# State of the Art in Electrically Conductive Adhesives

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## Abstract

This paper presents an overview of the current status of the use of electrically conductive adhesives (ECAs) in various electronics packaging applications, and of the fundamental issues being faced in their continued development, e.g. understanding of the electrical conduction processes. The solutions to past technical problems include the reduction of contact resistance drift due to corrosion, lower resistivities from the use of bi-modal silver flake as filler, and the identification of the source of impact resistance failure. Emphasis is placed on the recent development of surface mount and flip-chip technologies as the combination of these technologies with conductive adhesives represents the latest development in the area of electronics packaging. It is concluded that little practical use of conductive adhesives in surface mount has developed yet, but that both isotropically and anisotropically conductive adhesives (ICAs and ACAs) have been used in real flip-chip applications. More use is expected in the near future in this fast developing area.

## I. Introduction

### A. Technology Drivers

There are two primary categories of Electrically Conductive Adhesive (ECA):

- Isotropically Conductive Adhesive (ICA)
- Anisotropically Conductive Adhesive (ACA).
- ACAs are available as paste or film (ACF).

Both types conduct through metal filler particles in an adhesive polymer matrix.

ECAs have been used for electronics packaging applications for decades in hybrid, die-attach and display assembly. There has been growing interest from the electronics industry over the past decade in other kinds of electronics packaging applications. While toxicity issues and environmental incompatibility of the lead in tin-lead solders triggered that greater interest at the outset, it has been the other evident advantages continue to drive further research. ECAs can offer the following additional potential advantages:

- Fine-pitch capability especially when using ACAs for flip-chip
- Elimination of underfilling with ACA bonding;
- Low temperature processing capability;
- Flexible, simple processing and hence low cost.

In addition, the continuing and inevitable drive towards smaller joints reduces the failure time due to the formations of voids or brittle inter-metallics by diffusion in as the square of the dimensional shrinkage [1].

For these reasons, a lot of research work has recently been focused on surface mount and flip-chip applications. This paper presents an overview of the current status of the use of conductive adhesives in various electronics packaging applications, and of some fundamental issues relevant to their continuing development. The paper is organized with initial discussions of the basic concepts of ICAs and ACAs, both being focussed on structure-related electrical properties, followed by a survey of current applications and some comparisons of the two technologies.

### B. Isotropic Conductive Adhesives (ICAs)

Ag is usually used as the filler material due to its high conductivity and simple processing for ICA applications. Polymer based metal plated spheres or nickel fillers are mainly used for ACA applications. Figure  shows the microstructure of an isotropically conductive adhesive joint for a flip chip component on an FR-4 substrate. The metallic filler content is high enough (between 25-30 volume percent) to cause direct metallic contact.

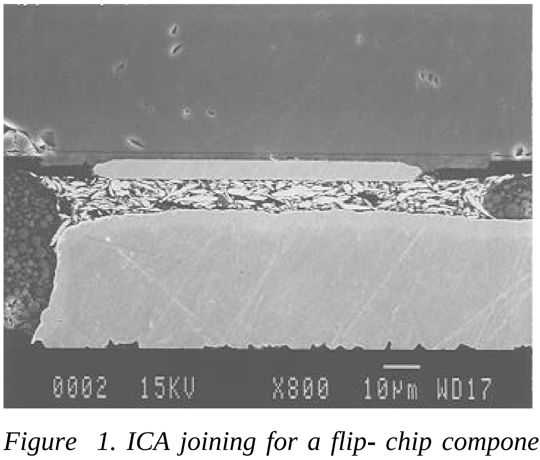


*Figure  1. ICA joining for a flip- chip component on an FR-4 substrate.*

### C. Anisotropic Conductive Adhesives (ACAs)

In an ACA joint, the filler particle is normally between 5-10 volume percent, and does not cause any direct metallic contact. It is only after pressurization during curing that the electrical conduction becomes possible in the pressurization direction as is illustrated in Figure 2. As there is no direct contact between the particles, ACA technology is very suitable for small pitch assembly, and is starting to find applications in flip-chip technology.

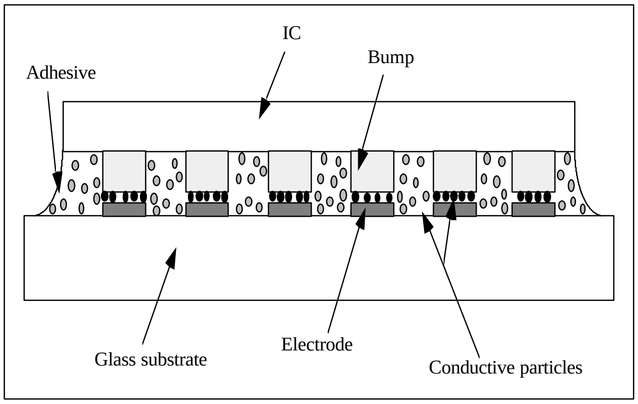


*Figure 2. ACA joint for a flip-chip component on a glass substrate.*

D. Non-Conductive Adhesive (NCAs.)

The complementary NCA technology will receive only a brief mention below. In this case, the contacts themselves are in direct metal-to-metal contact, held together by the NCA.

## II. Isotropic Conductive Adhesive (ICA)

A. Structure

As the proportion of metal in the polymer matrix is increased, the resistance drops only slightly until the “percolation threshold” is reached, when the first continuous metal path is established through the composite material [2]. The resistance continues to drop more slowly as multiple parallel paths are developed with the continued addition of more metal filler. Ideally one would like to use the minimum quantity of filler necessary to pass the threshold, but in practice manufacturing tolerances require a design target composition significantly beyond the threshold. Very small contact volumes increase the statistical spread of resistivities already inherent in a percolation structure. Minimal filler content is a requirement for both economic reasons (since silver is expensive) and to maximize the proportion of polymer adhesive. Both issues can be addressed by the use of metal flakes (or rods) instead of spheres as filler. The benefits can be readily understood by considering the extreme case of flakes of zero thickness, which would clearly establish a percolation threshold at zero metal content, i.e. at 100% adhesive with zero filler cost. Practical commercial materials achieve substantial reduction in the threshold composition by the use of flakes, by virtue of the increased connectivity which accompanies the increased surface-to-volume ratio, compounded by bi-modal particle size distributions. The efficacy of bi-modal particle distributions has been demonstrated [3] and both flakes and powders are used for the smaller particles [4].

Theoretical simulation has been carried out to optimize the electrical performance of a conductive adhesive joint using a bimodal distribution of metal fillers using computer modeling based on Kirchoff´s law using finite-element analysis. Two classes of metal fillers were used, i.e. nano-scale and micro-scaled particles. The goal was to decrease the metal loading to improve the mechanical performance for specified electrical properties. It has been shown that it is possible to decrease the total metal loading with good electrical conductivity using a bimodal filler distribution [5].

In addition, the flakes at the material surfaces seem to be aligned parallel to the surface to a depth of a few flake thicknesses. The effect seems to be universal, with squeegee or syringe dispensation and also appears inside air bubbles (Figure 3), probably due to surface tension [6]. One also sees particle alignment inside the material if pressure is applied [7], as seen in Figure 1. Particulate orientations are important for predictions of both adhesive strength and electrical resistance, and flow modeling of the ICA under stencil, print, or dispensation, and/or positioning pressure is important, but much more difficult than underfill flow modelling [8] due to filler sizes and shapes.

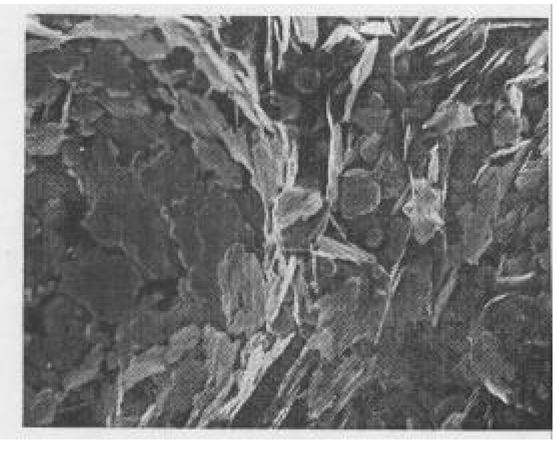


*Figure 3. ICA flake layering effects at surfaces, observed in an air bubble [6].*

There are various novel approaches to the improvement of electrical connectivity at a given metal content, including magnetic alignment of nickel filler rods [9], the use of polymer particles to force alignment of flakes [10], and electric fields

[11]. Anything that increases the packing density/efficiency of the particles also increases the connectivity and reproducibility of the structure, permitting the design composition to move closer to the percolation threshold, and a reduction in metal filler.

Modelling of the material structure for prediction of the electrical properties has included

- Distributions of uniformly sized spheres [12]
- 2D [13] and 3D [14] rectangular particles with limited size distributions and x, y, z orientations
- Rectangular particles rotated about the x, y, z axes in 1° increments [15].

The extension to bimodal flake representations requires a dramatic increase in computing power. The difficulty lies in the development of an efficient algorithm for the random placement of the particles, which must not impinge upon the space occupied by another. As the structure fills up, this process becomes more and more time consuming. A potential energy technique has proved effective [15], but the most recent advance is the use of a compression algorithm applied to initially well separated particles [16].

### B. Electrical Properties and Modeling

The electrical resistance of the ICA has four distinct components [2]. Three of these are obvious; they are the metal “intra-particle” resistance, the “inter-particle” contact resistance, and the “contact” resistance between the surface particles and the lead or contact pad. The fourth component comes from the meandering “percolation” path of the continuous metallic connection(s) through the material.

(1) *Percolation theory* is well developed for the elementary system of uniform conducting spheres (or cubes) in a perfectly insulating medium [17]. There are no analytical solutions, and the theoretical results are deduced by the averaging of multiple Monte Carlo randomized simulations. Conducting particles are randomly assigned to sites on a specified regular array. For any realistic random system, the site separations must be much less than the particle sizes, and the problem becomes how to fit new particles into the structure at high particle concentrations (as required here) with reasonable efficiency.

The percolation modeling literature commonly includes finite intra-particle resistivities, but inter-particle resistances are seen less often. This is partly because the most common systems of interest would assume electron tunneling between particles, and the exponential dependence of the tunneling probability on separation introduces a strong parametric dependence on a poorly characterized variable. Percolation models of the electrical resistance of ICA systems have included both intra-particle and inter-particle resistances, but with both grossly approximated so far, e.g. with the simplifying assumption of uniform tunneling thickness [12-15]. (To accommodate 1nm variations in a 1-10nm tunneling separation range between particles requires an underlying simulation grid with a 1nm pitch in a brute force approach, i.e. a substantial increase in resolution over that otherwise required for micron sized particles. It would be more efficient, however, and just as valid to superimpose the tunnel gap distribution on contacting islands distributed on a coarser grid.) The structural modeling requirements have been outlined above.

