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Relevance of Direct Write Processing

COMMERCIAL APPLICATIONS AND REVIEW FOR DIRECT WRITE TECHNOLOGIES

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ABSTRACT

Direct write in the past has generated the excitement of possibly replacing photoresist for all electronic applications. Removing the mask would substantially reduce the number of steps required to produce electronic circuits. A reduction in steps represented time and dollar savings. The advantage of being able to direct write a manufacturable device would also save time and money in the design process as well. With all of the obvious advantages, it seemed inevitable that research dollars would continue to mount and thus overcome the obstacles preventing this technology from becoming more than a novel technique used in laboratories. As Moore's law began to settle in, so did photoresist and direct write was little more than a novelty.

That was then, and this is now. Developers have come to terms with the true value direct write can supply to the manufacturers and design engineers. Techniques such as Focused Ion Beam (FIB), Laser Chemical Vapor Deposition (LCVD), ink jetting and ink penning have found real applications that are making a difference in industry. A summary will be presented describing the various direct write techniques, their current applications and the possible or probable applications.

INTRODUCTION

Direct-write processes are fast, flexible, and forgiving. Masking and screen-printing processes take several steps to complete a circuit. Making a mask or a new screen can take days, even weeks. A direct-write process has now demonstrated the possibility of turning weeks of prototyping into hours. With this kind of improvement, it seemed inevitable that direct-write processes would take the electronics industry by storm. A masking process can take as many as 24 steps [1]. A direct-write process to create the same circuit could be reduced to 5 steps. If these are facts, the obvious question that must be asked is, "Why is direct-write such a novelty?"

As one electronics-company representative stated, "speed, speed, speed" is everything [2]. While this may not be the only issue in the electronics industry, it is the only one that matters if a new process cannot reach specified standards. To replace such masking techniques as screen-printing or photolithographic patterning, direct-write methods will have to complete these tasks in seconds, not hours.

Competing with masking production rates has proven to be an onerous task. Many direct-write believers found a niche that would keep these methods alive—rapid prototyping (RP). The biggest complaint from rapid-prototyping consumers is not speed; RP techniques are far superior in speed. It is also not necessarily poor performance; many rapid-prototyping techniques have demonstrated superior results. The main issue is repeatability on a manufacturing floor [3]. Many direct-write techniques have proven to be very effective for demonstrating a concept or device, but the prototyping process was not repeatable in a mass-production manner. This disadvantage would completely remove the benefits obtained from the fast fabrication and characterization results. Direct-write methods have made a difference in technology; they will make more of an impact in the next decade, due to the need for rapid changes in technology. Some of the well-known and obscure direct-write techniques are discussed below, with some of their possible applications.

THE BEGINNING

Rapid-prototyping began with the invention of stereolithography by Charles Hull [4]. It was based on an innovative approach to integrating CAD/CAM, lasers, and materials. It met a marketplace need, the desire to get conceptual models faster. Stereolithography is a direct-write process. What are the elements that drove RP from that first stereolithography machine to an industry that is now worth over $1.1 *billion*? The answer is successful commercial application

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by appropriate use of the technology and a technology supplier base that consisted of more than one company. Companies are reluctant to try new technologies although they may seem faster, better, and more cost effective—because they are not proven. Companies are reluctant to buy expensive equipment when there is only one supplier because they do not want to be held hostage to a start-up company that may or may not succeed. Trying new technologies in their early stages can be a high-risk career move. If the implementers' efforts are successful, then further up the "food chain," other people take credit; if their efforts fail, they are blamed. The rule is straightforward—it helps to have more than one source for the technology. This reduces the risk for the innovator.

The rapid-prototyping industry started to grow when its customers began to see useful models being built by stereolithography. A critical mass of technology suppliers started to emerge. The first was enabled by "beta" programs and the advent of several service bureaus offering the technology on a per-part basis, because this enabled users to experiment with the technology without paying the high costs of equipment ownership. This reduced the risk for the consumer. The second was enabled by the emergence of competitors to the stereolithography approach, like selective laser sintering and fused deposition modeling. Competition gave the marketplace a sense of security that a lasting industry was emerging, not just a transient curiosity. The bottom line was that the growth of RP was driven by good applications in the marketplace, a critical mass of technology suppliers, and a critical mass of innovative service bureaus.

