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1/f Noise as a Diagnostic Tool to Investigate the Quality of Isotropic Conductive Adhesive Bonds

L. K. J. Vandamme, Marie Geneviève Périchaud, E. Noguera, Yves Danto, and Ulrich Behner

Abstract—Reliability assessment of conductive adhesive bonds by thermo-cycling up to 830 cycles is time consuming, and does not give much information about the details of the onset of degradation. There is a need for faster tests giving more details about degradation. In this paper, low frequency noise of such contacts is investigated. 1/f Noise stems from conductance fluctuations. The observed voltage noise is enhanced due to current crowding in the electrical contacts on a microscopic scale. In this research contact bonds were made and compared of isotropic conductive adhesives from three suppliers. The 1/f noise of the contact resistance can be interpreted in terms of a multispot contact behavior. We investigated the relative noise C versus contact resistance R in two ways:

- 1) after an increasing number of thermo-cycles;
- 2) after increasing mechanical stress.

The results often show an increase in relative noise of three orders of magnitude for poor quality polymer bonds. A maximum increase of one order of magnitude is observed for the best quality conductive adhesive. The contact resistance increases by a factor 1.7 and not more than 1.14 for the poor and best quality bonds, respectively. From the analysis based on a noise model for multispot contact, the onset of delamination can be characterized as a reduction in electrical contact area A_e . The relative noise is proportional to $A_e^{-5/2}$. The surprising result is that samples submitted to a mechanical stress show pictures similar to thermo-cycled samples. Thermo-cycling with less than 200 cycles leads to less noise, an increase in electrical contact area, and hence a contact improvement. This behavior is understood. Noise analysis under mechanical stress on nondegraded or slightly cycled bonds is a fast diagnostic tool for reliability characterization. The degree of delamination is expressed quantitatively by the D -factor, $D = A_{e_{\max}}/A_{e_{\min}} \cong (C_{\max}/C_{\min})^{2/5}$.

Index Terms—Conductive adhesive, contact resistance, electrical contact, failure analysis, fault diagnosis, 1/f noise, reliability.

I. INTRODUCTION

AN OVERVIEW of recent developments in polymeric electronics packaging and conductive adhesive intercon-

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nection technologies can be found in the June 1998 issue of the IEEE TRANSACTIONS ON COMPONENTS, PACKAGING AND MANUFACTURING TECHNOLOGY—PART A. Today, anisotropic conductive adhesives are the dominant connection technique for large area liquid crystal displays (LCD) [1]. Now there is growing interest in using conductive adhesives in, for example, automotive applications for interconnection between components and printed circuit boards for high current levels. Their reliability is normally evaluated during accelerated life tests through electrical and mechanical measurements [2]. By thermal cycling the contact resistance increases by a factor 1.7 and not more than 1.14 for the poor and best quality bonds respectively. Thermal cycle aging up to 800 cycles between -55 and 125 °C is a standard life test and takes about four weeks, making it rather time-consuming.

However, for rather good bonds, the increase in interconnection resistance often is very weak, which makes quality assessment very difficult [2]. 1/f noise in contact resistance often is a better diagnostic tool for degradation than resistance measurements only [3], [4]. Behner *et al.* [5], [6] used 1/f noise measurements to characterize conductive adhesive interconnections for the first time.

Here, we investigate the 1/f noise of contact resistances made by isotropic conductive adhesives focusing on reliability during lifetime stresses. The analysis of the results is based on a model for multispot contacts in [7]. In a special case of multispot contacts with k -conducting spots, with diameter $2a$, far apart from each other, k and a can be calculated [7], [8].

The noise of twenty interconnections in series was investigated to test:

- 1) whether or not the 1/f noise is a useful diagnostic tool for reliability assessment;
- 2) whether or not a 1/f noise analysis gives more detailed information on the real electrical area and the onset of delamination in thermo-cycled interconnections;
- 3) whether or not the amount of increase of 1/f noise measured under mechanical stress on nondegraded or slightly cycled interconnections can be used as a criterion to differentiate between reliable and unreliable conductive adhesives.

