Effect of Heating on the Electrical Resistivity of Conductive Adhesive and Soldered Joints

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Thermal cycling from room temperature to 60°C was found to cause the contact resistivity of a silver-epoxy conductive adhesive joint to decrease irreversibly, due to an irreversible decrease of the thickness of the joint. This effect was much smaller for a soldered joint cycled to 40°C. An extended period of current on-off cycling caused a slight irreversible increase in the contact resistivity of the adhesive and soldered joints, but thermal cycling using a heater did not. Within each thermal cycle, the contact resistivity increased reversibly with increasing temperature, due to the increase in volume resistivity of the solder or adhesive. Temperature variation caused fractional changes in contact resistivity up to 48% and 6% for adhesive and soldered joints, respectively.

Key words: Joint, conductive adhesive, solder, thermal cycling, electrical resistivity, silver, epoxy

INTRODUCTION

Electrical interconnections in the form of soldered joints are widely used in electronic packaging. However, they suffer from thermal fatigue, the environmental problem associated with the use of flux in soldering, the presence of lead in typical solders, and the large footprints. On the other hand, conductive adhesives do not suffer from these problems and provide low-temperature bonding, which is low cost. Therefore, conductive adhesives such as silver-particle-filled epoxy[1–7] are increasingly used in place of solder. The reliability of these joints greatly affects that of microelectronics.

Due to the increasing power and miniaturization, the heat generated by the operation of microelectronics is significant and can cause the temperature to reach 100°C or above (depending on the situation). The effect of heat on a conductive adhesive is of particular concern, because (1) there is a thermal expansion mismatch between the polymer matrix (epoxy) and the filler (silver particles) in the adhesive after curing, and (2) the molecules in the polymer matrix may move upon heating. These two issues are not present in the case of a soldered joint, because the solder does not have a filler and is not molecular. This paper focuses on the effect of heating on conductive adhesive and soldered joints.

Heating of an electrical interconnection may be due to heat emanating from its surroundings, which may be the electronic device. It may also be due to the passage of an electric current through the joint (i.e., Joule heating). Both modes of heating are used in this work.

The current density in electrical interconnections in electronic packaging increases as the power increases and as miniaturization continues. The current application results in Joule heating. It may cause electromigration[8] if the current density is sufficiently high. Both heating and electromigration can cause damage, thereby undermining the reliability of the interconnections.

Much attention has been given to the effects of stress and temperature cycling on the performance of soldered joints, due to the common occurrence of vibration and thermal fatigue. Relatively little attention has been given to the effect of current application. This paper addresses the effects of current application and current on-off cycling. In order to distinguish between a thermal effect and a current effect, this paper includes an investigation of heating by an external heater in the near absence of current through the joint, in addition to the effect of current application.

Because the electrical behavior pertains to the electrical performance of a conductive joint, the effect of

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heating on the electrical behavior is of practical concern. Furthermore, the electrical behavior is sensitive to even minor damage, so it serves as a sensitive indicator of the microstructural effects. Furthermore, electrical resistance is fast and nondestructive, thereby allowing real-time monitoring during heating and cooling. In contrast, mechanical testing in the form of joint strength measurement, as well as microscopy, is destructive. Therefore, this work uses electrical measurement to monitor in real time both the reversible and irreversible effects of heating on a conductive adhesive joint.

A joint involves the joining medium (e.g., the adhesive) as well as the interface between the medium and each of the two adjoining components. Thus, study of the joining medium by itself is distinct from study of the joint. Degradation of a joint is due to degradation of the interface or that of the joining medium. In order to address the electrical behavior of a joint, this work addresses the contact electrical resistivity of a joint rather than the volume electrical resistivity of the joining medium itself.

EXPERIMENTAL METHODS

The conductive adhesive was silver-particle-filled epoxy (CW2400 Circuit Works Conductive Epoxy, ITW Chemtronics, Kennesaw, GA). It is in two parts: part A is epoxy and part B is the hardener. Both parts contain 84 wt.% silver particles (actually flakes of size 1–2 μm). According to the manufacturer, the operating temperature range of the cured adhesive is −91°C to 100°C and the volume electrical resistivity of the cured adhesive is less than 0.001 Ωcm.

