A New Anisotropic Conductive Film with Arrayed Conductive Particles[a]

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ABSTRACT

A new anisotropic conductive film (ACF) incorporating arrayed metal conductors in an adhesive polymer is described. A photoresist pattern with round holes in triangular arrangement is formed on a stainless steel substrate. Using the substrate as cathode the holes are then electroplated to form metal bumps. After removal of the photoresist, the substrate is laminated to a solid adhesive film. The ACF is recovered by peeling off the adhesive film whereby the metal bumps are transferred from the substrate to the adhesive film.—The fine-pitch interconnection capability of this novel ACF was demonstrated by electrical testing of a 30 μm thick ACF consisting of an epoxy based adhesive film with nickel bumps. The latter were arrayed at 40 μm intervals in the film. Their diameters and heights were 20 μm and 12 μm, respectively. Ni/Au plated copper circuits of 200 μm pitch were attached to the ACF by thermocompression bonding. The bump arrangement was almost perfectly retained even after the bonding process. Electrical properties of the assembly, measured by the 4-wire method were contact resistance < 1 mΩ, insulation resistance > 10 GΩ, and high current-carrying capacity > 1 A per contact. Preliminary reliability tests on electrical performance were also carried out. The superior interconnection properties of the proposed ACF, compared with conventional ACFs that rely on randomly distributed conductive particles, are attributed to the arrayed, uniformly sized particles in the adhesive film.

INTRODUCTION

Anisotropic conductive films (ACFs), more appropriately referred to as anisotropic conductive adhesive films (ACAFs)[1], are widely used for fine pitch interconnections between liquid crystal display (LCD) panels and driver-IC tape carrier packages (TCPs). The finest interconnection pitch for LCD panels to date is as narrow as 70 µm. ACFs are also used for chip-on-glass applications[2] and TCP-to-PCB interconnections.

Conventional ACFs presently available in commerce are manufactured by dispersing in a random fashion electrically conductive particles in an adhesive polymer and forming this blend into solid films. The conductive particles, typically a few microns in diameter, are usually metal plated polymer spheres or nickel grains. The interconnection is established by placing the ACF between mating electrodes of the parts to be assembled, followed by thermocompression. Conductive particles contact the opposing electrodes and allow current flow perpendicular to the film plane, while lateral isolation is maintained by the adhesive surrounding the particles. During the thermocompression process the adhesive fills the space around mating electrodes and establishes physical interconnection.

The interconnection pitch achieved by commercial ACFs is limited by the random distribution of the conductive particles in the adhesive. For finer interconnection pitches, higher particle densities would be required to ensure that enough particles will contact an electrode. However, a higher particle density also increases the probability of formation of electrical shorts between adjacent electrodes. An attempt to provide for a more reliable interconnection using ACFs of this type has been reported. It utilizes a magnetic field to improve uniformity of the particle distribution[3].

In this paper a new method for producing an ACF with uniformly aligned conductive particles is described. Conventional electroforming technology is used to prepare a regular, ordered array of nickel particles in an adhesive film. The new method yields superior interconnection properties including fine pitch, low contact resistance, and high current-carrying capacity. The

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process for preparing products of this kind is described, electrical properties of samples prepared according to it and results of preliminary reliability tests are reported.

DESCRIPTION OF THE PROCESS

Figure 1 shows schematically the process steps for preparation of the new ACF. An electrically conductive substrate, usually a stainless steel or copper sheet with a polished surface, is used to form a photoresist pattern by photolithography. The pattern is chosen so that round holes form a two-dimensional array with the desired intervals between the holes. Subsequently, in the holes metallic, mushroom-shaped buttons (bumps) are electroformed with the substrate serving as the cathode. After removal of the photoresist pattern, an adhesive film is applied to the substrate either by laminating a solid adhesive film onto it or by coating bumps and substrate with a liquid adhesive that solidifies to a film. Lastly, the adhesive film is peeled off the substrate along with the metal bumps. The bumps, with their flat bottoms exposed on one side of the ACF, adhere to the adhesive layer, and the ACF comprising the arrayed conductive particles is produced.

