

Laser Direct-Write of Embedded Electronic Components and Circuits

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ABSTRACT

The development of embedded surface mount devices, IC's, interconnects and power source elements offers the ability to achieve levels of miniaturization beyond the capabilities of current manufacturing techniques. By burying or embedding the whole circuit under the surface, significant reduction in weight and volume can be achieved for a given circuit board design. In addition, embedded structures allow for improved electrical performance and enhanced function integration within traditional circuit board substrates. Laser-based direct-write (LDW) techniques offer an alternative for the fabrication of such embedded structures at a fraction of the cost and in less time that it would take to develop system-on-chip designs such as ASIC's. Laser micromachining has been used in the past to machine vias and trenches on circuit board substrates with great precision, while laser forward transfer has been used to deposit patterns and multilayers of various electronic materials. At NRL, we have been exploring the use of these LDW techniques to both machine and deposit the various materials required to embed and connect individual components inside a given surface. This paper describes the materials and processes being developed for the fabrication of embedded microelectronic circuit structures using direct-write techniques alongside with an example of a totally embedded circuit demonstrated to date.

Keywords: Laser Direct-Write, Laser Micromachining, Embedded Passives, Embedded Bare-die.

1. INTRODUCTION

The endless demand for new and improved consumer products such as cell phones, digital cameras and PDA's relentlessly pushes for higher functionality in increasingly smaller packages. In addition to the integrated circuits (ICs) required by these products, the number of passive components (resistors, capacitors and inductors) has increased dramatically with the growing number of features included with each new model. For example, the Nokia 6161 cell-phone houses a printed circuit board populated with 15 ICs and 405 passive components [1]. As this example illustrates, the passive components account for the majority of the parts placed on the printed circuit board, and occupy a significant fraction of the surface area available. In addition, each of the ICs take a large amount of space in the circuit board due to the packaging required to protect the individual silicon bare die inside each module. As a result, the overall size of the cell-phone is determined by the volume occupied by the required passive and active components

For military applications, miniaturization and functionality are also key factors. However, demand for customization for relatively small number of units requiring rapid development and fabrication times, results in higher production costs. For these applications, single chip solutions such as System on Chip (SoC) or application specific integrated circuits (ASIC) are not practical since they require long development and manufacturing times and do not allow for changes to their design once it is completed.

Rather than using single chip solutions such as SoCs or ASICs in order to achieve the required miniaturization and functionality, a more practical approach is to embed the components inside the substrate or circuit board. Embedded components offer the potential to reduce volume and overall weight while simultaneously increasing the device density and their electrical performance, resulting in enhanced functionality within the same form factor. The use of embedded

passive components such as resistors, capacitors and inductors within the circuit board has been around for years driven by high-density and high-speed applications [2]. Current trends require the use of flexible substrates such as polyimide, polyester or other polymer films which allow the fabrication of thinner circuits capable of higher interconnect densities than traditional rigid substrates. However, the use of these organic materials limits their processing to temperatures under 250 °C, which is far below what can be tolerated by ceramic substrates and thus limits the choice of materials required for the fabrication of the components and their interconnects. Progress has been achieved in this area with the development of integrated passive components such as resistors and capacitors made using polymer thick film (PTF) composites, which can be screen printed or doctor bladed onto the substrate and processed at the low temperatures compatible with the newer organic and flexible circuit boards [2]. However, this approach is not able to embed within a given substrate every single component required in a circuit such as: passive components that cannot be replaced by those made by PTF composites, active components such as bare dies and LED's, and power sources such as solar cells or microbatteries. What is needed is a new approach beyond traditional circuit board fabrication techniques in order to develop a true system embedding capability.

This paper describes the use of laser-based direct-write techniques for developing processes for embedding passive surface mount devices (SMD's) such as resistors and capacitors, surface mount light emitting diodes (LED's), semiconductor bare dies and the required metal patterns to interconnect each of them into a working circuit. The goal of this work is to demonstrate the use of laser direct-write processes to carry out the various steps required to fabricate a complete embedded circuit in a plastic substrate requiring low processing temperatures (≤ 100 °C).

