ℙ periodica polytechnica

Electrical Engineering
52/1-2 (2008) 39–44
doi: 10.3311/pp.ee.2008-1-2.05
web: http://www.pp.bme.hu/ee

RESEARCH ARTICLE

3D Flexible package formation using laser micromachining

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Received 2008-07-22

Abstract

A newly designed three dimensional (3-D) flexible circuit as a package with five IC chips has been established, and the prototype of the 3-D package using laser micromachining has been successfully demonstrated. Fabrication processes of the 3-D package consist of (1) preparation of printed wiring on the flexible substrate, (2) selective polyimide material removing on contact pads using UV laser (3) component placing and soldering, and (4) preparation of bending windows by laser micromachining. The production of the so-called bending window is a unique application of laser material processing. These windows can be used in flexible circuits to define the exact position of deformation. It is done by reducing the thickness of the flexible substrate in a well-defined, narrow line. The unique feature of this newly developed package is the 2-D design for a 3-D structure. According to this design, 70% area reduction can be obtained without any designing and overheating problems, which usually occur. Furthermore, the new 3-D package design can simplify processes such as I/O redistribution, chip cooling, and package formation. It is proven that the mechanical integrity of the prototype 3-D stacked package promises to meet the short-term requirements of a damp-heat test.

Keywords

3-D package · bending window · laser processing · laser ablation of polyimide · mechanical structures in polyimide · reliability test

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1 Introduction

As the complexity of electronic systems for portable electronic, aerospace, and military applications increases, more demands are placed on lightweight and compact packaging technologies. To meet these demands, the three-dimensional (3-D) packaging technology is now emerging as a breakthrough for overcoming the limitations of two-dimensional (2-D) packages. When considering PWB efficiency, the ratio of total chip area to the area of package 20–90% efficiency can be obtained from the current MCM packages. However, 3-D technology can provide more than 100% chip area/package area. Although 3-D packaging technology can offer remarkable advantages, there are still a few hindrances for this technology to be extensively applied.

Although conventional 3-D packaging increases circuit density, it decreases interconnect delay and reduces critical interconnect path lengths; their full potential has yet to be realized owing mainly to the shortage and difficulties of 3-D design principles. Therefore, there is a need for a simpler and more cost-effective 3-D packaging design and technology. One of the first studies and working high interconnect 3-D System in a Package was that of Chandler N. et al. [1] who solved the 3-D design problem. Another, 3D-Stacked IC model was employed by IMEC in 2006, where the connections were realized by microvias. Both assemblies used rigid materials and clumsy 3D design. In this study, a newly developed 3-D flexible package design and the reliability of the package has been evaluated with a dramatic improvement in compactness resulting in five power chips in a package with lower overall area needs [2],[3].

2 Experimental analysis

2.1 Laser ablation of polymers

Polymers are interesting materials for many different applications due to their unique mechanical, electrical, and processability properties. With its versatility, laser processing by selective ablation of surface patterns can be used to fabricate structures into flexible polymer substrates. This research is focused on the laser ablation process of polymers with UV laser pulses of the nanosecond pulse width. An empirical correlation can also be used to describe the relation between the ablation rate $\mathrm{d}(F)$ and the irradiation fluence F[4],[5]:

$$d(F) = \frac{1}{\alpha_{\text{eff}}} \ln\left(\frac{F}{F_{Th}}\right) \tag{1}$$

where F_{Th} is the threshold fluence and α_{eff} is the effective absorption coefficient.

This equation is independent of the applied ablation mechanism, but usually the exact dependence of the ablation rate on the irradiation fluence cannot be described by the use of such a simple equation of two parameters. Therefore, this empirical correlation is used mainly to determine the ablation threshold F_{Th}, below which no material removal by the laser pulse is observed, while the effective absorption coefficient α_{eff} is a kind of measure to describe the penetration depth of the laser during the ablation process [6, 12].

2.2 3-D packaging with bend-and-stay flexibles

When the composite structure, which is called a flex circuit, is bent, the metal is plastically deformed and gives a mechanical strength to the structure. The objective during bending makes certain that the metal can exceed the elasticity of the polymer to hold the final shape. There are two different paths: making the copper thicker may make etching a bit more difficult; it will also take longer to etch and will use more chemistry. An alternative to reduce the thickness of the polymer along a well-defined, narrow window is preferred. This bending window generation is a unique application of laser material processing. A bending window can be used to define the exact position of the bending edge as well as the radius and the angle of the deformation [7].

