Crimson Publishers
Wings to the Research

Mini Review

Conductive Particles in Anisotropic Conductive Films

Federico Trupp[1], Roberto Cibils[2] and Silvia Goyanes[1]*

[1]Physics Department, University of Buenos Aires, Argentina

[2]INVAP, Argentina

Abstract

Anisotropic Conductive Films (ACFs) are the major products used for fine-pitch interconnection technology in electronic packaging because of their low incidence in electrical interconnection issues such as high contact resistance and open/short-circuit failure. ACF are conductive adhesives composed of a suitable binder and electrically Conductive Particles (CP). These CP can be selected from a variety of materials to meet specific applications or requirements. In this Mini Review we describe the different types of conductive particles that can be used in ACF, the advantages and disadvantages of each type, as well as other relevant issues such as particle size, concentration, and capture rate. This work could serve as a guide for any group that is interested in research on ACFs.

Keywords: ACF; ACA; Microparticles; Conductive adhesive; Solder balls; Bonding; Resin

ISSN: 2770-6613

***Corresponding author:** Silvia Goyanes, Physics Department, University of Buenos Aires, Int Güiraldes 2160, Ciudad Autónoma de Buenos Aires, Argentina

Submission: 📅 January 26, 2022
Published: 📅 February 17, 2022

Volume 3 - Issue 1

How to cite this article: Federico Trupp, Roberto Cibils and Silvia Goyanes*. Conductive Particles in Anisotropic Conductive Films. Polymer Sci peer Rev J. 3(1). PSPRJ. 000554. 2022.
DOI: 10.31031/PSPRJ.2022.03.000554

Introduction

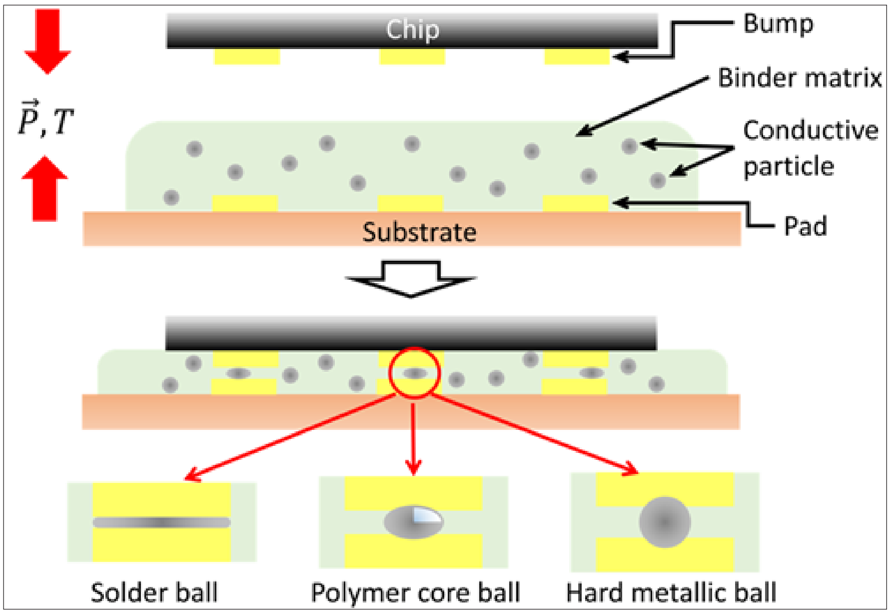

Figure 1: Scheme of the ACF before and after bonding. The three types of conductive particle are schematically shown after thermo-compression.