2. LASER DIRECT-WRITE

Laser direct-write (LDW) is a general term that encompasses modification, subtraction and addition processes that can create patterns of materials directly on substrates without the need for lithography or masks [3]. The interaction of the laser with the substrate, or any other surface for that matter, results in material modification (melting, sintering, etc.) or material removal (laser micromachining). The later allows the generation of the trenches or pockets where the devices are to be embedded inside the substrate. Subtractive LDW can generate patterns by either moving the substrate or rastering the laser beam or a combination of both. In additive mode, the LDW technique behaves effectively as a "functional materials printer" as shown schematically in Figure 1. Simply stated, powders of the material to be deposited, i.e. Ag powders (to make electrically conductive metal patterns), are combined with a liquid carrier to form an ink. This ink is spread on a glass plate to form what is referred to as the ribbon. The ribbon is held above the substrate surface separated by a distance of 100 to 200 μm so it can move independent of the substrate. A pulsed UV laser (DPSS Nd:YVO₄, 355 nm, 30 nsec) irradiates the ink from behind the glass plate to propel a mass of material forward to the substrate below. This laser printing process takes place by rastering either the beam or the substrate to produce a pattern of material. Different materials can be deposited by simply changing the composition of the ribbon.

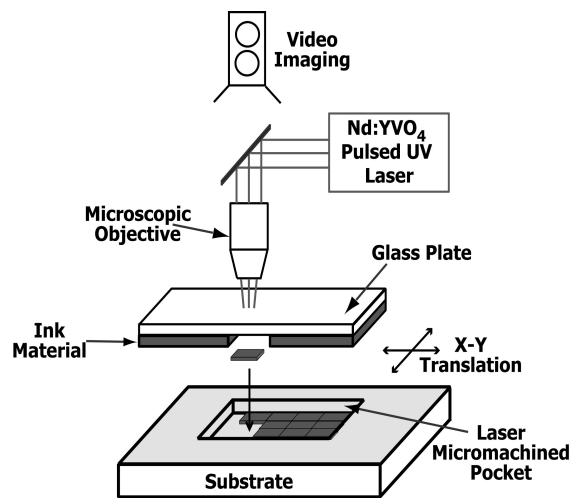


Figure 1. Schematic of laser direct-write addition process showing deposition within the substrate.

Details of the LDW process as applied to sensors, microbatteries, antennae, solar cells and interconnects have been presented elsewhere [4,5,6,7,8]. More recently, we have reported on the ability to embed individual bare die semiconductor components and the establishment of their electrical connections without damaging the fragile bare die using LDW [9]. However, the use of LDW to embed and interconnect several different types of components within the same substrate in order to fabricate a complete working circuit has just recently been demonstrated and it is described for the first time in the following section.

3. FABRICATING AN EMBEDDED CIRCUIT USING LDW

An astable blinker circuit was selected in order to develop the steps required to fabricate a totally embedded electronic circuit using the LDW technique. This circuit comprised of six passive SMD components (4 resistors and 2 capacitors), two SMD LED's and one unpackaged IC (bare die). The passive SMD components used for this circuit have a size of 1.60mm x 0.80mm x 0.30mm and correspond to the 0603 SMD series. The LM555 MDC, known as 555, bare die chip (dimensions: 1.32mm x 1.37mm x 0.33mm) made by National Semiconductor, is a very common IC used for timing and pulse generation applications. Using these components a planar circuit layout was developed which occupied a smaller footprint than the packaged LM555 chip. Figure 2 shows the resulting circuit diagram for the embedded blinker circuit occupying a total area of less than 1 cm².

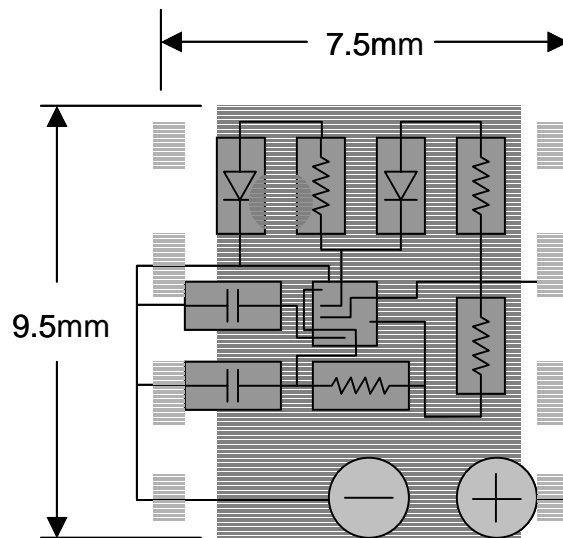


Figure 2. Circuit diagram for the embedded 555 blinker circuit. The light grey background shows the footprint occupied by a single packaged LM555 chip.