To achieve optimum bump transfer, depending on the materials selected for bumps and substrate, it may be desirable to anodize or chromate treat the substrate surface prior to initiating the electroforming step. In the study described here, optimum bump transfer was achieved readily by selecting nickel and stainless steel for bump and substrate, respectively. Surface treatment was found to be not necessary.

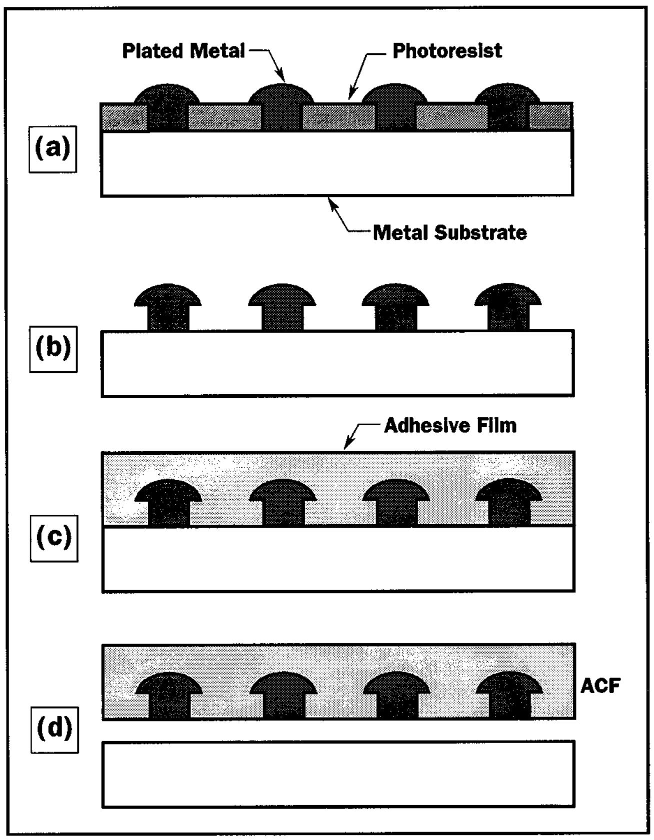

Figure 1. Schematic of steps for preparation of arrayed particle ACFs. The metallic substrate serves as cathode during the electroforming process. (a) after completion of electroforming of the conductive buttons (bumps) but before removal of the photoresist. (b) buttons resting on the metal electrode after removal of the photoresist; the alignment attained during the electroforming process is maintained. (c) application of adhesive film. (d) ACF after removal from the substrate.

EXPERIMENTAL

Arrayed particle ACF technology was demonstrated using nickel bumps and commercially available B-stage epoxy-based adhesive films. In preparing the ACF the first step was the spin-coating of photoresist to form a 7 µm thick film on a stainless steel substrate having the dimensions 60 mm X 60 mm X 0.3 mm. The substrate has an electropolished surface with roughness $R_{max} = 0.22$ µm. The photoresist was exposed and developed to create holes of 12 µm diameter at 40 µm intervals in triangular arrangement. The nickel bumps were electroformed from a sulphamate bath at a plating rate of 0.9 µm/min. Typical bump heights were 12 µm, typical bump diameters 20 µm. To improve electrical contact a 0.03 µm thick layer of gold was then electroplated onto the nickel bump head. After removal of the photoresist by acetone, an epoxy adhesive film of 30 µm thickness was laminated onto the substrate at room temperature by applying 4.8 MPa pressure for 10 seconds. This procedure caused the nickel bumps to adhere firmly to the film, which was then peeled off the substrate to form the ACF.