The solder used was the eutectic tin-lead alloy (63Sn-37Pb). Its melting temperature was 183°C.

Both of the components to be joined by the use of the conductive adhesive were copper-clad continuous glass fiber epoxy-matrix composites in the form of laminates, as provided by Polyclad Laminates, Inc. (W. Franklin, NH; product no. PCL-FR-226, tetrafunctional FR-4 laminate, T_g = 140°C). The glass fibers were E-glass of style 1080. The copper cladding was 13-μm thick on one side of the laminate and 48-μm thick on the other side. The side with the thinner cladding was used for making a soldered joint. The glass fiber polymer-matrix composite was 76-μm thick. The total thickness of the clad laminate was 137 μm.

Adhesive joining using silver epoxy as the adhesive was conducted by (1) mixing equal amounts of part A (epoxy) and part B (hardener) for at least 2 min, (2) applying the mixture within 5 min on the surface of one of the components to be joined (width 5.1 mm), (3) placing the other component to be joined (width = 4.9 mm) on the adhesive, (4) applying a weight of 0.95 kg on the joint area (5.1 × 4.9 mm) to give a compressive stress of 38 kPa, and (5) allowing the epoxy to cure at room temperature under the compressive stress for 24 h. The thickness of the silver epoxy was 152 ± 76 μm.

Soldering was conducted by (1) applying molten solder (melted by using a soldering iron) in the absence of a flux on the surface of one of the components to be joined (width = 1.7 mm) while the surface was hot at 190°C, as rendered by a hot plate; (2) placing the other component to be joined (width = 1.6 mm) on the molten solder, while it was hot at 190°C, as rendered beforehand by the hot plate; (3) turning off the hot plate after 5 min and letting it cool to room temperature in 6 h, and (4) turning on the hot plate to reach 80°C and conducting 4 h of annealing at 80°C. The joint area was 1.7 × 1.6 mm. The thickness of the solder was 125 ± 75 μm.

An electrical contact in the form of silver paint in conjunction with copper wire was applied to the copper cladding of each of the four legs of the crossed bars (Fig. 1). In the four-probe method, two of the electrical contacts (A and D in Fig. 1) were for passing current; the remaining two contacts (B and C) were for measuring voltage. The voltage divided by the current gave the contact resistance of the joint. The resistance multiplied by the contact area gave the contact resistivity. A Keithley (Keithley Instruments, Inc., Cleveland, OH) 2001 multimeter was used.

A DC power supply capable of voltage up to 40 V and current up to 50 A was used for current application. The current was also used for resistance measurement. In the on-off cycling of the current, the current was on for 240 sec and then off for 65 sec in each cycle. The current density was around 225 A/cm^2 when the current was on.

For investigation of the effect of heating using an external heater (powered by a 10 V DC power supply), the contact resistivity was continuously measured while the temperature was cycled between 25°C and 45°C by using a small resistance heater for heating and using compressed air and a copper tubing with flowing water for cooling. Each cycle

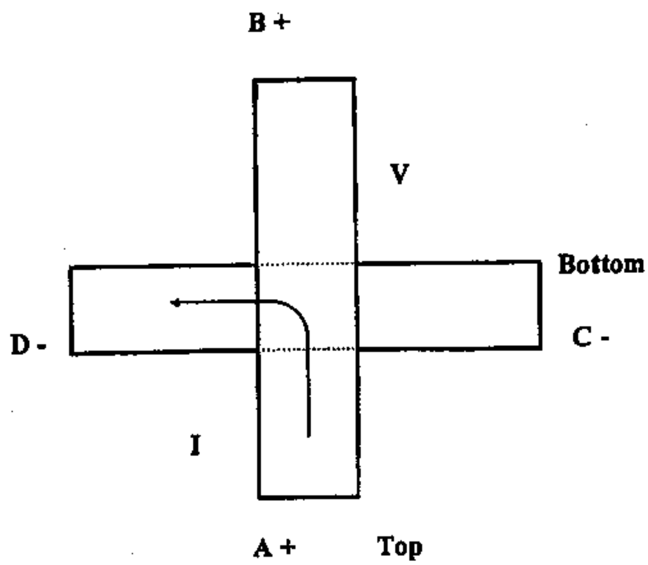

Fig. 1. Specimen configuration.