Electrical modeling requires the addition of the conduction processes discussed below to each of the elements: intra-particle, inter-particle, and contact, with the structural model itself providing the percolation component. Existing models confirm the effects of surface layering at a qualitative level [14], and size effects [12, 18], i.e. the increase and decrease in effective conductivity respectively for limited ICA sample dimensions parallel and perpendicular to current flow.

As models improve, one expects eventual quantitative agreement [19]. It is probably satisfactory to continue to ignore the effect of finite polymer conductivity, but this assumption should be checked for new materials. One prediction of percolation theory which has never been validated in these systems is the frequency dependence of the conductivity in terms of the coherence length [20], which appears to be masked by the particle skin effect (see below.)

Resistivity measurements must be made on genuinely isotropic samples of suitable size, unless size or layering effects are the actual object of the measurement. On the other hand, the interconnect application will actually include both. So will measurements along a long thin sample, but with the opposite effects [2]. The measurement of small resistances with sufficient sensitivity to detect early corrosion, etc., is difficult and usually accomplished by depositing the long specimen just mentioned or by daisy-chaining multiple interconnect samples. In future, the impedance transformer should see increased application to solve this problem [2].

It is noted here that there is evidence of percolation chains dropping in and out of the conduction paths during thermal cycling. This effect is demonstrated by reproducible hysteresis in resistance versus temperature plots during thermal cycling of ICA structures where only a limited number of percolation paths are expected to exist, i.e. for very small contact areas. [21]

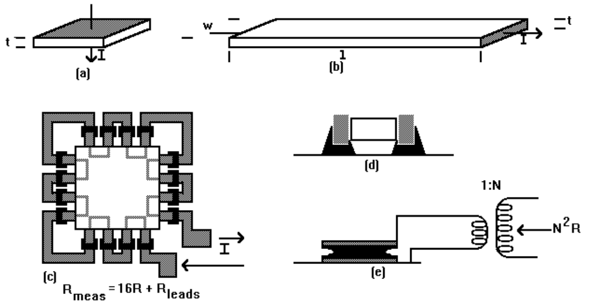


*Figure4. ICA test patterns; (a) models the interconnection joint; (b) increases the sample resistance; (c) uses a daisy-chain dummy chip; (d) uses a "zero-ohm" resistor chip; (e) increases the test resistance of (a) with an impedance transformer.*

(2) *Inter-particle conduction* is generally assumed to take place directly from metal to metal, or by tunneling through an insulating layer, whether of intervening polymer or of surface contaminants, or by conduction through a surface oxide film, which for silver would be a conductive degenerate semiconductor. There is a range of tools available to characterize conduction mechanisms, including frequency effects, non-ohmic high field behavior, temperature dependencies, etc., and the absence of any observation of negative temperature coefficient of resistance (TCR) or non-ohmic behavior is sufficient to eliminate most other conduction mechanisms from contention. Silver is typically tarnished, and presumably would oxidize within the polymer, even if initially “clean,” but it is not clear what effect the surface lubricants identified on flake surfaces [22] would have on this process. An XPS surface analysis of the flake surfaces should be carried out to distinguish between the presence of silver oxide and the oxygen content of the lubricant and/or polymer residue.

No matter which of the mechanisms apply at the gap itself, the contact area is accepted as being typically small, of diameter, $d$, 10nm or less [6]. Clearly there will be some constriction of current flow between particles at the contact, and the Holm theory specifies this contact resistance to be $\rho/2d$ [2]. With the constriction resistance proportional to $d^{-1}$, and the tunneling or oxide resistances proportional to $d^{-2}$, one should be able to identify the dominant contribution from a pressure dependence, which has been theoretically matched to experimental data for a $d^{-2}$ dependence, but not for an ICA [23]. The internal pressure exerted by the curing process will be discussed further below. Returning to the differences between the contact conduction mechanisms, the TCR will be zero (or slightly negative) for tunneling and positive for the oxide. Unfortunately, it is difficult to find data on the exact electrical properties of the oxide, which are subject to local formation conditions, so it is not known whether the TCR would be less or greater than the metal particle TCR. It would appear from the formula that the constriction resistance would have the same TCR as the metal particles’, but the derivation does not include the mean free path reduction which will be associated with contact dimensions less than the bulk value in the particles; this extension to the theory is necessary.

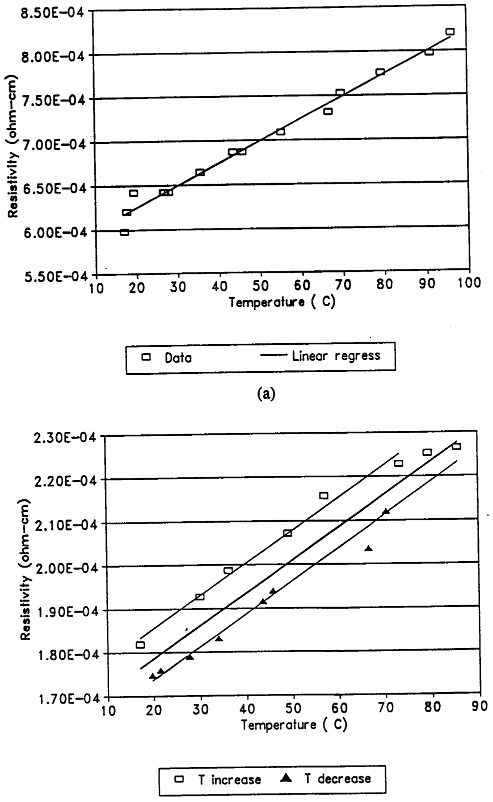
The inter-particle conduction mechanism remains undetermined, and the points made above, which reflect those in the literature, are very general. What is needed is a comprehensive basic study of the metal-polymer interface, to investigate charge transfer and band effects in the polymer(s), time and temperature effects, and how the process proceeds during curing. In addition, actual contact points need to be located and isolated, and the potential distribution plotted across the boundary from one particle to the other. Electrical noise measurements are also often a useful diagnostic tool, and there is noise data in the literature [24, 25], but as is often the case, the interpretation is ambiguous.

Frequency dependencies are easily determined and can be definitive in the identification of some conduction mechanisms. In the ICA case, a.c. measurements were expected to short circuit the tunnel gaps between particles, with the corner frequencies providing the means to separate out the particle resistance from the inter-particle gap contribution. The method was validated by a.c. measurements before cure. Resistivities below the percolation threshold decreased with frequency to limiting values similar to those above it [25]. (This experiment suggests the use of impedance spectroscopy as a manufacturing quality test for ICAs, as for solder paste.) When applied to cured ICAs, however, no such effect was observed (see below), so either there is no tunneling gap (i.e. conducting oxide or metal-metal contact) or the tunnel resistance is just much less than the particle resistance [2, 4].

(3) *Intra-particle resistance* accounts for a substantial proportion of the measured ICA resistance, and in some cases essentially all of it. This conclusion is based on TCR measurements on a variety of commercial ICAs, where the TCR values range downwards from the bulk metallic value, but are always positive [2, 4, 20]. Within the limits of experimental accuracy, the data are consistent with a model of the intra-particle metallic resistance in series with a zero TCR contact resistance, but cannot be totally conclusive

(Figure 5). Thermal testing needs to be extended to much lower temperatures to resolve this point.

For ten micron diameter flakes one micron thick, and micron-sized smaller particles, the electron mean free path is not going to be reduced significantly from the bulk value, and no accounting is needed for size effects in the particles. (Note that this would not apply to the nano-particle ICA variant [27].) But the nature of the surface (i.e. rough or smooth for diffuse or specular scattering) could be important for the assessment of mean free path limitation for constriction resistance.



(a)

(b)

Figure 3.1: Resistivities for various temperatures. (a) Brass stenciled CT-5047-02 thermoset sample (TCR= 0.0039/°C). (b) CSM-933-65-1 screen printed thermoplastic sample. (TCR= 0.0038/°C)

*Figure 5 [4]. The slopes match the TCR of Ag.*

The a.c. measurements mentioned above were run on the same ICA materials which gave TCRs identical to the bulk value for silver, and so it is not surprising that the a.c. characteristics were in total accordance with the predictions of skin effect resistance and inductance for silver [4]. These experiments should be duplicated for materials with greater inter-particle resistances.

At frequencies where skin effect is dominant, the lower resistance advantage enjoyed by solder disappears, as the effective cross-sectional area shrinks with skin depth for solder and ICA alike.

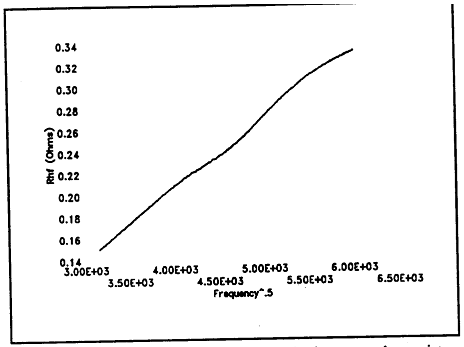


Figure 3.5: This graph shows the linear relationship between the resistance at high frequencies and the square root of frequency.

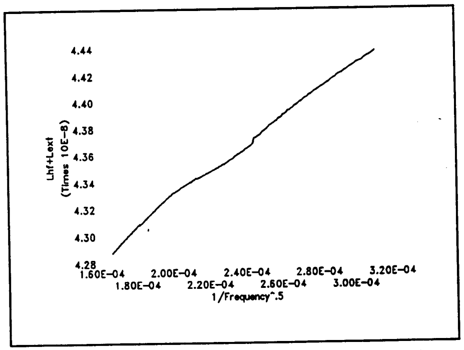


Figure 3.6: This figure exhibits the linear relationship of the inductance at high frequencies with $f^{-1/2}$.

*Figure 6 [4]. The R, L data match Ag skin effect.*

(4) *Contact resistance* can be isolated from the bulk composite resistivity by the combination of three-terminal measurement with the more common four-terminal [28]. It is the contact resistance which has been shown to be the source of electrical reliability problems [29-31]. The oxidation (corrosion) of copper or the tin in Sn/Pb contact pad or lead coatings has been demonstrated, and explains the greater long term stability of noble metal contacts (gold or palladium) under thermal cycling and 85/85 stress testing. More recently galvanic corrosion has been identified between dissimilar metals [32, 33]. One would fully expect to see the effects of interfacial diffusion in the longer term (albeit limited by low process temperatures), and the formation of brittle inter-metallics; although these would probably have no discernible effect on mechanical reliability, the electrical impact could be significant, given the limited number of low diameter contact points to the percolation paths. The solution to these problems would be to eliminate the dissimilar materials, and the use of silvered contacts with silver-based ICAs would seem logical. However, silver on copper introduces much the same problems, and requires a barrier layer (e.g. of Ni.)

