Key Concepts, Issues, and Trends in ACF Interconnect Technology

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ABSTRACT

Anisotropic Conductive Film (ACF) has been a part of the display engineer's toolbox for over thirty years, but it remains in many ways a poorly-understood technology. This paper attempts to cover the key concepts an engineer must understand to successfully use ACF, as well as to address several of the most important issues and trends in ACF assembly today. Topics covered include an overview of the basic assembly process, innovations in the required manufacturing environment, ultrasonic bonding and new ACF formulations.

INTRODUCTION

Anisotropic Conductive Film (ACF) is one form in which Anisotropic Conductive Adhesive (ACA) can be supplied. Another is Anisotropic Conductive Paste (ACP). Because ACF is by far the most widely-used form of ACA, for the purposes of this paper we will use the term ACF to refer to any type of anisotropic conductive material.

In 2009 ACF will enter its 35th year as a commercially available product, This alone surprises many people who are not directly involved in display module assembly because despite being around longer than BGA technology and almost as long as C4, ACF still retains an aura of the new, the continually-under-development, and the unproven. Much of this due to ACF's historical focus on getting signals from the controller board to the display glass, which has limited its exposure to the greater electronic assembly community. As ACF has matured, however, it has pushed out from the display module and now is a widely-used technology for flex-on-board (FOB) and flex-on-flex (FOF) assembly. Display designers can use these new capabilities to extend their own reach and to arrive at more sophisticated display modules.

THE ACF MATERIAL SET

ACF is made up of two main components. First is the adhesive itself, typically a formulation of epoxy resins, acryl resins, or a blend of the two. The adhesive composition changes depending on what materials are being assembled, so an ACF designed for use in a flex-on-glass (FOG) assembly is usually not suitable for use in a chip-on-glass (COG), FOB, or any other configuration. It is specific to the application for which it was originally designed.

The second component of ACF is the conductive particles used to conduct electricity from one side of the bond to the other. Depending on the application, conductive particles range from 3.5µm to 30µm in size and can be made from nickel-gold plated polymer spheres, gold-plated nickel particles, or more recently, from lead-free solder materials. Particles may also be individually coated with a polymer to insulate them from other uncrushed particles, but which will crack open and allow electrical conduction if the particle is trapped and crushed between two pads during assembly. Finally, ACF particle loading ranges from 250,000 particles/mm^3 up to 3,500,000 particles/mm^3, depending on the size of the pads being bonded and the space between them.

THE ACF ASSEMBLY PROCESS

ACF is assembled in a thermocompression process that typically uses three stages.

ACF Lamination

ACF, supplied on a reel, is cut to the required length, laminated to the substrate using around 80℃ and 1M Pa of pressure for between 1 and 2 seconds. The amount of time, temperature, and pressure used to laminate the ACF depends on the ACF used and the material to which it is being laminated. It is desirable to use the lowest amount of time, temperature, and pressure possible while maintaining a high quality lamination. After the ACF has undergone this process and been transferred to the substrate, the release liner is removed, leaving the laminated ACF with a top surface exposed to accept the second half of the assembly. The lamination process must place the ACF accurately and without trapping any air under the ACF.

Mounting

Once a substrate has been prepared with ACF, the second half of the assembly is aligned to the substrate and mounted on to the ACF using 0.5-1MPa of force for 1-2 seconds and temperature ranging from ambient room temperature to 100℃. The pressure and temperature required to successfully mount the top half of the assembly to the substrate is a function of the ACF used, the materials used, and how much handling the assembly will see prior to completion of the bond process. It is desirable to use the lowest amount of time, temperature, and pressure possible while reliably mounting the second half of the assembly to the substrate. In all cases it is very desirable to keep the mounting temperature lower than the laminating temperature. The accuracy at which the two sides of the assembly are mounted to each other is critical. Inaccurate assembly limits the amount of contact area, potentially increasing contact resistance and lowering reliability.

Bonding

The range of times, temperatures, and pressures used for Bonding the ACF, which cures it and completes the assembly, varies widely depending on the type of bond and type of ACF used. The table below can be used for a reference.

Table 1: Common ACF Assembly Conditions[1, 2]

Assembly Type	Adhesive Type	Time (Sec)	Temp (℃)	Pressure
Flex-on-Glass (FOG)	Epoxy	10-12	170-200	2-4 MPa▲
Chip-on-Glass (COG)	Epoxy	5-7	190-220	50-150 MPa※
Chip-on-Film (COF	Epoxy	5-10	190-220	30-150 MPa※
Flex-on-Board (FOB)	Epoxy	10-12	170-190	1-4 MPa▲
Flex-on-Board (FOB)	Acryl	5-10	130-170	1-4 MPa▲
Flex-on-Flex (FOF)	Epoxy	10-12	170-190	1-4 MPa▲
Flex-on-Flex (FOF)	Acryl	5-10	130-170	1-4 MPa▲

▲ Pressures for flex assemblies (FOG, FOB, FOF) are measured across the entire area under the bondhead.