took 33 sec. The temperature was measured by using a Type-T thermocouple placed at the top surface of the junction shown in Fig. 1.

For investigation of the effect of heating on the dimension of the cured conductive adhesive, a joint specimen in the form of a sandwich (as described above) of lateral size 8.5 × 8.0 mm and thickness 1.5 mm was subjected to measurement of its thickness during temperature cycling between 28°C and 45°C, with the heating provided by a small resistance heater. The heating and cooling rates were 5°C/min. Both thickness and temperature control were provided by a thermomechanical analyzer (Perkin-Elmer Corp., Norwalk, CT, TMA7). A compressive stress of 1.6 kPa was exerted by a probe on the top surface of the specimen throughout the measurement.

RESULTS AND DISCUSSION

Conductive Adhesive Joint

Effect of Heat Application

This section pertains to the effect of heat application using an external heater.

Figure 2 shows the effect of repeated heating from 20°C to 60°C on the contact resistivity. Figure 3 shows the expanded view of the initial eight cycles (at 0–500 sec), whereas Fig. 4 shows that of the later cycles (at 4000–4500 sec). The contact resistivity increased with increasing temperature in every cycle, due to the increase in volume electrical resistivity of the adhesive as the temperature increased and the silver particles became farther from one another. This effect diminished as cycling progressed. After the first cycle, the resistivity irreversibly increased (Fig. 3). However, subsequent cycling caused the resistivity baseline to decrease gradually (Fig. 2). As cycling progressed, the behavior became more and more irregular (Figs. 2 and 4). Nevertheless, the resistivity baseline dropped significantly (by as much as 75%) and leveled off after about two-dozen cycles (Fig. 2).

Effect of Current Application

Figure 5 shows the effect of current on-off cycling (current density shown in Fig. 6) on the contact resistivity. Figure 7 shows the temperature variation during current on-off cycling. The temperature increased reversibly in each cycle. The resistivity increase was partially reversible. In particular, the resistivity baseline increased during the first few cycles and subsequently gradually decreased, level-

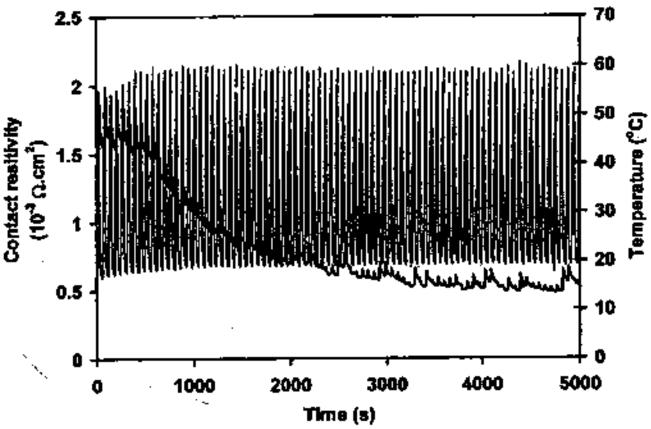

Fig. 2. Variation of the contact resistivity during thermal cycling of the adhesive joint using an external heater. Thick curve: resistivity. Thin curve: temperature.

