Flex-Based Packaging Solutions – from CSPs to MEMS

By Ken Gilleo
ET-Trends
gilleo@ieee.org

Abstract
Flex is the original chip carrier that solved problems decades ago for the fledgling IC industry when packaging was just being invented. Flex has improved over the years to become the most versatile packaging and interconnect system in the world. Flex offers the highest density and the thinnest substrate while adding the magic of conformability. The conformable substrate reduces thermomechanical stress and also enables 3D designs. Thinness not only reduces weight, heat transfer is greatly increased since thermal conductivity is inversely proportional to thickness. Flex is used to package some of the hottest and most powerful CPUs.

Today, flex-based packaging (too often referred to as tape) brings unique, cost-effective solutions to Chip Scale Packaging (CSP). The ease of fabricating micro-vias and gaining access to both sides cuts complexity and cost. But flex is also solving some of the newest and toughest packaging challenges including those presented by MEMS. Micro-Electro-Mechanical System (MEMS) chips are considered to be the most difficult ICs that the packaging industry has yet handled. MEMS combines logic, mechanical motion and even optics – all on one chip. MEMS with its brainpower, sensing ability and control may be the most important technology of this decade. Some chips require selective encapsulation so that motion is not restricted and light isn't blocked thus making conventional packaging a doubtful choice. But flex has already solved MEMS and MOEMS (add "optics") dilemmas. This paper will discus the *how and why* of flex-based packaging with real examples ranging from CSPs to MEMS.

Introduction
Flexible circuitry is the premier chip carrier and ultra-high-density package with a heritage that goes back to the 1960's. Many early packaging concepts struggled to survive but only three arrived with the new millennium: Tape Automated Bonding (TAB), Direct Chip Attach (DCA) and wire bonding. While there are many subsets and derivatives, all IC interconnections can be classified into one of these three basic systems. TAB relies on cantilevered beam leads to connect to IC pads but it is really a specialized flex circuit. Although TAB is in wide use, there are several newer derivatives using the flex inner lead connection to the IC. Pure TAB requires soldering the flexible outer leads to a PWB. But some of the newest area array packages replace the outer leads with metal posts, connection bumps or solder balls to enable surface mounting. Flex-based BGAs are therefore lightweight, low profile and easy to assemble by SMT. The common theme in all of the TAB type packages is the direct bonding of the inner lead flex conductors to the chip pads. IBM's Tape Ball Grid Array (TBGA) and Tessera's μBGA are both flex-based packages. There are endless offshoots of these two TAB concepts. Figure 1 compares TAB and flex-BGAs.

Flex is not limited to TAB style interconnects, however. Flex substrate is used with DCA, commonly called Flip Chip, and for conventional wire bonding. The high-density characteristics of flex allow all of these connection formats to be made small enough to qualify as Chip Scale Packages (CSP). All of these flex packages, including pure TAB, are in high volume use today throughout the world. But why is flex used so extensively?

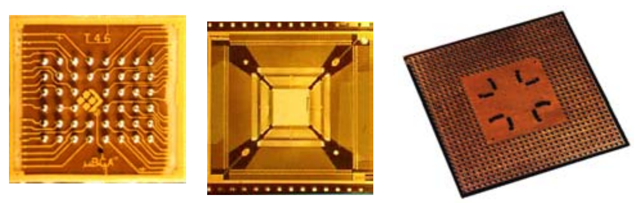

Figure 1 – μBGA, TAB and TBGA (Not to scale)

The primary reason for the popularity of flex packaging is maximum performance and ultimate density. AMKOR has pointed out that by the late 1990's, packaging density was finally ahead of the pitch demands of perimeter configured ICs thanks to flex. Another reason for using flex is to reduce cost. This may seem like a paradox, but there are many flavors of flex and one of them provides low cost processing and materials. Next we will look at the special characteristics of flex materials and then at the unique processes that they make possible.

Flex Materials
One of the most important characteristics of flex from the packaging perspective is thinness. Flex, of course, is the thinnest circuitry, packaging and interconnect material available. Flex substrate has been produced as thin as 12.5 microns and even less for special projects. We can point out the obvious that a thin material will be lighter and smaller (lower profile), but there are more important benefits. Flex provides excellent heat dissipation. Heat transmission is inversely proportional to thickness so thin

is a win. A 1- mil (25µ) flex substrate will transfer heat 30 times better than a 30-mil hardboard if thermal conductivity is similar. Flex is also available with enhanced thermal conductivity. This is why IBM chose flex for the TBGA®, Texas Instruments uses it for the MicroStar® and AMKOR builds the *FleX*-BGA®. The TBGA and some of the other flex packages use a metal heat spreader attached to the flex chip carrier to get a substantial boost in thermal dissipation.