※Pressures for chip assemblies (COG, COF) are calculated on the cumulative surface area of the bumps on the chip.

In addition to the more standard configurations listed above, ACF is also currently used in chip-on-board (COB), chip-on-chip or silicon-on-silicon (SOS), and various assemblies of flexible substrates not conforming to the normal polyimide base film construction used in most flexes today. ACFs designed for these applications may have assembly conditions that vary greatly from those described above and are not covered in this paper.

MANUFACTURING ENVIRONMENT

ACF has traditionally been used in a Class 10,000 (ISO 7) or Class 1,000 (ISO 5) manufacturing environment. Ito Corporation has developed a different set of criteria to determine the appropriate cleanliness level for a given ACF assembly. In the Ito cleanliness model, we step away from the focus on photolithography and attempt to bring a more practical and cost-effective perspective to bear.

Cleanliness Requirements for ACF

The FED and ISO standards often used in ACF manufacturing are listed in *Table 2*. Plainly evident is the focus on very small particles, particularly those under 1µm in size. It is our belief that these sub-micron particles are irrelevant to ACF assembly except in the following conditions.

1. They are of a material that adversely reacts with the ACF or assembled materials.
2. They are of such quantity that they form a layer on one or both of the substrates, preventing adhesion.

As a practical matter, the best solution to the first issue is to remove the source of contamination. As we see from *Table 2*, even the HEPA (High Efficiency Particle Air) filters used in cleanrooms will allow some particles to pass, so removing the source is necessary. In the second case, the volume of particles would be immense, suggesting a need to clean the substrate prior to use, not filter the air around it.

Table 2: ISO 14644-1 Cleanroom Standards[3]

Class	maximum particles/m³						FED STD 209E equivalent
	≥0.1 µm	≥0.2 µm	≥0.3 µm	≥0.5 µm	≥1 µm	≥5 µm	
ISO 1	10	2					
ISO 2	100	24	10	4			
ISO 3	1,000	237	102	35	8		Class 1
ISO 4	10,000	2,370	1,020	352	83		Class 10
ISO 5	100,000	23,700	10,200	3,520	832	29	Class 100
ISO 6	1,000,000	237,000	102,000	35,200	8,320	293	Class 1000
ISO 7				352,000	83,200	2,930	Class 10,000
ISO 8				3,520,000	832,000	29,300	Class 100,000
ISO 9				35,200,000	8,320,000	293,000	Room air

Another aspect to consider is that ACF uses particles that typically range from 3.5-10µm in size. These particles are then compressed during bonding so that the gap remaining between the two sides of the assembly is around 50% of the starting diameter of the particles. In the case of soft polymer particles, the particles are deformed by the bonding process and flatten to the desired gap. In the case of hard particles such as nickel, the particles embed themselves into one or both sides of the bond in order to achieve the desired gap.

Figure 1: Particle Size Comparison

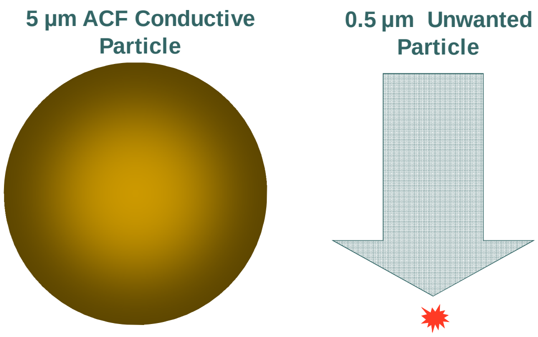
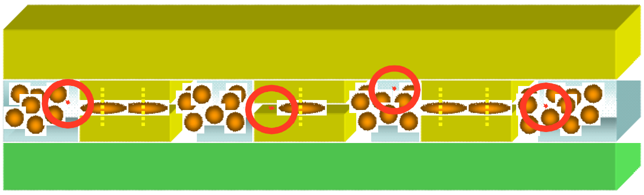


Figure 1 shows a typical 5µm particle in comparison to a 0.5µ particle, and *Figure 2* shows the same two sets of particles in an ACF bond with a 2.5µm gap. Clearly there is no interference with the bond process, and we can safely ignore these particles if they exist in moderate quantities.