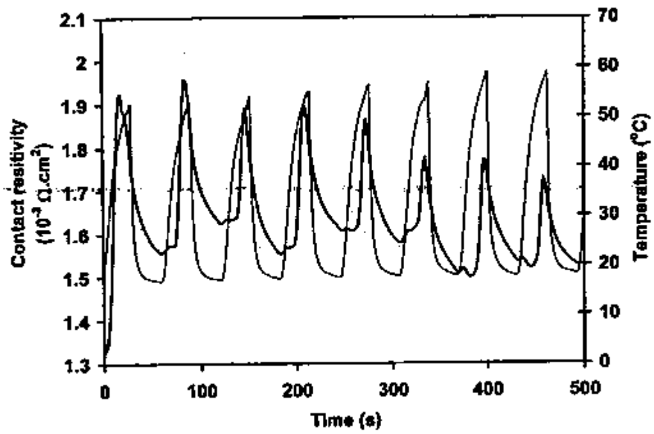

Fig. 3. Expanded view of Fig. 2, showing the initial cycles.

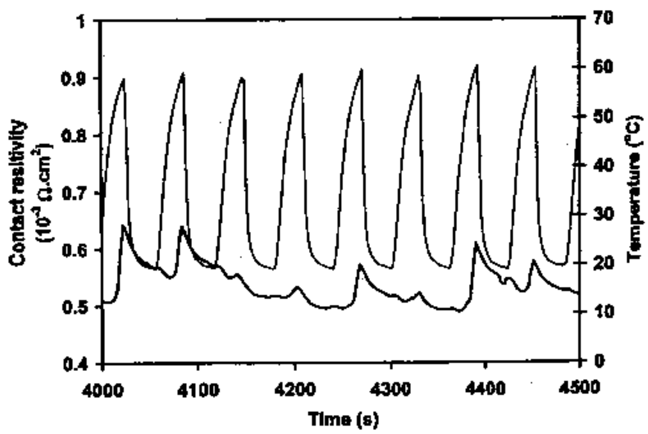

Fig. 4. Expanded view of Fig. 2, showing the later cycles.

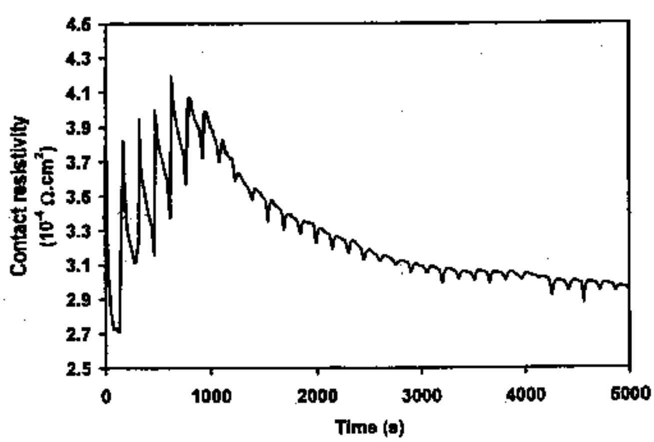

Fig. 5. Variation of the contact resistivity during current on-off cycling of the adhesive joint.

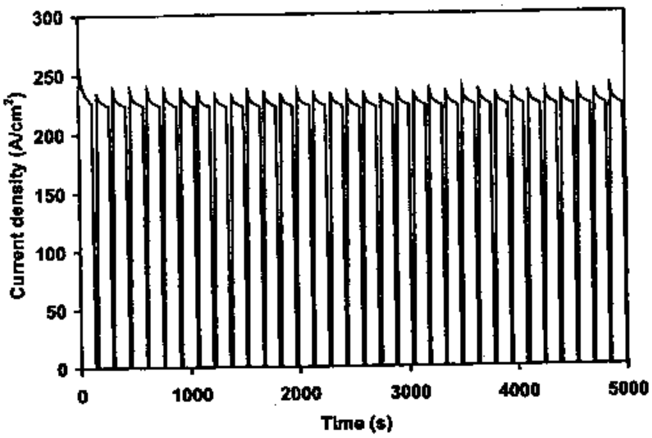

Fig. 6. Variation of the current density during current on-off cycling of the adhesive joint.

