

Development of Ultra-Thin Microelectronic Multi-chip Assemblies

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Abstract

Ultra-thin, flexible microcircuit assemblies using thinned die (down to 20 μ m in thickness) and multilayer, thin film substrates (up to 4 conductor layers (five dielectric layers) at an overall thickness of approximately 10 μ m) have been fabricated. Such circuits offer significant promise in many advanced packaging applications such as: biomedical implant and monitoring devices, wearing apparel electronics, conformal antennas and receiver/ transmitter systems, and appliques of all types.

Key Words: Ultra-thin substrates, flexible substrate, thin-film multilayer substrates, ultra-thin assemblies, advanced microelectronic packaging, ultra-thin packaging

Introduction

To meet the ever-decreasing profile requirements in single and stacked die packages and assemblies, processes for producing thinned die are in widespread use for three dimensional packaging. As we have shown previously [1,2] thinned die on polyimide flex offers a means of further reducing package thickness.

In the previous thinned-die on flex activity, we showed that flip chip assemblies both with and without underfill were extremely reliable, surviving thousands of thermal cycles from minus 40°C to plus 125°C. Even though the non-underfilled assemblies were extremely reliable, the selection and application of a low modulus [1,2] underfill provided additional stress reduction on the solder joints so that no solder joint failures occurred after 4,000 temperature cycles (after which the test was terminated). The flex substrates were photolithographically patterned to hold and daisy-chain interconnect four large (10mm x 10mm) test die, each containing 1,368 eutectic tin-lead solder bumps on a 250 μ m pitch. The flex was held flat during the oven solder reflow process by a vacuum fixture. Following reflow and cooling, underfill, if used, was applied and cured with the assembly still on the vacuum fixture. Lifetime testing was conducted using a special

test board containing four of our 30 x 30mm modules [1,2].

The work reported in this paper is the next step in producing the “ultimate” thin electronic assembly. In this effort, we have replaced the one- or two-conductor layer flex circuit board described previously with a thin-film polyimide substrate containing four conductor layers and five dielectric layers with a nominal thickness of 10 μ m. This substrate was fabricated on an oxidized silicon carrier using a conventional polyimide dielectric thin-film multilayer scheme with copper metallization and chromium adhesion layers. An etch barrier layer was placed between the initial polyimide layer and the oxidized carrier surface to allow separation of the thin film substrate from the carrier after assembly.

The following sections describe the test die and the substrate fabrication, assembly, and reliability testing of circuit assemblies on both standard flex and flexible thin film multilayers.

Test Die

The test die was a 10 mm X 10 mm daisy-chained silicon chip with 1368 full area array eutectic tin-lead solder bumps on a 250 μ m pitch. Each device had two separate daisy chains that can be tested independently and were routed next

to each other as they serpentine back and forth across the chip. These devices were processed with a layer of HD Microsystems PI-2611 polyimide dielectric onto the silicon followed by a layer of chrome/copper interconnect and finally with a layer of the same polyimide with areas etched out for the I/O pads. The die were of sufficient size that significant stresses could be realized on the outermost solder balls. PI-2611 has an anisotropic coefficient of thermal expansion (CTE) of 3 ppm/°C in the X-Y direction, which closely matches that of silicon and minimizes thermally induced shear stress at the polyimide/silicon interface of the die. A photomicrograph of a thinned die with solder balls on a silicon carrier or handle is shown in Figure 1.

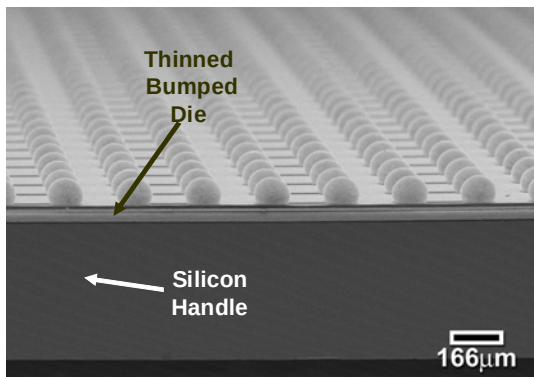


Figure 1. Bumped thin die on handle.