Electrical properties of the ACF interconnection were evaluated with 50 µm and 200 µm pitch flexible printed circuits (FPCs). Both FPCs consisted of polyimide and carried parallel lines of copper that were plated with 0.3 µm thick gold over 2 µm thick nickel. The respective copper thicknesses for the 50 µm and the 200 µm pitch FPCs were 5 µm and 18 µm.

For contact resistance measurement the FPC, connected to the ACF, was attached to a 4 mm wide copper electrode, which was plated with gold over nickel. The so prepared specimens were then subjected to a 4-wire test with 10 mA current in a circuit shown in Figure 2. This setup allowed measurements with an approximate error of $\pm 3\%$ at a resistance of 1 mΩ. Within this study, the term *contact resistance* is defined as the total resistance through the ACF thickness. It includes both the bulk resistance of the bumps and the resistance between substrate and bumps. In the experimental arrangement of Figure 2 I-V characteristics were also determined for currents up to 2 A.

For insulation resistance measurements, the FPC was bonded to

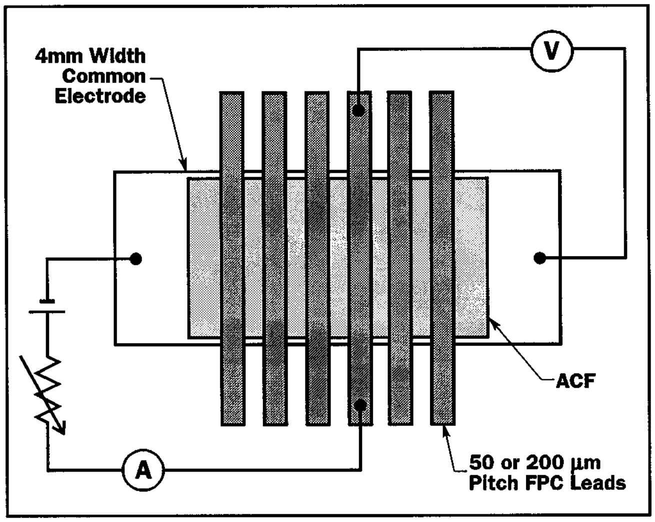

Figure 2. Circuit diagram for contact resistance measurement by 4-wire method. The polyimide film carrying the leads of the FPC is not shown.

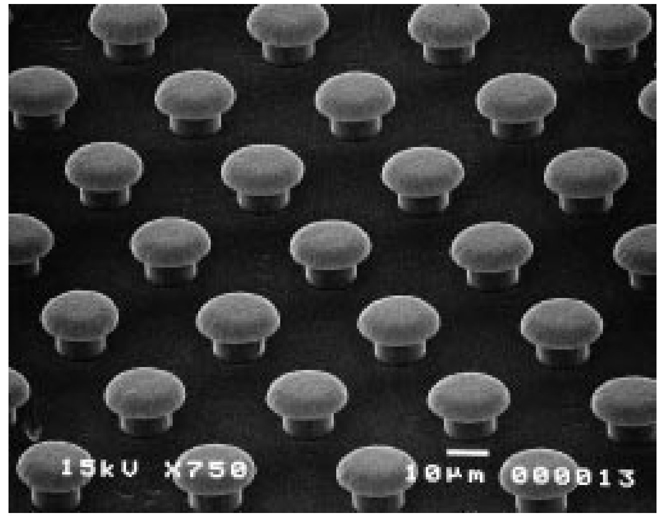

Figure 3. Scanning electron micrograph of arrayed, mushroom-shaped nickel buttons (bumps) formed on a stainless steel substrate. This figure corresponds to Figure 1(b).