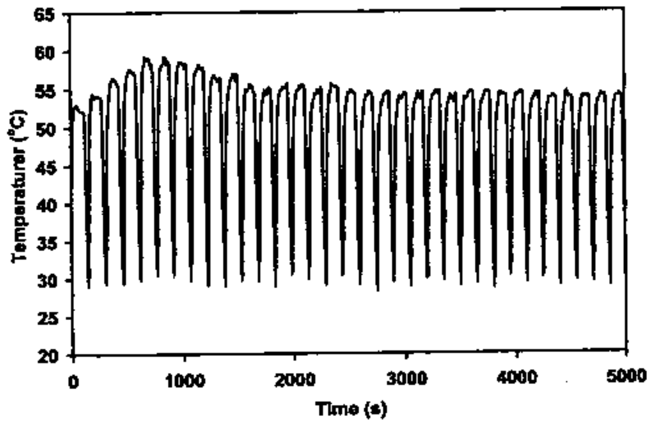

Fig. 7. Variation of the temperature during current on-off cycling of the adhesive joint.

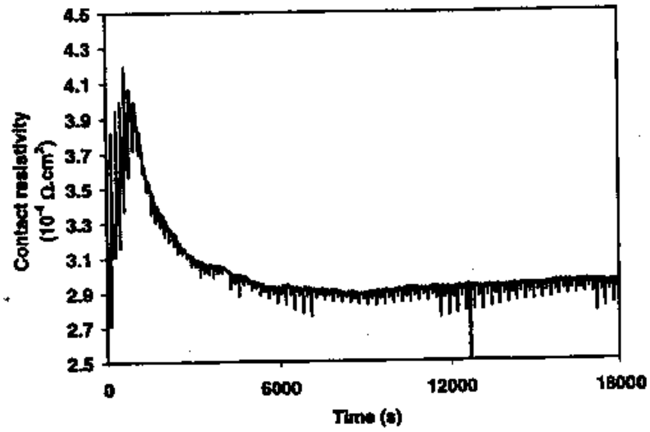

Fig. 8. Variation of the contact resistivity during long-term current on-off cycling of the adhesive joint.

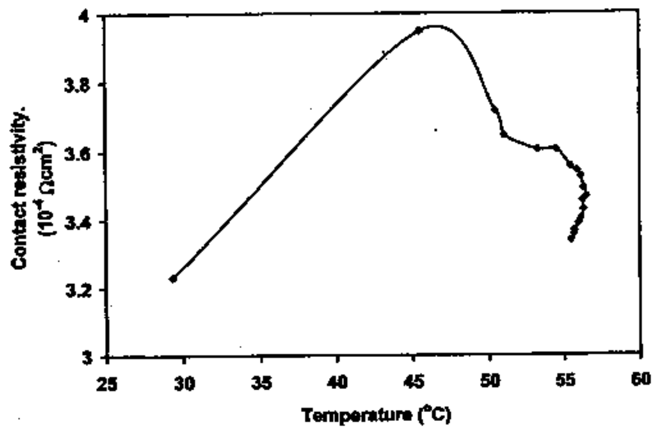

Fig. 9. Variation of the contact resistivity with temperature during the second cycle of current application to the adhesive joint.

ing off after about two dozen cycles. The decrease and subsequent leveling off of the resistivity baseline in Fig. 5 is akin to that in Fig. 2. Although heat application (Figs. 2 and 3) did not give a gradual increase in the resistivity baseline in the initial few cycles, the baseline was abruptly increased after the first cycle. Thus, heat application and current application had similar effects.

The gradual increase in the resistivity baseline in the initial few cycles in Fig. 5 is associated with the gradual increase in the peak temperature of a cycle in these cycles (Fig. 7). Although the peak current density was constant (Fig. 6), the peak temperature was not (Fig. 7), probably due to the variation in resistivity (Fig. 5).