2.3 Experimental results

To overcome the 3-D design limitations, an alternative bend-and-stay approach that is based on bending technology using laser-processed bending windows is proposed. This design can be done in 2-D, then the PWB can be bent to a 3-D object. Packaging efficiency can be very high because five pieces of ICs can be built together as a cube formation, as shown in 2.4.

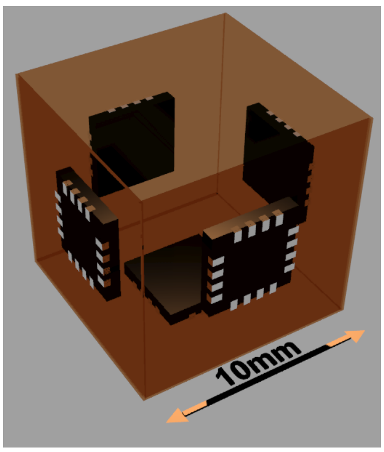

Fig. 1. 3-D solution for IC arrangement (Black: IC, light grey: IC bumps, dark grey : polyimide)

If the applied number of the ICs or other characteristic heat dissipating components is lower or higher than five, another geometric arrangement, like tetrahedron, octahedron, or cubo-octahedron could be used instead of the simplest cube.

In this package, the heat-dissipating ICs are close to each other, and they cannot dissipate heat easily. For this reason, all the ICs in the package are connected to an internal heat sink, which can dissipate the energy using heat-pipe technology (Fig. 2).

The components in the package are connected to the copper wiring with microvias [8]. As the copper wire lies in the outer surfaces, it can easily be connected to any other packages or circuit modules.

The application of bend-and-stay flexible-printed circuit boards to the unique 3-D circuit module construction requires dimensionally very precise and well-controlled bending technology. It is also important to avoid mechanical degradation of the materials; therefore, the bending process must not cause excessive deformation. This is the reason for investigating the possible application of laser-processed bending windows.

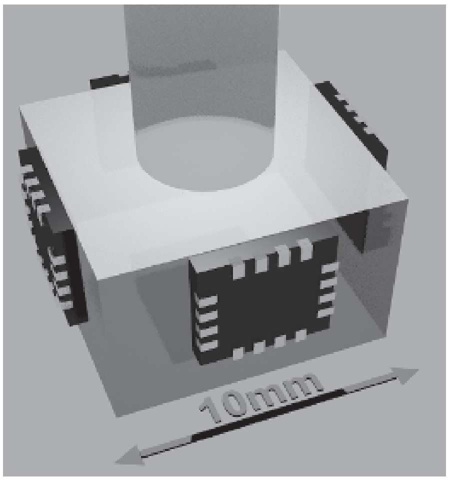

Fig. 2. Possible solution for IC cooling (Cube: heat sink, cylinder: heat pipe)

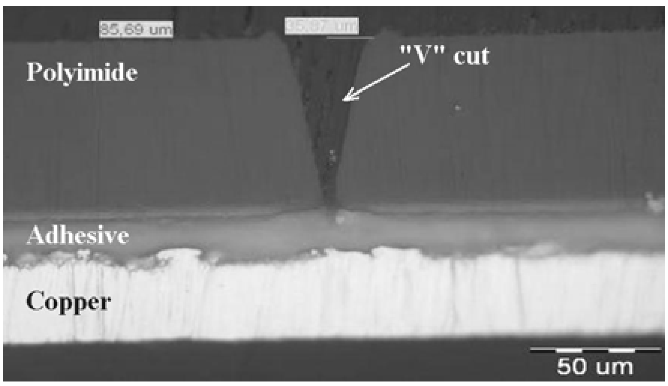

Fig. 3. Cross section of 'V' form bending window, where the cut almost reached the copper layer