Figure 2: Unwanted 0.5µ Particles in an ACF Bond



Figures 3 and *4* show the two sets of particles that concern us in our model. In *Figure 3* we have a particle

that is hard, or uncompressible. Such a particle could act as a standoff in an assembly, preventing the desired gap from being achieved and thereby limiting the reliability of the bond. In our model, therefore, no uncompressible particle larger than 1/2 the diameter of the ACF particles being used is allowable. In reality, hard particles are typically heavy and they almost always can be traced to either a material input or to the equipment processing the material. In a normal manufacturing environment, air cleanliness is not a driving factor in their presence or absence.

Figure 3: Glass Particle Acting as Stand-off in ACF Bond

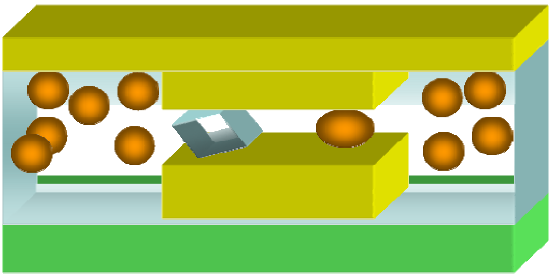
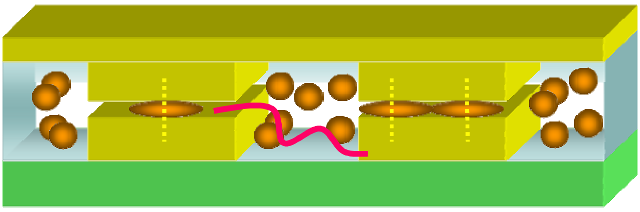


Figure 4 shows a very large particle, but one that is soft or compressible such as a fiber. Given the high forces used in ACF bonding, this particle will not act as a stand-off and the proper gap can easily be achieved. However, should this particle be large enough to span two adjacent contacts within the bond, it creates the potential for current or signal leakage. As a result, any particle that can span two contacts, whether soft or hard, is not allowable.

Figure 4: Large Particle Spanning Multiple Contacts



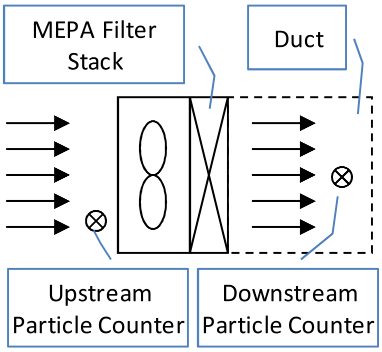
HEPA vs MEPA

As a result of this new cleanliness model and the data we have taken (*Table 5*), Ito now recommends MEPA (Medium Efficiency Particle Air) filters over HEPA (High Efficiency) filters for most of our clients. Filters in this set can be used in a standard SMT environment (TYP 650,000 particles/ft^3) at a 50% duty cycle for one year before needing to be replaced, resulting in significant cost savings. It is important also to note that the lower density of the MEPA filter structure allows much higher air flows than with HEPA filters – up to 600% higher for a filter of the same size. The higher airflow helps to maintain positive air pressure inside the assembly equipment, allowing it to be placed in a standard manufacturing environment while maintaining the required internal clean levels. As ACF continues to move strongly into the FOF and FOB application area, we expect to see more equipment vendors following this model and allowing their equipment to avoid the expense and complexity of running a cleanroom.

Table 5: MEPA Filter Efficiency (Red area shows particles which could affect ACF bonding.)

Particle Diameter	Upstream Particle Count (ft^3)	Downstream Particle Count (ft^3)	Efficiency
0.3µm≤	1290000	336061	73.9%
0.5µm≤	116797	13900	88.1%
0.7µm≤	16677	1128	93.2%
1.0µm≤	5786	181	96.9%
2.0µm≤	1121	10.4	99.1%
3.0µm≤	231	0.8	99.7%
5.0µm≤	65	0.2	99.7%
10.0µm≤	22	0.1	99.5%

※ Note: Particle counts are an average of 10 separate measurements.



BONDING TECHNOLOGIES

The actual process of bonding or curing ACF has not changed much over the course of ACF use, but new technologies are on the horizon that may lead to faster cure rates. Among the most interesting of those is the use of ultrasonic energy as the heat source. While several different approaches are being developed, the Nano Packaging and Interconnect Lab (NPIL) at the Korea Advanced Institute of Science and Technology (KAIST) has developed a way to use vertical ultrasonic (VUS) movement to create reliable ACF bonds.[4, 5]

In the VUS process, the ultrasonic horn is used to first apply pressure to the bonding area as in a normal ACF bonding process, but unlike either a standard thermocompression bond the horn is kept at room temperature. The horn is then energized and vibrated in the vertical axis and as shown in *Figure 5*, the ACF loss modulus is utilized to generate a rapid heating of the ACF.

