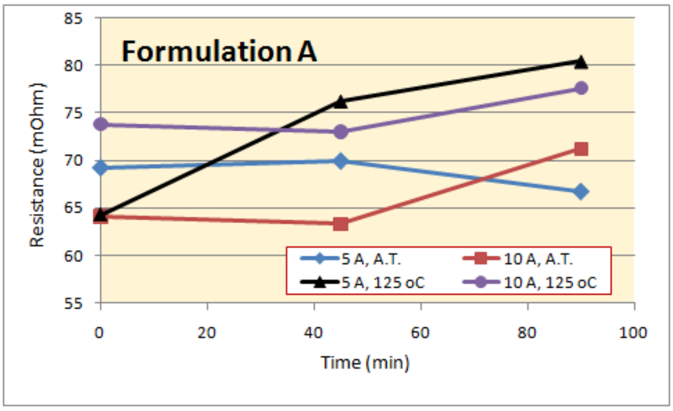

Figure 1. Resistance of adhesive joints formed of formulation A during loading with current pulses with amplitude 5 A and 10 A. Abbreviation A.T. means that loading has been carried out at the ambient temperature.

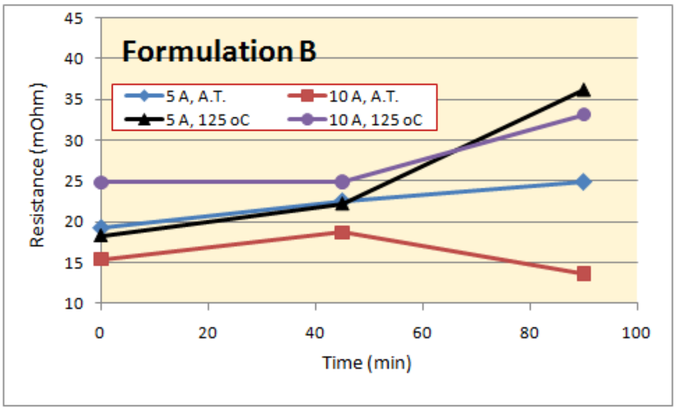

Figure 2. Resistance of adhesive joints formed of formulation B during loading with current pulses with amplitude 5 A and 10 A. Abbreviation A.T. means that loading has been carried out at the ambient temperature.

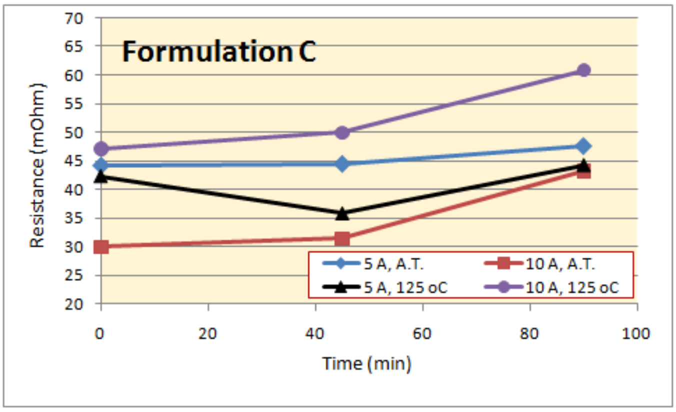

Figure 3. Resistance of adhesive joints formed of formulation C during loading with current pulses with amplitude 5 A and 10 A. Abbreviation A.T. means that loading has been carried out at the ambient temperature.

III. DISCUSSION OF RESULTS

Measured results have had big dispersion, especially for formulation C. The reason is that adhesives have been applied by dispensing. The use of dispensing gives worst results in repeatability of the joints resistances than stencil printing.

Repeatability of the joints resistances, when adhesive is applied by dispensing, depends on stability of adhesive viscosity during the dispensing process strongly. Adhesive viscosity has to be constant for all the time of adhesive application. With respect to the high number of test boards, on which the jumpers have been mounted using adhesive assembly, the condition of constant adhesive viscosity has not been accomplished. Viscosity depends on the adhesive temperature as well. Therefore a significant condition of high quality dispensing process is stability of the temperature of adhesive and test board.

Results of measurements, which have been significantly different from the results of measurements of other adhesive joints, formed of the same type of adhesive and loaded by the same way, have been deleted using mathematical smoothing. Therefore influence of these values on the final results has been minimal.

Decrease of the joint resistance is caused with additional curing of adhesive matrix, which has not been sufficiently cured during the standard curing process. This additional curing causes shrinkage of resin and decrease of the total volume of the adhesive joint [5]. Due to the fact that the number and volume of filler particles in adhesive are constant, these particles are more and more mutually overpressed.