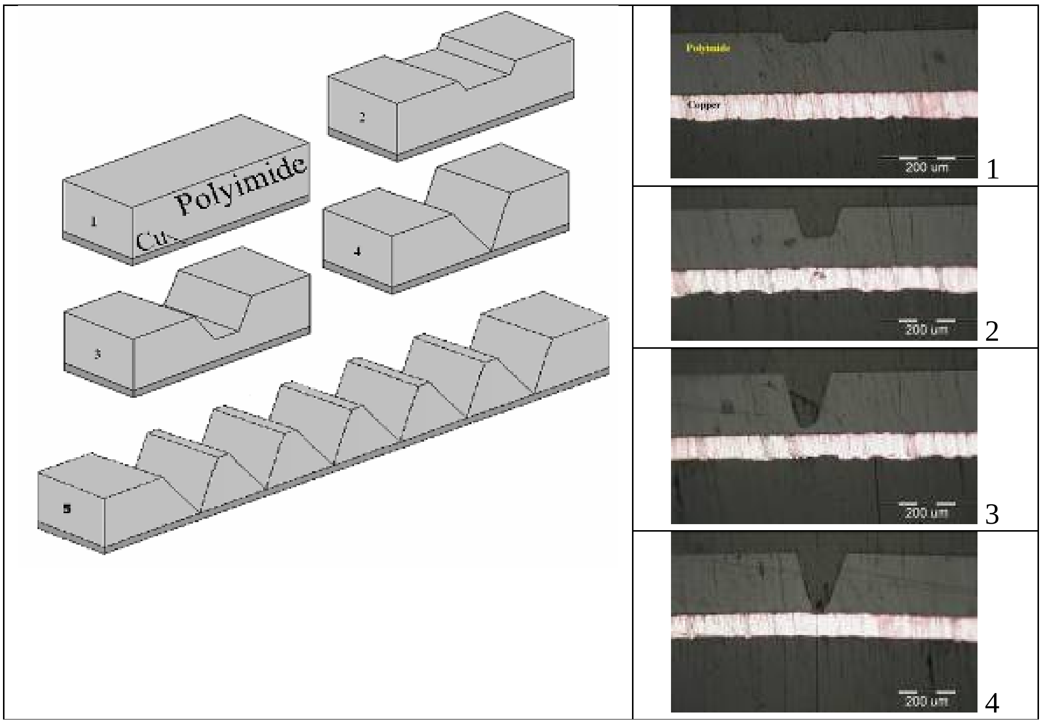

Fig. 5. Steps of Multilevel laser machining1–4: Steps of 1 ‘V’ shape, 5: Multi ‘V’ Shape

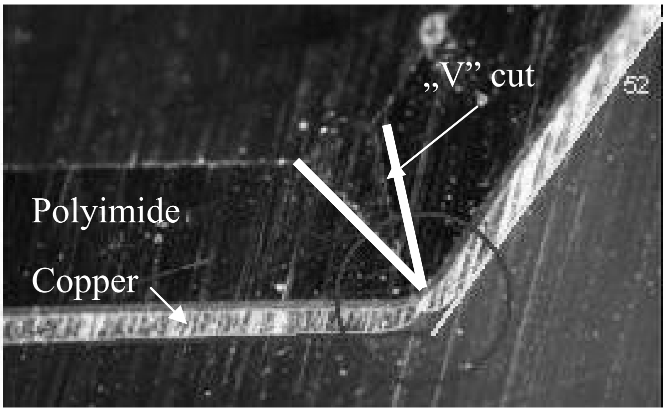

Fig. 4. Cu cracks at the edge (bending angle 52°)

2.4 Bending window opening by laser processing

In the experiments, a one-sided DuPont Pyralux flexible substrate was involved (FR9150R). The thickness of the insulation layers of the sample was 125 μm.

The material removing process is a simple step-by-step work where the material is removed layer by layer, moving the laser beam in parallel lines. The whole ‘V’ shape is roughly 40 μm wide (2.5).

2.5 Multilevel laser machining

Investigation on the different geometrical forms of bending windows has proved that the application of a single ‘V’ form window for 90° bending is not reasonable (Fig. 4).

Bends over 90° place the greatest stress on formed areas. To decrease the mechanical stress, bending with distributed parameters was used. The bending is not concentrated at one point.

Fig. 5 shows the processing steps of multi-shaped bending windows, while Fig. 6 shows the cross section of a physical form. The ‘V’ shapes angle and raster can be calculated in the function of the bending radius and the bending angle (Fig. 7).

If the bending radius is known (usually it should be smaller and smaller), for example, 300 μm, the number of the laser cuts and raster, the distance between the cuts and the window wall angle can be calculated.

2.6 Provide the largest bend radius possible

The designer is always advised to provide the largest practical radius through bend areas. For single metal layers, it is about 3–6 times the circuit thickness. This design approach is especially important, not only for dynamic flex, but also in flex applications that are apparently static in nature, for example, bend-and-stay structures. In Fig. 8, the graphic and simple equation illustrates the effect of bend-radius diameter on the copper foil.