DIRECT-WRITE METHODS

Several approaches exist to direct-write methods, depending on function and device size, but all direct-write methods have three things in common: (1) materials; (2) delivery process; and (3) conversion process. In some approaches, the delivery process also serves as the conversion process. It is also important to note that direct-write systems use a computer aided design package to implement the desired pattern, shape, size and location of the deposits.

Physical Methods

Stereolithography (SLA) was developed by Charles Hull in 1986. His company, 3D Systems, is the trailblazer of the rapid-prototyping industry; it turned a niche demonstration into a multi-million-dollar business. SLA is capable of producing a vast number of unique objects in two or three dimensions. Its basic premise involves a platform of liquid polymer cured by an ultraviolet laser. The platform lowers as, layer by layer, the laser cures the desired pattern. Once the device is completed, it will need to be rinsed, and supports (built during the process) will be removed [5]. The practical resolution of SLA is on the order of 50 μm in the *z* direction and 75 μm in the *xy* plane [6]. The possibility of increasing resolution to less than 10 μm is being investigated; however, a significant thrust for this feature size has not yet emerged.

Carl Deckard patented *Selective Laser Sintering* (SLS) in 1989. This technique uses a CO_2 laser to fuse various materials. SLS is a bit more flexible than SLA in that it is not restricted to UV-curing polymers; it can be used on powders of nylon, elastomers, or metals. A new layer of powder must be applied to the part, then leveled for processing. Excess powder in each layer helps to support the part during the build. SLS machines are produced by DTM of Austin, TX.

The *Laser Engineered Net Shaping* (LENS™) process is a new solid freeform technology capable of producing metal parts with excellent materials properties directly from CAD files. The LENS™ process was initially developed at Sandia National Laboratories and is now commercially available through Optomec Design Co. This process goes beyond conventional rapid prototyping, which produces parts in plastic, to produce near-net-shape metal parts in a variety of materials, including stainless steel, tool steel, and titanium.

Fused Deposition Modeling (FDM) works by extruding molten material through an *xy*-plane-controlled nozzle onto a build platform. The build material is pushed through heated tips on the nozzle as it moves and extrudes. As each layer is completed, it hardens and "fuses" to the previous one. The platform is lowered and the process continues. Layer by layer, material is deposited until a 3D part or model is complete. Stratasys (Eden Prairie, MN) makes a variety of FDM machines. The first commercial systems were introduced in 1992.

Electrical Methods

The *Laser Particle Guidance* (LPG) process was developed by Michael Renn of the University of Colorado, who later joined Optomec [7]. A red, detuned laser beam is launched into the hollow region of a hollow-core fiber. Atoms in the guide propagate in a manner similar to that of light in a multimode fiber—axial motion is unconstrained and transverse motion consists of a series of lossless reflections from the potential established by the optical fields. Atoms exit the fiber through a numerical aperture that increases with increasing guiding-light intensity. Renn showed that atoms can be steered through the bends of the flexible fiber. This work has also involved transporting atoms through a portion of fiber exposed to atmosphere, demonstrating that the glass walls are sufficient to maintain vacuum in the guide.

The *Matrix Assisted Pulsed Laser Evaporation* (MAPLE) method was developed by scientists at the Naval Research Laboratory (NRL), this technology uses a laser to remove material from the backside of the disk and deposit on a substrate[8]. Resolution of this technique can reach sub 10 micron, depending on the spot size of the laser. A wide variety of materials can be directly deposited using this method.

Several groups have worked on the *Laser-Assisted Chemical Vapor Deposition* (LCVD) technique in hopes of reducing the number of steps required to produce integrated circuits. The original research work was done in the early 1970's; work continues today [9]. LCVD has been combine with other laser-assisted chemical processes and commercialized. Dan Ehrlich was one of the pioneers in this technology and started the company Revise, Inc., which manufactures etching/LCVD machines. Various chemical precursors can be introduced into a vacuum chamber to dissociate into desired products when elevated to a specified temperature, or dissociation can be photoinduced. In either case, a laser provides localized heating or photolysis leading to deposition.