After the resistivity baseline leveled off, further cycling caused the baseline to increase slightly (Fig. 8), probably due to minor damage.

Figure 9 shows the relationship between contact resistivity and temperature in the portions of the first cycle in which the current was on. The resistivity increased as the temperature increased. As the temperature increased beyond about 45°C, the resistivity dropped. The behavior was similar for the various cycles. It is attributed to the decrease in thickness of the specimen at the elevated temperatures, as described in the next section.

Thickness of Joint upon Heating

Figure 10 shows the effect of thermal cycling on the thickness of the adhesive joint. The thickness increased upon heating by up to 0.28% in the first cycle, at least partly due to thermal expansion of the adhesive. After subsequent cooling (i.e., at the end of the first cycle), the thickness decreased even below the initial thickness, though the thickness during cooling was higher than that during heating at the same temperature for all temperatures above 30°C. The second and third thermal cycles show behavior similar to the first cycle, with the thickness after cooling (i.e., at the end of a cycle) decreasing as cycling progresses. This decrease in thickness is attributed to irreversible softening of the adhesive due to exposure to elevated temperatures. The concave shape of the curves in Fig. 10 supports this interpretation, as the nonlinearity means that thermal softening and thermal expansion both contributed to the observed thickness change. This interpretation is further supported by the low values of the apparent coefficient of thermal expansion (apparent CTE, as given by the