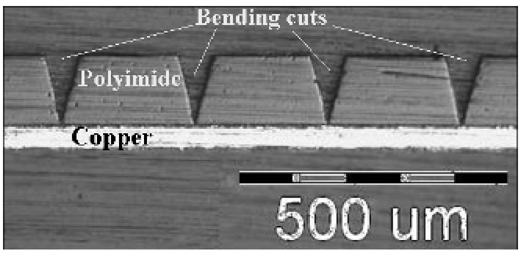

Fig. 6. Polyimide after multilevel machining

The elongation requirements for the copper foil increase significantly as the bend radii decrease. During the bending procedure, the elongation limit of the material should not be reached to avoid copper breaking. The copper’s elongation at break is 40%. Fig. 9 shows the elongation values at different bend radii

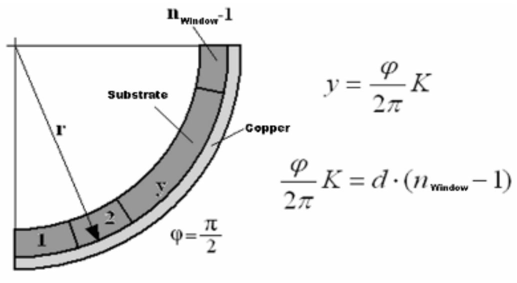

Fig. 7. Calculating the bending
r: radius, ***n***: number of 'V' shapes, ϕ: bending angle

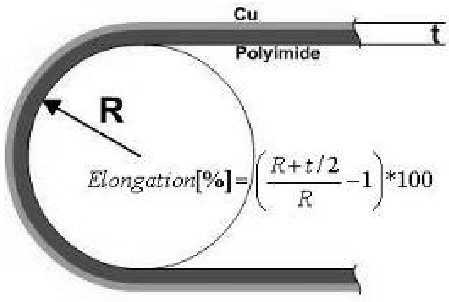

Fig. 8. Equation of elongation

and substrate thicknesses [9].

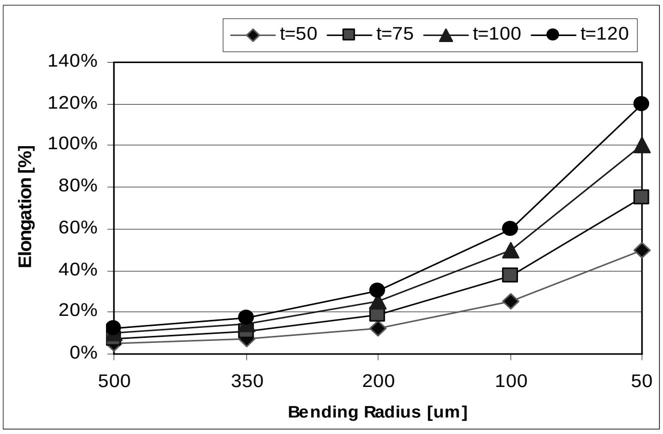

Fig. 9. Elongation vs. bend radius and thickness

Normally, if the bending radius is smaller than 200 μm, it results in more than 40% elongation, which is the limit for copper break. With multilevel bending window formation, the mechanical stress and the elongation have been decreased by distributed bending. As a result, a 180° bended polyimide substrate is seen in Fig. 10. The bending radius is just about 50 μm, reached with six smaller bending windows ($6 \cdot 30°$).

2.7 Creating a 3-D package

Using the developed technology, the ultimate goal is to build a 3-D formation for five power chips from one-sided flexible substrate. This 3-D IC carrier contains individually packaged IC chips that have been attached to the PWB by reflow soldering. The process steps of 3-D package formation can be seen in Fig. 11. The final form is shown in Fig. 11f. The working prototype is a white LED driver, one IC for four LEDs.

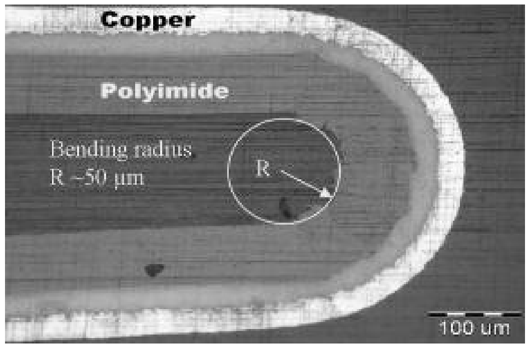

Fig. 10. Polyimide bended at the angle of 180°

A working prototype with adequate cooler can be seen in 2.8. The cooler itself is able to cool down five power chips in a time. The geometry of the cooler can be adjusted to the geometry of the 3D polyimide structure. If it consists more than five ICs, other geometries could be used instead of the simplest cube (see in section 2).

