Laser Thermal Transfer Printing with Curable Inks

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Abstract

The semiconductor industry requires high definition, highly legible markings on semiconductor parts which may be made of various materials. The prints must withstand solvents, solder flux, heat, and abrasion without becoming illegible. Gravure printing, the traditional approach, requires wet inks and printing plates and does not offer the flexibility of digital printing. Laser marking is increasingly used and offers digital printing advantages, but legibility of direct laser prints is poor because of lack of satisfactory contrast mechanisms.

We have developed and sold a novel laser thermal transfer marking system for this application which allows dry, high contrast, durable, 500 dot/inch digital prints to be made on silicon, nickel, gold, ceramic and epoxy surfaces. The images are cured with UV or thermal energy. This process required the design of a novel laser printing head which is capable of applying proprietary thermal transfer foil onto small parts while exerting a minimum of force on the parts.

We will present the requirements for the application, some of the technical approaches that were tried for design of the marking engine, and describe the solutions selected.

Introduction

Semiconductor chip packages, electronic components, circuit boards, and many other industrial products must be printed for identification purposes. This is a very demanding task. For instance, semiconductor chips require high image quality. They also require an image which is resistant to the action of solvents, solder flux, detergent solutions, and abrasion during subsequent assembly processes. The prints are expected to retain legibility in service for years at high service temperatures with frequent temperature cycling. Substrates may include silicon, nickel, gold, ceramic and thermoset plastics.

As the substrates are often dark, pigments must be used to create a highly contrasting mark. For durability, the pigmented ink must be cured with thermal or UV means to ensure resistance to solvents and abrasion.

Offset gravure printing is a poor fit to marking short run and serialized components. The volatile solvents used in some gravure inks are environmentally unacceptable.

Although direct laser marking is often used to mark electronic parts since it is reliable, fast, and does not require printing plates, direct laser does not generally produce an easily readable, high contrast mark. Laser light may damage active circuitry if the depth of penetration is too deep. Electrophotographic processes are not suitable as electronic parts can be damaged by the high voltages in this process. Conventional thermal transfer printing does not work with hard surfaces. Ink jet printing does not easily handle the highly pigmented curable inks required by the application.

We have developed a laser thermal transfer printer which uses curable inks to print on epoxy molding compounds, ceramic, gold, nickel, silicon, and other industrial surfaces. The printer produces legends with high print quality and has the ability to serialize using a dry imaging process.

History

Transfer of colorant material between the ink donor and receptor material using laser energy was demonstrated as early as the 1960s' and 1970s'[1-3]. This was done with the donor and receptor materials in contact as well as across air gaps of 200 microns. More recently, laser thermal transfer has found application in the field of pre-press proofing.

First Experimental System

For initial experiments, a thermal transfer ink layer was coated on a polypropylene carrier film to make a printing foil. We decided to hold the printing foil tightly against the object being printed to eliminate potential loss of resolution associated with the ink crossing a gap. Because of this, it was critical that no gasses be generated in the process. The laser power must be sufficient to melt the ink film, but not enough to vaporize or decompose it. The melted portion of the ink layer would then adhere to the substrate to form an image while the carrier film was peeled away.

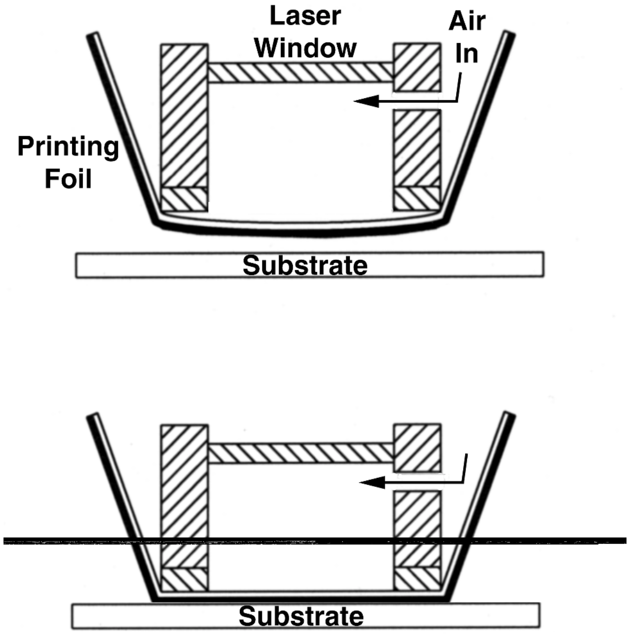

Figure 1. First system, raised (top) and lowered (bottom)