Anisotropic Conductive Films (ACFs) are a type of Anisotropic Conductive Adhesive (ACA) used globally at industrial scale in a wide range of applications (FOB, FOG, COG, COF, CIF, etc). ACFs are adhesives typically composed of thermosetting polymer resins (usually epoxy, acrylic or a combination of them), and micron-sized electrically Conductive Particles (CPs). The CP filled polymeric resin is set between the chip and the substrate as shown in Figure 1. The bonding process usually consist in the application of heat and pressure in the z-axis in a highly controlled manner, which cause the curing of the resin and, in most cases, the deformation of the CPs. After bonding, the ACF allows electrical conductivity in the z-axis, and insulation in the x-y plane. The failure mechanisms of the ACF assembly, such as cracking and fracture, deformation, delamination and thermal fatigue, can occur during production and service due to temperature and mechanical induced loading [1]. The reliability of ACFs will therefore depend on the thermomechanical properties of the resin and CPs, the bonding process, and the operation conditions. In this work we will focus on the CPs, which can be selected from a variety of materials to meet specific applications or requirements. Depending on their physical properties, size, shape, volume fraction in the resin, bonding process and the medium in which they are immersed, the resulting ACF will have different performance regarding electrical conductivity, resistance to temperature cycles, mechanical stress and so on. However, we have not found brief and concise works that show the relevance of the topic and its current state of the art. In this Mini Review, we attempt to reunite the knowledge accumulated by relevant studies in the last decades, and help answering the crucial question regarding ACFs manufacturing and research: which particles are best for ACF reliability?

Mini Review

Types of particles/materials

There are mainly three types of conductive particles for ACF: Solder Balls (SB), Metal Balls (MB) and Metal-Coated Polymer Balls (MCPB).

Solder balls: SB are metallic particles consisting of a relatively low-melting temperature (90 °C - 450 °C) metal or alloy. There are many commonly used solder alloys with different melting points, chemical reactivity, mechanical properties, toxicity, and so on. Some examples of commonly used solder balls are SAC305 (96.5%Sn-3%Ag-0.5%Cu), SnBi58 and Sn52In.

Metal balls: MB consist of a hard metal (usually Ni), sometimes plated with another metal with better conductive properties (Ag, Au).

Metal-coated polymer balls: MCPB consist of a thermoplastic polymer micron-sized ball, commonly Polystyrene (PS), Polymethyl Methacrylate (PMMA) or Polyethylene (PE), coated by a thin layer of one or two highly conductive metals, usually nickel (Ni), nickel-gold (Ni/Au) or silver (Ag). The reason of using Au/Ni instead of Au alone is because Ni is required to produce strong adhesion between the polymers typically used for the microspheres and noble metals, such as gold [2]. Few weights percent addition of gold coating is sufficient to completely cover Ni particles and produce low volume resistivity that is resistant to elevated temperature and humidity [3]. Finite element analysis has shown that the optimal thickness of the Au coating is about 75nm [4].

Some researchers have shown that modifying the MCPB surface may increase their electrical stability and reliability in ACF interconnections. Adding metallic projections with sizes between 2.5 and 15% of the Ni/Au-coated particles diameter, helped increase the contact of the deformed particle with the pad and bump in COG interconnections after bonding, even after 1200 thermal cycles [5]. Cho et al have recently fabricated enhanced electrically conductive microspheres by adding carbon nanotubes through dry particle coating process to self-assembled PS/AuNPs particles. They showed that the combination of 0-D and 1-D conductive fillers is an efficient way to achieve higher conductivity at lower filler concentration [2].

Bazilchuk et al. [6] compared the influence of metallization and particle size on the resistance of MCPB for ACAs [6]. Based on the electromechanical nanoindentation results, Ag-coated CPs yield superior resistance characteristics than Ni/Au and Au-coated particles. However, the Ni/Au coated polymer balls performed significantly better than Ag-coated CPs of the same coating thickness. This supported the conclusion that the properties of CPs in adhesive may differ greatly from those in air at room temperature.