2.8 Lifetime prediction

A cycled temperature–humidity-bias (THB) life test is one of a range of overstress reliability tests performed to evaluate the reliability of nonhermetic packages in humid environments. It employs conditions of temperature cycling, humidity, and bias that accelerate the adsorption and permeation of moisture through the external protective material (encapsulant or seal) or along the interface between the external protective material and the metallic conductors that pass through it.

Many tests have been carried out to determine the mechanical limits of the flexible substrates and the best processing parameters. For testing the composite 3-D package's lifetime, the highly accelerated stress test (HAST) has been done to prove that the degradation in time at bending positions is controllable, and that the material with its circuitry are not damaged. JESD22-A100-B (April 2000) standard was used [10].

The effect of temperature (T) and humidity (H) caused theoretical considerations for the acceleration factor (AF) [11] that lead to the following formula, called the S-H model:

$$AF = \exp\left(X\left(RH^n_{\text{test}} - RH^n_{\text{life}}\right) + Y\left(\frac{1}{T_{\text{life}}} - \frac{1}{T_{\text{test}}}\right)\right) \quad (2)$$

in which

RH	is the relative humidity in %
X and Y	are coefficients related to particular failure mechanisms,
n	is 2 for integrated circuits.

This equation means that the logarithm of the lifetime is proportional to the reciprocal of the absolute temperature and inversely proportional to relative humidity. AF symbolizes the acceleration factor of the test.

A reliability stress test must be related to the intended long-term application condition. If we select a sub-tropical operating life, then the environmental condition is 29^o/86%RH [11]. If we