3.1 Embedding the individual components

A 1mm thick thermoplastic polyetherimide resin board, ULTEM 1000, was selected as the substrate for embedding the blinker circuit components and interconnects. This resin offers good heat resistance to withstand the heat curing cycles of resins, encapsulants and conductive pastes used to fabricate the circuit, excellent chemical resistance against all the materials used in the embedding process, and good laser energy absorption with minimal debris formation during laser micromachining. Each of these properties are critical for substrates used for embedding circuits using LDW.

Since the components are to be interconnected at the surface of the substrate, it is necessary to embed them flush with the top surface of the substrate. At appropriate locations on the substrate, controlled depth laser micromachining is used to create pockets for the components. The depth of each laser machined trench can be precisely controlled by adjusting the right combination of energy, frequency, spot size and spot to spot translation [10]. A series of laser pulses with a spot diameter of 15µm and a fluence of 60 J/cm² are used to machine the component pockets shown in Figure 3(a). The active and passive components are placed inside the machined pockets and are secured to the bottom with epoxy,

ensuring that their top surface is flush with the ULTEM surface. An optical micrograph of the components placed inside the pockets is shown in figure 3(b). After the epoxy is cured, the substrate with the components is covered with a thin 75µm Kapton HN polyimide film with an adhesive backing. This film and adhesive composite acts as a sealant/cover and provides a surface where the interconnects required by the blinker circuit can be laser micromachined and then filled with electrically conductive pastes.

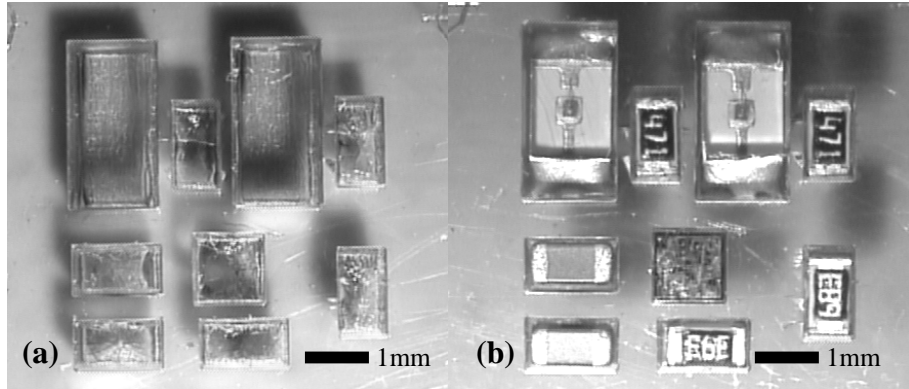


Figure 3. Optical micrographs of an ULTEM 1000 substrate showing: a) the laser machined trenches, b) the populated trenches with the blinker circuit components.

3.2 LDW of the interconnects

In order to fabricate the electrical connections between each of the components of the embedded blinker circuit, 50 µm wide channels are laser micromachined on the Kapton film surface using laser pulses with a 50µm x 50µm square spot size at a fluence of 2 J/cm². Once the channels are machined, they are filled with an electrically conductive paste (DuPont CB-230). Both LDW and “doctor blade” techniques are examined for the purpose of filling the channels with CB-230. In the LDW technique, as explained in section 2, a CB-230 “ribbon” is held over the substrate at a distance of 100µm and laser pulses with a fluence of < 0.8 J/cm² are used for the LDW transfer process. The conductive paste is deposited into the laser machined 50µm channels, thus making a complete interconnect layout for the blinker circuit. For comparison purposes, identical sets of laser micromachined channels are filled with CB-230 by doctor blading. Once the channels have been filled, either by LDW or doctor blading, the substrate is baked at 100 °C for 1 hour. The recommended 170°C cure temperature for the CB-230 conductive paste is not followed because of temperature limitations of the embedded active and passive components. During curing, shrinkage of the CB-230 paste occurs due to evaporation of solvents in the paste resulting in under filling of the channels, as shown in the SEM image in Figure 4. Repeating the filling steps can be used to mitigate this problem; however, it was found that the electrical conduction of the filled channels was sufficient for the blinker circuit to operate.