Flex can also have thin conductive layers unlike rigid laminates that must use relatively thick sheets of copper. Adhesiveless clads are available all the way down to 3µ copper since the metal can be vacuum deposited using a continuous roll process. The importance of a thin metal layer is derived from the ability to produce extremely fine widths and features for maximum density. Fine line etching is always a battle with the "etch factor" that produces angled, undercut and imperfect conductor walls. Etching tends to be isotropic so that undercutting and irregular sidewalls occur even with the best etchants and equipment. But thin copper can be etched into finer lines and spaces. Yamamoto, et al[2] carefully measured vertical and horizontal etching as a function of thickness and determined that copper must be 12-µ or less for 75-µ lines and space. But for 50-µ l/s, the foil had to be 5-µ or less. They pointed out that rigid laminate could be made using such ultra-thin copper made with a removable carrier. While this expensive process is certainly feasible, flex clads are available in this range made by direct processes. Figure 2 shows the carrier/foil[2].

Figure 2- Ultra-thin Copper on Carrier

The cost-effective semi-additive process can produce even finer traces with straight walls. This semi-additive process involves depositing a plating mask over the thin copper followed by patterning. Metal is then plated up into the openings of the resist. The resist is stripped away leaving conductors that perfectly replicate its walls. Resist with 90° sidewalls will yield a well-defined rectangular conductor cross-section with superior properties. The final step is a "flash etch", brief exposure to mild etchant that removes the few microns of "seed layer" copper that carried the plating current. The flash etch tends to polish the conductors with very little metal removed. This method can form conductors down to less than one-half mil (12µ) and even 5µ lines have been achieved. Build-up processes that use thin deposited copper are reported to have a production capability minimum line width of 12-microns[3]. The micron-range traces with near-perfect sidewalls give the best electrical performance, especially at high operating frequencies. Thinness enables one more important benefit that will be covered in the process section, but let's examine the dielectric first.

The flex-base material is typically a polyimide (PI) with no reinforcement. The polyimides are noted for very high temperature performance and most can be processed up to 300°C. The flex polyimides will have no problems with higher melting lead-free alloys. The impressive thermal stability of PI allows fast TAB inner lead bonding since the bonding tool can be set to high temperatures without damaging the dielectric. These junctions do not melt during solder board-level assembly of the packages.

Very low cost, but temperature-limited thermoplastic films are also used for flex that can be utilized for some packaging if solderless assembly is employed. Polyester, typified by Dupont's Mylar®, is probably the lowest cost higher performance electrical substrate. The big drawback for polyester is a processing temperature limit of about 150°C. This would seem to preclude its use for packaging. However, a considerable number of polyester TAB packages are made. While the inner leads can be bonded to the chip, outer leads do not tolerate soldering very well. The simple solution is to use conductive adhesives, especially anisotropic film. Millions of calculators are produced each month using polyester TAB, perhaps the world's lowest cost package. Figure 3 shows polyester TAB.

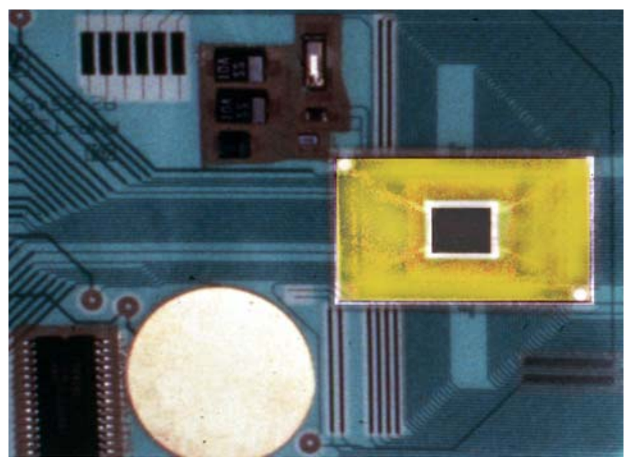

Figure 3 – Polyester TAB or Calculator

There is one more fascinating and clever use of polyester for packaging found in the radio frequency identification (RFID) area. A tiny flip chip is assembled to a small section of polyester that contains a simple antenna. Conductive adhesive is used to create the chip connection at a temperature that doesn't damage the flex film. The "package" may be underfilled, encapsulated or a flex film can be laminated on top. Electromagnetic energy and RF digital signals are sent to the chip through the antenna. The chip responds back with a transmitted RF digital signal. But is this really a flex-based package? One can argue that this simple RFID is a package since it contains an IC and that it is connected to the main system (reader).