II. SAMPLE DESCRIPTION

The conductive adhesives of three different suppliers were investigated. All have Ag grains. The DM4030 SR, Polysolder, and Ablebond have resistivities of 1.1×10^{-4} , 2×10^{-4} , and 5×10^{-4} Ωcm, respectively. The details from microscopic

Fig. 1. (a) Cross section showing the length L of the printed circuit board with the metal bridges bonded on gold plated Cu-Ni lines. The 10 soldered metal bridges in series form together the resistance R_P of a path under investigation. (b) Perspective view of one single bridge showing the area $A = 0.5 \text{ mm} \times 1.6 \text{ mm}$ of a single conductive adhesive bond with thickness $t = 20 \mu\text{m}$. (c) Cross section of a printed circuit board under mechanical stress bent in an arc of a circle of radius R . The equation only gives an indication of strain due to bending.

analysis and pictures of cross-sections can be found elsewhere [2]. The Ablebond has a grain size in the range of about $1\text{--}50 \mu\text{m}$. The others two have grain sizes in the range of $1\text{--}10 \mu\text{m}$. The DM4030 SR is a product from DIEMAT Inc., with longer polymer chains in the matrix and a less homogeneous distribution of silver grains than in the Polysolder [2]. The cross-sections of the conductive adhesive bonds that can be found in Fig. 1(a) and (b) show perspective views of a bonded bridge, with the details of the adhesive contact area $A = 0.5 \text{ mm} \times 1.6 \text{ mm}$ and thickness of the conductive adhesive $t = 20 \mu\text{m}$.

In our configuration, ten metal bridges are bonded on a goldplated pattern on a printed circuit board to study the average resistance and noise behavior of 20 bonds in series. The width of the metal bridge is 1.6 mm .

Fig. 2. Noise measuring setup showing the samples R_{P1} and R_{P2} in a Wheatstone bridge, and the transformer preamplifier. The fast Fourier transform analysis is not shown.

Stress in the samples was avoided in the tests on noise versus thermo-cycling. Stress was applied on purpose in other tests by bending the printed circuit board as shown in Fig. 1(c). Two different lengths L of the printed circuit board were available, one with a length of 88 mm , the other with a length of 68 mm .

For noise measurements under mechanical stress a maximum bending up to $p = 3 \text{ mm}$ was applied, which resulted in a curvature radius R of about 323 mm and a relative change in length of $\Delta L/L$ in the printed circuit board of 9×10^{-3} at most. The relations between p , L , R , and $\Delta L/L$ are in arbitrary values and based on the approximation that the printed circuit board is bent with a matrix shaped in an arc of a circle with radius R and fixed boundary conditions for the printed circuit board. Hence $R \approx L^2/8p$, and $\Delta L/L \approx p^2/(L^2/8 - p^2)$. The strain in the conductive adhesive will depend on its thickness and the ratio between the Young moduli of the board, adhesive, and bridge material. These problems are ignored here and the equations are only given to show that bending the board strains the joints. The equation will not be used here.

III. NOISE MEASUREMENT SET-UP

In order to be able to measure the noise of conductive adhesive bonds with resistance values between 14 and $18 \text{ m}\Omega$, we chose to put ten bonded bridges in series, resulting in 20 bonds in series. The total resistance of a line R_P then becomes approximately 0.45Ω . The applied constant current through R_{P1} and R_{P2} was kept below 200 mA , which results in macroscopic current densities in the bonds below $J = 25 \text{ A/cm}^2$. The real current density is at least ten times higher, because the real electrical contact area A_e is maximally 10% of the apparent contact area A . This has also been discussed by Kotthaus *et al.* [9]. The maximum allowable current density is 100 A/cm^2 in order to avoid degradation. We have chosen a bridge measurement system consisting of $R_{P1} \approx R_{P2}$ as shown in Fig. 2. The advantages of putting 40 bonds in series ($0.8 \Omega < R_{P1} + R_{P2} < 1 \Omega$), as shown in Fig. 2, are twofold.

- 1) Thermal noise of $R_{P1} + R_{P2}$ is slightly higher than the background noise of the amplifier with its equivalent noise resistor R_{eq} of 0.8Ω for the range $3 \text{ Hz} < f < 15 \text{ kHz}$.
- 2) Direct measurement of the average behavior of 40 bonds is possible.