Substrates

The flex substrate design is shown in Figure 2. It incorporated 4 independent die sites per substrate. Each assembly had 5472 solder bumps and sufficient routing was provided in order to access each daisy chain on each individual die. The substrates were designed to be used in conjunction with custom test boards, which hold 8 substrates and distribute signals to and from the substrates while still allowing them to move freely, independent of the test board, during temperature cycling. Substrates were attached to the test boards by hand soldering thin wire from rectangular pads along the top and bottom sides of the substrates to corresponding pads on the test board.

The flexible substrates were manufactured from 50 μm thick Dupont Pyralux® AP copper-clad laminate. This is an all-polyimide composite of polyimide film bonded to copper foil. The base material had an in-plane CTE of 25 ppm/°C. The rolled annealed copper foil was 18 μm thick. The metallization pattern was etched in the

copper foil using standard photolithographic processing. Following the copper patterning, a liquid photo-imageable solder mask material was applied and cured. This solder mask was also applied to the reverse side of the substrate to balance process-induced stresses and prevent curling. Windows in the solder mask above the bonding pads were formed by exposure through a mask and subsequent developing of the photo-imageable material. The resulting copper pads were electroless nickel plated to a thickness of 4 μm. Then, a thin protective immersion gold layer (0.25 μm in thickness) was deposited onto the nickel.

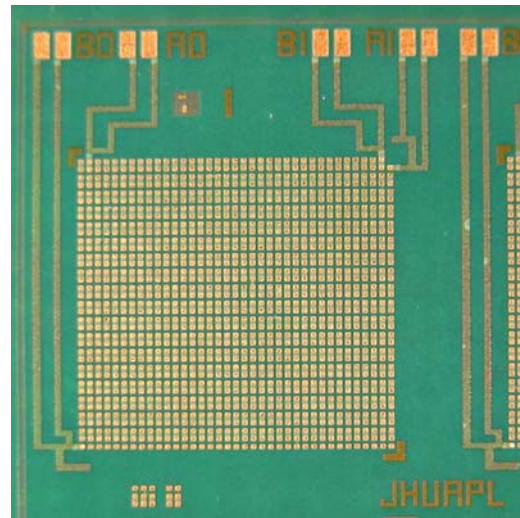


Figure 2. One quadrant of the Flex-Substrate showing the details of the daisy-chain connection bars.

Given the success of the thinned die on flex assemblies (see reliability test results below), there was increased interest in building an ultra thin flexible, multichip module. There are two possible approaches to the creation of an ultrathin, multichip assembly. Approach one called for the fabrication of a “thin” flexible freestanding substrate and then the subsequent attachment of the bumped die to the substrate by solder reflow. This approach required the development of assembly processes that could reliably handle the thin flexible multilayer substrate. The development of these processes would borrow from the previous experience gained in assembling the thinned die on flex [1,2].

The second approach would be to fabricate a multilayer thin film interconnection substrate (on a sacrificed rigid substrate), followed by the flip

chip reflow of the die onto the substrate, and then the final removal of the rigid carrier either by etching it away or releasing the thin film substrate from the carrier by dissolving a sacrificial layer after assembly. The second approach required the development of a carrier etching process or a release layer dissolving process that is compatible with a fully assembled microcircuit. We will focus our attention on the second approach.

The fabrication steps for the multilayer thin film copper-polyimide substrate used in this work are generically in the flow chart of Figure 3. A silicon wafer is used as the rigid sacrificial substrate.

A photograph of a “released” thin film, flexible substrate is shown in Figure 4. The “release” process will be described below.

The circuit pattern contains four conductor layers, many test structures, and three bonding sites for the thinned test die used previously for the thinned die on flex circuitry.

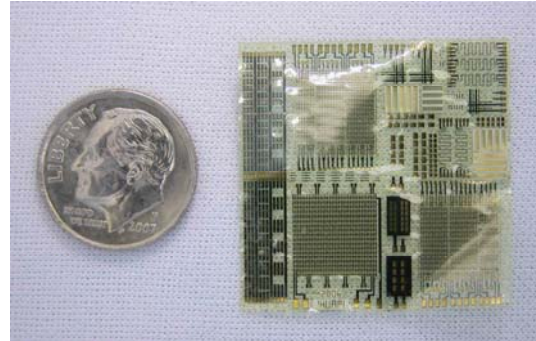


Figure 4. Ultra-thin, flexible multilayer substrate after “release” from the silicon carrier. Substrate is approximately 10µm in thickness and contains four levels of conductors.