The "chip-to-board" connection, however, is electromagnetic radiation instead of solder. Figure 4 shows an RFID tag.

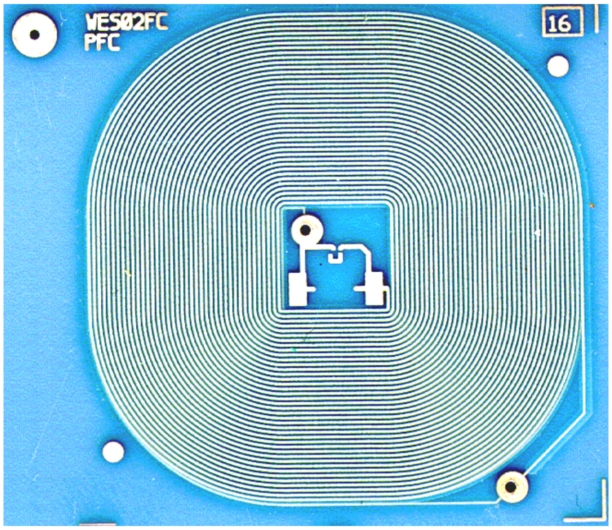

Figure 4 – RFID

Flex Processes

The extreme thinness of flex base film and conductors permits unusual processing that produces unique packages. First let's recall that flex does not use glass reinforcement as do rigid laminates. Polyimide is dimensionally stable and strong enough so that this can be avoided. Glass fiber, of course, would degrade the flexural properties and make it impossible for a disk drive circuit or other dynamic application to be flexed hundreds of millions of times. The processing payoff is that microvias can be easily produced with high quality. Lasers and punches can produce tiny opens quickly since the material is so thin and homogeneous. The absence of fiber increases the hole precision, quality and repeatability. Glass weave can produce many variations since there will be regions with no fiber, one strand and cross-fibers. The absence of glass also keeps the dielectric constant low in the range of 3.0 to 3.5 for PI and polyesters.

Flex circuits and flex packaging can take advantage of a unique process to produce "back-bared" or "double-access" constructions. The method is used for single-conductor flex circuits. A via or larger opening is formed in the base dielectric film that communicates with the conductor on top. This is not to be confused with windowing used in TAB where an open window is produced. Older processes required that the openings be formed in the base film before copper foil was laminated. Then the circuit pattern was etched taking care to cover the openings. One alternate method uses etching solution that dissolves polyimide instead of copper. Etch resist is applied over the dielectric and opens are formed in the film followed by stripping the resist. The dielectric etching method is still in use today, but lasers are becoming the norm. The right laser can ablate away dielectric and stop at the copper layer. The idea is to connect to the copper from the bottom of the circuit – hence, the double access term.

While dielectric removal methods can produce the cantilevered beam leads for TAB they are also very useful for fabricating BGAs. The method has also become popular for forming microvias intended for solid metal posts. Since the vias end at the copper layer, electroplating is quite practical. Application of a DC plating current to the copper allows metal to be plated into the vias although care must be taken when openings are very small. Continued plating will form a bump as the metal plates out and over the base dielectric. Careful control can produce an area array package with non-fusible bumps. This is exactly how Tessera produced the first micro-BGAs. Today's more useful process is to plate up metal posts and then mass attach solder balls to build a ready-to-assembly BGA.

Flex Packages

TAB

Let's start with Tape Automated Bonding since that is where the history of flex packaging began. Several early packaging engineers were intrigued by the properties of flex and realized that here was an ideal system. One early developer was Dr. Francis Hugle of San Jose, California. Her concepts embraced the flexible characteristics leading to an easy-to-automate tape & reel approach. The flex substrate was Dupont's polyester Mylar since Kapton® was just being introduced and was not as widely available. The IC connection was DCA (Direct Chip Attach) with localized heating so that the temperature-sensitive film survived. Figure 5 shows the patent drawing and the innovative sprocket design in the "Flip Chip Strip". The idea was to use the sprocket holes to move the reel of packages just like movie film. Note how the copper is used to frame the circuit and enhance strength. Ms Hugle had some advanced ideas of protection including overmolding the chip-on-flex as shown in Figure 6.