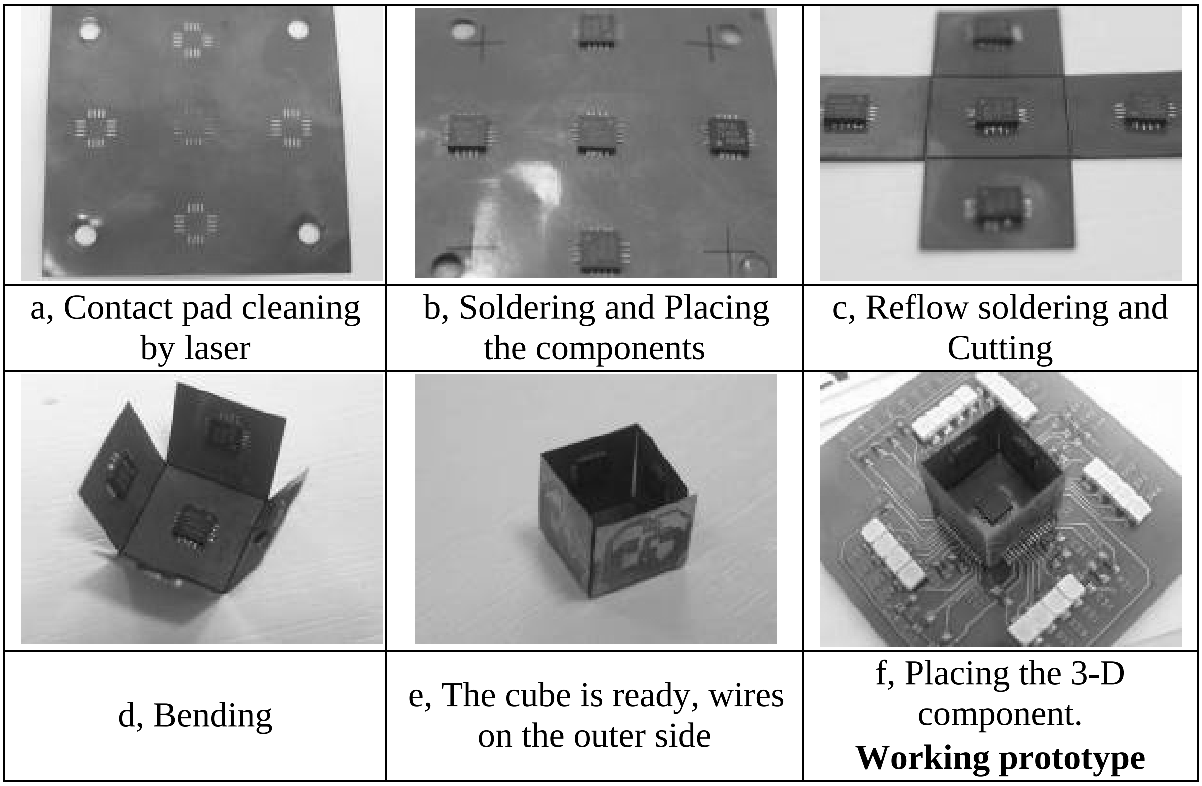

Fig. 11. Process steps of 3-D package formation

apply a HAST stress condition of 130^{o}C/85%RH, then, using the published values for X and Y [11] the calculated value AF is 845.

In the work we undertook our initial HAST test was conducted for a short 60 hours. This is the minimum time recommended for HAST testing [11]. So, the results must be regarded as indicative only, and not conclusive yet. From Eq. (2) and the estimated AF of 845, we estimate a HAST simulation of a sub-tropical life time equivalent to 51,000 hours.

For testing the flexible IC package a THB 130˚C/85% test was carried out. The samples were monitored and the failures have been registered automatically. The failure probability is shown in 3.

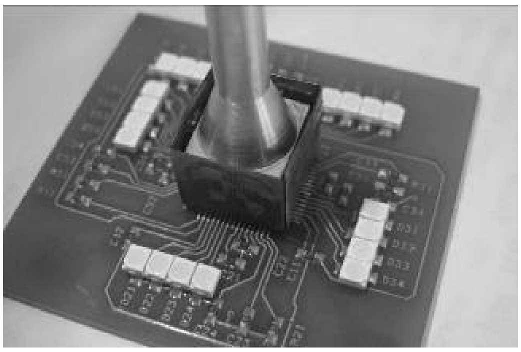

Fig. 12. Working prototype with IC cooler

Using Eq. 2, the AF was calculated to be 845 (but note this is always an estimate unless proven specifically for this technology), so the package's lifetime can be estimated on [11]. Most of the components malfunctioned after the 38-h testing period.

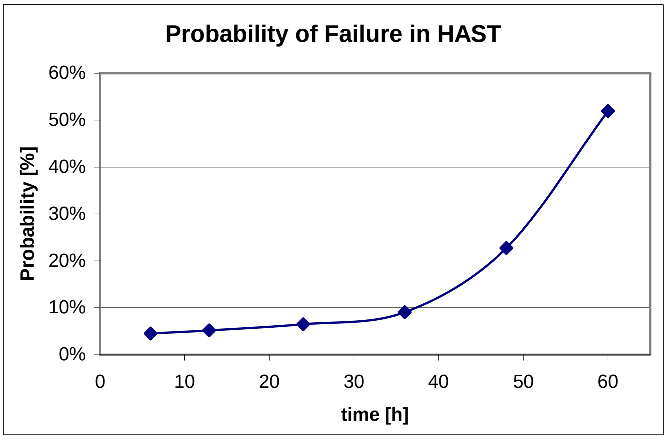

Fig. 13. HAST result

It means that 90% of the packages may work continuously without failure for about 3,5 years. However, we recognize that 38 hours is much shorter than minimum duration of a HAST test, so our result must be regarded as indicative only.

3 Conclusion

From the result of the experiments, it can be stated that laser processing of polymeric materials using optimum processing parameters has proved to be an efficient tool for the fabrication of interconnect substrates.

Most of the materials based on polyimide-type polymer can be processed by UV Nd:YAG laser, and high-resolution patterns can be generated. The polyimide layer was ablated by the laser to fabricate 'V' form bending windows at 90˚ and 180˚, and the copper was not damaged.

Our alternative multilevel bending approach for bend-and-stay formation proved the mechanical stress and the elongation can be decreased so extreme small bending radius can be reached at a well defined position and angle.

Modern packaging technologies require new configurations like 3-D arrangement. The HAST proved that the processed polyimide is usable for bending in small radius forming 3-D package. The results from limited HAST testing indicates that the 3-D assembly including the IC packages have a potential to function with 90% survival for a few years. It is clear that the technology must be developed to be more robust to be suitable for high reliability applications. This technology is very likely to be applicable for creating 3-D configuration.

With today's emphasis on micro-packaging likely to intensify, the benefits of designing with flex circuitry become more appealing than ever.

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