Figure 5: Heat Generation by Cyclical Deformation

$$dQ = \frac{\int (\Delta\varepsilon)^2 E''}{2}$$

dQ=Heat Generated
∫=Vibration Frequency
△ε=Strain at the ACF Layer
E"=ACF Loss Modulus

VUS bonding has advantages over other ultrasonic bonding techniques for ACF due to the fact that heat is generated from within the epoxy resin, limiting the thermal impact on surrounding materials and devices and generally allowing a higher curing temperature and faster bond cycle. Horizonta vibrationl ultrasonic bonders also exist, but in addition to the scrubbing mechanism to generate heat they typically also use a conventionally heated horn and cannot heat as fast or as high as VUS units. VUS units also have the advantage of being able to be used in the same manner as pulsed heat thermocompression heads with very rapid heating and cooling cycles.

NEW ACF FORMULATIONS

As mentioned previously, ACF is comprised of an adhesive system and a distributed matrix of particles suspended in that adhesive in order to conduct electricity across the two sides of an ACF assembly once the bonding process has been completed. New developments in both the adhesive systems and the types of particles being used have accelerated the adoption of ACF as a valid technology for FOB or FOF applications such as interconnecting a display module flex tail to the main board of the assembly.

The Rework Factor

For many years various phenyl, bi-phenyl, tri-phenyl, and other epoxy resins were the basis for most ACFs. While these materials offered and continue to offer a fast and robust bond, they are very hard to rework, limiting their use to applications that are already inherently unreworkable, have yields high enough such that reworkability is not a concern, or where there is no viable alternative to ACF for the assembly process. Today, however, every ACF vendor also has at least one ACF based on acryl resins or some blend of acryl and epoxy resins.

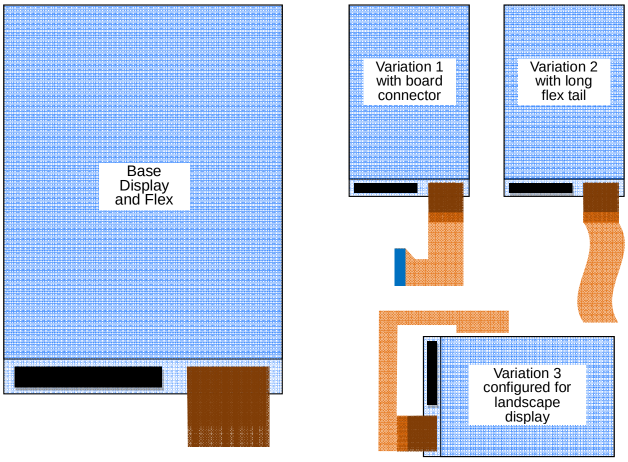
In *Table 1* we can see that the required bonding temperature for acrylic ACFs is 20-40℃ lower than t hose for epoxy materials. The time required at this temperature is also less, leading to faster cycle times off of the same equipment. Acrylic materials can also be easily reworked with isopropyl alcohol or methanol, making them popular choices for many high-volume consumer products. In comparison to epoxy ACFs, however, they currently lack the ability to go through solder reflow processes or hit the temperature extremes required of some applications, such as those in the automotive industry. As a result, usage is now split between the two technologies, with both acryl and epoxy resin formulations expected to continue in the market.

Flex-on-Flex and Flex-on-Board Requirements

The cost of tooling up a display and the cost advantages once high volume manufacturing is achieved are causing some user to look at using ACF to modify a display configuration in order to use a single display module design across multiple product lines. In the easiest implementation of this idea, a base display is designed and built in high volume, with product customization available through the bonding of subsidiary flexes to the display flex. These subsidiary flexes can then be connected to the mother board in any way suitable for that design. A simple example is shown in *Figure 6*.

Another growing requirement for FOF and FOB bonds is the capability to bond to OSP surfaces. OSP, or organic solderability preservative, is a lower-cost alternative to the gold plating that ACF assembly has traditionally used. Because of the cost savings available through using OSP, many companies have pushed for this capability for years[6]. The first products to successfully use OSP in a high volume production process are now out in the market, with many more expected to arrive in 2009.

Figure 6: Customizing a Display Module Using ACF FOF Bonding



CONCLUSION

The packaging portion of display design and assembly is often a secondary concern compared to the optical performance of the display. By leveraging the rapid advances in ACF packaging technology, both from a capability and a cost perspective, a company can capture significant value not otherwise realized.

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