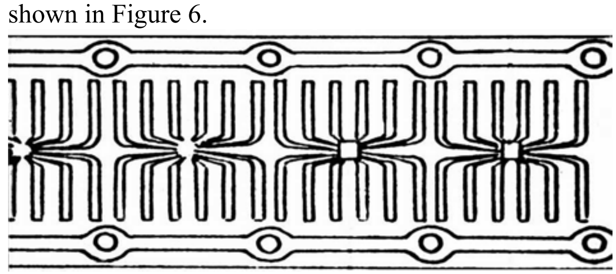

Figure 5 – Flip Chip Strip

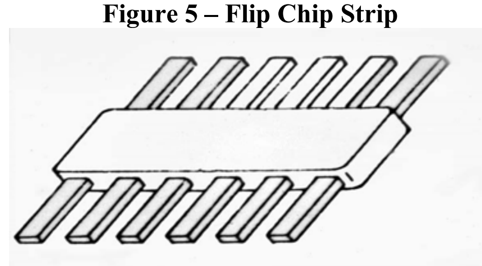

Figure 6 – Molded Flex

General Electric patented a similar tape & reel flex package called Minimod that is generally considered to be the first TAB although the patent date is later than the Hugle invention. Two significant differences for Minimod is that the flex is Kapton and the chip connection used cantilevered beams. Figure 7 shows the principles. Note that Hugle chose round holes while GE liked square ones. Modern TAB more or less follows the GE design.

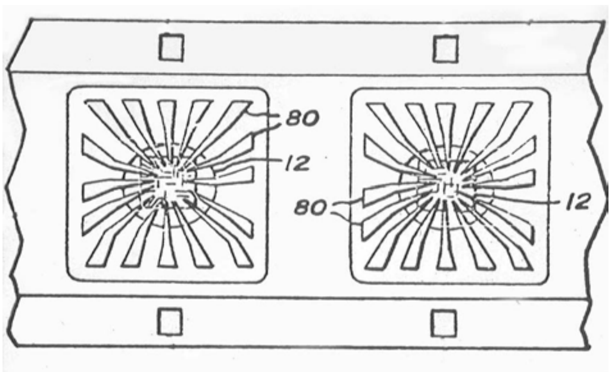

Figure 7 – Minimod

TAB is widely used today in products ranging from low-end calculators to high-resolution displays. Dedicated equipment is required to do both the chip Inner Lead Bonding (ILB) and the package-to-board Outer Lead Bonding (OLB). One increasingly significant attribute of TAB packages is the low profile. Intel took advantage of this low height feature for laptop computers beginning in the late 1990's. The Pentium chip was packaged in TAB that Intel called a Tape Carrier Package (TCP). A thermally conductive die attach adhesive film is placed between the circuit board (with a heat sink platform) and packaged so that a thermal path is created at the same time that the outer leads are hot bar solder bonded. Figure 8 shows the TCP. Later we will look at BGA-TAB, but first, let's look at one more very high volume flex package with a built in circuit.

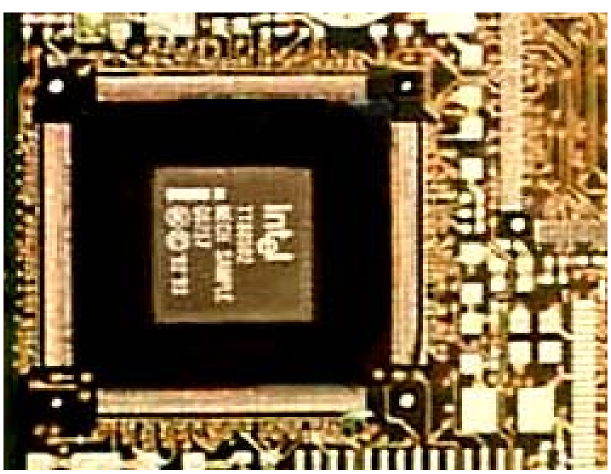

Figure 8 – Tape Carrier Package
ITAB (Integrated Tape Automated Bonding)

The HP Ink Jet cartridge uses one of the earliest high volume MEMS devices. MEMS chips have always have some form of mechanical motion. The ink jet chip "fires" micro-droplets of ink at the paper using a thermally activated propulsion mechanism. Epson is reported to use piezoelectric "guns" in their MEMS ink jet chip. The packaging challenge for HP was multiple: (1) protect the chip without blocking the jet holes, (2) incorporate the chip and packaging into an ink-filled cartridge, (3) provide an electrical connection to the printer.