Focused Ion Beam (FIB) systems use a gallium-ion beam to make precision modifications to wafer samples. A FIB machine can mill away material; alternatively, in the presence of an organometallic vapor, it can deposit metals and insulators in a process called ion-beam-assisted deposition (IBAD). The resolution of FIB devices can be less than 10 nm; therefore, their primary application is in the semiconductor industry. Uses include semiconductor sample preparation and analysis, modification of prototype circuits directly on the wafer, and chip repair.

Ink-jet and *nozzle/pen* techniques encompass a variety of machines that spray layers of material in droplet form onto a build platform. For example, 3D Systems uses "waxes" to create thermoplastic models with its ThermoJet Solid Object Printer. Other applications include MicroFab's MicroJet printing of solder. Droplet size is controlled by the print head aperture. Depending on the droplet material, feature resolution has reached 50 μm [10]. Ink-jet technology has been shown to reliably write a variety of materials very quickly. One of the main concerns of ink-jet technology is the viscosity of the material being dispensed—if it is too high, the piezoelectric pump cannot move it.

The highest value a nozzle or pen can bring to the direct-write arena is the variety of materials that can be dispensed through it. Pastes, which by implication have high viscosities, are normally used in screen-printing. Pastes can easily be transferred to a pen-dispensing system, thereby exploiting an established materials base. Pen-dispensing issues can be summed up as start/stop and agglomeration. Several companies have worked in this area, on a variety of projects, but one of the long established products in this area is the MicroPen™ from OhmCraft.

Optical Techniques

One of the newest members to join the direct-write family involves the laser/optical arena. The direct writing of optical waveguides has been demonstrated using a femtosecond-regime pulsed laser [11]. The team demonstrated the capability to write optical waveguides not just on the surface of a solid piece of glass, but internally as well by adjusting the focus depth. Interestingly, optical technology has lagged behind electronic technology in all areas, from demonstration to production to tools. The optics industry is now moving very quickly due to the advancements made in laser technology during the past decade, including ultrashort-pulse technology. Two years ago, "femtosecond" was a rare word in laser technology; today, it is possible to purchase a femtosecond-regime direct-write waveguide tool [12].

DIRECT-WRITE APPLICATIONS

Applications for direct-write methods have a vast array of possibilities, which include the mechanical/physical, electrical, and optical areas of engineering. The physical aspects of direct-write have an established market and products; however, ample room exists in which to grow and improve. The electrical engineering aspects have mostly been demonstration-oriented or commercially very small. The newest member to the direct-write family is in the optical engineering regime, but there it has tremendous promise. Materials with diverse properties have been produced with a broad range of tools and processes. Physical strength is the primary issue when dealing with such mechanical structures as tools. In direct-write electronics, a multitude of characteristics must be considered, including dielectric constant, conductivity, resistance, permeability, and physical strength. These constraints place rigid demands on materials and processing conditions to achieve specified goals.

The first and most obvious application is for rapid prototyping. Since the mid-1980's this area has grown significantly in dollars and more in interest. These machines can be very expensive ($500,000 to $2.2 million), but the return on the investment is great in terms of time, money, and flexibility. The SLA RP industry is well recognized; however, a very large market has opened in the semiconductor business for RP. FIB is a household name in the semiconductor business. FIB machines are used to cut traces and to add new ones. In the strictest since, this process should be labeled rapid alteration, but the "rapid" in the name carries the same implications. Semiconductor devices can have short lives; therefore, it is important to reach the market very fast. The masking process is slow to provide results; therefore, if several iterations through the design process are required, the turnaround time to get this done could extend beyond the need for the chip. The FIB is an expensive piece of equipment, but the savings it provides in time and reduced masking setup have made a major impact in this field.

LCVD is a competitor to FIB in some situations, but most of the time these processes complement each other very well. LCVD is fast compared to FIB. It also produces superior depositions with higher conductivity, and with a change of precursors it will etch without damaging the wafer. FIB has the required resolution to work with semiconductor circuits. The combination of these two can be advantageous to a vast array of semiconductor devices including "flip chips."

LCVD also has the ability to write in three dimensions by controlling the focus. This provides limitless possibilities for fractal antennas, vertical interconnects, bridges, and bumps for solder. The resolution of LCVD is superior to mechanical dispensing methods. Therefore, it fills a gap between the submicrometer and ten-micrometer regimes.