Recently, the high-frequency ICA data of Li et al [4] have been extended by Wu et al [34] and by Dernevik et al. [35] Li and Wu focused mainly on the MHz region, and Dernevik on the GHz region.

Wu reported that ICA joints can change their high frequency properties during bending, which means that ICA joints are not controllable at high frequency under bending. A natural question that one may ask is if we perform temperature cycling which will cause thermal-mechanical stress in the joint, will the high frequency properties of ICA joints change?

### C. Mechanical Properties

The vast majority of the published ICA data is comprised of electrical resistance and adhesive strength measurements, both presented in the context of reliability testing. But while there has been some parallel effort to interpret the electrical properties in terms of both structure related and physical failure models, there has been little similar effort to understand the mechanisms of adhesion at a comparably fundamental level. Obviously, such a study requires a systematic approach to the measurement of adhesive strengths for a matrix of metal surface and polymer combinations. It is clear that surface cleanliness plays a crucial role in effective adhesion [36] (and one which may be overlooked in the desire to apply ICAs as drop-in replacements for solder), so surface treatments must be included as a secondary variable, with consideration of roughening effects also included. While this could be regarded as an empirical study, the fundamental goal of determining the relative contributions of various adhesion mechanisms (e.g. chemical, mechanical, electrical) should not be lost sight of.

Plasma cleaning of the adherent surfaces would seem to be a logical step, but so far preliminary data shows no improvement in adhesive strength with either Ar or $O_2$ plasma treatments, despite the demonstrated removal of organic contaminants and oxides [11, 37].

Published ICA adhesive and shear strengths are on the same order as those of solder, usually a little less [38], occasionally higher [36], but anyway adequate. The problem has been the drop test failure rate, leading to the widespread adoption of the NCMS criteria [39] as a de facto standard. In general, it is the larger devices which are most at risk, and indeed current commercial materials seem adequate for smaller devices such as SMT passives, which have been in mass production with ICA attachment for some years [40]. Improved understanding of this particular phenomenon is currently leading to the development of ICA materials specifically designed to address the drop test problem. The key lies in the imaginary component of the complex Young's modulus, which represents energy dissipation in the material, as opposed to the energy storage of the simple deformation represented by the conventional form of Hooke's Law. The complex modulus is therefore directly analogous to the complex dielectric constant, and dynamic stress-strain relationship actually includes a phase shift. When one examines drop test survival data, the success rate correlates with the (imaginary) dissipation modulus rather than with adhesive strength [41, 42]. One way to design materials with high dissipation modulus is to select polymers with glass transition temperature $T_g$ below the operating range, i.e. below room temperature, in general. However, operating polymers above $T_g$ carries its own penalties, e.g. higher temperature coefficients of expansion, so the next step is to develop adhesive polymer blends with high mechanical absorption without those disadvantages. There are energy-absorbent material options other than low $T_g$ choices, however, and these are under study [43].

With the primary goals of satisfactory electrical performance, adhesion, and drop test survival all apparently within reach, attention will undoubtedly turn to the same testing regimen which dominates solder research, i.e. the coefficient of thermal expansion, mechanical compliance, fracture modes, and fatigue failure, all with the objectives of reliability lifetime prediction and extension. The expectation is that the compliance characteristics derived from the polymer base will be much better than solder's, and carry through to superior thermo-mechanical stress fatigue performance. Naturally the properties of the composite should be modeled in terms of the structure to demonstrate that their physical origins are understood.

### D. Materials

The polymers in common use in ICAs are thermoset epoxies, with sufficient thermoplastic mixed in to allow for softening and release for rework under moderate heat. Up until now, the polymers used in ICAs have been adapted from those developed for other purposes. The results of research programs specifically intended to develop polymer adhesives tailored to ICA applications have yet to appear on the market, but in the meantime the identification of the need for mechanical energy dissipative materials may have already made them obsolete. Certainly the search for new materials must now focus on this property, but without compromising on others. Polymer adhesion is a fundamental property which must be understood, with fundamental contact angle wetting experiments for ICA base polymers a first step.

The cure process has been modeled successfully by remarkably simple mathematical expressions [28, 44], but which require accurately determined parameters from experimental Differential

Scanning Calorimetry (DSC) data. The success is demonstrated by the observation of the sudden decrease in resistance, interpreted as indicative of complete cure, at the predicted point of 100% cure [6, 44]. The assumption is that the resistance drop is due to physical shrinkage of the polymer matrix with complete cure, but this particular property, i.e. physical shrinkage and the development of an internal pressure to squeeze filler particles together, has not been measured, and does not appear to have been modeled. The measurement of a dimensional shrinkage with cure should not be a major problem, nor should the measurement of internal pressures.

The metal of choice as filler has been silver, but the warning that silver is accompanied by electromigration problems keeps on coming up. Certainly the existence of the electromigration problem has been documented [45], but it does not seem to be a problem in practice. It is evident in un-cured material [11, 46], and it has been suggested that commercial additives to the polymer seal the silver surface, defeating migration tendencies. There also appears to be a field threshold [47], and moisture is requisite, but systematic study is required to establish the boundaries to the effect. In addition, the diffusion and clustering of metals in polymers is well established [48, 49], and should be investigated for silver in appropriate polymers as the limiting zero-field phenomenon.

The approach of current research to establish a processing methodology based on process boundaries for underfill [50] should be immediately applicable to ICAs

E. Reliability

(1) *Cure schedule* control is undoubtedly very important for joint reliability. It seems that the electrical resistance of the joint is related to the curing degree, especially for non-noble metal surfaces, as can be seen in Figure 7. Figure 7 shows the electrical resistance vs. curing time for an epoxy conductive adhesive cured at $150^0$C and at various curing times after the damp heat treatment at $85^0$C, 85%Rh, 1000 hours on the Sn37Pb bonding surface [51]. The corresponding curing degree varies between 65 and 90 %. The curing degree was determined by the DCS measurement. Below a critical curing degree (for this adhesive, the critical curing degree is 77%), the electrical resistance of the joint increases significantly, because an incompletely cured epoxy can absorb a significant amount of moisture, which in turn causes oxidation/hydration of the Sn37Pb bonding surface [52]. If a noble metal, for instance Au or Pd is used as the bonding surface, no electrical resistance change is observed, despite the fact that the curing degree can be very low, as can be seen in Figure 8.

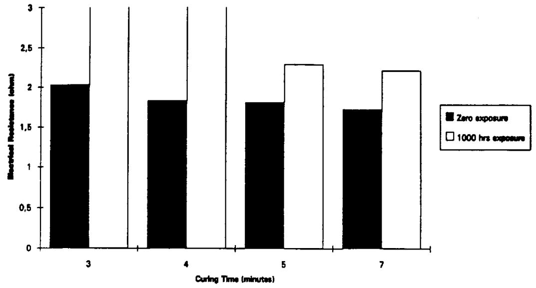


*Figure 7. Contact resistance of 10 Sn37Pb plated chip components in series before and after exposure to humidity up to 1000 hours, at 85 °C and 85 % RH, using an epoxy based conductive adhesive on Sn37Pb-plated boards.*

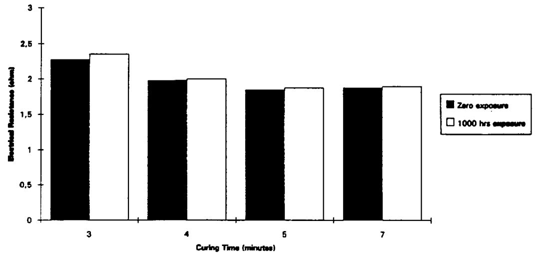


*Figure 8. Contact resistance of 10 Ag/Pd plated chip components in series on Au-plated boards before and after exposure to humidity up to 1000 hours, at 85 °C and 85 % RH, using the same epoxy based conductive adhesive as the one used to obtain the data in Figure 7.*

Once a critical curing degree is reached (72%), it seems that the shear strength of the joint on the Sn37Pb bonding surface can be maintained at a constant level as is illustrated in Figure 9.

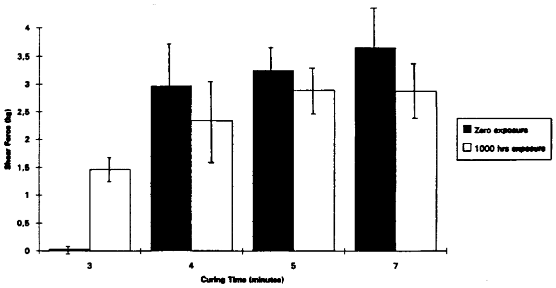


*Figure 9. Average shear strength of 10 Sn37Pb plated chip components as a function of curing time, before and after exposure to 1000 hours at 85°C and 85 % RH, using the same epoxy conductive adhesive as the one used to obtain the data in Figure 4 and Sn37Pb-plated boards.*

However, on the noble metal bonding surface, the shear strength of the joint is almost independent on the curing degree in the range between 67 to 92%, as can be seen in Figure 10.

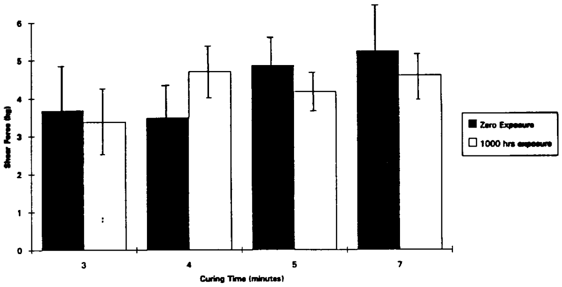


*Figure 10. Average shear strength of 10 Ag/Pd plated chip components as a function of curing time, before and after exposure to 1000 hours at 85°C and 85 % RH, using the same epoxy conductive adhesive as the one used to obtain the data in Figure 6 and Au-plated boards.*

At full cure conditions, the electrical resistance and the mechanical strength of conductive adhesives are also guaranteed [53].

In summary, it can be said that a minimum curing degree appears to be required to provide a certain level of mechanical and electrical performance in the adhesive system. Once this is achieved, increasing curing times do not result in significant improvement.

The above results also indicate that for conductive adhesive joining, noble metal surfaces are preferred to non-noble metal surface.

(2) *Moisture effects* on the polymer degradation in conductive adhesives have been studied by Khoo et al [54]. Moisture sorption effects may be reversible or irreversible, and are usually small enough to make detection of the molecular changes during absorption/adsorption very difficult.

Figure 11 shows the FTIR spectra of an anisotropic conductive adhesive in the following manner: (a) after curing and 41 hours conditioning at 85°C and 85% RH, (b) after curing, and (c) the difference spectrum (a)-(b). (c) thus represents the changes occurring due solely to exposure to the moisture conditions at 85°C and 85% RH.