The system pictured in Figure 1 was constructed. The foil was held under tension across a rubber frame that was large enough to cover a print area of approximately 2.5 cm square. Before the foil was lowered into contact with the substrate, air pressure was applied from behind the foil, which caused the film to bulge out. As the foil approached the substrate, the pressure bulge in the film would roll across the substrate and push out all air between the inked film and the substrate (with any gap at all, the laser melted ink would just re-solidify on the carrier film leaving no mark). Air pressure was maintained during printing to hold the foil in intimate contact with the substrate. Two galvos were then used to raster scan the print area. After the full laser scan was completed, the foil and rubber frame were retracted, leaving a printed substrate.

With this apparatus we began to see the potential of the process, yet the overall print quality was not acceptable due to variations in opacity and edge definition. These effects could not be eliminated by re-formulation of the ink layer. An operating window of radiant exposure did exist where the ink film would be melted and adhered to the substrate, and yet not vaporized or decomposed.

One problem was that for a raster scan image, the first line printed in an image had about 3 seconds longer to cool than the last line before stripping the film. A further problem was that the film stripping angle was poorly defined and varied across the part. Both caused non-uniformity across the print.

Final System Design

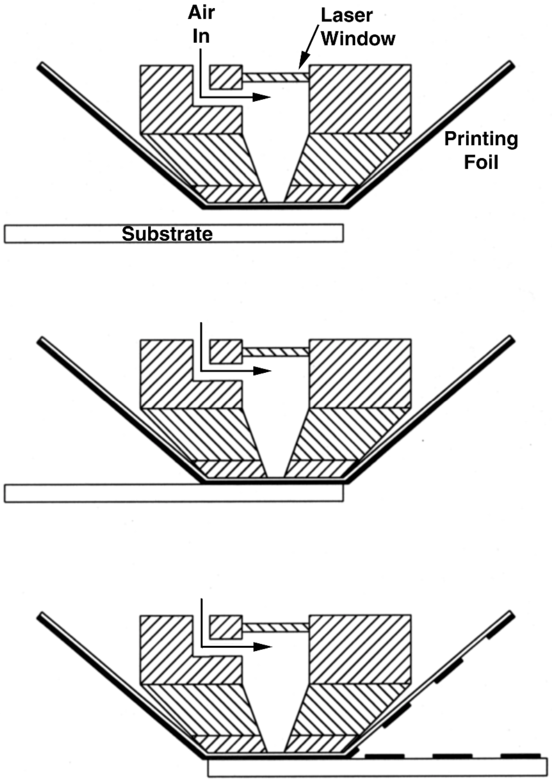

Figure 2. Final print tip, raised (top), lowered (middle), and after printing (bottom)

After several intermediate designs to address these problems, the final design uses a Teflon® coated rubber print tip to frame a single scan line of the print. At the start of a print cycle, the rubber tip is lowered into contact with the substrate, pinching the printing foil. The force pressing the tip to the substrate is maintained at a constant value with a pneumatic actuator, while the foil is maintained in intimate contact with the surface using air pressure behind the print tip. A single galvo scanner is used to create one axis of scan. The printhead, including the tip, then translates across the substrate perpendicular to the scan of the galvo to create the second axis of scan. The foil rolls on to and off of the substrate while it follows the contour of the tip.