Significantly, each direct-write process can be different and still make an impact. SLA works well for RP models of a boat propeller, but would make a poor propeller. The materials in SLA would also make a poor conductive line, despite making a "nice"-looking line. These disadvantages do not make SLA useless; it has demonstrated its worth, so its disadvantages make it specialized. Plenty of such specialization exists. In fact, an overflow of specializations that currently exist right now must be filled. In direct-write electronics being developed today, each method has a different set of strengths. These strengths provide a large coverage area of the marketplace within that spectrum of opportunities. It is highly probable that each technique mentioned above will find a home.

Consider how powerful the potential for direct-write electronics is in the commercial sense, how pervasive this family of technologies may be in five years. One door opening is the field of hybrid and multi-chip module (MCM) circuitry. A direct-write tool capable of writing resistors, capacitors, and inductors would significantly impact this industry. These new hybrid and MCM chips would have less solder and therefore be more efficient and use less power. This would reduce battery size, thus making the device lighter or longer lasting. It would also make the circuit operate with less heat, thus reducing the cooling requirements.

Let us imagine the addition of a battery to a direct-write menu, then go one step further and add solar-cell capability. This is not a large stretch of the imagination because DARPA is funding both of these projects. Another interesting fact is that DARPA is funding direct-write antennas [13]. The direct-write processes for batteries and antennas are providing unique opportunities in these areas which cannot reasonably be done using other techniques. Fractal antennas have tremendous potential to impact the Global Positioning System world. Current GPS antennas are large in comparison to PCS antennas. Incorporating GPS onto PCS telephones would be highly desirable; however, this cannot be reasonably obtained with current antenna technology. Direct-write will impact this area. It could be considered a niche market, since it is strongly bent toward 3-D fractal antennas, but a niche this big could change the definition of niche market.

One of the most promising opportunities for direct-write methods is sensors. Sensors that exist today range from sensors for heat to those that can detect parts-per-billion concentrations of toxic gases. The number of sensing devices continues to grow as research continues to explore new possibilities. Such a heat-sensing device as a thermocouple, which is as simple as two wires pressed together, has a market that exceeded $500 million in 1998 in the United States alone. The direct-write techniques mentioned above can do this today. BioMEMS is many times an extension of sensing, but also has extended possibilities that could revolutionize the ways that health-care delivery systems function. Most present health-care systems are financial nightmares. BioMEMS platforms offer the key to changing that fact. Successful direct-write commercialization will play a keynote in the success of BioMEMS by enabling the use of cost manufacturing techniques. The range of devices and capabilities needed to satisfy the BioMEMS opportunities are certainly covered, from SLA to FIB.

FROM NICHE TO MASS PRODUCTION

Success in this field will not come by accident. The best way to accomplish success is to look for a historical model from which to learn. Direct-write proponents are fortunate to have a very recent model in the birth and growth of the rapid-prototyping industry. Direct-write proponents as a group can learn a great deal from this experience. Jeffrey Moore's book *Crossing the Chasm* is a classic text describing the process through which a new technology goes in becoming a commercial success [14]. The growth of the rapid-prototyping industry is a classic example of what Moore teaches; direct-write electronics will be also. It is important to learn from experience; the existing RP industry has been a good teacher.

The existing RP industry did many things correctly, but its most significant contribution was to fill a need. Industry will not necessarily notice it *has* a need, but when the competition begins to move ahead, things begin to stir. Strategic partners in industry, who are willing to take risks, are very important. These groups can provide technical, real-life feedback. They are willing to accept "substandard" performance and high prices during the development and growth stages; however, they can grow impatient and demanding if improvements do not happen. The company Apple provides a good example of stirring industry in a positive fashion with less than ideal products. They did very well and made a huge impact upon the computer industry. However, when the time comes to change and raise standards, noncompliance can be costly [15].

Daily inroads are being made in the direct-write arena, providing new possibilities and changing industry. The performances of devices made via direct-write methods are in some cases superior to those made by conventional methods. Also, the speed at which these devices can be explored has been dramatically enhanced, and in some cases even enabled. Looking ahead, the compliance requirement for direct-write methods will be to make better-performing devices, but a major obstacle will be speed. If the devices made cannot be made fast enough to mass-produce, then that shortcoming will reduce the effectiveness of direct-write methods. It will not kill it; some applications are so important it will be accepted. This problem can be addressed in two ways: (1) better tools/processes; and (2) better materials.