The most obvious real changes are the negative bands at 868, 916, 1345, 3005 and 3058cm$^{-1}$, implying decreasing epoxy functionality, and thus further progress of the cure reaction. The new bands at 3560 and 3350cm$^{-1}$ may both be attributed to hydroxyl groups, of which the former are free groups, which could be formed on further curing, or as an oxidation product resulting from thermooxidative/degradative processes. The latter are attributed to hydrogen-bonded hydroxyl groups, indicating the type of bonding of the adsorbed water to the epoxy resin. The slight rise at about 1640cm$^{-1}$ indicates the presence of absorbed water in the epoxy resin. Finally, new ester linkages again indicative of further curing, are indicated by the presence of a broad absorption region between (1000-1300cm$^{-1}$).

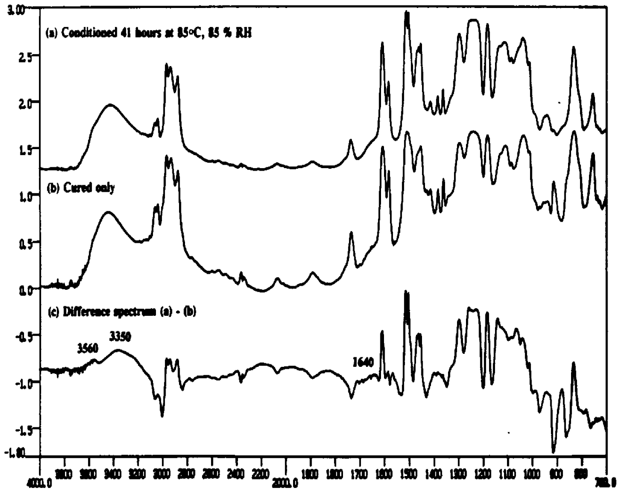


*Figure 11. FTIR spectra of adhesive an anisotropic conductive adhesive in the following manner: (a) after curing and 41 hours conditioning at 85°C and 85% RH, (b) after curing, and (c) the difference spectrum (a)-(b).*

Figure 12 compares the molecular events happening on further exposure to these same conditions. The figure shows the difference spectra (a) after 41 hours conditioning, (b) after 162 hours conditioning, (c) after 821 hours conditioning, all at 85°C and 85% RH. It is observed firstly that the subtracted spectra all show the same profile, indicating that the subtraction procedure has been consistent and that the subtraction spectra are valid.

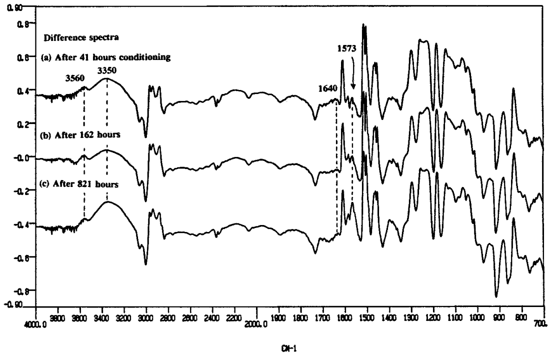


*Figure 12. FTIR difference spectra (a) after 41 hours conditioning, (b) after 162 hours conditioning, (c) after 821 hours conditioning, all at 85°C and 85% RH.*

A closer scrutiny of this figure also shows that the bands at 3560, 3350, 1640, 1573cm$^{-1}$ are increasing in intensity with increasing conditioning time. Both the increases at 3350 and $1640cm^{-1}$ follow the increasing adsorption of water in the epoxy. The steadily growing absorption at $1573cm^{-1}$ is tentatively attributed to unsaturated vinyl structures ("C=C") which are formed as a result of degradative reactions. Moisture degradation is felt to occur by hydrolysis of the ester linkages ("R-(C=O)-OR'). Such hydrolytic attack breaks the polymer chain creating two new end groups, a hydroxyl and a carbonyl. Although it is difficult to see a new emerging carbonyl group in this figure, the presence of the band at $3560cm^{-1}$,.which indicates free hydroxyls, supports the suggestion of degradative reactions occurring with increasing exposure to heat and humidity at 85°C and 85% RH.

Hence, in conclusion, it can be said that on exposure of the cured adhesive to 85°C and 85% RH, both moisture adsorption and further curing can be observed. After a certain time, however, further curing will not be observed, but instead, degradation effects may be seen.

(3) *Galvanic corrosion* at the contact interfaces has been demonstrated by Lu et al [32, 33]. They correlated the degree of contact corrosion (as indicated by resistance increases) to the electrochemical series, and demonstrated the requirement for moisture in the process. With this understanding of the process, it was shown that resistance drift could be inhibited by the addition of corrosion inhibitors and/or oxygen scavengers to the polymer matrix [55].

## III. Anisotropic Conductive Adhesive (ACA)

### A. Structure

A software package has been developed to calculate the average resistance of the ICA contacts for pastes or randomly loaded [56], with statistical distribution. Input parameters include particle size and distribution, particle loading, pad size and pad spacings. The program also performs the inverse calculations, i.e it determines the particle loading requirements for a specified minimum number of particles per pad, (i.e. minimum conductance.)

It is implicit in the program above that the particle distribution is well behaved, but for pastes, the realities of flow around and over pads as pressure is applied will dramatically alter the distribution. So the program has only been validated against ACFs, and studies on the entrapment of particles between pads continue. There have been efforts made to model ACA paste flow [57], and the problem should be more tractable than underfill flow modeling [8], due to the smaller particles, but there appears to be no result suitable for inclusion into a particle distribution model.

### B. Electrical Properties and Modeling

We move now to conduction through an individual particle between two contact pads. Shi et al [58] have calculated the resistance of a solid spherical contact particle analytically as the sum of the bulk resistance and constriction resistance components, and then extended the result to include distributed particle sizes and the influence of pressure on the particle contact area. Both elastic and plastic deformation models were included.

Yim and Paik [59] also developed an analytical model, but also, like Oguibe et al [60], performed finite element modeling of both solid sphere and coated polymer particle systems. There is direct comparison with experiment and good agreement is claimed.

High frequency properties of ACA joints have been characterized by Dernevik et al [33] on rigid and flexible boards in the frequency range between 500 MHz to 8 GHz, and on duroid mounted flip-chips and bridges in the range in the frequency region between 1 to 30 GHz. The results have been compared with soldered flip-chip joint with the same configuration as can be seen in Figure 13.

The losses above are mainly due to two mechanisms. Losses in the bulk material are due to the finite conductivity in the silicon and an excessive coupling to neighbor transmission lines at certain frequencies. Simulations in the electromagnetic solver HP Momentum show how power is coupled to other transmission lines which act as antennas and radiate power away.

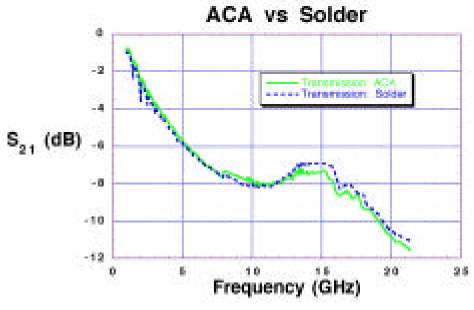


*Figure 13. A comparison in transmission parameter of S21 between an ACA bonded and a solder bonded flip-chip interconnect [33].*

As we can see, the curves for the adhesively bonded flip-chip and the solder bonded one agree very closely. Therefore, it was concluded that ACAs perform equally well in comparison to soldering. The characteristics shown owe more to the transmission line set-up than to either the solder or ACA joints, which both contribute comparably negligible loss to the overall system.

Figure 14 shows the high frequency properties up to 30 GHz using a micro-strip copper-foil bridge arrangement. The losses in the adhesive are around 1 dB across the entire frequency range investigated, which is acceptable for most purposes.

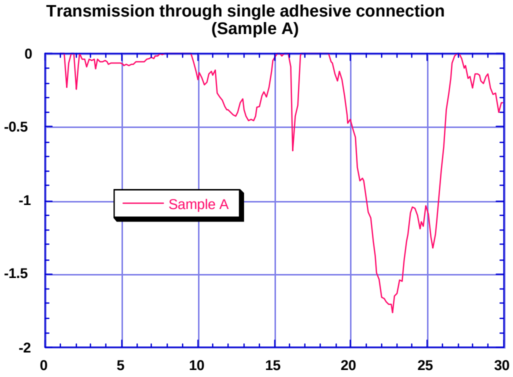


*Figure 14. Transmission through a single adhesive interconnect in a copper microstrip-copper foil joint [33].*

The flip-chip structure has also been subjected to climate testing. After a total of 985 one-hour cycles in the temperature interval -55°C to +125°C, the differences in transmission characteristics of the samples examined before and after the temperature cycling were negligible.

C. Mechanical

Wang et al focused on quantification of criteria for a good ACA flip-chip joint, as this is one of the most important issues during the ACA bonding process [62]. The purpose of their work was to study the relationship between bonding pressure and the deformation of conducting particles in ACAs. It has been shown that the deformation of filler particles plays an important role in both bonding quality and the reliability of ACA joints.

The deformation degree as a function of bonding pressure during ACA film flip-chip bonding is shown in Figure 15. As can be seen, deformation and bonding pressure exhibit a linear relationship. The deformation could be initiated under a critical pressure depending on the particle size, bump size/pad size relationship and adhesive material.

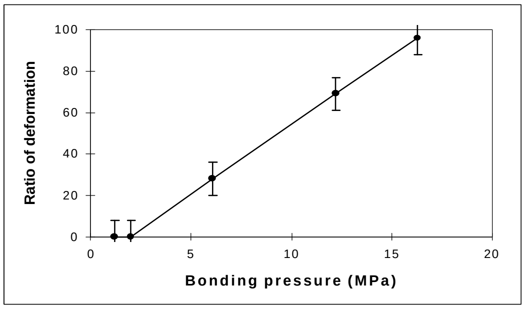


*Figure 15. The relationship between nickel particle deformation and bonding pressure during ACA flip-chip bonding.*

As the mechanical properties of a thin layer adhesive material differs from its bulk material properties, it is important to know the ACA material properties for mechanical model and simulation purposes. Because of this, Young's modulus of the ACA film has been determined by Zribi et al [63]. The measurements were carried out in the temperature range of 15 to 60°C for both cured and uncured adhesive. The dependence of the Young's modulus and the Poisson's ratio of the temperature of ACA film material are shown in Figures 16 and Figure 17.