The right packaging, connection and circuit solution was flex – one single unit! The chip is interconnected using TAB-like cantilevered beam leads. The TAB is integrated into a flex circuit that warps around the plastic ink cartridge to provide a pressure connection to the printer. We chose to call this type of flex Integrated-TAB (ITAB) although it has been called Flex-Featured TAB[1]. The chip is protected by dispensing a liquid encapsulant over the connection site while staying clear of the holes in the chip. Figure 9 shows the flex package-circuit and Figure 10 shows an automatic dispenser used by one of the manufacturers.

Figure 9 – HP Ink Jet Cartridge

Figure 10 – Needle Dispensing Machine (Speedline)

Before moving on, let's look at one of the most fascinating newer MEMS chips. Texas Instruments' Digital Micro Device™ is based on an array of movable micro-mirrors crafted by semiconductor fabrication processes. Each mirror can be pointed toward the lens (on) or away (off) to form detailed images. Although the chip with its thousands of movable mirrors is packaged in ceramic with a glass lid, the interconnect is flex as seen in Figure 11. This allows the mirror module to be positioned and aligned with the lens, color filters and light source. Some designs use 3 sets of mirror modules for primary colors that are mixed to generate millions of colors. The mirror module is used in digital projectors and is being tested for digital cinema use. Soon, movies may arrive at the theater via the Internet. The most important use of MEMS mirrors may be to switch light beams for the fiberoptic Internet backbone.

Figure 11 – TI DMD

TBGA

IBM has always had packaging challenges because of the inherent characteristics of their powerful computing machines. Power and speed typically equate to heat and thermal management issues. While the big mainframes can use elaborate liquid-cooled manifolds, this is not practical for workstations and most servers. IBM therefore developed a flex-based package with high heat management capacity. Flex was chosen for its thinness since heat could readily pass through the few mils of dielectric film. The chip connection utilized TAB-type cantilevered beam leads since this connection would not melt under high temperatures as would solder joints. But rather than terminate with conventional outer leads, metal spheres were attached to form a Ball Grid Array package. A metal heat spreader can be bonded to the flex to allow considerable heat dissipation. Some configurations added a large heat sink to the heat spreader. Figure 12 shows IBM's Tape Ball Grid Array (TBGA) that is just one more great flex circuit.

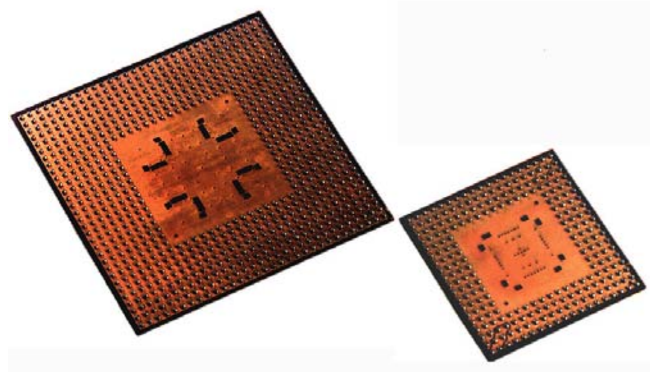

Figure 12 – TBGA

µBGA

The IBM product was not intended to be a chip scale package since the primary goal was heat management in a cost-effective, low profile package. Tessera, founded by former IBMers, used the TAB-connection concept to build a very small TAB-BGA type package. Their design fanned the leads inward to reduce area and stay about the same size as the chip. Originally, the 2nd level interconnect was made by forming blind vias in the dielectric and plating up metal balls with copper or nickel. Holes were formed with an excimer laser and metal was plated up using the flex copper layer as the bus after masking the top surface. Plating with pure gold formed the circuit pattern after the post or post/bump formation step. The remaining thin copper was then etched away leaving the gold cantilevered beam leads. Today, Tessera's µBGA uses mass attached metal spheres that are typically made of eutectic solder. There are now several versions of this flex based packaging including wafer-level systems that can accommodate area array chip pad layouts. All are flex circuits.