CONCLUSIONS

Direct-write proponents are fortunate that DARPA has had the vision to fund several different technical approaches to address the issues associated with direct-write electronics. This vision helps ensure that its goal will be met and that the creation of a critical mass of tool suppliers is well on its way to becoming a reality. Proponents are also fortunate that they have learned to work together. They are building an industry together and they need each other for successful development of technologies and credible entry into the marketplace. Now what are needed are good applications of the technologies and continued production of superior materials, tools, and devices. Proponents need to match the marketplace expectations of what can be delivered to what they can actually deliver. This is not an easy process. As technology develops, each step forward will be heralded as it should be. Unfortunately, the amount of work required to go from one good deposition of the appropriate electronic materials to *ten million* good depositions is often underestimated. This is why it is so important that direct-write proponents have invited potential users of direct-write technologies into the program at the very beginning.

A direct-write industry is being created by researchers, developers, entrepreneurs, government agencies, and large corporations. Their work will lead to the development of a host of new, as yet unforeseen devices. Their work will also lead to improvements in quality and reductions in the costs of products people use every day. These everyday applications are the applications that will insure success.

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REFERENCES

1. R. Terrill, *IEEE Aerospace Applications Conference Proceedings* (Proceedings of the 1997 IEEE Aerospace Conference, 3, Snowmass Village, CO, 1997) pp. 481 - 488.
2. R. Terrill, K. Church, M. Moon, *IEEE Aerospace Applications Conference Proceedings* (Proceedings of the 1997 IEEE Aerospace Conference, 1, Snowmass Village, CO, 1997) pp. 377-382.
3. T. Plunkett, *Time-Compression Technologies,* 2000, *5(2)* 46
4. www.3dsystems.com, online reference, 2000.
5. M. Griffith and J. S. Lamancusa, "Rapid Prototyping Technologies," *Rapid Prototyping*, 1998, http://www.me.psu.edu/lamancusa/me415/rpintro2.pdf.
6. Ken Cornealy, Mark Moler, Tech Inc. (Stillwater, OK), private communication, 2000.
7. M. Renn, Phys. Rev. Lett. 75 (18), 3253 (1995).
8 Pique, A., (Mat. Res. Soc., San Francisco, CA) 1998.
9. D. Ehrlich, R. Osgood Jr., R. Deutsch, IEEE J. Quantum Electronics QE-16 (11), 1233-1243 (1980)
10. D. J. Hayes, D. B. Wallace, and W. R. Cox, "MicroJet Printing of Solder and Polymers for Multi-Chip Modules and Chip-Scale Packages," in *Proceedings of the IMAPS International Conference on High Density Packaging and MCMs, Denver, April 1999.*
11. K. Miura et al., Appl. Phys. Lett. 71, 3329 (1997).
12. P. Bado, Laser Focus World, April 2000, 73-78 (2000).
13. R. M. Taylor, K. H. Church, J. Culver, and S. Eason, "Direct-Write Techniques for Fabricating Unique Antennas," in *Materials Development for Direct Write Technologies*, edited by D. B. Chrisey, D. R. Gamota, and H. Helvajian (Mater. Res. Soc., Pittsburgh, PA, 2000), in press.
14. G. Moore, *Crossing the Chasm*, (Harperbusiness, New York, 1999).
15. G. Kawaski, Garage.com Bootcamp for Startups, Seattle, WA, 2000.

Real-World Applications of Laser Direct Writing

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Abstract

Laser microchemical direct write deposition and etching methods have found an essential niche in debug and design for yield of wire-bonded and flip-chip integrated circuits. Future applications should develop in package-level system modification.

Introduction

In research dating back to the early 1980's laser and focused ion beam (FIB) direct write deposition and etching have been developed with an eye to a variety of microelectronic needs. The two methods referenced share much in the way of capabilities. Over time the two approaches have specialized and have been integrated into a powerful set of methods uniquely important to the microelectronics industry.