The bridge is balanced with R_{V1} and R_{V2} in such a way that $R_{V1} \times R_{P2} = R_{V2} \times R_{P1}$. The advantages of bridge measurements are described in [10]. By using a Wheatstone

bridge configuration, the parasitic current noise, e.g., from the batteries, the disturbance due to temperature drift or fluctuations common to all elements of the bridge can be regarded as common mode signals. Common mode signals have no influence on the measurements if the bridge is in perfect balance [10]. Between Q_1 and Q_2 an ultra-low-noise transformer-amplifier from Stanford Research (SR554) is used as shown in Fig. 2. The dc power supply U is a 12 V lead-acid battery. The series resistance R_{V1} and R_{V2} are well shielded; they are type 1408 two-decade bank resistor from Burster Prazisions-messtechnik with a resolution down to 0.01 Ω and negligible contact and resistance noise. The values of R_{V1} and R_{V2} are chosen to be at least 100 times larger than the sample resistors R_{P1} and R_{P2} to realize a constant current. Values for R_{V1} and R_{V2} are about 60 or 100 Ω for noise measurements at current levels of about 200 and 120 mA, respectively. The decade bank is used to realize a voltage difference $V_{Q1}-V_{Q2}$ across Q_1Q_2 as low as a few μV . No blocking capacitors in series with the transformer are used in order to realize the lowest possible cut-off frequency. With a source impedance of about $R_{P1}+R_{P2} \cong 1 \Omega$ the low pass cut-off frequency is less than 1 Hz. Replacing the battery by a short circuit results in a background spectrum as shown in Fig. 3(a). This background level of $4 kT(R_{P1}+R_{P2}+R_{eq})$ is put in the memory of a HP 35665A spectrum analyzer. The spectral values obtained with a current through the sample are corrected for the background. The corrected spectra in all samples show a $1/f^\gamma$ noise with a frequency index $1 < \gamma < 1.2$. We call it $1/f$ noise. Immediately after applying mechanical stress the frequency index γ becomes larger than 1.3 due to drift; but then after a few minutes γ drops back down to 1.3 or less again. We tried to avoid transient phenomena. The contact noise of conductive adhesives at current levels lower than 120 mA can be measured with an ac excitation instead of a dc current [5], [6], [11]. All the fluctuations in the contact resistance R_{P1} and R_{P2} are transformed around the carrier frequency. Hence, low frequency fluctuations in the resistance values of R_{P1} and R_{P2} at for example $f_L = 0.1$ Hz are transformed into voltage fluctuations in the frequency range $f_{\text{carrier}} \pm f_L$. This is far away from the frequency range, where the $1/f$ background noise of the preamplifier becomes important, and far away from the frequency where the transformer shows its low pass cut-off frequency. A double lock-in amplifier followed by a dual channel FFT analyzer is often used to demodulate and get rid of the thermal noise [5], [6], [11].

IV. EXPERIMENTAL RESULTS

For two resistors with $S_{R_{P1}} \approx S_{R_{P2}} = S_{R_P}$ and $R_{P1} \approx R_{P2} = R_P$ in series as in Fig. 2, the observed voltage fluctuation $S_{V1/f}$ across Q_1Q_2 is doubled and given by

$$S_{V1/f} = 2(IR_P)^2 \frac{S_{R_P}}{R_P^2} = \frac{2V^2C}{f}. \quad (1)$$

The thermal noise becomes

$$S_{Vth} = 4 kT(2R_P). \quad (2)$$

Fig. 3. (a) S_V versus f : background ($\bullet$), with $I = 166$ mA for 830 cycled sample ($\blacksquare$), with $I = 186$ mA for the 450 cycles sample ($\blacklozenge$). The so-called $1/f$ noise with proportionality $S_V \propto 1/f^\gamma$ has a frequency index $1 < \gamma < 1.2$. (b) The relative noise C in the Polysolder sample versus the number of thermo-cycles showing an improvement in the contact up to 200 cycles (annealing) and beyond that gradual decrease in electrical contact area resulting in a gradual increase in C .