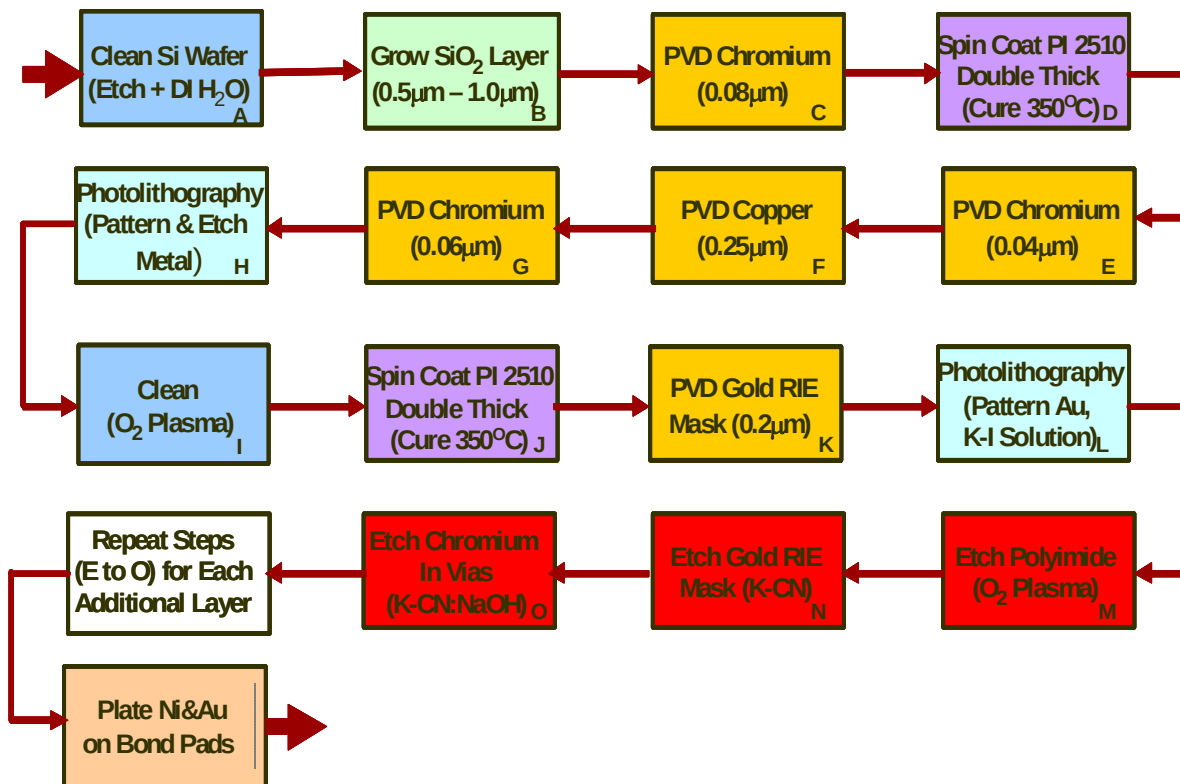


Figure 3. Flow Diagram for the Ultra-thin film substrate fabrication process.

Thinned Die Processing

A robust precision wafer thinning process was used which has been successful at thinning wafers, wafer segments, and commercial die to thicknesses as little as 8 μ m. Details of this process have been presented previously [1,2]. Key to this thinning is an effective double handle process and the ability to bump wafers after thinning, while still attached to the handle wafer thereby reducing the possibility of damage to the front side solder balls. Prior to thinning, a Cu/Cr electroplating base was sputtered onto the wafers. Then the wafers were thinned. After release of the front side support wafer, thick photoresist was applied and imaged. Eutectic Sn/Pb was electroplated onto the die pads and the solder was reflowed.

The photoresist was then stripped and the Cu/Cr plating base was etched. All of these operations took place while the thinned silicon wafer was still supported by the transfer (handle) wafer. Wafers were then sawn, leaving thinned die still attached to handles. Figure 1 above shows a photomicrograph of a 50 μ m bumped die with its accompanying handle segment.