This paper will briefly summarize some of the established and emerging applications to more or less conventional circuit design debug; the elaboration of these methods to the particularly demanding testing and debug of packaged flip-chip parts, and the further evolution to package level debug. Surprisingly, the importance of this class of methods has been greatly intensified over the last several years. Leading microprocessor companies have begun to use FIB and laser direct writing methods to adjust designs to increase manufacturing yield and binning count at the factory as well as at the design center.

This paper will emphasize the practical applications of laser direct write methods and the integration of laser and FIB methods. The microchemical writing speed of the laser techniques are 2 to 6 orders of magnitude greater than they are for the ion beam analogs. Additionally, the electronic material quality of the laser deposited thin films are much higher, e.g. resistivity is typically 2 orders of magnitude lower than for the best focused ion beam deposited films. In the best cases the resolution of the laser techniques equal that of the dominant production technology for integrated circuits (ICs), which is optical lithography, but it cannot match the resolution of focused ion beams. As a result, users combine the virtues of both direct writing methods in actual practice. The diverse microchemical process technology used in laser direct writing is reviewed in Ref. 1.

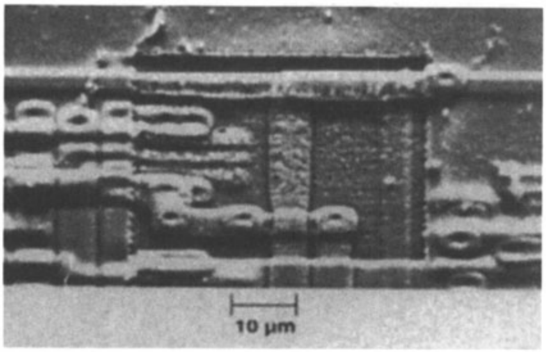

Figure 1: Conventional debug of a wire-bonded front-surface part requires penetration of a passivation layer. In this case a compound silicon nitride/silicon dioxide layer was removed by a laser technique. Laser methods for chip depassivation are generally chosen for their process speed.

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Design Modification of Conventional Wire-Bonded Circuits

The modification of conventionally bonded (circuit up) parts has been relatively straight forward as the electrical connection to individual transistors was possible through the passivation layer and the top of the part. Laser methods were chosen for long length discretionary interconnects over the passivation layer where the high conductivity and rate of laser deposited metal greatly exceeds FIB metal. Another application was removal of passivation, silicon dioxide, silicon nitride, polyimide, etc., where the rate of laser depassivation greatly exceeds the FIB (e.g., see Fig. 1). Two developments have complicated these applications; (1) the low accessibility of transistor connections due to multi-layer metallization, which now often covers >90% of the available surface, and (2) a strong trend toward nearly exclusive use of flip-chip circuits for high end systems. Both developments are driving design debug from the backside of the chip through the full thickness of the silicon wafer.

Flip-Chip Repair Process Flow

The debug/repair of flip chip parts imposes one new problem, the removal of the bulk silicon substrate in order to access the active device. Once this step is accomplished, probing and repair can proceed in analogy with more conventional front surface rework; examples being the use of a focused ion beam (FIB) to edit a circuit, or make probe points and a 3-beam prober for testing the circuit [3]. In fact access of active areas from the backside is often simpler and more easily interpreted than access through multi-level metallization. On integrated circuits in which the metallization completely covers the active device, diagnostic techniques such as photoemission must be completed from the backside.

Figure 2 depicts a flip-chip repair process flow. The first step is to globally thin the flipped part to a thickness that still maintains adequate mechanical strength and thermal dissipation capability. Typically a flip-chip may be globally thinned to 200μm using mechanical polishing without risking stress-induced fracture. This thickness is also sufficient for infrared through wafer viewing and global photoemission surveys.

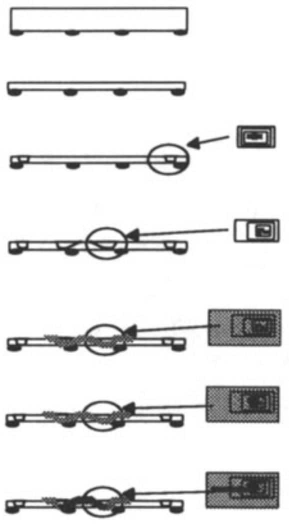

Figure 2: **Flip-Chip Repair Process Flow**