Comparison between particle types

The characteristics of each type of particle lead to different properties after bonding. The solder balls are fused and deformed achieving a very intimate contact with the pad and bumps. The hard metal balls on the other hand, tend to maintain its shape. The polymer balls suffer plastic deformation under T/C bonding and the thin metal layer deforms two, gaining some contact area with the electrodes. A schematic of these behaviors is shown in Figure 1. Park et al. [7] have shown that Ni balls have a much higher contact resistance after thermo-compression bonding in FPC-ACFs interconnections than Sn52In solder balls and Ni/Au-coated polymer balls [7]. Furthermore, Ni-filled ACF interconnection was shown to be less reliable than the Au-coated polymer sphere-filled ACF after different environmental aging tests [8]. Flexible particles can increase the contact area, which leads to the decrease of conductive resistance, by deforming the inner polymer balls. Nonetheless, Paik et al compared the reliability of the electrical contacts of 3µm-Ni/Au-coated polymer balls and Sn3.0Ag0.5Cu solder balls in ACAs interconnection of fine pitch (25µm) COF assembly [9]. They showed that the z-axis contact resistance of the SB-ACAs was 12% lower than that of the MCPB-ACAs because of continuous metallurgical solder alloy contact rather than physical contact of polymer balls. Besides surface contact after bonding, several factors determine the electrical reliability of CPs in ACFs. Environmental aging of the ACFs has been tested via Pressure Cooker Test (PCT) which helps evaluate the assembly's response to humidity. According to Park et al. [7] findings, metallurgical joints of SB-ACFs produce more stable interconnects during a PCT than those of MCPB-ACFs [7]. This agrees with the work of Paik et al, who showed that after PCT, the Ni/Au-coated polymer balls ACAs contact resistance rapidly increased after 12h, and about 7% of the total contact joints failed after 48h. These problems were attributed to the hygroscopic expansion of polymers (even though the core polymer of the CPs was not specified). On the other hand, the z-axis contact resistances of SB-ACAs were much more stable, and no failure joint was observed after the PCT test [9].

Another important factor is the matching between CP and resin Coefficient of Thermal Expansion (CTE). Kuang et al. [4] have theoretically shown that introducing almost the same coefficient of thermal expansion between the MCPB and the polymer matrix can reduce the undesired thermal stress disadvantages [4]. Zhang et al. [10] showed that the reliability of ACFs with SAC305 solder particles increased from acrylic, epoxy, multifunctional epoxy, and cationic epoxy resins due to smaller CTE mismatch [10]. Thermal stress from CTE mismatch between MB and adhesive could also be the main factor in interconnection failures of Ni-filled ACFs [8]. Mechanical reliability of the assembly is also of importance. Lin et al have shown that repetitive bending of FOF-ACF cause MCPB to crack and delaminate leading to increasingly higher electrical resistance of ACF packages. Special emphasis the authors directed to bonding conditions and conductive particle size uniformity [11]. Nonetheless, Lin et al reported that MCPB ACFs showed the best dynamic bending reliability of the tree types, showing stable bump contact resistance up to 160k slide bending test, bending cycles for CIF assemblies [12]. The authors attributed it to the high elastic compliance and fatigue resistance of the polymer balls. Multiple chip cracks were found in the CIF packages with Ni ball ACFs, but no interconnection cracks. In the SB joints, on the other hand, cracks were observed which were correlated with the electrical failure. In general, solder-based Intermetallic Compound (IMC) materials are known to have poor fatigue property due to their brittle nature under cyclic deformation [13]. Park et al. [7] however, showed that no failure was observed after a dynamic bending reliability test of the low-temperature (130 °C) bonded ACF with Sn52In solder balls [7]. The dystopic findings of these works indicate that both SB-ACFs and MCPB-ACFs may result in good dynamic bending reliability depending on the remaining factors, such as resin properties, bonding process, and testing details. For high-frequency applications, Sn58Bi solder balls achieved better transmission performance than Au/Ni polymer balls in ACF, bonded at the same conditions [14]. The authors attributed the lower performance of the MCPB to narrowing of the electrical path caused by lower skin-depth, mainly of nickel, for being a ferrite material. The same type of solder balls (Sn58Bi) has been efficiently bonded by ultrasound, showing up to 30% lower contact resistance than traditional thermo- compression bonded Au-plated Ni particles [15]. They have also achieved more than 60% current handling capability and much better autoclave reliability as well.