This approach maintains a relatively constant time between printing and stripping for any part of the image, and also maintains a constant strip angle across the print. Rubber was used to allow the print tip to conform to slight irregularities in the substrate surface. The contact pressure of this rubber tip pressing the film against the substrate provides the seal necessary to allow the chamber within the tip to be pressurized (6.9 – 34.4 kPa, 1-5 PSI) while the film is sliding by.

The rubber tip also isolates the printing zone from variations in the foil tension. The foil tension necessary to strip the foil from the substrate depends on the substrate and the actual image being printed. This force can be up to about 9 Newtons (4 lb.) to strip a solid area of a 35 mm wide print. Once the printed image is complete, the printhead motion must continue until the last scan line has cleared the tip and been stripped. During this time, the tip continues to exert a downward force on the substrate, holding it in place. Once the last line of print has been stripped, the adhesive force of stripping the printed foil from the substrate no longer exists, so the tip can be raised without lifting the substrate.

Pressing the foil against the substrate also allows the foil to be driven at the exact print speed by the relative motion of the substrate. Because the foil must slide over the tip, a low coefficient of friction between the foil and the tip is required, so the rubber tip is covered with a layer of Teflon® Since not all friction between the tip and the printing foil can be eliminated, some drive force must be provided to the foil. This comes from friction between the substrate and the inked side of the printing foil. Some substrates may have a very low coefficient of friction which can cause slippage between the foil and the substrate, instead of between the foil and the tip. To overcome this, the system can maintain independent control over the incoming and outgoing tension of the printing foil. By precisely maintaining the tension of the rewind side of the foil higher than the supply side, the force needed to move the foil over the tip approaches zero. This reduces the force that the substrate must provide to move the film, and allows printing on surfaces with relatively low coefficients of friction, such as gold, nickel and silicon.

The tip also encloses the laser beam during printing which reduces the hazard from exposure to the laser beam.

The printing tip is key to controlling the three basic requirements of the process:

- to press the foil against the object being printed with no voids so that molten ink will adhere to the substrate,
- to maintain a relatively constant time between ink is melting and ink stripping,
- to strip the printing foil at a constant angle.

Meeting the first requirement avoids unprinted portions of the image. Meeting the second and third requirements allows consistent process conditions across the print, and allows the ink formulation to be optimized for optimum print quality.

Laser Source and Optical System

Carbon dioxide, neodymium YAG, and diode lasers were all used in the early process work, and all were shown to work. For primarily economic and power considerations, a carbon dioxide laser was chosen. This type of laser also offers some advantages in safety. Other types of laser may offer advantages in the formulation of the inks.

The function of the optical system (Figure 3) is to provide a modulated focused spot that is scanned in a line. The laser beam first enters a beam expander/collimator to provide the correct beam size for an acoustic-optic modulator. An external modulator is used to achieve the high data rate (200 kHz) for printing. Binary (on-off) modulation is used; the system does not reproduce levels of gray on a pixel by pixel basis.

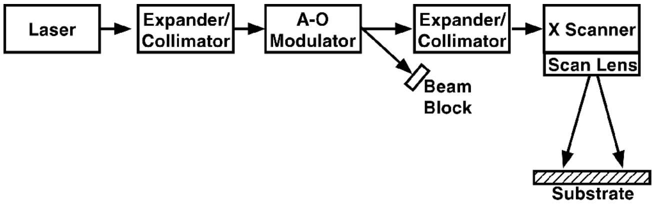

Figure 3. Block diagram of optical system

After the acoustic-optic modulator, the beam enters another expander/collimator to provide the correct beam size for the scan mirror and scan lens. For building an X-Y raster image, scanning the X axis is accomplished by a galvo scanner before an F*theta lens. (The Y axis of scan is provided by relative motion of the substrate to maintain the required constant foil geometry as discussed above.)