Some barriers between the particles are broken and quality of contacts between them increases. Other reason, which can contribute to improvement of the contact resistance, is migration of silver ions [6]. This migration is increases if the amplitude and frequency of the current pulses increases. On the other hand, it seems that influence of migration of silver ions, which improves the joints conductivity, is smaller in comparison with the origin of new, probably chemical, layers, which worse conductivity of contacts between particles. These layers are created as a result of temperature destruction of resin. This process is followed with release of products of these reactions. These products create new chemical barriers between particles and worse quality of contacts between them.

Deformation of resin in surroundings of conductive particles at the time when the joints are loaded with the current pulses and are heated can be other reason of downgrade of contact conductivity. The dimensions of particles decrease after their cooling to the ambient temperature and quality of contacts between them decreases.

Basic mechanism of electrical conductivity between two conductive particles, separated by an insulating barrier, is tunneling [7]. This process depends on the thickness of an insulating barrier significantly. Thickness of an insulating barrier, which makes tunneling possible, is approximately 2 to 3 nm. The resistance of the tunneling contact depends on this thickness exponentially. Therefore small increase of thickness of this barrier causes high increase of the tunneling resistance of the contact.

Courses, which have been measured for formulation A show that the curing process of adhesive has been sufficient. In the case, that this process would be insufficient, the value of the joint resistance falls to some minimum after some time of loading with the current pulses and then starts to rise.

The course of the joints resistance for loading of the joints with the pulses of the amplitude 5A shows weak growth in the first part of loading and marked fall in the second part of loading. The weak growth can be explained with tolerances of measured values, marked fall with partial sintering of conductive particles or with the fact that some insulating barriers have been broken with the current pulses. Conductivity of the conductive net inside adhesive has increased, because a tunneling mechanism of conductivity has been substituted with a mechanism of a phonon-electron interaction. This mechanism is typical for conductivity in metals and is more intensive in comparison with the tunneling. The result is that the resistance of the adhesive joint decreases [8].

The course of the resistance of the joints loaded with the current pulses with the amplitude of 5A at the temperature of 125 ^{o}C shows that the adhesive is fully cured. Combination of the load and high temperature causes degradation of adhesive. The result is the increase of the joint resistance.

Formulation B shows that the curing process has been sufficient, because all samples show downgrade of the joint resistance after loading with the current pulses at the normal temperature as well as at the temperature of 125 ^{o}C. One sample only has shown improvement of the electrical resistance after the longer time of loading. It is surprising that it has been a sample loaded with the pulses having the amplitude of 10 A. The primary resistance increase has been probably caused by the temperature dilatation of the conductive adhesive, decrease of the joints resistance, which has followed this initial resistance increase, can be caused with the partial sintering of filler particles of conductive adhesives. It seems that the formulation B has been a little bit over-cured.

Formulation C has shown a weak increase of the joints resistance in the primary part of loading with exception of the joints loaded with the pulses having amplitude of 5A at the temperature of 125 ^{o}C. It has been found a small additional curing for these joints. This curing has been followed with the decrease of the joints resistance. It has been also found that loading of the joints for the longer time has caused increase of the joints resistance. It is again assumed that the reason of this increase is degradation of adhesive matrix.

The results have shown that the adhesives have been mostly cured on a proper level. It has been surprising, because it is possible to meet with insufficient curing of adhesives very often; in spite of they are cured in accordance with recommendation of a producer. The reason is that the insufficient curing extends the life time of adhesive. Several starting years of the use of such the way cured adhesives they are additionally cured and their electrical as well as mechanical quality improves. After this time the adhesive starts to worst its properties.

IV. CONCLUSIONS

Measurement of influence of current pulses of high amplitudes on the joint resistance affords information significant for adhesive assembly of power electronic components. It has been found, is some cases that conductivity of adhesive joints grows for some time after the start of current pulse loading, but after this time conductivity decreases. In other cases the conductivity decreases immediately after the start of loading. The reasons of these changes are as follows: migration of silver ions in adhesive or disruptive breakdown of insulating barriers between silver particles improves joint conductivity. Degradation of resin in surroundings of point contacts between filler particles can cause forming of new insulating barriers in these contacts and cause downgrade of electrical conductivity of a joint. Which of these processes is dominating depends on the type of binder, on the level and time of curing, on the level of pulse load and on the type of adhesive.

It has been found that the use of adhesive assembly for power electronic components is not reliable due to changes of electrical parameters of adhesive joints caused with their loading with the current pulses.

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