Wire Bonded Flex BGAs

There is only one other chip connection method and that is wire bonding, the workhorse of the industry. Texas Instruments and others are using flex substrates to build CSPs and larger area array packages. The chips are typically attached to the flex with die attach adhesive followed by standard wire bonding. The chip is protected using either liquid encapsulant or epoxy molding compound. The final step is to attach the solder spheres to the bottom of the chip carrier by a reflow process. TI's MicroStar™ flex packages is one of the highest volume CSPs and it has been used on all kinds of products including the now-famous Sony HandyCam. Once again, it is the thinness, lightness, robustness and high-density capability that makes flex the winner in packaging.

Flip Chip BGAs

Flex and flip chips are a synergistic combination. Both provide the highest density, smallest footprint and maximum performance. The first flip chip-on-flex was probably the Hugle Flip Chip Strip discussed earlier. Today, many of the OEMs and contract packaging foundries use flex packaging employing all of the chip connection processes that have been described. Each connection method has its place in the grand scheme of packaging with benefits that favor different applications. Flip Chip, or direct chip attach, becomes the preferred method as lead count goes up. The crossover point may shift depending on progress in each area, but flip chip becomes increasingly attractive above 500 I/Os. This does not mean that FC-BGAs should be used for low count, but rather that other methods become increasingly problematic above the 500 to 600 I/O ranges. Flip chip is a mass connection process where all bonds are made at once so that cost per pin drops as count goes up. Flip Chip also provides the densest interconnect with a capability of at least 10,000 bumps.

Flip chip assembly involves first applying flux to the chip bumps or to the circuit pads. SMT pick & place equipment and flip chip bonders can be furnished with a fluxing wheel that provides a flux reservoir for dipping the chip and thereby coating the chip bumps. Epoxy-based flux has become popular because it is compatible with epoxy underfill, the major class. Any loss of underfill adhesion due to the wrong flux can result in solder joint fatigue during thermal cycling. The flip chip assembly is now run through a reflow solder line causing the solder bumps to reflow, wet the circuit pads and form joints. High volume packages can be run as strips or full sheet array with hundreds of individual packages.

Underfill must be used even though the thin substrate is somewhat compliant. The micro dimensions of the flip chip joints are not able to withstand the expansion forces of the carrier. Although underfill is most commonly applied after the solder joints are formed, newer pre-applied flux/underfill can be used to eliminate some steps. The flux/underfill, also called "No Flow" underfill (NUF) serves as the flux during solder reflow and then hardens by thermally induced polymerization in the reflow oven. Underfill can also be applied by a new transfer molding process where the flip chip assembly is placed in a special mold with molding compound designed to flow under the small chip-to-board gap. The underfill and overmold processes can be performed simultaneously with the right mold design.

Encapsulation and solder ball attach can be done in the array form with singulation as the last step. One encapsulation method involves overmolding a strip of packages or a full sheet. The overmolded packages are singulated by sawing.

Conclusions

Flex is the ideal material for packaging offering the thinnest and highest density microcircuits anywhere. The high temperature resistance is also a plus, especially if the industry goes to higher melting lead-free alloys. Many of the polyimides can handle 300^{o}C or higher assembly temperatures. The polyimides are also halogen free.

Adhesiveless flex, or clad, offers special advantages for packaging. One of the most valuable is thin copper that permits ultra-high density semi-additive processing with features down to a few microns and near-perfect straight sidewalls.

Thinness and absence of inorganic reinforcement fiber or weave enables microvias. In fact, flex makers were producing microvias before it became popular for rigid laminates years later. Thin polyimide can be laser machined quickly and with high precision since glass fibers can not intrude to upset the process. Blind vias are easily produced with lasing that permits Ball Grid Array packaging to be made economically.

In summary, no other system offers the size and weight reduction, the toughness, and the versatility of flex. Flex is the original chip carrier and, almost 40-years later, the very best. This is why flex is used for the smallest CSPs to the most complex MEMS devices.

References

[1] Gilleo, K., Handbook of Flexible Circuits, Van Nostrand Reinhold, NY 1992.

[2] Yamamoto, T., *et al*, "Allowable Copper Thickness Related to Fine Pitch Pattern Formed by Subtractive Method", S07-3-1, Tech. Proc. Printed Circuit Expo, April 2 – 6, 2000, San Diego, CA.

[3] Sakamoto, K., et al, "The Evolution and Continuing Development of ALIVH High-Density Printed Wiring Board", S09-5-1, Tech. Proc. Printed Circuit Expo, April 2 – 6, 2000, San Diego, CA.