Two modes of galvo scanning have been developed. In the first mode, the galvo scanner moves the spot in one direction while printing, and then retraces as fast as possible without printing on the retrace. Pixel positioning is accomplished open loop by timing the AO modulator to print pixels when the scan mirror is assumed to be in the correct position. Although there are slight errors in the accuracy of the galvo, the repeatability is sufficient that the pixels will line up accurately with the line previously printed, so these slight errors are not obvious to the eye. This mode is not very efficient because of the time required to return the galvo scanner at the end of each scan line can be more than 50% of the time available.

In the second mode, we print bidirectionally, on both the forward and the reverse scan. The wasted time can be largely saved. This creates two new problems. The first is that while the slight errors in galvo position cancel when printing in one direction, the errors add when printing in both directions. This requires an accurate position sensor to control pixel timing in a closed loop system. This is accomplished by using a low inertia optical encoder attached to the galvo mirror. The second problem is that when using the relative motion between the tip and the substrate for the second axis of scan, the opposite scan lines form a zigzag. This is corrected by using a second galvo scanner to straighten each scan line to make them perpendicular to the motion direction. Although two galvo scanners are used, the second is only used for removing this zigzag. Relative print head motion is still used for the second (Y) axis of scan to maintain the control of the film stripping as noted above.

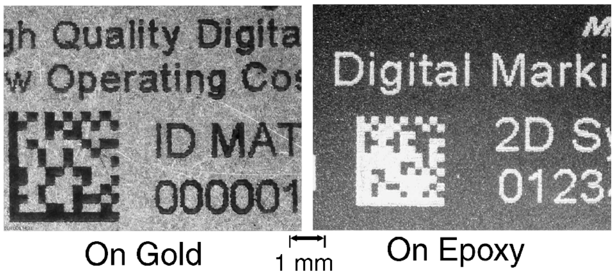

Figure 4. Sample prints from the system. Both are at the same magnification.

A black ink print on gold and a white ink print on epoxy are shown in Figure 4.

Multi-Color Imaging

An early system was built which demonstrated 3 color (non-process) operation[4]. The system used an acousto-optic modulator to send the laser beam on a pixel by pixel basis to one of three scanning mirrors mounted on a common shaft so that they moved in synchronism with each other. At each of three transfer printing stations, one of the 3 colors was laid down on a substrate. In operation, the substrate would pass sequentially through the 3 printing stations, receiving ink of the corresponding color at each station. After proceeding through the three print stations, the three color image was complete on the part and all colors were registered to each other. Because of the requirement for the laser beam to be at only one of the three stations during any scan line of an image, this system was not capable of laying a pixel of one color on top of a pixel of a different color. The three color system was not developed into a commercial system.

Finite Element Modeling

We observed that the laser power required to melt the ink at the ink layer/substrate interface was highly dependant on the substrate material and the ink color. Specifically we noted that the radiant energy required to print white ink on an epoxy substrate was insufficient for printing on a silicon surface. Black ink would print on either surface.

We used ANSYS finite element modeling software to better understand the observed differences in printing on silicon and epoxy. Using a 2 dimensional model with axisymmetric elements, we modeled the deposition of laser energy and subsequent temperature rise (using a 65 micron diameter Gaussian beam) within the carrier film, ink layer and substrate and the subsequent flow of heat energy for both cases. The heat of fusion associated with ink melting was included in the models.

Table 1. Materials properties for FEA analysis[5-7]

Property	Silicon	Epoxy
transmittance – %/μm	99.98	90
specific heat - J/(kg * K°)	668	1500
thermal conductivity W/(m * K°)	83.7	0.67

While printing on epoxy substrates, little of the laser energy is converted to heat within the carrier film or the ink layer due to the low absorption of laser energy in these thin layers. The epoxy substrate absorbs the laser energy quite well (Table 1) and forms a reservoir of heat just below the ink-substrate interface. Since the epoxy has relatively low diffusivity, the heat diffuses only slowly from the heated region through the epoxy layer allowing conducted heat to melt the adjacent ink in the ink layer by conduction. The size of the printed dot, defined as the maximum diameter of the ink melted zone created from one laser pulse, continues to grow long after the laser pulse had ended. For a typical 4 microsecond laser pulse, the size of the melted spot on ink continued to grow for 1000 microseconds after the end of the laser pulse.