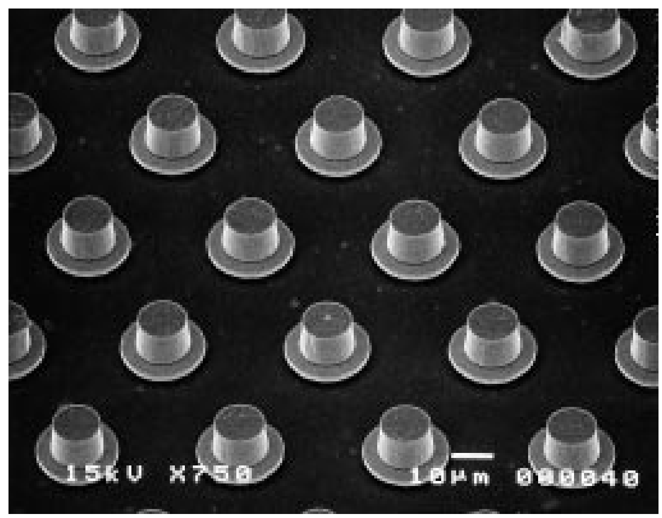

Figure 4. Scanning electron micrograph of arrayed, mushroom-shaped nickel buttons (bumps) attached to the adhesive film.

a glass substrate and the resistance between adjacent FPC lines was measured with a high-resistance meter at 100 V DC applied for 1 minute. This assembly was also used for observation of the bumps with an optical microscope.

Interconnection by thermocompression was achieved by temporarily bonding the ACF onto the substrate at 130°C and 2.3 MPa pressure for 1 second. This step was followed by permanently bonding the FPC to the substrate at 200°C and 2.3 MPa pressure for durations varying between 2 and 30 min. The ACF was bonded to the substrate with the surface carrying the bump bottoms face down. To carry out the preliminary reliability tests, such samples were exposed to an elevated temperature and humidity environment of 85°C and 85% relative humidity and to periodic temperature cycling of 30 minutes at −55°C and 30 minutes at approximately +85°C.

RESULTS AND DISCUSSION

In Figure 3 is shown an array of nickel buttons (bumps) on the substrate immediately after electroforming. Figure 4 shows the array after the transfer to the adhesive film. A comparison of both figures illustrates how well the immaculately aligned bump configuration on the substrate is retained after their transfer onto the film. Figure 4 also shows that the stems of the mushroom-like buttons protrude from the film surface. This indicates that the pressure applied for attaching the adhesive to the electroformed bumps while they were still in the substrate was sufficiently high to cover the bumps. But it was also sufficiently low to avoid adherence to the substrate surface. The desirable morphology shown in Figure 4 occurs because of the low force required for bump transfer. Because the adhesion between substrate and adhesive is very small, deformation of the delicate adhesive film is kept to a minimum.

As shown in Figure 5 the triangular arrangement of the bumps is retained very well even after thermocompression bonding of the ACF onto the FPC. No significant distortion of this pattern is observed, neither for the bumps located at the FPC copper lines nor for bumps between these lines. On the other hand, the conductive particles of a conventional ACF tend to wander from the electrode while the adhesive flows during thermocompression. Figures 6(a) and 6(b) illustrate the different behavior of the new and the conventional ACFs. Particle movements of the kind shown in Figure 6(b) decrease the particle density available in the ACF at the electrodes, thereby reducing interconnection reliability. The same movements also tend to increase in a random fashion the density of conductive particles locally in the space between adjacent electrodes thus increasing the probability for occurrence of electrical shorts.

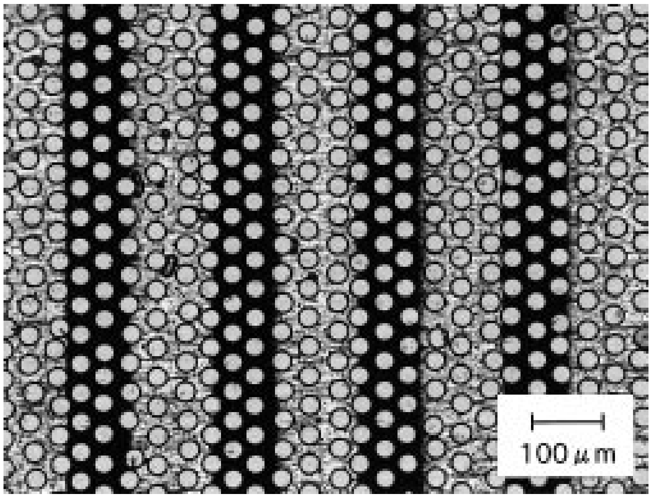

Figure 5. Optical micrograph of a 200 µm pitch FPC bonded to a glass substrate with an arrayed particle ACF prepared according to this study. The picture was taken through the transparent glass substrate.