For the corner frequency f_c for which it holds that $S_{Vth} = S_{V1/f}$ is given by

$$f_c = \frac{I^2 R_P C}{4kT} \quad (3)$$

where $S_{V1/f}$ is due to $1/f$ noise in the bond resistances represented by S_{R_P} , and C is the relative $1/f$ noise in the sample defined by $C = f S_R / R^2$ [3]. This equation gives an indication of the current needed to have a reliable $1/f$ -spectrum over a large enough frequency range. The corner

Fig. 4. (a) C versus R : Ablebond (■), Polysolder (●), DM4030 SR (▼). A power law $C \propto R^m$ can approximate the results. From the noise model for multispot contacts it follows that a high value for m and a small range in C after a forced life test are indicators of a high reliability. (b) C versus R for DM4030 SR (▽, ▼) and Polysolder (●, ○) under mechanical stress with the maximum stress corresponding to $p = 3$ mm. The first subscript in C indicates the number of thermo-cycles before applying mechanical stress. A higher C -value and a lower m -value for samples submitted to more cycles points to a lower electrical contact area A_e for such bonds.

frequency f_c is independent of the number of bonds in series if the noise of the preamplifier can be ignored. From (1) we see that C values down to 10^{-17} are detectable applying currents up to 200 mA and accepting f_c values of about 12 Hz. In Fig. 3(a), two S_V spectra are shown for two Polysolder samples submitted to two different forced life tests by thermo-cycling (450 and 830 cycles). In Fig. 3(b), the relative noise versus the number of thermo-cycles is shown for the Polysolder bond. The resistor increase by thermal cycling is a factor 1.7 and not more than a factor 1.14 for the poor and best quality joints, respectively. In Fig. 4(a), the relative noise, C , versus resistance ($R = R_P$) is shown after different numbers of thermo-cycles for three conductive adhesives. In Fig. 4(b), C versus R due to an applied mechanical stress is shown. The relative noise is calculated from experimentally observed noise spectra at $f = 10$ Hz, as in Fig. 3(a) with [see (1)]

$$C = \frac{1}{2} \frac{f S_V 1/f}{V^2}. \quad (4)$$

If we consider N conductive adhesive bonds in series in R_P , which are uniform in resistance and $1/f$ noise (statistical properties), then for one single bond the resistance R_b and the relative noise C_b are given by

$$R_b = R_P/N \quad \text{and} \quad C_b = CN. \quad (5)$$

Here we ignore the $1/f$ noise contributions of the metal bridges and the metal strips on the printed circuit board, which are negligible [3]. The values of R_b and C_b are inversely proportional to the physical area of the bond A (the so-called apparent area) which is always larger than the real electrical contact area. If the thickness of the adhesives is the same and we can assume statistical uniformity of grain contacts then a bond can be represented by characteristic values for resistance and relative noise, R_{us} and C_{us}

$$R_{us} = R_b A \quad \text{and} \quad C_{us} = C_b A. \quad (6)$$

All our samples showed a contact resistivity $R_{us} = 2 \, \Omega\text{cm}^2$, which is rather high compared with what is achievable in micro-electronic devices where uniform ohmic metal-semiconductor contact resistivities can be as low as $10^{-5} \, \Omega\text{cm}^2$. The relative noise C versus the number of thermo-cycles shows a minimum at about 50 cycles for the Ablebond and DM4030 SR. $C_{\min}$ is about 5.5 times smaller than the C_0 -value for a nondegraded sample. This improvement of the noise after some thermo-cycling is due to a decrease in current density at a microscopic scale [3]. Even after manufacturing curing of the bond, thermal cycling still results in a shrinking of the polymer matrix. Another possible mechanism for the decrease in C while R remains about constant is the wearing away of the smallest contact asperity spots as the particles slide relative to one another as they are strained to form larger contact spots that have less noise. The so-called coalescence is discussed in [12] and [13]. These mechanisms can be considered as a kind of

TABLE I
SUMMARY OF EXPERIMENTAL RESULTS

	DM4030SR	Polysolder	Ablebond
C_0	1×10^{-16}	2×10^{-16}	1.5×10^{-16}
$C_{\min}$	$C_{50} = C_0/5.5$	$C_{250} = C_0/12$	$C_{50} = C_0/5.5$
C_{830}	$2 \times C_0$	$10^2 \times C_0$	$5.5 \times C_{50}$
m	25	15	6
$C_{0, p=2}$	C_0	$10 \times C_0$	$3 \times C_0$
$C_{x, p=3}$	$C_{450, p=3} = 1.8 \times C_{450, p=0}$	$C_{100, p=3} = 5.7 \times C_{100, p=0}$	$C_{450, p=3} = 2.8 \times C_{450, p=0}$

annealing. The Polysolder conductive adhesive [see Fig. 3(b)] shows a minimum C value at about 200 thermo-cycles, with $C_{\min}$ about a factor 12 lower than the starting value, C_0 . For this reason the C values of nondegraded samples are not presented in Fig. 4(a). A measuring procedure on one and the same sample will result in less scatter. Here the results are presented from different samples of the same batch each submitted to different thermo-cycles, which explains some scatter in the results.