Ultra-thin Substrate "Release" Process

An etched wafer process was used that made use of the buried silicon dioxide or chromium layers as etch stops. In this process, the silicon carrier would be etched away from the backside, leaving behind the ultra-thin, flexible, multilayer substrate. Results of this process were quite successful, with electrical test structures on the substrate performing the same both before and after "release." A released substrate is shown in Figure 4 above. The generic steps [3] in this release process are shown in the flowchart of Figure 5 below.

Flex Assembly

The presence of a releasable handle on each die greatly facilitated the assembly of the thinned die, allowing them to be flip chip assembled just as one would assemble normal thickness die. The only additional process step needed is the handle release process which was done after assembly of die onto the substrate.

Because the substrate was flexible and tended to warp during assembly at elevated temperature [1,2], a means for holding the substrate flat during reflow was needed

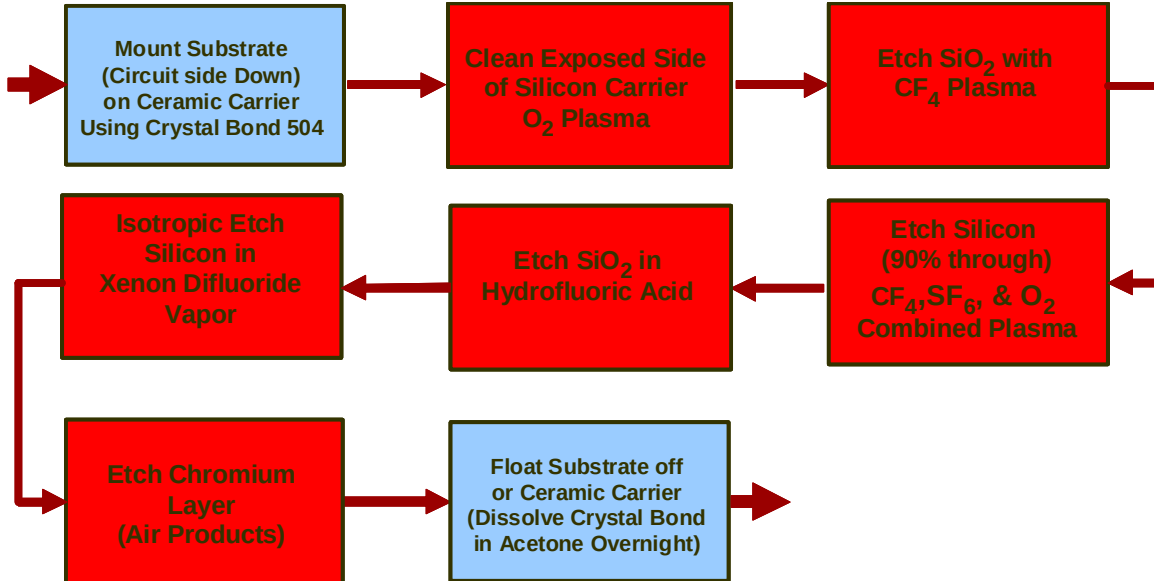


Figure 5. Substrate release process flow diagram. The carrier wafer is removed from the reverse side of the ultra thin film substrate by etching using a buried layer etch stop.

This problem was solved with a vacuum fixture that was constructed with a porous sintered block of stainless steel and connected to the house vacuum with a silicone hose. The flex substrate was held flat on the vacuum fixture during all the stages of assembly: placement, reflow, underfill dispensing and curing. The vacuum fixture was pictured in a previous publication [1,2]. With the substrate held by the vacuum fixture, the flip chip die was assembled with an automatic pick and place machine using a 25 μ m thick Kester TSF-6522 dip flux. With substrate vacuum still applied, parts were reflowed using a standard Heller 1800 reflow furnace at 230 °C peak temperature. The parts were reflowed in nitrogen (50-60 ppm of oxygen). The substrate vacuum hose was fed along with the assembly as it moved through the furnace. For volume production, a built-in vacuum system integrated into the rails of the reflow oven could be incorporated, eliminating the need for the vacuum hose. The flex substrate was sufficiently flat at room temperature to allow die placement; the vacuum hold down was only required during reflow and underfill cure (thermal exposures). After reflow, the assembly was released from vacuum and soaked in acetone to release the backside handle. The handle must be removed prior to underfilling, since the formation of an underfill fillet attached to the handle would prevent subsequent removal of the handle. Figure 6 shows the curvature for 50 μ m, 75 μ m and 125 μ m die on polyimide flex after handle release, but before underfill. Due to the CTE mismatch between silicon and polyimide, the curvature increased with decreasing die thickness. The CTE of the substrate was greater than that of silicon. Thus on cool down from the solder melting temperature the substrate shrunk more than the silicon and the curvature increased.