As illustrated in Figure 6(a), unlike in conventional ACFs, the bump bottoms in the new ACF described in this study are exposed. This facilitates a secure mechanical contact between the substrate of a FPC circuit and the bumps. The positional stability of the bumps in the new ACF during the flow of the adhesive in the thermal bonding process can be explained by considering the high friction that results from this secure mechanical contact. Contributing to the stability is also the submerged position of the bumps inside the adhesive film. Flow during thermal bonding occurs mainly in the upper portion of the film when the heat is applied with a tool head through the FPC. Therefore, control of the film thickness is essential to prevent excessive adhesive flow, which may disturb the bump configuration.

The number of bumps N_b on a copper line in Figure 5 can be estimated by

$$N_b = \frac{2LW}{\sqrt{3}d^2}$$

where

L = length of the copper line,

W = width of the copper line,

d = nearest distance between adjacent bumps.

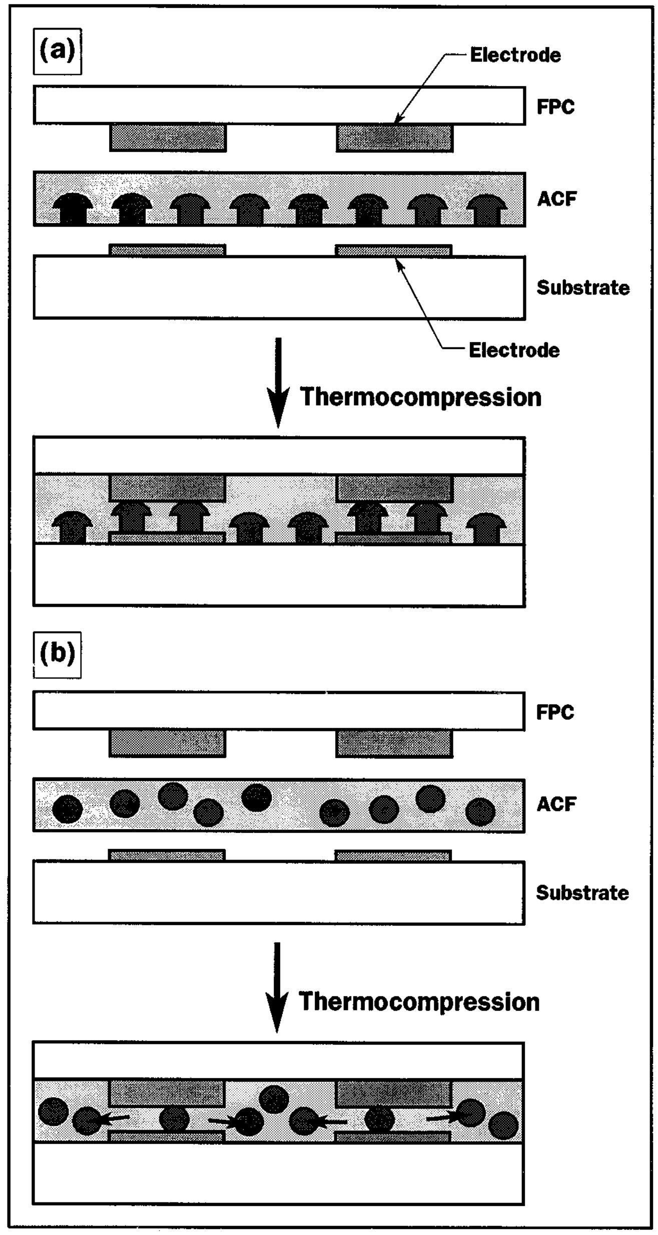

Figure 6. Cross sectional views of location of critical elements before and after thermocompression bonding. (a) arrayed particle ACF. (b) conventional ACF with randomly distributed conductive particles.