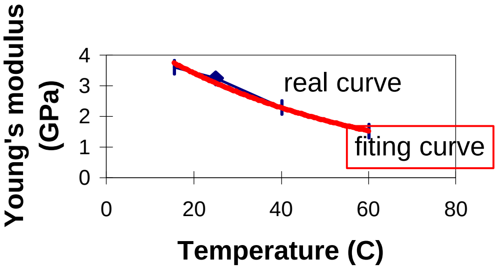


*Figure 16. Young's modulus of ACA film vs. temperature after cure.*

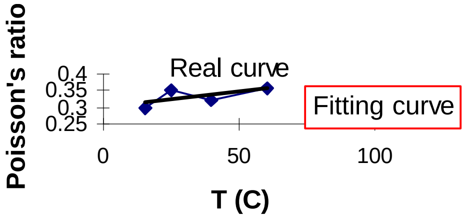


*Figure 17. Poisson's ratio of ACA film vs. temperature after cure.*

Research at Loughborough University has focused on understanding of flow behavior and mechanisms for shorting during ACA bonding. Their work has resulted in a guideline for selecting and optimization of bonding parameter such as pressure, pressurization speed etc [64].

A group at Chalmers University, Sweden, has recently carried out theoretical simulation in order to explain the microscopic mechanism of the electrical contact conduction through the metal fillers for the anisotropic conductive adhesives. By comparing with experiments performed at Wang et al [62], it was concluded that the deformation of the metal filler is plastic even at rather low external loads. Further theoretical simulation reveals the two aspects of the conductance characteristics. The conductance is improved by increasing the external load, but the dependence of the conductance becomes stronger on the spatial position of the metal filler [65].

Solder-filled adhesives have been mainly developed by the Helsinki University of Technology [66] and IBM. The basic idea is to form a metallurgical joint using the adhesive as a mechanical support and to some extent as a fluxing agent. Work performed at Helsinki University shows that good metallurgical joints can be achieved when the metallizations of bonding surfaces are compatible with the solder filler, for instance, Sn-Bi filler with coated Sn on the bonding surface, as can be seen in Figure 18.

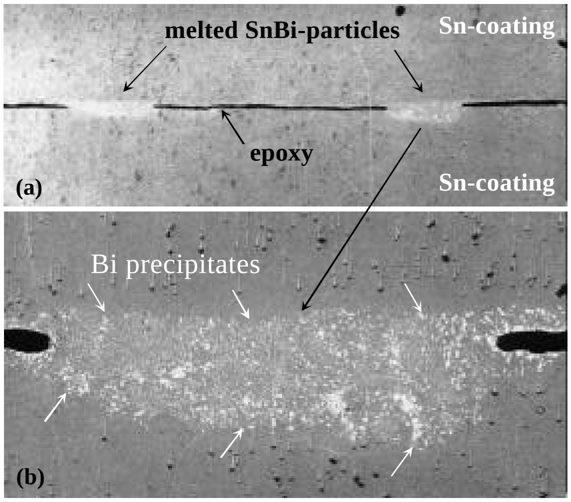


*Figure 18 . SEM-micrograph showing a microjoint between adhesively bonded Sn-layers with Sn58Bi particles at 180°C for 1 min. Note white Bi precipitates in the Sn-matrix [66] (courtesy of the author).*

Figure 19 shows the reliability data of Sn-Bi filled ACA paste on various substrates. Best results are obviously obtained with the Sn-coated substrate which is compatible with Sn-Bi. With Ni/Au or Cu substrate, so much Sn is used to react with the bonding material that only Bi is left. As a result of the reaction, a mechanical joint is formed with Bi.

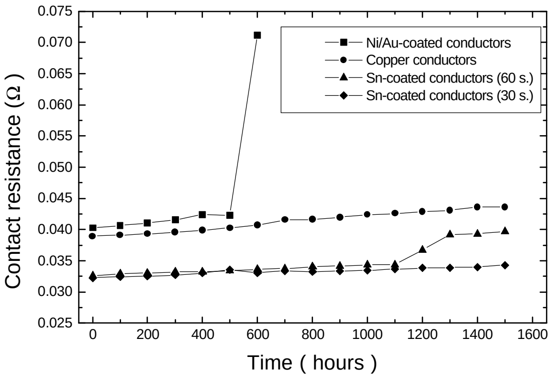


*Figure 19. Daisy chain resistance values of flexible test circuits with various conductor metallizations bonded with Sn58Bi-filled ACA after temperature cycling from temperatures -40°C and +100°C (three hour cycle) [66]. (courtesy of the author).*

## IV. Applications

A. Display Applications

Japanese companies continue to dominate the large area LCD market, but several Korean and Taiwanese companies have begun mass production. In Europe, Philips is one of the companies that manufacture their own LCD displays. In the USA, Planar International focuses on electroluminescent technology. Manufacturing yields have increased significantly and prices have dropped sharply because of over-capacity and competition.

(1) At *SINTEF Electronics and Cybernetics*, Norway, non-conductive adhesives have been used to connect TAB circuits to glass (Figure 20). The parts were aligned in the bonding equipment and the adhesive was cured for one minute at 150°C under pressure. The reduced temperature, compared to ACF bonding, was an advantage because it reduced the thermal expansion of the flexible circuit. The mechanical alignment was simplified by the use of a non-conductive adhesive, as opposed to ACF [67].

The contact resistance obtained was significantly lower than with the use of ACA when employing bare copper tracks or gold plated tracks. The contact resistance was stable to 1000 thermal cycles within 1%. The sample connected with tin/lead plating had poor results. Compared to ACA bonding, variation in contact resistance between the different samples was much smaller, indicating a more stable and reproducible contact.

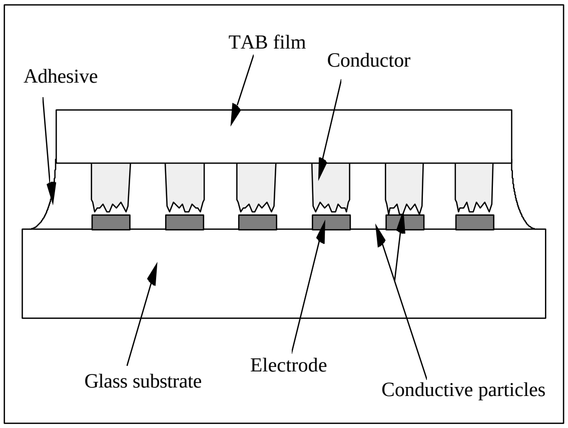


*Figure 21: The NCA connection technology for TAB on glass, developed at SINTEF.*

(2) *Hitachi* has developed another advanced double-layer ACF which consists of an adhesive layer and a monolayer of particles [68]. Conventional ACF has only one layer of adhesive in which the conductive particles are dispersed in a random distribution. In Hitachi's ACF, the conductive particles layer and the adhesive layer are formed separately and attached together later. The conductive particle layer is thin, similar to the diameter of a conductive particle, and has a high-viscosity thermosetting material in which conductive particles are arranged in a monolayer. The adhesive layer is thick (depending on the bump height) and has a low viscosity (lower than that of particle layer) pure thermosetting resin. The conductive particle layer contributes to electrical interconnection, while the adhesive layer contributes only to attaching and binding the two components. So this material can only be supplied as a film, and requires driving ICs with bumps.

The thickness of a conventional ACF is much greater than the diameter of a conductive particle. During the bonding process, the conductive particles beneath the bumps become a monolayer. The other conductive particles, which do not contribute to this monolayer, are squeezed between the bumps thereby causing potential short-circuiting. However, since Hitachi's double-layer ACF already has a monolayer of conductive particles with a much higher viscosity than the adhesive layer, the conductive particles are not squeezed out but remain in the same place, thereby preventing short circuiting. Figure 21 shows a schematic view of the bonding process of double-layer ACF. Hitachi claims to have successfully achieved 10-μm pitch interconnection in laboratory experiments using their double-layer ACF, and will commercialize this newly developed double-layer ACF soon for Flip-Chip-on-Glass (FCOG) applications with 20- μm pitch interconnection. This double-layer ACF will be a promising FCOG material if it is cost-effective. The double-layer design is reported to increase the number of particles on the interconnection electrodes.

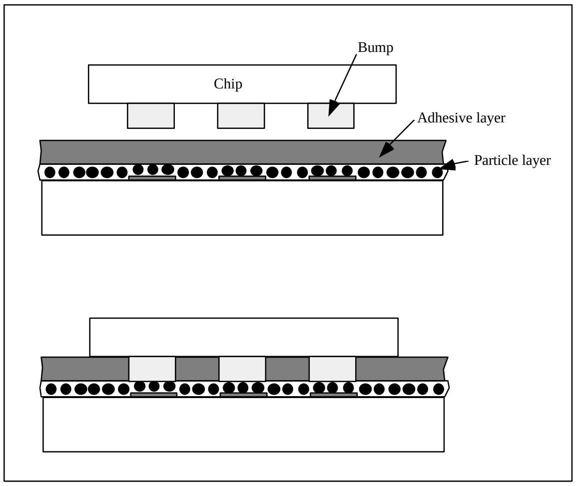


*Figure 21: A schematic of the Hitachi double layer ACF process. The high viscosity in the particle layer implies that there is a very small change in the particle distribution before and after the bonding.*

(3) *Samsung* (Samsung Display Devices) and Zymet, an American manufacturer of anisotropically conductive adhesives, have co-developed a modified ACA FCOG bonding method using peak-shaped dielectric dams between the electrode pads of the glass substrate. These dams are formed by a backside imaging process. The dams function as a block, insulating the two electrical interconnections on the right and left. The dams eliminate short-circuiting by preventing any conductive particles from being positioned on top of them. This method requires driving ICs with bumps and glass substrates with opaque electrode pads, and uses a conventional ACA material.

The backside imaging process is done as follows:

- Application of a negative-acting photo-sensitive dielectric to the glass substrate by the screen printing, stenciling or syringe dispensing method.
- Projection of light from the backside of the glass substrate to expose the negative-acting photo-sensitive dielectric, which resides between the two opaque electrode pads.
- Removal of the negative-acting photo-sensitive dielectric on the electrode pads, which are not exposed to UV light, thereby forming the peak-shaped dielectric dam.

The bonding process is the same as in conventional flip chip bonding, but the dielectric dams themselves can serve as an alignment-guiding dam. The gap between the top of a dam and the passivation layer of a driving IC, should be less than the diameter of a conductive particle to prevent any lateral short-circuiting. The wall angle of the dam should be made to have a peak shaped top, according to the distance from the surface of a glass substrate to the passivation layer of a driving IC and to the gap between two opaque electrode pads of a glass substrate.

(4) *Matsushita* has developed a process uses a conventional ball-bonder to form the Au ball bumps (Figure 22) [69]. Using a 20 μm diameter wire, the size of the pads can be reduced to 70 μm in square. An even finer wire has been tested but the result was a reduction in yield. The ball bumping speed is significantly faster than a complete wire bonding. In this way the traditional sputtering and plating processes in "normal" bump formation have been omitted.