Underfill

Extensive testing and modeling of underfill materials was conducted [1,2] and a low modulus, low CTE, high T_g, low stress capillary underfill manufactured by the Lord Corporation was chosen. The basic properties of this underfill are: Elastic Modulus, flexural (<T_g) 5 GPa; CTE (<T_g) 30 ppm/°C; Glass Transition Temperature (T_g) 163 °C; and Equivalent Plastic Strain 65 X 10⁻⁵.

Prior to underfilling, the assemblies were baked overnight at 125°C for dehydration and to drive out the solvent from the handle release process. In the underfill process, the challenge was to dispense the underfill without allowing

the material to encroach on top of the very thin silicon die. Experiments concluded this could only be achieved if the total thickness of the underfill material dispensed was less than the distance from the top of the die to the substrate surface. An argon plasma treatment was used to enhance the wetting of underfill to the substrate, decreasing the contact angle, and increasing the underfill flow rate. Details of the dispensing process were also given previously [1,2].

Figure 6 shows a cross-section of a 50 μ m die after underfill. Uniform shaped solder joints were obtained with a stand-off height of approximately 50 μ m or about sixty to seventy percent of the original solder bump height. Work is planned with reduced height solder balls to minimize the height of the overall assembly.

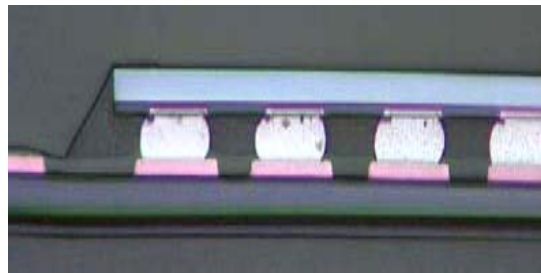


Figure 6. Cross-section of 50 μ m Thick Die Assembly after Underfil

Figure 7 shows the flexibility of the completed assembly. Besides curvature, a surface ripple was detected for all thinned die less than 250 μ m thick. Examples of the ripple have been shown previously [1,2].

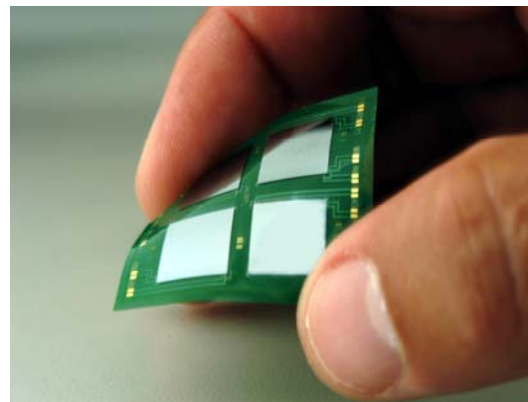


Figure 7. Example of the flexibility of the thinned die on flex.

Ultra-thin Substrate Assembly

The assembly of the thinned die to the thin film multilayer on the silicon carrier follows the

flip chip attachment process described above for the flex assembly, but because of the rigid carrier the vacuum hold down was not necessary. Once the circuit was assembled (three thinned daisy chained test die $30\mu\text{m}$ in thickness) a modified bare substrate separation process was developed. Since the die and other components now extend above the thin-film multilayer substrate surface a ceramic interposer with cutouts must be used to accommodate the die (or other components) and produce a flat surface for the attachment of the protective ceramic carrier. There are now two mounting procedures [3], one that attaches the interposer to the multilayer thin film assembly and the other that would mount the interposer and the electronic assembly to the protective carrier.