In the next section, it will be explained that a high value of the exponent m in the C versus R^m relation and a small increase in C are both quality indicators.

The experimental results are summarized in Table I. The average value of the relative noise for nondegraded samples, C_0 , is given in the first row. The minimum values of the relative noise versus number of thermo-cycles are indicated in the second row. $C_{\min}$ is compared with C_0 . The subscript x in C_x shows the number of thermo-cycles needed to obtain this minimum. The third row shows the relative noise after 830 thermo-cycles. The fourth row shows the value of the exponent m in the power law $C \propto R^m$. The fifth row shows the increase in noise on nondegraded samples under static mechanical stress of one cycle with $p_{\max} = 2$ mm. The first index in C indicates the number of thermo-cycles of the sample (zero for row five). The sixth row shows the noise increase for a mechanical stress corresponding to $p_{\max} = 3$ mm. Part of the scattering in the results is due to deviations in homogeneity between bonds. One out of 20 bond contacts with a resistance of 30 m Ω , instead of the average value of 16 m Ω , can result in a relative noise two orders of magnitude higher than for homogeneous bonds in series. After replacing the weak bond by a short circuit in the resistance path, normal values for the noise are again observed. The anomalous value is not represented in Fig. 4(a).

The Polysolder showed the highest C value of all the nondegraded samples, which were all between 10^{-16} and 2×10^{-16} . This indicates that noise measurements on nondegraded samples without application of mechanical stress are less sensitive as a diagnostic tool for quality assessment (see first row of Table I). The results under mechanical stress, however, show larger noise increase factors and reveal the advantages of noise measurements under mechanical stress as a diagnostic tool [see fifth and sixth row of Table I and Fig. 4(b)]. The noise increase factors are one ten and three for $p = 2$ in DM4030SR, Polysolder, and Ablebond, respectively. This is an indication for a reduction of the electrical (internal) contact area by a factor one (no reduction at all); $10^{2/5}$; and $3^{2/5}$

for DM, Polysolder, and Ablebond, respectively. This will be explained by (13) in the next section.

V. MODEL FOR THE NOISE IN CONDUCTIVE ADHESIVE BONDS

The experimentally observed resistance value of a single conductive adhesive bond is at least two orders of magnitude higher than the simple relation $R = \rho_{adh}t/A$ predicts, where ρ_{adh} is the resistivity of the conductive adhesive, t the thickness, and A the area of the conductive adhesive layer. This discrepancy of at least a factor of 100, which is often observed, can only be explained by considering the microscopic details of the contact between conductive adhesive layer and the two metal layers. We assume a multispot contact behavior on both sides of the conductive adhesive as shown in Fig. 5(a) and (b). The semicircles in Fig. 5(a) indicate the cross-section of the equipotentials around the narrow conducting spots on the metal bridge and printed circuit board side. Fig. 5(b) shows the top view of a multispot contact; for simplicity it is assumed to be completely regular. The patchiness parameters k and a are the number of spots and the spot radius, respectively, while $2l$ is the distance between the spot centers. The resistance and $1/f$ noise were calculated for a general multispot contact [7]. The electrical contact area $A_e = k\pi a^2$ is smaller than the apparent conducting area A , which explains the discrepancy between experimentally observed resistance and calculated resistance from $\rho_{adh}t/A$. The characteristic length b with $\pi b^2 = A$ will show up in the equations for resistance and noise.

Formulae for the contact resistance of an assembly of a -spots were previously published [7], [8], [12], [14], [15]. Multispot contacts can be simplified in two limiting cases and a transition region henceforth denoted by region II contact.