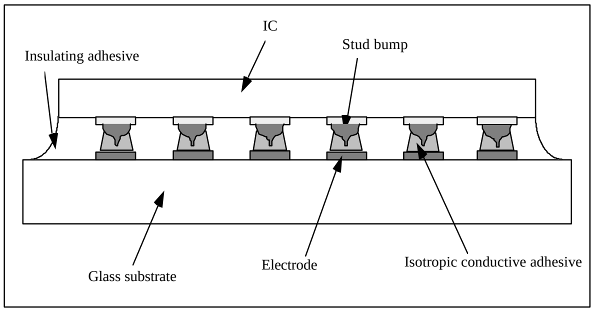


*Figure 22: A schematic of the Matsushita stud bump process.*

To prevent the bond area from becoming too large, the bumps are formed in a conical shape. The bumps are pressed level by a flat surface and the heights adjusted. The bumps are dipped into a thin film of adhesive so the adhesive is only transferred to the tips. A specially formulated isotropically conductive adhesive is used, containing 20 % palladium in a silver palladium alloy. This is done to avoid any problems with silver migration. An optimum amount of filler has been obtained to combine the flexibility of the adhesive with a low resistance.

Matsushita has developed an interesting approach to the problem of electrical testing naked dies, by a two stage curing process. After the first stage, an electrical contact is obtained and a test can be done. If necessary, repairs are done. In the second and final step the cure is completed. This two stage curing has been obtained by using two different solvents with different boiling points. The minimum bonding pitch is reported to be 50 μm, and the contact resistance measured by a 4-probe technique is less than 1Ω. An insulation resistance of better than 100 GΩ has been reported.

A silicone resin is used to seal the chips and bumps after the final curing process. After this process, the adhesion strength is better than 10 kg/cm$^2$.

## B. Surface mount Applications.

Surface mount application has been one of the intensive research topics during the last decade due to the concern about a ban on the use of lead in electronics manufacturing [70]. Efforts have been focused on process development and reliability testing of conductive adhesive joints for surface mounted QFP and chip components. Really, conventional die-attach conductive adhesives were simply adapted for surface mounting in the hope that the materials would work for this application as well. In fact, most conductive adhesives still suffer from poor impact strength, as discussed above.

Kotthaus et al focused on using nano-sized metal particles to improve the electrical conduction. With nano-scaled particles, agglomerates will be formed due to surface tension effects [71]. This technology may suffer from poor printing behavior as no real filler is used in the adhesive. Another approach is to simply decrease the loading of metal fillers to improve the impact strength [70]. However, in this case, only micro-sized particles were used. As a result of that, electrical properties of the conductive adhesives decrease. Thus, none of these approaches, alone, are expected to be enough to create a mechanically and electrically reliable conductive adhesive joint for high volume electronics manufacturing.

Another recent development in the use of conductive adhesive joining technology is being demonstrated by Combitech Electronics, Sweden, where a conventional soldered surface mounted board will be replaced by conductive adhesive joining technology. Conformal coating will be used to improve mechanical strength if necessary. Conformal coating has been demonstrated to improve the impact strength of conductive adhesive joints [73].

## C. Flip-chip on rigid board application

(1) *ICA*: The reliability of flip-chip technology using ICAs on rigid substrates has recently been reported by Penanen et al [74] and Nysether et al [75]. It has also been part of a large IVF program on solderless flip-chip program using conductive adhesives with participants from Alfa Laval Automation, Ericsson Components and Ericsson Telecom, MYDATA Automation (Sweden,) Robert Bosch and Deutsche Thomson-Brandt (Germany,) DELCO Electronics, Delphi Packard Electric Systems, and Epoxy Technology (USA,) Gul Technologies (Singapore,) Hitachi Chemical, Matsushita Electric Industrial, Namics, and Toshiba Chemicals (Japan,) Philips (The Netherlands,) and Schneider Electric (France) [76].

ICA flip-chip joints on FR-4 substrates have been shown to have reliable electrical resistance data after temperature cycling from -40 to $+125^0$C after 2000 cycles using 15 minute hold temperature times, as can be seen from Figure 23.

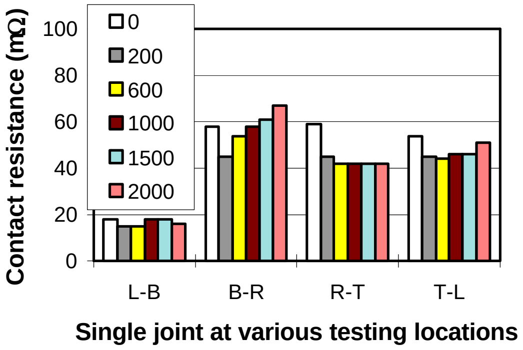


*Figure 23. Single joint reliability testing data of some ICA flip-chip joint on an FR-4 substrate after underfilling and curing and after temperature cycling from -40 to $+125^0$C after various cycles up to 2000 cycles using a hold time of 15 minutes at hold temperature. The chip size was 6.4x6.4 $mm^2$.*

Therefore, it seems that reliability is quite good with ICA flip-chip joining on rigid board. The difficulties with the ICA flip-chip joining technology are the poor processability and small process window in handling of the flip-chip module directly after assembly. To our knowledge, no practical applications have yet been reported on this polymer bump technology with the FR-4 application. However, one still can imagine some advantages with the technology. It is a very simple process where ICA pastes are printed over the entire board even at the locations for the chip components. Thus, it ends up with a fluxless, clean and low-temperature process, which may in many cases be competitive.

(2) *ACA*: While ICA flip-chip suffers from the processing problem, most research work in this area has been done on ACA flip-chip joining technology as this technology offers:

- Fine pitch capability
- ACA base polymer materials act as underfill eliminating the underfilling process

In Japan, significant achievements have been made in using ACA film based flip-chip technology for real products. Hitachi has assembled SDRAM modules using ACA film based technology in the latest lap-top computer. Casio has assembled both transistor radio and electronics for a Personal Digital Assistant notebook (PDA) using ACA flip-chip technology [77]. Toshiba has recently reported that they use ACA paste based flip-chip technology for digital camera applications. Therefore, a lot of manufacturing experience has been gained by some of the large electronics manufacturers.

High speed manufacturing of flip-chip assemblies with ACF on FR-4 can be followed by ICA attachment of additional SMT components [78, 79].

Simultaneously, most university and institute research groups are focusing on more fundamental issues to optimize the ACA flip-chip bonding process and find out failure mechanisms and critical issues for this novel technology. IVF has focused its work on failure mechanism understanding, reliability test, and low-cycle fatigue study of the conductive adhesive joint [63, 76].

There are two features of ACA flip-chip joining technology, which are different from other microelectronic interconnection techniques, such as flip-chip soldering, surface mounting etc. These are:

- Application of bonding force
- Simultaneous bonding of all bumps of a chip

As the conductivity of ACA joints is directly determined by the mechanical contact between the terminals of chips and the electrodes on chip carriers, the bonding force plays a critical role in the electric performance. High bonding pressure is certainly favorable to an intimate contact, and thus to a low contact resistance. In addition, because the bonding of all bumps of a chip is performed simultaneously, uniform conductivity of all joints in the chip requires the bonding situation of every joint to be completely the same. In other words, every joint in the chip must have:

- Same bonding pressure
- Same number of conducting particles
- Same particle size
- Same bump and pad geometry

In practice, these requirements are hardly met. Many factors can affect the bonding situation, including:

- Distribution of bonding pressure on bonding tool
- Alignment
- Variation of conductive particle size
- Distribution of particles in bonding area
- Pad planarity
- Bump planarity
- Variation of substrate thickness

It was found that the electrical resistance across the whole chip side varies as a function of the distance to the glass fiber in the FR-4 substrate, and neighboring joints often had different contact resistance. Figure 24 (on the following page) shows an example of such ACA flip-chip bonding.

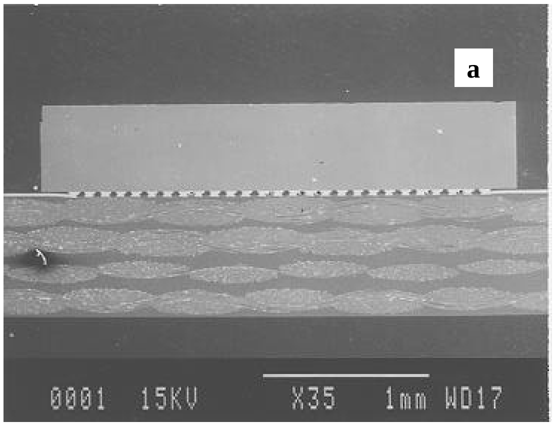
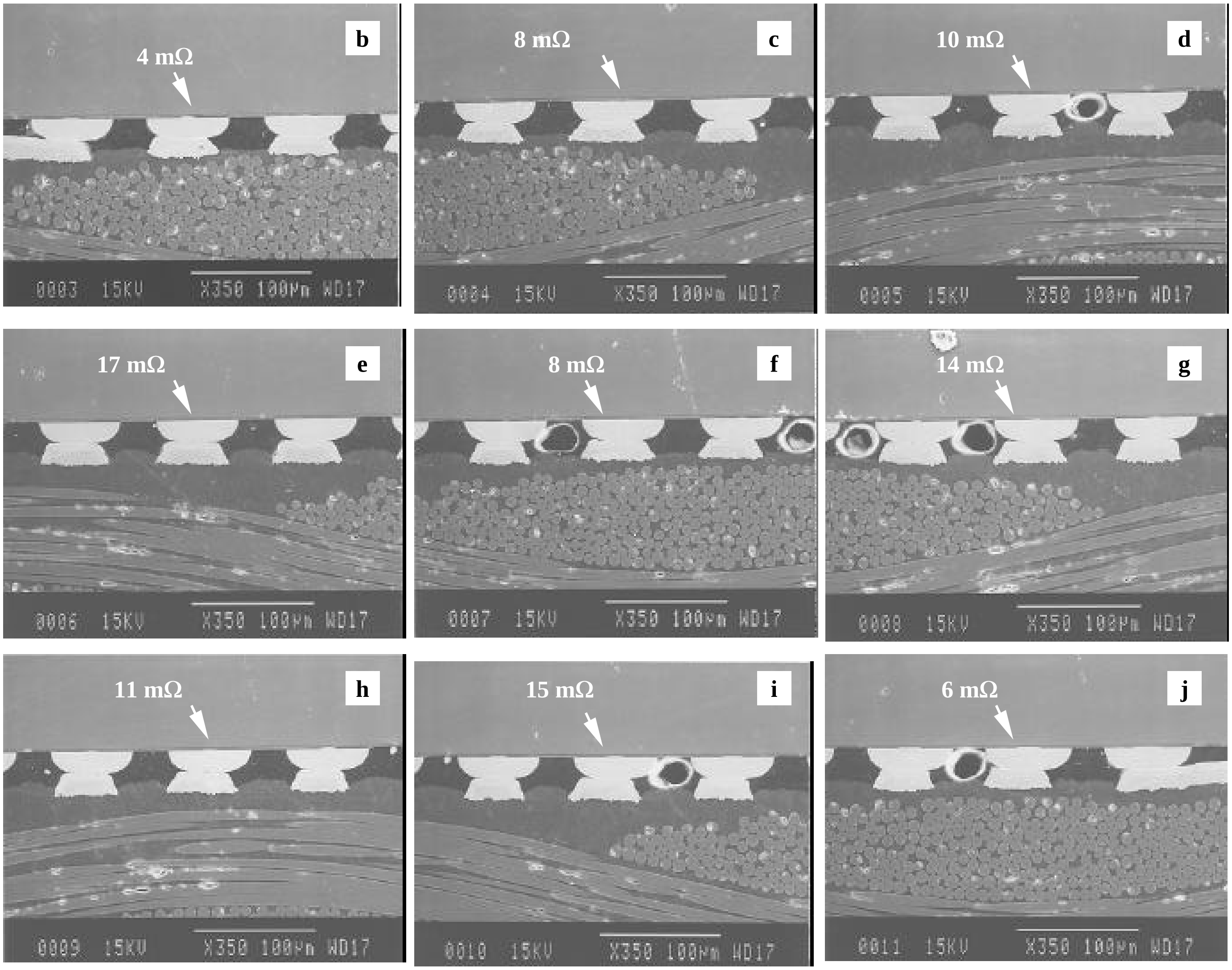