Both the ceramic interposer and the ceramic carrier are attached using the crystal bond process described above

Once the silicon carrier is etched away, the remaining assembly is soaked in acetone. The acetone dissolves the crystal bond, allowing the carrier and interposer to be removed. The acetone soak also provides an additional benefit. Not only are the carrier and interposer removed during the soaking process, but also the back side handles on the die are separated, yielding a truly thin and flexible assembly. A schematic representation of this assembly process is shown in Figure 8. Photographs of the released assemblies are given in Figure 9.

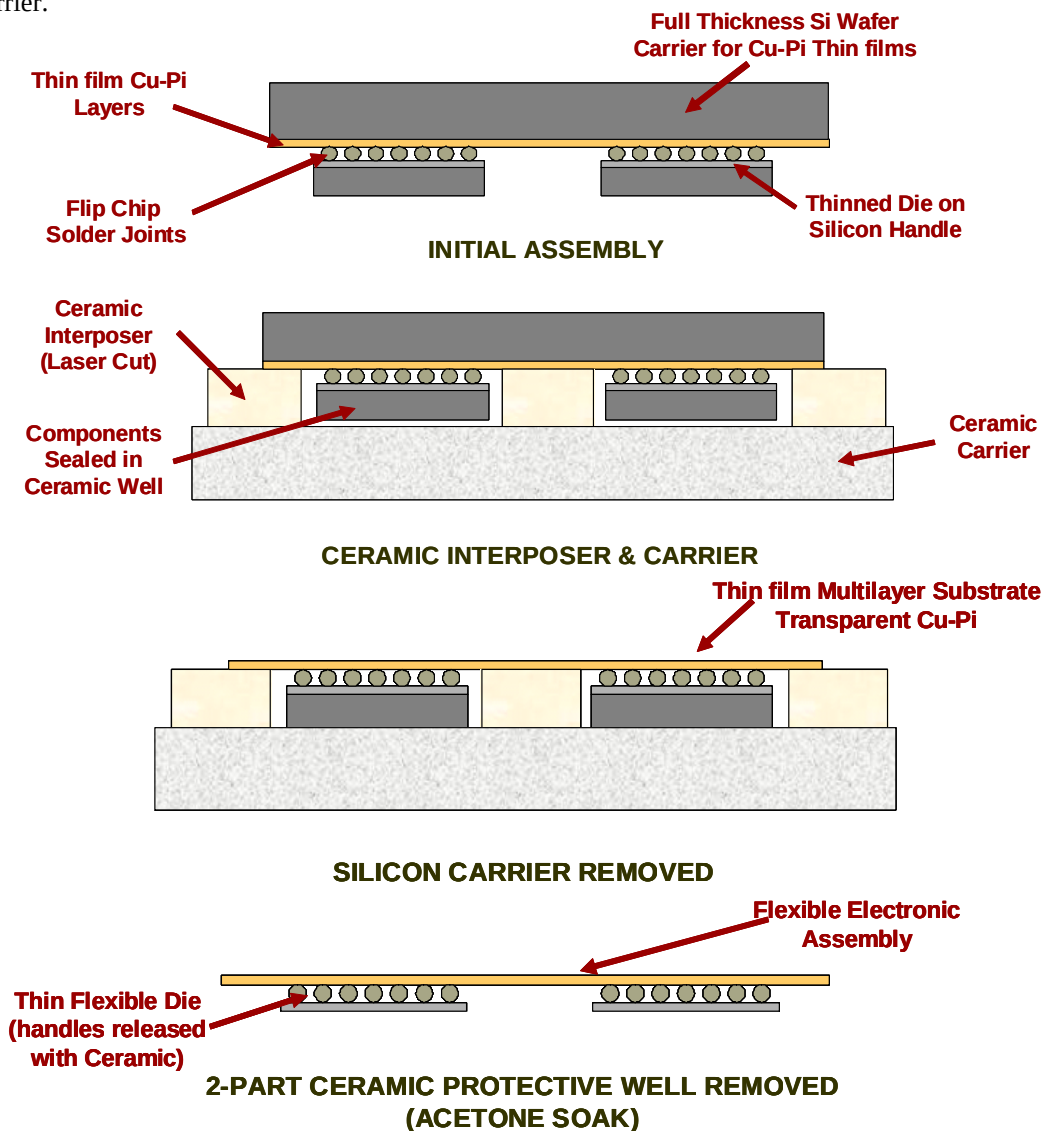


Figure 8. Schematic representation of the separation process for the ultra-thin film substrate assembly