We observed that the silicon substrate could not be easily printed under the same conditions. The model showed us that the silicon is more transparent to laser radiation than epoxy and allows much of the laser radiation to pass through without depositing heat energy. The increased thermal diffusivity of the silicon layer quickly carries away any heat that is produced away from the substrate-ink interface layer.

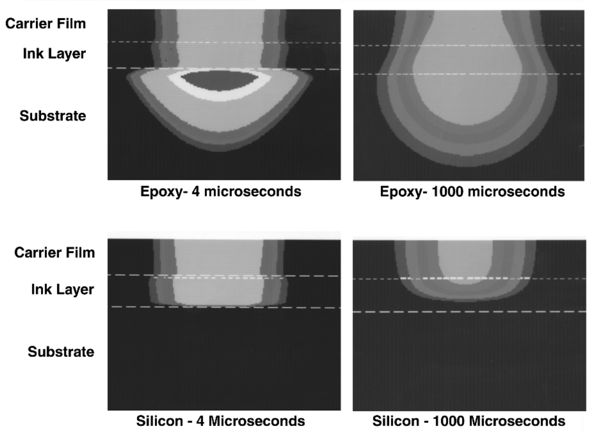

Figure 5. Temperature distribution vs. time for epoxy substrate (top) and silicon (bottom)

The comparison of the FEA model for epoxy and silicon is shown in Figure 5. By changing to an ink layer with a higher absorbance, printing on silicon became possible. We found very good correlation of the calculated results on the model with actual performance of the system.

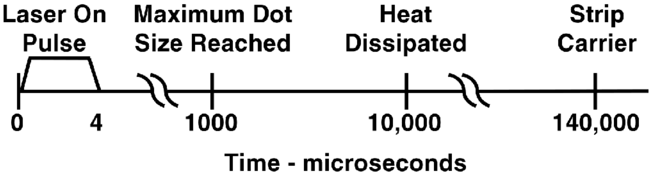

Figure 6. Time scale for laser transfer printing

One surprise was the wide range of time scales involved in the process. In one case which we modeled, laser energy was completely deposited within 4 microseconds, yet heat flow caused the diameter of the melted zone of ink to continue to grow for 1000 microseconds. The ultimate size of the printed spot corresponds to the maximum diameter of the ink melted. After 10,000 microseconds, local temperatures had returned to approximately the starting values for both materials.

Laser Transfer Printing Foils

The laser transfer foils are comprised of a dried pigmented water based ink layer coated onto a surface treated 22.5 micron polypropylene carrier film. The ink layer thickness ranges from 2-15 microns. Current commercial offerings include both UV and thermal curable ink layers which are available in black or white.

Final System Specifications

1. Laser: sealed RF excited CO2 – 50 Watts
2. Addressability: 500 dpi (20 dots/mm)
3. Pixel diameter: ~80 microns
4. Transfer energy: 2 to 5 J/cm^2
5. Print area: 35 mm by 60 mm maximum, larger by tiling
6. Print speed: 380 mm^2 per second maximum
7. Colors: white, black
8. Curing: heat or UV
9. Print format: text, graphics, bar codes, 2D codes.

Conclusion

We have demonstrated laser thermal transfer printing of 1-bit 500 dpi ink images on silicon, nickel, gold, ceramic and thermoset plastics. The transferred ink film is subsequently cured to achieve high print durability. This technology has been successfully made into a product.

Acknowledgment

The authors wish to thank Jeffrey Brooks and Roy Sunter for their work on FEA modeling of the laser thermal process.

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Biography

Alan Boyer received his B. S. Degree in Chemistry from Bowling Green State University in 1974. He has been working on various aspects of printing and imaging technology for the past 20 years, including electrostatic, ink jet, gravure, resistive and laser thermal transfer, and direct laser printing. He is an inventor on 5 US patents. E-mail address – aboyer@markem.com.