Concentration, size, and deformation of CPs

As previously mentioned, the bonding process plays a significant role in the reliability of ACFs. In particular, the bonding pressure determines the surface contact and deformation of the conductive particles. Nghiem et al has shown that there is an optimal deformation percentage of Ni/Au polymer balls (3μm), in the range of 35-75% between bump and pad for achieving a stable and reliable ACF [16]. For lower deformations, trapping a thin layer of adhesive between the particle and contacts may occur, strongly increasing the contact resistance. At more than 70% deformation, the crushed particles showed the largest relative increase in resistance after humidity testing. This is in accordance with the work of Yim et al. [8] who reported that the contact resistance of MCPB decreased by increasing bonding pressure, up to a point where it started to increase again, presumably by the delamination of the Au layer over the deformed polymer ball [8]. Chung et al. [5] found that after 1200 thermal cycles (-40 to 150 °C) ACF joints with low bonding pressure (37.5MPa) had less open failure rate than those with high bonding pressure (75MPa) [5]. They also reported that it was due to lower elastic recovery of the MCPP caused by plastic deformation and cracks within the polymeric core. This also supports a concern about possible reliability issues with too high bonding force. The size and concentration of CPs plays a critical role in guaranteeing good electrical conductivity in the z-axis and avoiding bridging failure in the x-y plane. The relation in sizes between de CP diameter, the bumps and the spacing between them must be considered, as well as the concentration of particles in the resin, which is in direct relation with the number of CPs per unit area.

Starting from a 1 wt.% content of particles in the resin, up to 8 wt.%, the connection resistance rapidly decreases and then become constant [8]. This is because the counter-effect of two opposing factors, the decrease in resistance by increasing number of conduction paths, and the increase in resistance by a decrease of contact area per particle at the same bonding pressure. By adding more CPs, the ACF gets close to the percolation threshold which leads to a complete bridging failure. Before that point, there may also be problems by the accumulation of particles in the spacing between the pads or bumps. The failure probability as a function of the volume fraction of particles, has been analyzed via the V-shape curve method, finding an optimal value at the tip of the V-shaped curve [17]. The curve, in turn, depended on the length and height of the pads, and the distance between them, for a fixed-sized particle. Chen et al have recently modeled the failure probability of ACAs depending on size of bumps and distance between them, and diameter and concentration of CPs [18]. Opening failure and bridging failure are mutually restricted. They reported that when the interconnection size is fixed (25μm), the optimal volume fraction of ACA is between 2.5 and 11%, and the optimal diameter of CPs is less than 1.6μm. When pitch is fixed in 25μm, 15μm-bumps, and 10μm-gaps between them is the most suitable choice.

Increasing the capture rate, which is the ratio between trapped CPs between pad and bump and the total number of CPs, will also lead to less failures for the same concentration of particles. For 100μm- pitch FOF, the capture rates of 20μm MCPP were ~30% higher than those of 10μm particles, as shown in Table 1. This was attributed to the fact larger size balls have shorter time before being captured between pad and bump [19], which restricts their mobility. It was also shown that the 20 wt.% concentrations for both sizes of particles, led to agglomeration between bumps, and bridging failure after main bonding. An effective way to increase the capture rate was developed by fabricating a scaffold polymer structure containing the CPs. For that end, electrospinning was investigated with great results [9]. The capture rate was increased from 31 to 65 and 8% for PVDF electrospun nanofiber scaffold in a 20μm-pitch and 7μm-bump spacing with 3.5μm-diameter MCPPs in COG assembly without affecting the electrical conductivity after aging tests [20]. Thermo-compression and plasma etching of the CP- filled nanofiber sheet led to a further increase up to 81% capture rate [21]. More recently, the same authors have developed an Anchoring Polymer Layer (APL) containing the CPs achieving up to 90% capture rate maintaining good reliability, considerably simplifying the fabrication process [22,23]. The APL solder ACF required only a 12% of the number of CPs than traditional AFC to achieve the same electrical contact performance [24]. Finally, Byeon et al. [25] have use magnetic field to disperse the Ni-coated polymer particles within the APL and achieved an 80% capture rate, and no electrical short-circuits for 11.5μm-pitch and 3.25μm-diameter Ni/Au-coated polymer balls [25]. The capture rates of the previous studies were measured by simple counting of particles through SEM imaging, which is ok for lab-scale studies. However, effective detection of CPs plays a key role in the quality control of COG in industrial production. For that end, some researchers have recently developed convolutional neural networks to detect CPs successfully and automatically within the ACF after bonding [26,27].