- 1) Region I contact has a high patchiness density ($0.25 < A_e/A < 1$). In such almost uniform contacts there is hardly an evolution in resistance and noise for a change in a and k values.
- 2) Region III contact has a low patchiness density ($A_e/A < 0.25 \times 10^{-2}$).

The general relation for the resistance of a multispot contact can be written as follows [7, (1)]:

$$R = \frac{\rho_{adh}}{2\pi b} \left[\left(\frac{l}{a} - 1 \right) \frac{l}{b} + 1 \right] \quad (7)$$

where b is the radius of the circular multispot contact or the radius of a circle with the same area as the apparent area A of the contact ($b = (A/\pi)^{1/2}$). That relation is also applicable to contacts with slightly unequal spots that are spread over the apparent contact area [15].

Fig. 5. (a) Cross section of a bond showing two equal multispot contacts in series, consisting of k a -spots in parallel and (b) top view of a multispot contact between a conductive adhesive and metal line or metal bridge consisting of a -spots spread uniformly over A . The circles represent the contact spots in a nondegraded condition, diameter $2a'$; the full spots show the shrunk size of the a -spots after degradation (change in a only).

The general relation for the relative noise of a multispot contact is given by [7, eq. (3)]

$$C = \frac{\alpha}{10\pi b^3 n} \left[\frac{(l/b)((l/a)^5 - 1) + 1}{((l/b)(l/a - 1) + 1)^2} \right]. \quad (8)$$

For (7) and (8) it holds that $l/b = k^{-1/2}$ and $l/a = (b/a)k^{-1/2}$ and $a/l = (A_e/A)^{1/2}$. From (7) and (8), simplified equations can be derived for regions I, II, and III [7], [12]. From our analysis it follows that conductive adhesive bonds are region II contacts. A region II contact with $2 < l/a < k^{1/3}$ is a transition region between regions I and III. The a/l range results in an A_e/A ratio of less than 25% for $k > 20$. C is very sensitive but R is less sensitive to changes in l/a .

The degradation process is characterized by onset of delamination leading to a reduction in electrical contact area. Here we distinguish between two types of onset of delamination.

- 1) Degradation, with k constant and a decreasing.
- 2) Degradation with a constant and k decreasing.

A small decrease in $A_e = k\pi a^2$ will result in a C versus R that can be approximated by a power law $C \propto R^m$ with typical values for the exponent $m \gg 3$. The exponent m can be as high as 25 as is shown in the calculated C versus R plot in Fig. 6(a). The general relations for noise and resistance applied to region II multispot contacts, as derived in [7], explain why $1/f$ noise can be successfully used as a diagnostic tool to investigate the quality and robustness for degradation by thermo-cycling and mechanical stress. The change in A_e is easily observable in C but not in R . Fig. 6(a) shows the onset of delamination in a multispot contact where k remains constant and A_e changes by a reduction in spot size. Fig. 6(b)

shows the effect of an onset of delamination by a change in k and hence in the average value of l while a remains constant. The transition between region II (high m -values) and region III contacts (low m -values) becomes clear. Thermo-cycling or mechanical stress provoke degradation resulting in an onset of delamination and a reduction of A_e . The plots in Fig. 6(a) and (b) are calculated with (7) and (8) in arbitrary units. The experimental results obtained on the three different conductive adhesives shown in Fig. 4 display the same behavior as the simulated ones in Fig. 6 for the onset of delamination.

Under the assumption $l/a \geq 10$, (7) and (8) can be approximated by [7]

$$R = \rho_{adh}/k\pi a \quad (9)$$

$$\frac{S_R}{R^2} = \frac{C}{f} \propto \frac{1}{ka^3}. \quad (10)$$

From these two independent equations k and a can be calculated from experimental results if all other parameters are known [8]. The onset of delamination with k constant for a region III multispot contact results in a $C \propto R^3$ behavior as can be seen from (9) and (10). The onset of delamination with a constant results in $C \propto R$ or $m = 1$ as can be seen from (9) and (10).

Uniform contacts without current crowding on a microscopic scale and suffering from delamination due to a reduction in A , will show $m = 1$ because

$$\left. \begin{array}{l} R \propto 1/A \\ C \propto 1/A \end{array} \right\} C \propto R. \quad (11)$$

From the experimental results in Fig. 4(a) the exponent m in the power law $C \propto R^m$ is well above 3, hence our conductive adhesive bonds are neither region III multispot contacts nor uniform contacts but region II contacts. For region I contacts neither C nor R changes with small changes in A_e . Hence, such contacts cannot be characterized by a power law with a specific value for m .