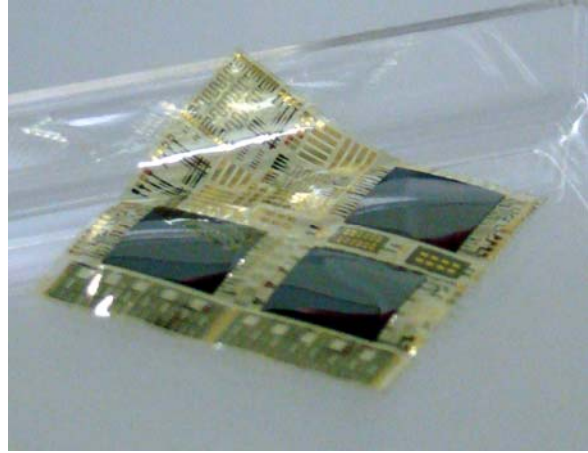
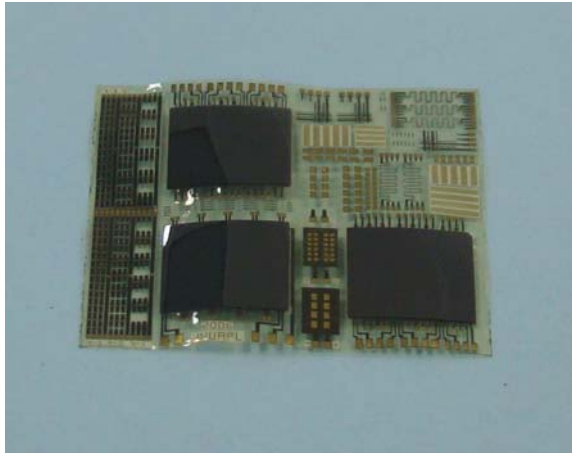


Figure 9, Different views of a completed and separated ultra-thin electronic assembly

Post Assembly Verification

Both the thinned die on the flex and the thinned die on multilayer thin film substrates were tested to determine structure continuity and the viability of each independent daisy chain on each die while ensuring that no shorts existed between individual chains. Moreover, no differences in daisy chain resistances were found between assemblies with different thickness die. For the ultra-thin assemblies only thinned die (nominally 30 μ m) were used. Daisy chain continuity was verified on these assemblies and chain resistance measured. Although somewhat different from that on flex, the difference is attributable to the difference in thickness and composition of the substrate metallization. After assembling almost 200 die, both on flex and the ultra thin multilayer thin film substrates, the assembly yields realized were 100%.

Reliability Testing

Thermo mechanical reliability testing has been performed on hundreds of thinned die on flex and is in its initial stages for the ultra-thin microelectronic assemblies. The authors have no reason to believe that these more flexible assemblies will be any less reliable than their flex counterparts.

The thermomechanical reliability of these devices were assessed through temperature cycling. Assemblies were wired to boards with 34 AWG transformer wire while allowing the substrates to expand and contract with temperature unconstrained by the test board. Temperature cycling was conducted between -40 °C and 125 °C with 30 min ramp time, and 15 min dwells, totaling 90 minutes per cycle.

Daisy chain resistances were monitored through computer-driven, continuous, event detection with automated data logging. Two sets of assemblies were cycled: 1) 30 μ m die assembled to polyimide flex without underfill and 2) 30 μ m die assembled to polyimide flex with underfill. The presence of two, equally long, independent via chains on each die enabled reliability data to be collected on a per via chain and a per die basis. A via chain failure was recorded if any via chain exhibited a resistance greater than 100 ohms. A die failure was recorded when either of its two via chains failed.