Conclusion

Conductive particle choice plays a decisive role in ACF reliability. Research seems to indicate that both solder balls and metal-coated polymer balls are more reliable than hard metal balls on their electrical contact throughout ACF aging and thermo-mechanical testing. However, no clear preference can be stated between the other two types. Solder balls showed more reliability in hygroscopic and high-frequency applications but may result more failure-prone in mechanical tests. Overall, various factors must be considered when choosing a conductive particle for ACF interconnects, including CTE matching between the particles and the resin and optimal bonding temperature and pressure. The relation between the size and concentration of particles, the bump's length and height and the space between bumps must be considered for reducing connection failure probability, both open circuit failure and bridging failure, which are mutually restrictive. Very low concentration may lead to open circuits and high resistance, and very high concentration leads to bridging failure between bumps. Finally, adding a polymeric scaffold structure by electrospinning or anchoring polymer layer has shown to be a very efficient technique to increase the capture rate of CPs, reducing bridging failure, increasing the efficiency of the CP content, while maintaining excellent electrical contact and reliability after aging tests.

References

1. Kristiansen H, Zhang ZL, Liu J (2005) Characterization of mechanical properties of metal- coated polymer spheres for anisotropic conductive adhesive. Mater Process Prop Interfaces, pp. 209-213.
2. Cho YM, Lee SS, Park CR, Kim TA, Park M (2021) Enhanced electrical conductivity of polymer microspheres by altering assembly sequence of two different shaped conductive fillers. Compos Part A 149: 106562.
3. Callen BW, Kozculab E (2006) High performance gold coated nickel powders for packaging applications in electronics. In: 39th International Symposium on Microelectronics. pp. 945-948.
4. Kuang J, Hsu C, Lin A (2015) A study on the conductivity variation of Au coated conductive particles in ACF packaging process. J Nanomater 2015: 485276.
5. Chung CK, Sim GD, Lee SB, Paik KW (2012) Effects of conductive particles on the electrical stability and reliability of anisotropic conductive film chip-on-board interconnections. IEEE Trans Components, Packag Manuf Technol 2(3): 359-366.
6. Bazilchuk M, Kristiansen H, He J (2018) Influence of metallization and size on the conductive properties of metal-coated polymer particles in anisotropic conductive adhesive. Proc - Electron Components Technol Conf, pp. 1920-1925.
7. Park JH, Park JC, Shin S, Paik KW (2019) Low-temperature bonding of PZT ($PbZrTiO_3$) and flexible printed circuits using Sn52In solder anisotropic conductive films for flexible ultrasonic transducers. IEEE Trans Components, Packag Manuf Technol 9(11): 2152-2159.
8. Yim MJ, Paik KW (1998) Design and understanding of anisotropic conductive films (ACF's) for LCD packaging. IEEE Trans Components Packag Manuf Technol Part A 21(2): 226-234.
9. Paik KW, Suk KL, (2018) Nanomaterials in anisotropic conductive adhesives (ACAs). In: Morris J (Ed) Nano packaging: nanotechnologies and electronics packaging. (2nd edn), Springer, Cham, Switzerland, pp. 369-408.
10. Zhang S, Yang M, Wu Y, Du J, Lin T, et al. (2018) A study on the optimization of anisotropic conductive films for Sn-3Ag-0.5Cu-based flex-on-board application at a 250 °C bonding temperature. IEEE Trans Components, Packag Manuf Technol 8(3): 383-391.
11. Lin CM, Chen DC, Liu YC (2019) Investigation on fracture and conductivity of flex-on-film flexible bonding using anisotropic conductive film considering repeated bending. Microsyst Technol 25:3017-3026.
12. Kim YL, Lee TI, Kim JH, et al (2016) Effects of the mechanical properties of polymer resin and the conductive ball types of anisotropic conductive films on the bending properties of chip-in-flex package. IEEE Trans Components, Packag Manuf Technol 6(2): 200-207.
13. Goh Y, Haseeb ASMA, Liew HL, Sabri MFM (2015) Deformation and fracture behaviour of electroplated Sn-Bi/Cu solder joints. J Mater Sci 50: 4258-4269.
14. Zhang S, Park J, Park G, Song H, Kim J, et al. (2022) A study on transmission properties of AuNi coated polymer ball joint and Sn58Bi solder joint for flex-on-board interconnection. J Adv Join Process 5: 100099.
15. Lee K, Saarinen IJ, Pykari L, Paik KW (2011) High power and high reliability flex-on-board assembly using solder anisotropic conductive films combined with ultrasonic bonding technique. IEEE Trans Components, Packag Manuf Technol 1: 1901-1907.
16. Nghiem GM (2018) Anisotropic conductive film (ACF) bonding: effect of interfaces on contact resistance. 7th Electron Syst Technol Conf.
17. Lin CM, Chi MC, Liu YC (2018) Random dispersion effects of conductive particles on anisotropic conductive film's (ACF's) bonding yield. Microsyst Technol 24(1): 49-53.
18. Chen G, Wang Y, Xiao X (2021) Failure analysis of anisotropic conductive adhesive packages in narrow-pitch flip chip packaging. 22nd Int Conf Electron Packag Technol ICEPT, pp. 1-5.
19. Park JH, Kim TW, Zhang S, Paik KW (2016) Effects of polymer ball size and polyvinylidene fluoride nanofiber on the ball capture rate for 100-μm -pitch flex-on-flex assembly using anisotropic conductive films and ultrasonic bonding method. IEEE Trans Components, Packag Manuf Technol 6: 1127-1134.