For the 200 µm pitch assembly circuit, with d = 40 µm, L = 4 mm, and W = 110 µm it is $N_b \approx 320$. This number was believed to be large enough to insure sufficiently low contact resistance. As discussed below this was verified. Typical values of contact and insulation resistance for the 200 µm pitch assembly circuit are shown in Figure 7. The contact resistance represented by the lower curve is below 1 mΩ, the insulation resistance between 10 GΩ and approximately 1 TΩ. Both sets of data indicate excellent electrical performance although they do vary over the 150 contacts.

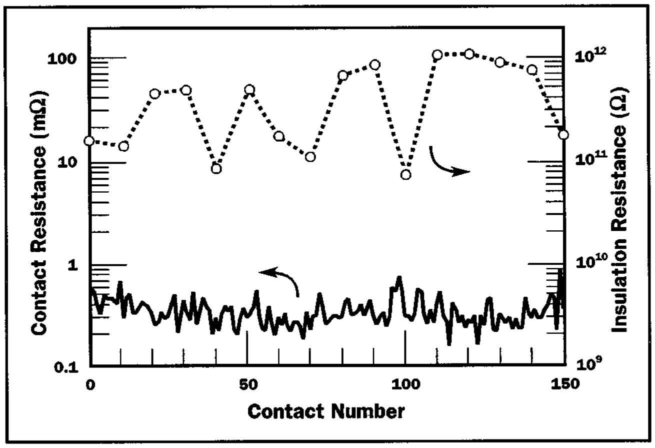

Figure 7. Contact and insulation resistance versus contact number in a 200 μm pitch assembly circuit. The contact resistance shown in the lower curve represents results of individual measurements for all 150 contacts. The insulation resistance was measured for every 10 contacts.

On 50 µm pitch assemblies similar results were obtained for both properties, but there were short circuits between a few adjacent contacts. This indicates that the bump diameter of 20 µm is too large for a 50 µm pitch FPC, which has a line spacing of 30 µm. A new ACF with reduced bump size and finer bump pitch is under investigation.

Since the bump bottoms of the proposed ACF are exposed and not covered by the adhesive, oxidation of the nickel surface was a concern. To address this, some ACF's were stored in a laboratory environment for 3 months and then used for preparing samples. No deterioration of contact resistance was observed.

For a 200 µm pitch assembly circuit the I-V characteristics were determined. Results are shown in Figure 8. For these measurements the current was raised to a maximum value and then decreased at a rate of 25 seconds per current cycle. The contact voltage was found to be proportional to the current if the latter was below 1 A. Figure 8(a) shows this behavior. Repeated measurements yielded well reproducible data. For maximum current above 1 A hysteresis was found. Two hysteresis loops are shown in Fig. 8(b). The second set of data, identified as *Run 2* in the figure, was obtained from a repeat measurement, which was carried out after an adequate time. An increase in contact voltage was observed as shown in Figure 8(b). These results can be understood in terms of reversible and irreversible changes of contact resistance due to current induced heat. The latter originates from deterioration of the physical contact, which can be attributed to thermal mismatch between the bump metal and the adhesive polymer. Figure 9 shows the contact resistance as function of time measured at a constant current of 1 A. A slight increase in contact resistance was measured after a 10 minute duration. However, compared with the contact-to-contact variations shown in Figure 7 this change is not significant. The above results indicate that the current-carrying capacity of the new ACF is as high as 1 A per contact, which is equivalent to a current density of 2.3 A/mm^2.