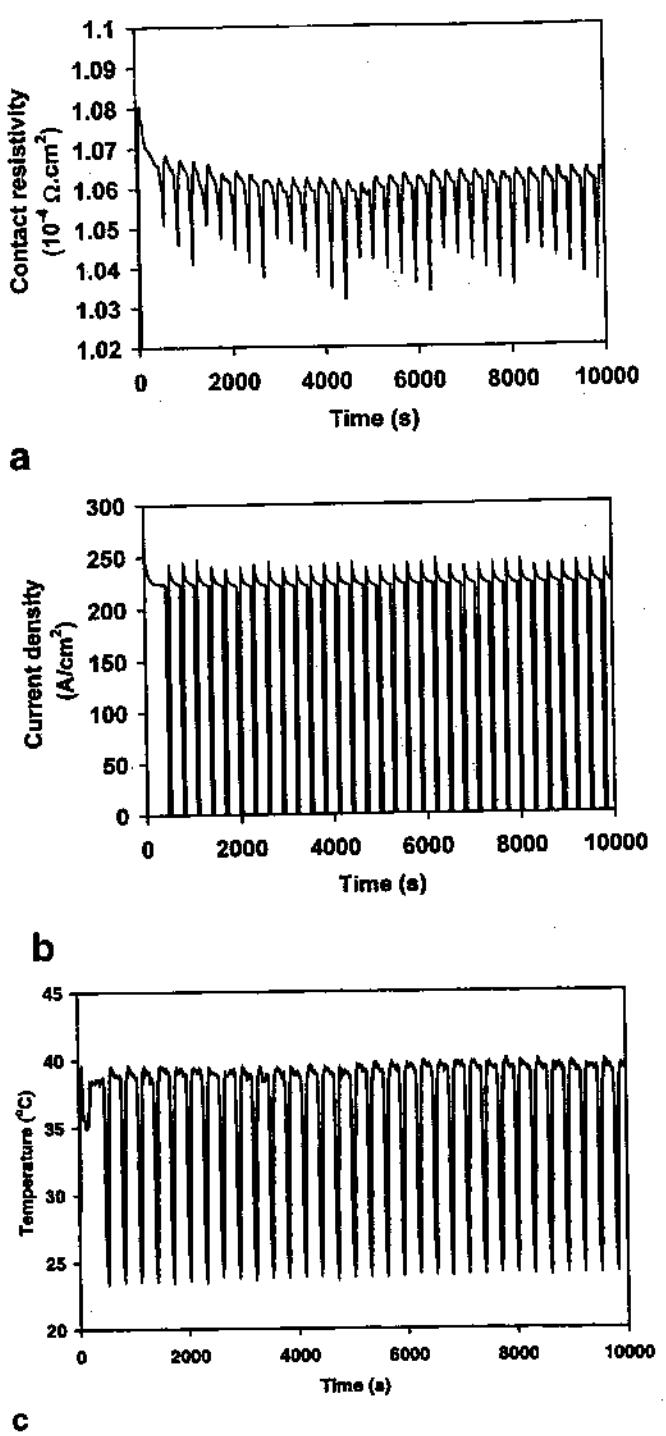

Fig. 13. Variation of (a) contact resistivity, (b) current density, and (c) temperature with time during current on-off cycling of the soldered joint.

of the joint. That the current application gave a similar effect as the heat application means that the current effect is essentially a thermal effect within each cycle. This is reasonable since the current density used was not very high.

Figure 13a shows that the contact resistivity irreversibly decreased in each of the initial few current on-off cycles. After that, the contact resistivity irreversibly increased slightly and gradually cycle by cycle. Such trends were absent in the case of thermal cycling in which heating was provided by a heater (Fig. 11). The temperature excursions are similar in Figs. 11 and 13c. Thus, current on-off cycling caused irreversible effects, whereas purely thermal cycling (using a heater) did not. This suggests that current on-off cycling is more damaging than thermal cycling. The irreversible resistivity decrease during the initial current on-off cycling is probably due to annealing; the irreversible resistivity increase afterward is probably due to minor damage. The damage may occur at the solder-copper interface or within the solder. It is associated with the generation of defects that cause the contact resistivity to increase irreversibly. Due to the fact that the current density is low compared to the level (e.g., 10^4 A/cm^2) associated with electromigration, the damage is probably not related to electromigration.

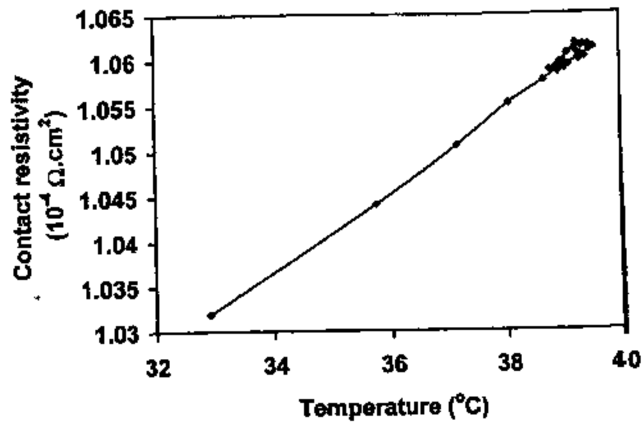

Fig. 14. Variation of the contact resistivity during the fourth cycle of current application to the soldered joint.

Comparison between Adhesive and Soldered Joints

The effect of heating on soldered and conductive adhesive joints showed that the reliability of the soldered joint was superior to that of the conductive adhesive joint.

Temperature variation caused fractional changes in contact resistivity up to 48% and 6% for adhesive and soldered joints, respectively. This is probably because the volume resistivity of the adhesive has a sharper temperature dependence than that of solder.

CONCLUSIONS

Thermal cycling from room temperature to 60°C, whether by heat or current application, was found to cause the contact resistivity of a silver-epoxy conductive adhesive joint to decrease irreversibly, due to an irreversible decrease of the thickness of the joint. This effect was much smaller for a soldered joint cycled to 40°C. An extended period of current (current density = 225 A/cm^2) on-off cycling caused slight irreversible increase of the contact resistivity of the adhesive and soldered joints, but thermal cycling using a heater did not.

Within each thermal cycle, the contact resistivity increased reversibly with increasing temperature, due to the increase in volume resistivity of the solder or adhesive. Similar behavior was observed, whether the heating was from an external heater or from current application. Temperature variation caused fractional changes in contact resistivity up to 48% and 6% for adhesive and soldered joints, respectively.

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