The onset of delamination in region II multispot contacts can be studied in a quantitative way for degradation of type (i) (a -reduction only) and type (ii) (k -reduction). For a region II contact we find from (7) and (8) that $C \propto A_e^{-5/2}$ holds, and hence for the ratio between the maximum value and the minimum value for the relative noise after a degradation process, we have

$$\frac{C_{\max}}{C_{\min}} \cong \left(\frac{A_{e\max}}{A_{e\min}} \right)^{5/2}. \quad (12)$$

We choose for the notation where the maximum amount of noise $C_{\max}$ corresponds with the minimum value of electrical contact area $A_{e\min}$ and vice versa. Thus from noise measurements we can quantitatively express the degree of delamination by a D -factor defined as

$$D = \frac{A_{e\max}}{A_{e\min}} \cong \left(\frac{C_{\max}}{C_{\min}} \right)^{2/5}. \quad (13)$$

In Fig. 7(a), C versus A_e/A and R versus A_e/A are plotted for the region II multispot contact with an onset of delamination by a -reduction only. In Fig. 7(b), C versus A_e/A and R versus

Fig. 6. (a) Calculated C versus R simulates the degradation of a multispot contact by an a -reduction only. The coefficients before the square brackets [ ] in (7) and (8) are taken to equal one. The range for l/a is $1.47 \leq l/a \leq 6.81$, which is equivalent with a range for $46\% > A_e/A > 2\%$. The exponent m in the power law $C \propto R^m$ changes from $m = 14, 18, 20$, and 30 for $k = (b/l)^2 = 50, 100, 200$, and 400 , respectively. The more spots in parallel and the higher the a -value, the higher the m -value and the larger the range in l/a values before entering region III. (b) Simulation of C versus R due to a reduction by a factor 10 in the electrical contact area $A_e = k\pi a^2$ by a k -reduction. The calculation is based on (7) and (8) taking into account that if k changes l -values on the average change into $l/b = k^{-1/2}$ and $l/a = bk^{-1/2}/a$, too, while the k -range is set to $50 \leq k \leq 500$. The following holds for $b/a = 100, 150$, and 300 for the range of exponent m -values $2.5 < m < 14$: $2.2 < m < 9.5$ and $1.3 < m < 2.6$, and for the range of ratios A_e/A becomes: $5 \times 10^{-3} < A_e/A < 5 \times 10^{-2}$; $2.2 \times 10^{-3} < A_e/A < 2.2 \times 10^{-2}$ and $5.6 \times 10^{-4} < A_e/A < 5.6 \times 10^{-3}$, respectively. For $b/a = 300$ and $k \rightarrow 50$ we observe a region III multispot contact behavior.

A_e/A are plotted for the region II multispot contact with an onset of delamination by k -reduction for a reduction in A_e by a factor 10. A power law $C \propto (A_e/A)^{-\beta}$ with β slightly less than $5/2$ can summarize the simulation in Fig. 7(a) and (b). The calculations in Fig. 7(a) and (b) are made in arbitrary values for C and R . Again the relative noise C is far more sensitive to changes in the real electrical contact area A_e than the resistance value R as can be seen from Fig. 7(a) and (b).

VI. CONCLUSION

The classical forced life test by thermo-cycling is an important, although time-consuming way of testing, and it gives few details about the onset of degradation. The contact resistance increases by a factor 1.7 and not more than 1.14 for the poor and best quality bonds, respectively. Therefore we investigated the low frequency ($1/f$) noise of the contact resistance of different conductive adhesive bonds. The observed increase in relative resistance noise C versus contact resistance R with increasing number of thermo-cycles is a very good indicator for the reliability of conductive adhesives. Even experimentally observed C versus R from nondegraded or slightly degraded bonds under mechanical stress can be used as a fast diagnostic tool. However, neither the C -value nor the R -value measured before life tests (zero thermo-cycles) are a good indicator for reliability assessment if no mechanical stress is used. If a solder has more noise because it has a larger range in particle size and more inter particle contacts which

generate more noise then this is not necessarily an indication of being a bad joint.