The non-underfilled parts were stressed over a 270 day with 4000 temperature cycles. By that time, 53 of 64 via chains had failed and all die exhibited failure. Weibull plots of the cumulative failures have been given previously [1,2]. Statistical mean cycles to 50% failure for the non-underfilled via chains was found to 2,409 cycles, while the statistical mean cycles to 50% failure for the die as a whole was 1,285 cycles. After temperature cycling was concluded several non-underfilled samples were collected, potted, and cross-sectioned to determine the nature of their failures. The failures were solder joint fatigue that occurred in the high strain regions of the die which occurred in the joints nearest the die corner (i.e. the farthest distance from the Neutral Strain Point at the center of the die) as expected. Cross sections of failed joints have been shown previously [12].

Six different die thicknesses were assembled to the same flex substrates to determine the effect of die thickness on reliability. The Weibull plot shown in Figure 10 compares the cumulative failures (lifetimes) for 30 μ m, 50 μ m, and 500 μ m die thickness without underfill. The number of cycles to failure increased dramatically as the die thickness decreased.

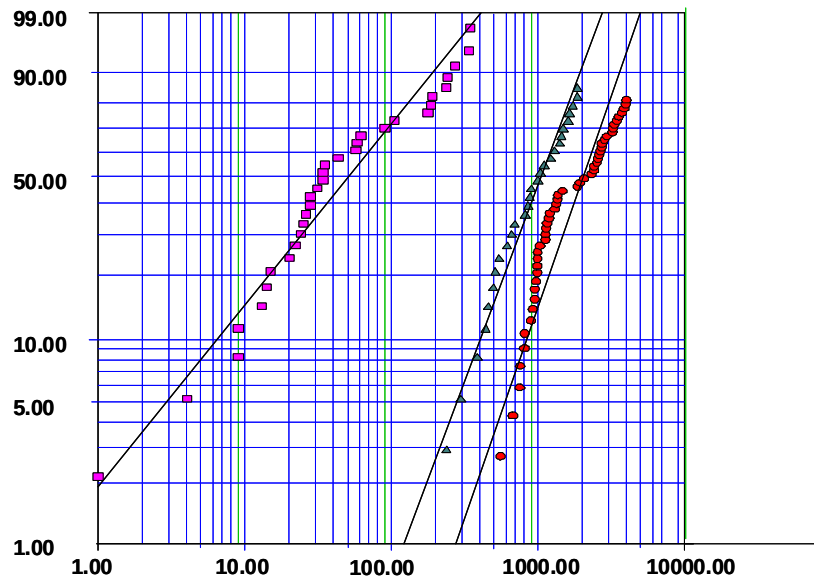


Figure 10. Weibull Reliability Data as a function of die thickness (no underfill). The left curve is 500 μ m thick die, the middle curve is 50 μ m thick die, and the right curve is 30 μ m thick die.

The underfilled parts were also stressed with 4000 temperature cycles. There were only two via chain failures, both occurring on the same die. Each of these failures occurred very early in the test. Post testing analysis revealed these failures were board related and not a result of a failure on the actual assembly. Both of these via chains, through post-cycling test, were found to be functional. Therefore, no fatigue-related failures occurred as a result of this stress testing. Thick underfilled die also exhibited early failures when compared to the thinned die results.

Summary

Flexible microcircuit assemblies using thinned die (down to 20 μ m in thickness) and either flex or multilayer, thin film substrates (up to 4 conductor layers (five dielectric layers) at an overall thickness of approximately 10 μ m) have been fabricated. Such circuits offer significant promise in many advanced packaging applications such as: biomedical implant and monitoring devices, wearing apparel electronics, conformal antennas and receiver/transmitter systems, and appliques of all types.

While the thinned die on flex has already found its way into several current product applications, it is the thinned die on thin film multilayer that holds significant promise for the future.

The released chip-substrate system is truly flexible and easily conformed to a curved surface. Without the thinned die the substrate itself is extremely pliable and can easily form bends of 90° or greater without any damage. Because the substrate is fabricated on a silicon carrier it can be made in relatively any size depending upon the diameter of

the silicon wafers available. In addition, since the substrate can contain at least four metal layers, the ability to fabricate integral capacitors and low-value resistors is inherent in the process. Similarly, planar antenna elements, wave guides, and optical guides can be constructed. Given that the polyimide layers are the same or greater thickness than our very thin die, it may also be possible to fully embed these die within the substrate itself, thus forming truly integrated flexible thin film assemblies with overall thicknesses much less than 50 μ m.

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