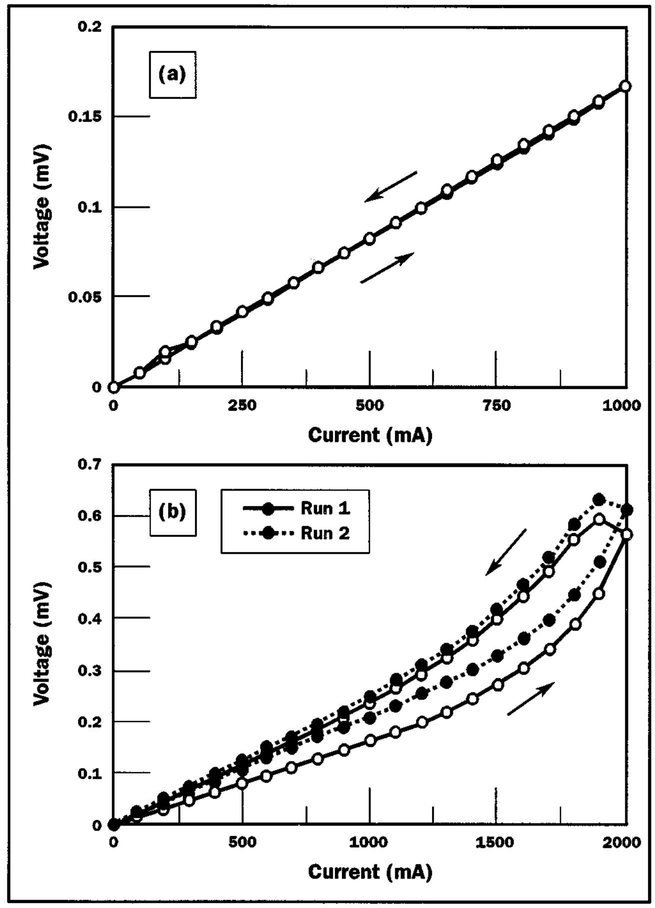

Figure 8. I-V characteristics measured on a 200 μm pitch assembly. (a) for a maximum current of 1 A per contact. (b) for a maximum current of 2 A per contact.

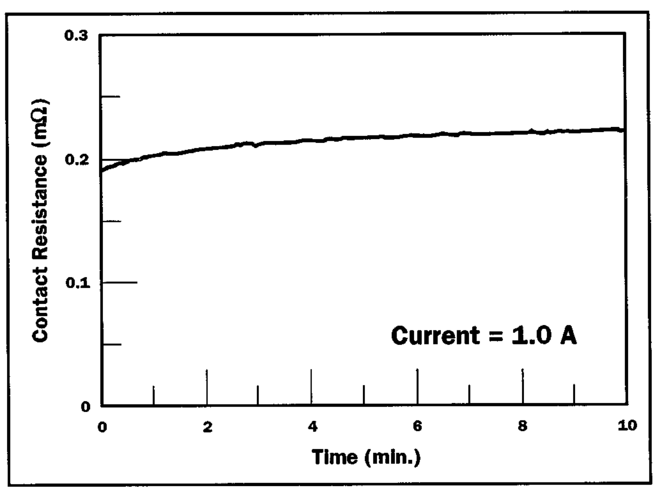

Figure 9. Time dependence of contact resistance. Data were taken every 2 s.

Figure 10 shows results of exposure of a 200 µm pitch assembly to high temperature, 85°C, and high humidity, 85% RH, for 500 hours. The lower curve represents contact, the upper insulation resistance. During the first 50 hours contact resistance increased with time and then became almost constant. For 150 contacts the maximum contact resistance remained below 10 mΩ, even after 500 hours. During the entire test period the insulation resistance retained values above 10 GΩ for all contacts.