The analysis of our results is based on a general model for the resistance and noise in multispot contacts formerly published by Vandamme and Tjiburg [7]. The weak dependence of R and the very strong dependence of C on changes in the real electrical contact area $A_e = k\pi a^2$ are a typical behavior of the so-called region II multispot contact. For a region II contact it holds that the ratio between the average distance $2l$ between a -spots and their diameter $2a$ is in the range $2 < l/a < k^{1/3}$ with k the number of spots in parallel. This is equivalent to a ratio between electrical contact area to the apparent area, A_e/A of at most 25%, but higher than 0.25%.

The degree of increase in noise and degree of reduction in A_e due to thermo-cycling or mechanical stress allows us to assess the quality of conductive adhesive bonds. The degree of delamination is quantitatively expressed by the D -factor, $D = A_{e_{\max}}/A_{e_{\min}} \cong (C_{\max}/C_{\min})^{2/5}$. Two types of onset of delamination can be considered: a -reduction only or k -reduction. The analysis of relative noise versus contact resistance in terms of the value of the exponent m in the power law $C \propto R^m$ gives a less time-consuming and more sensitive criterion for quality assessment. The high values for m ($6 < m < 25$) are a strong indication for region II multispot contact with an onsets of degradation due to a shrinking of the electrical contact area A_e .

Good contacts show a small amount of increase in C and a high value of the exponent m . This is equivalent to contacts

Fig. 7. (a) Calculated C versus A_e/A and R versus A_e/A plots from (7) and (8) for a region II multispot contact with $0.25\% < A_e/A < 25\%$ due to a -reduction only (for $k = 100$ and $k = 1000$). (b) Calculated C versus A_e/A and R versus A_e/A plots due to a reduction in k . The reduction in A_e is a factor 10, and the substitutions $l/b = k^{-1/2}$ and $l/a = b/ak^{-1/2}$ are made in (7) and (8). The parameters $a/b = 10^{-2}$ and $a/b = 5 \times 10^{-3}$ are used.

with a high value of k and a and hence with A_e/A close to 10%. A_e almost remains constant during stress tests.

Delamination of a region III multispot contact with reduction in k only or delamination by reduction in A result in an

exponent $m = 1$. Delamination for a region III contact with a -reduction only results in $m = 3$. This has not been observed under mechanical stress or in samples after thermo-cycling [see Fig. 4(a) and (b) with $m \gg 3$]. This means that the investigated conductive adhesives bonds are region II contact.

From the analysis of a C versus R plot it is hard to distinguish between onset of delamination by an a -reduction only or by a k -reduction. Both types of delamination result in a proportionality of about $C \propto A_e^{-5/2}$.

The grain size in the conductive adhesive is similar to the thickness of the bond ($t = 20 \mu\text{m}$). The contact area A between bond and pad consist of a large number of contacting grains in parallel, resulting in a real electrical area A_e . A minority of these conducting paths consists of a pair of grains in series. If such a grain-grain contact breaks, then the total number of multispot contacts in parallel is reduced by at least one. Making grain-grain contacts can then result in an increase in k and a reduction in noise. This is a possible explanation for the annealing observed after about 100 thermo-cycles. From the C versus R plots it is hard to distinguish between a reduction in A_e at the conductive adhesive interface with the pad or at the grain-grain contact.

The Ablebond conductive adhesive shows the lowest value of the exponent m in the C versus R plot in Fig. 4(a), which points to a multispot contact with fewer contacts in parallel. The grain size of the silver particles in the Ablebond is larger than in the other two conductive adhesives, which makes the observed trend from noise analysis explicable. The Polysolder shows a high [factor 100 in C ; see Fig. 4(a)] increase in relative noise. This points to a reduction in A_e by a factor 6.3 ($D = 6.3$). From our analysis DM4030 SR has the best reliability and the lowest D -factor is observed ($D = A_{e\text{max}}/A_{e\text{min}} = 2.2$). Considering the small range in relative noise and the high value for the exponent m in Fig. 4(a) and (b), we consider the DM4030 SR conductive adhesive to be the best and the Polysolder to be the poorest. Hence, the $1/f$ noise analysis of the contact resistance of conductive adhesives bonds is a quantitative tool for investigating the quality of isotropic bonds.

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