*Figure 24. The joints with different contact resistances during an ACA flip-chip bonding on an FR-4 substrate: (a) Overview of the assembly, (b) 4 mW, (c) 8 mW, (d) 10 mW, (e) 17 mW, (f) 8 mW, (g) 14 mW, (h) 11 mW, (i) 15 mW, (j) 6mW.*



This means that the rising and falling glass fibers induced the variation of contact resistance of ACA joints in this case. The reason was attributed to the softening of epoxy at the bonding temperature, which was above the glass transition temperature ($T_g$) of the epoxy matrix.

Cumulative fails after the temperature cycling test from -40 to +125$^0$C for 3000 cycles with a hold time of 15 minutes at hold temperature are shown in Figure 25. The number of fails is dependent on the definition of the failure. Figure 25 shows three statistics on the cumulative fails respectively based on the different criteria: >20% of contact resistance increase; >50 mΩ; >100mΩ. When the criterion was defined at 20% of resistance increase, after 2000 cycles, all joints failed. This definition might be too harsh for those joints having a contact resistance of only several mΩ. The 20% increase means only variations of a few milliohms are allowed. In some cases, the limitation is still within the margin of error of the measurement. Therefore, it is reasonable that the criterion be defined according to the production requirements. However, if we define failure as 50 or 100 mΩ, the mean times between failures (MTBF) become 2500 and 3100 cycles respectively.

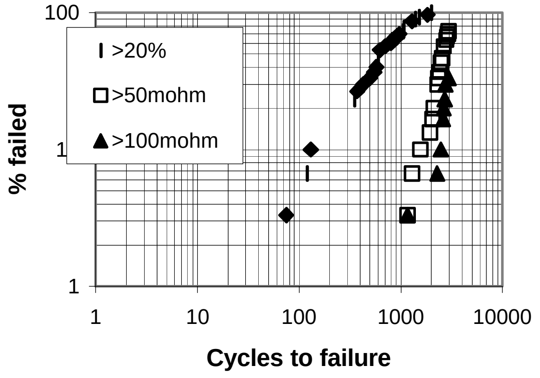


*Figure 25. Cumulative failure of an ACA film flip-chip joint in temperature cycling test measured by single joint contact resistance measurement [76].*

In order to predict the real service life under different environmental conditions, a low-cycle fatigue testing machine was used to perform low-cycle fatigue experiments on ACA made joints in both dry and humid environments at different temperatures. The final goal was to predict the real service life using the fatigue life data generated under different plastic strain loads. The plastic strain is a function of the temperature cycling interval, frequency and temperature ramp rate etc.

The daisy chain resistance curves versus the number of cycles are shown in Figures 26 and 27. A fairly significant decrease of the load level was noticed during the test. The load level ranged for both samples between 1N and 0.7N.

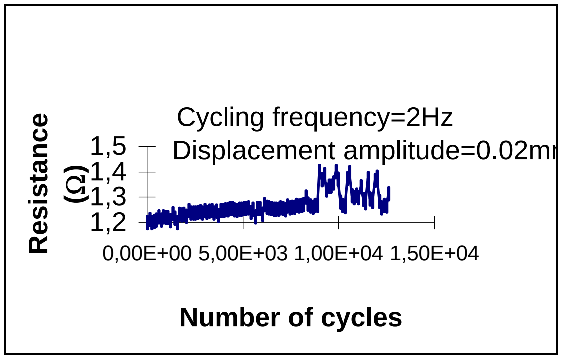


*Figure 26. Electrical resistance of a daisy chain versus the number of cycles. Sample tested in dry environment[63].*

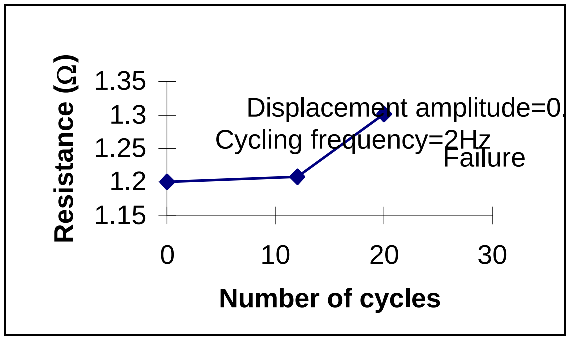


*Figure 27. Evolution of the electrical resistance with the number of cycles. Sample tested in climate chamber (85 °C and 85%RH) [63].*

According to the test data plotted in Figures 24 and 25, failure occurred in the humid environment much faster than in the dry environment, which was physically expected. In fact in the humid atmosphere, the joints are subjected to very severe operating conditions (expansion of the adhesive due to moisture uptake, creep of the adhesive under exhaustive conditions).

D. Smart-card Applications

The major joining process of integrated circuits (IC's) on smart-card substrates is still aluminum wire bonding technology [80], but ICA joining technology for smart-cards has been commercialized by KSW-Microtec (Germany) and Epoxy Technology (USA.) Thermo-setting ACF technology has also been used for volume smart-card production. The major driving force of using conductive adhesives is simple processing and low assembly temperature capability. Thus this technology is suitable for use on the polyester or poly-carbonate substrates typical for use in smart-card applications. In order to increase the manufacturing speed, a recent development is to use light-curable anisotropically conductive adhesive for smart-card application [81]. Using this technology is expected to reduce the production cost of the joined module by 50% and the production time by a factor of 10 in comparison to the existing processes. This development has now been sponsored by the European Union as a BRITE/EURAM CRAFT program consisting the following companies: FOAB Elektronik and IVF (Sweden,) Dyno Particles (Norway,) Delo and Fine Tech (Germany,) EM Microelectronics (Switzerland,) Picopak (Finland,) Hywel-Connection and TNO (The Netherlands.) Each company's tasks are shown in Table 1.

The work was carried out in the following steps:

- Development of conducting fillers for ACAs
- Formulation of light-curable ACA
- Modification of assembly equipment necessary
- Development of assembly process

The basic idea of using light-curable conductive adhesives for electronics manufacturing has been discussed by Bayer [82]. One way is to use light to initiate cure and then off-line cure the whole assembly to achieve full cure.

For the smart-card process, the work was conducted in the following way:

- Light exposure time prior to die placement a few seconds
- Die assembly by flip-chip under pressure
- Post-cure at elevated temperature for certain time

The first step of this BRITE/EURAM program is finished and development work will continue.

*Table 1. Participating partners and their role in a European BRITE/EURAM program on development of smart-card assembly using light-curable anisotropically conductive adhesives.*

| Partner | Country | Function |
|---|---|---|
| FOAB Elektronik | Sweden | Design of substrates and development of smart-card assembly process. |
| Dyno Particles | Norway | Development of metal filler particles for light-curable anisotropically conductive adhesive. |
| Delo | Germany | Preparation of light-curable anisotropically conductive adhesives. |
| EM Micro-electronics | Switzerland | Supply of IC’s for smart-cards |
| Picopak | Finland | Bumping of IC’s for smart-cards |
| Fine Tech | Germany | Supply of flip-chip conductive adhesive bonding equipment modified for light-curable ACA |
| Hywel-Connection | The Netherlands | Manufacture of substrates for smart-cards |
| IVF | Sweden | Reliability prediction and simulation by low-cycle fatigue in dry and humid atmosphere |
| TNO | The Netherlands | Reliability testing |

### E. Microwave Applications

The use of ACA technology for microwave InP device bonding has recently been developed within the "National Swedish Consortium on Environmentally Compatible Materials Research in Electronics Manufacturing (MMF)." The work was sponsored by the National Swedish Board for Industrial and Technical Development (NUTEK,) and by a number of leading electronics companies in Sweden, including Ericsson Components, Ericsson Radio Systems, Combitech, Saab Ericsson Space, ABB Automation, and Volvo. This work is being coordinated by IVF and is currently ongoing. Also four university partners in Sweden are participating in this consortium.

Recently, assembly of InP on a LTCC substrate has taken place. Reliability tests are being planned by temperature cycling between -55 to $100^0$C for 500 cycles, and by vibration testing to 20g, randomly distributed from 20 Hz to 2 kHz.

### F. Optoelectronics Applications

To promote the use of conductive adhesive joining technology in Europe, an adhesive network has been established [83]. This work is currently being coordinated by VDI/VDE, Germany. One of the tasks is to facilitate use of adhesive materials for opto-electronics applications. One of the possible areas that adhesives may find a large use is in laser joining and protection. However, very little work has been reported in this area so far.

## V. ICA/ACA Comparisons

### A. Electrical Modelling

The goal of any physical modeling exercise is to demonstrate that the physical processes are well understood. Validation is achieved by agreement of the model predictions with experimental data. It is clear for both ICAs and ACAs, that successful comparisons of electrical modeling with experimental results require accurate structural modeling first. For ICAs, there have been only superficial efforts at accurate structural modeling to date, and as a result, comparisons of electrical models with experiment are either strictly qualitative [13, 14] or subject to parameter adjustment to achieve a fit [15]. A similar situation exists for ACAs, although one would expect less difficulty in structural characterization. For ACAs, though, the general form of the match of theory to experiment for the resistance variation with pressure [58] is convincing, even recognizing the need for fitting parameters. For ICAs, similar results are achievable for “dry” test systems [9], i.e. without epoxy, but cannot be correlated with actual ICA internal pressures because these are unknown. Real progress in realistic ICA structural modeling has bee made only recently [16].