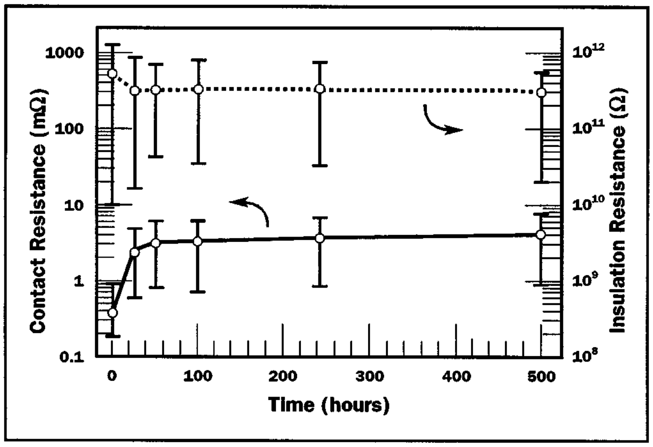

Figure 10. Change of contact and insulation resistance of a 200 µm pitch assembly circuit as function of time during high temperature and humidity testing. The error bars indicate the range of measurements for 150 contacts, the open circles represent the means.

Other 200 µm pitch circuits were subjected to temperature cycling. For 500 cycles the lower curve in Figure 11 shows typical changes of contact resistance, the upper that of insulation resistance. In each cycle the sample was first held at −55°C for 30 min, heated to approximately 85°C, held at this temperature for 30 min, and then cooled down to −55°C to start the cycle again. During the first 50 cycles contact resistance increased to a relatively large mean value of about 20 mΩ. This phase was followed by an additional small increase during the remaining 450 cycles. Deterioration of contact resistance during temperature cycling was greater than that observed during static high temperature, high humidity testing. This behavior is understandable because the difference in thermal expansion of the bump material and the adhesive must be expected to manifest itself more drastically in a temperature cycling test than in a static test. Of interest is the improvement in insulation resistance with increasing number of cycles. The measurements show that values above 1 TΩ were reached after about 100 cycles. These results indicate that the new ACFs have considerable reliability although some improvements may be required in retaining low contact resistance during temperature cycling.

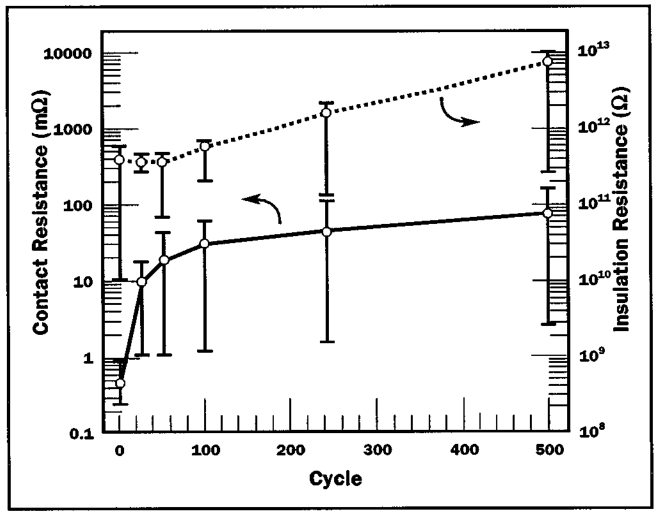

Figure 11. Change of contact and insulation resistance of a 200 µm pitch assembly circuit as function of number of cycles during temperature cycling test. Error bars and open circles mean the same as in Figure 10.

CONCLUSIONS

A new approach to arrayed particle ACF technology with nickel buttons (bumps) representing the conductive particles and epoxy-based films the insulating matrix is described. The new process employs electroforming to prepare a regular array of conductive buttons (bumps), in particular nickel bumps. This array is then transferred to an adhesive film. The bump arrangement in the so prepared ACF was shown to be retained almost perfectly during assembly of a 200 µm pitch circuit. Electrical tests showed very low contact resistance, high insulation resistance, and high current carrying capacities. The superior interconnection performance of the ACF described in this study, compared to that of conventional ACFs with random distribution of the conductive particles, is attributed to the arrayed, uniformly sized particles in the adhesive film.

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