20. Lee SH, Kim TW, Suk KL, Paik KW (2015) Nanofiber anisotropic conductive films (ACF) for ultra-fine-pitch chip-on-glass (COG) interconnections. J Electron Mater 44: 4628-4636.

21. Lee SH, Paik KW (2017) A study on the nanofiber-sheet anisotropic conductive films (NS-ACFs) for ultra-fine-pitch interconnection applications. J Electron Mater 46(1): 167-174.

22. Lee SH, Yoon DJ, Paik KW (2019) A study on the conductive particle movements in polyvinylidene fluoride anchoring polymer layer anisotropic conductive films for 20- mm fine-pitch interconnection. IEEE Trans Components, Packag Manuf Technol 9: 209-215.

23. Yoon D, Paik K (2018) Effects of the Anchoring Polymer Layer (APL) materials on conductive particle movements for ultra-fine pitch chip-on-glass (COG) interconnection. IEEE Trans Components, Packag Manuf Technol 8: 1113-1116.

24. Yoon DJ, Lee SH, Paik KW (2018) A study on the anchoring polymer layer (APL) solder anisotropic conductive films (ACFs) for ultra-fine pitch flex-on-flex (FOF) assembly using an ultrasonic bonding method. Proc - Electron Components Technol Conf pp. 15-20.

25. Byeon JH, Yoon DJ, Paik KW (2019) A study on the magnetic dispersion of the conductive particles of anchoring-polymer-layer anisotropic conductive films and its fine-pitch interconnection properties. IEEE Trans Components, Packag Manuf Technol 9(7): 1235-1243.

26. Tao X, Ma W, Lu Z, Hou Z (2021) Conductive particle detection for chip on glass using convolutional neural network. IEEE Trans Instrum Meas 70: 3519310.

27. Liu E, Chen K, Xiang Z, Zhang J (2020) Conductive particle detection via deep learning for ACF bonding in TFT-LCD manufacturing. J Intell Manuf 31: 1037-1049.