### B. Thermal Characteristics

The thermal performance of an adhesively assembled chip is of vital interest as power dissipation in the chip increases. Both power dissipation of ICA and ACA flip-chip joints have been simulated by Sihlbom et al [84].

The ACA flip-chip joint has a very thin thermal passage over the joint but only a very low percentage of metal contact in the joint. The thin thermal passage will facilitate heat dissipation. Figure 28 shows a transient thermal temperature response after 100 ms in a flip-chip module mounted with an ACA material.

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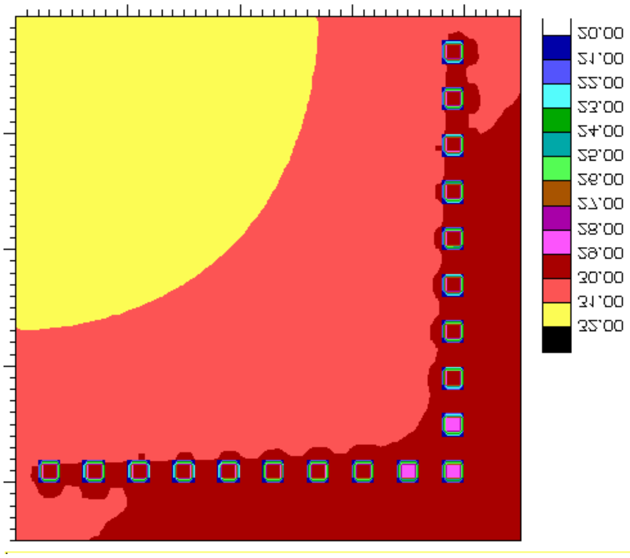

*Figure 28. 100 ms transient temperature response in the adhesive joint layer, for a flip-chip module mounted with an ACA material.*

After 100 ms the chip has reached more than 10K over the board temperature. It can be seen how the centre of the chip, at the left side of the temperature image of the 1/4 chip modeled, is considerably warmer than the chip periphery. The relatively good thermal conduction performance of the joints can be seen.

An ICA flip-chip joint has a relatively thicker thermal passage across the joint. Figure 29 shows the heat dissipation pattern for the same amount of power generation (4W) as for Figure 28. One second after power-up, we can see the chip temperature rise of more than 20K, which is close to the steady state temperature in the chip.

Sihlbom et al concluded therefore that in normal flip-chip applications with normal I/O counts, pitch size etc, ACA joints have better thermal performance than ICA joints.

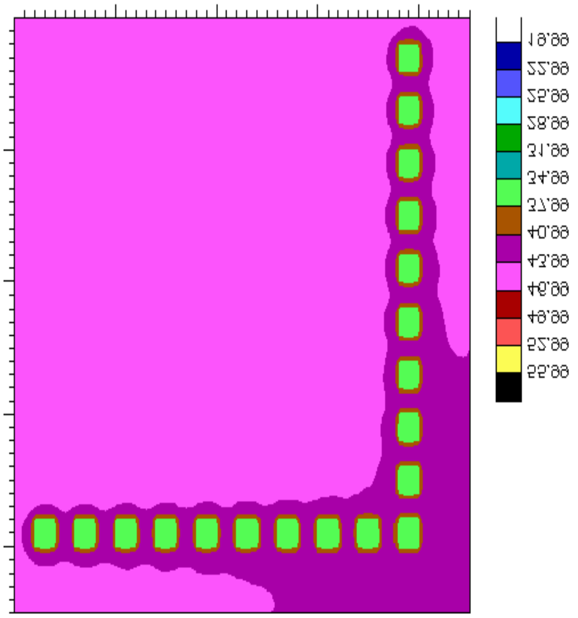

*Figure 29. One-second transient temperature response in the adhesive joint layer in a flip-chip module assembled with an ICA material.*

C. Maximum Current Carrying Capacity

Dernvik et al have also studied the effect of maximum current carrying transmission capacity through the ACA adhesive joints at high frequency [35]. The copper bridge structure has been subjected to a maximum transmission of 25W of average pulsed power, with a pulse length of 10µs and peak power of 250W, and an exposure-time duration of 10 minutes, and with a work of 1, 5 and 10%. In all cases the peak power was approximately 250W and the frequency 3.2GHz. The result indicated that bonding pressure has a strong influence of the joint quality. At 150 N, no electrical transmission loss is observed.

For 75N bonding force, some deterioration was observed after the final power exposure. Figure 30 shows the transmission characteristics before power testing and after 1, 5 and 10% work factors. However, this effect is small, about 0.5dB.

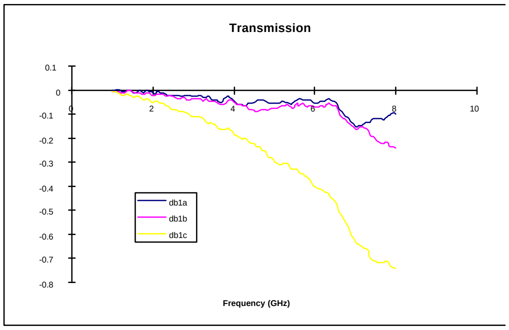

*Figure 30. Transmission through an adhesive joint at 3.2 GHz at 1,5 and 10% work factors in the power test. This sample was cured with an applied pressure of 75 N.*

It would again appear that the ACA performance exceeds that of the ICA, since in a similar study of ICAs, Morris et al found that two of the three materials studied failed at 9A/mm$^2$ [11]. Failure correlated directly with temperature rise, which in turn correlated with the joint resistance, and hence power dissipation. The breakdown mechanism was clearly polymer degradation, accompanied by the emission of noxious fumes.

Bauer et al has studied the power dissipation performance of Non-Conductive Adhesive (NCA) joints under DC conditions. It was found that up to 25 A/mm$^2$, NCA joints still show ohmic behavior [85].

## VI. Discussion

A. Environmental Impact

The environmental impact of ECAs has been studied by several research groups [86-88]. Segerberg et al compared use of conductive adhesive joining with soldering for SMT applications and concluded that it is really dependent on the mining condition of silver when determining the environmental load of the conductive adhesives. If silver is mined in a silver mine, then the environmental load is much smaller compared to soldering. On the other hand, if it is mined as a by-product in a copper mine, then conductive adhesive joining technology will have a much larger environmental load index compared to soldering.

Westphal et al came to the conclusion in their study that conductive adhesives are generally better in terms of environmental loading compared to soldering [35]. In our opinion, more work is needed to clarify this topic further.

### B. Future Research Issues

As conductive adhesives are made of polymers and metal fillers, light may break the polymer chain. How this works is still unclear as there is no report on this work.

A similar situation is noted as to how various gases affect the polymer chain stability in conductive adhesive applications, although it is clear that polymer chains may be affected and broken by the corrosive gases.

One of the major important questions that need to be addressed is the estimation and prediction of the real service life of a conductive adhesive joint. As conductive adhesives consist of a metal part and an epoxy part, it is a composite material. Therefore, it is unlikely that the acceleration laws used for prediction of the real service lives of pure metals and pure polymers can be directly used for conductive adhesives.

As it is apparent that mechanical fatigue and creep are important factors that cause failure of the adhesive joint, and also that moisture can attack a conductive adhesive joint through both bulk and interface diffusion. Therefore, it will be interesting to study the low-cycle mechanical fatigue behavior of the conductive adhesive joint in a humid environment.

As ICAs are so heavily loaded with metal particles to guarantee the electrical performance, the mechanical properties of the joint suffer. For instance, on an ICA joined SMT board with a size of 250 x 300 $cm^2$, cracks were observed in the surface mount QFP joints at the center of the board when bending the board on a 10mm cylindrical rod placed at the center of the board. Therefore, better adhesive/metal-particle ratio optimization is necessary to enhance the bending performance.

Repair represents another area that needs further study as it is clear which strategy shall be used when working with conductive adhesives. Generally, it is understood that conductive adhesives cannot be inspected in the same way as solders. Therefore, the need for functional test is considered to be one of the most critical criteria for quality control. However, what happens with the module which is not good? Throw it away or repair it? What about the cost aspect? It seems that there is no general rule in this issue and it is strongly related to the product quality and volume. One has to make final decision once the product volume and cost of the product are clarified.

### C. Education

ECAs represent a fairly narrow slice of the electronics packaging field, and education in the field has been confined primarily to short courses presented to industry professionals at conferences, etc. Nevertheless, a full academic course is currently presented at Chalmers University, using the text which figures prominently in the references below [89]. Furthermore, it is intended to expand this course's availability to the Internet [90].

### D. Conclusions

Conductive adhesives for surface mount applications have been tested and examined during the last decade. It can be concluded that that no single conductive adhesive has so good electrical and mechanical performance that it can work as a ”drop in” replacement. Instead, modification of production process steps, components geometry and component metallization or conductive adhesive itself are necessary to replace solder.

ICA joining for flip-chip applications have found their applications in the smart card application. ACA flip-chip are also now being used for modularized assembly in consumer electronics products. However, still, there is not enough reliability data concerning ACA flip-chip joining for various applications. Figure 31 shows that maturity of various joining technologies as a function of technology complexity and time scale.

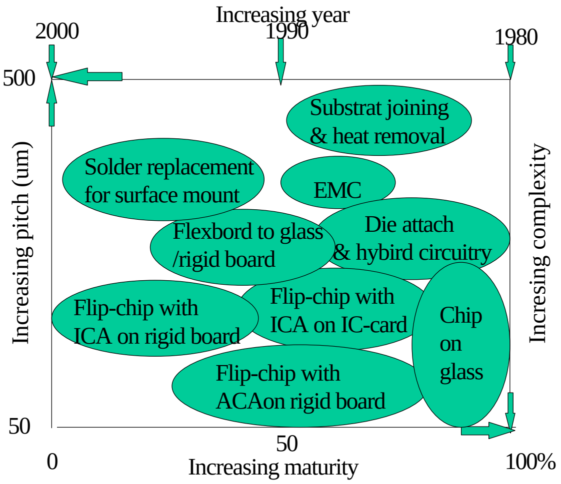

*Figure 31. Maturity of various electronics packaging technologies using conductive adhesives.*

From this figure, it can be seen that die attach, EMC, display, chip-on-glass, flexible board to rigid board interconnect represent more or less the matured part of the conductive adhesive technology. ICA flip-chip on smart-card is being accepted for high volume manufacturing and ACA flip-chip is just in its way to get increased maturity. More reliability data in various applications are required to achieve this. Finally, ICA joining for surface mount and for flip-chip technology still represents the areas that further work is needed.

## VII. Acknowledgements

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