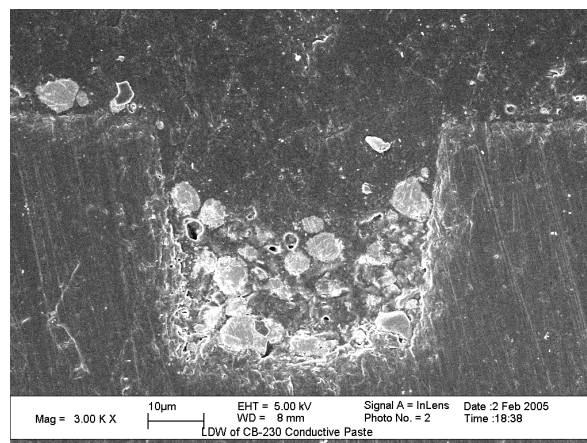


Figure 4. Cross-section SEM micrograph of a channel filled by LDW with CB-230 conductive paste after curing at 100°C.

To measure the resistivity of the CB-230 filled Kapton trenches, 2 cm long serpentine test patterns, with square contact pads at their ends are laser machined in 75 μm thick Kapton foils. The patterns are made to closely reproduce the interconnects used for the embedded circuits. An optical micrograph of the serpentine test pattern is shown in Figure 5. A series of patterns are fabricated by LDW CB-230 inside the serpentine trench, while another series is prepared by doctor blading. The patterns are then baked at 100 $^{\circ}\text{C}$ for one hour, thus exactly duplicating the embedded circuit interconnect preparation process. Resistivity measurements performed on the two test patterns are shown in table 1. The data shows that the resistivities of both the LDW and doctor bladed samples are similar ($\sim 2 \times 10^{-5} \Omega \text{ cm}$). However, in both cases the resistivities are about an order of magnitude higher than that of bulk silver ($1.6 \times 10^{-6} \Omega \text{ cm}$). This is expected since the CB-230 filled trenches were cured at lower temperatures than those recommended by the manufacturer. Despite this, it is worth pointing out that the obtained values for the resistivity of the trenches are similar to the resistivities of typical lead/tin soldering alloys used to connect components to a circuit board ($1.4 \times 10^{-5} \Omega \text{ cm}$). Other types of electrically conductive pastes compatible with the LDW process and requiring low curing temperatures are currently being tested.

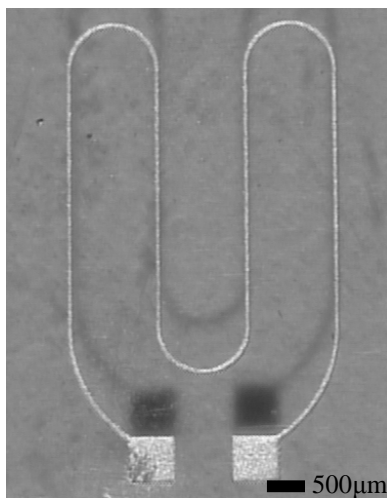


Figure 5. Optical micrograph of a serpentine test pattern machined on Kapton and filled with CB-230 conductive paste by LDW.

Material	ρ ($\Omega \text{ cm}$)
Silver (bulk)	1.6×10^{-6}
Solder (Sn63/Pb37)	1.4×10^{-5}
CB-230 LDW deposited	1.6×10^{-5}
CB-230 doctor bladed	2.6×10^{-5}

Table 1. Average resistivities obtained from the serpentine test patterns filled with CB-230 conductive paste using LDW or doctor blading. The bulk resistivity of silver and a typical lead/tin solder alloy are included for comparison.

3.3 Connecting individual components by LDW

After the interconnects are made, the next step is to laser drill and LDW fill vias from the interconnects down to the contact pads of each device. Fabrication of the vias for the SMD components is pretty straightforward since the contact pads on each SMD are very large ($\sim 500 \mu\text{m}$). On the other hand the fabrication of the vias required to connect the pads on the 555 bare die to the interconnect patterns of the blinker circuit requires the drilling of $100 \mu\text{m}$ vias without damaging the thin contact pad region on the bare die. Using $50 \mu\text{m} \times 50 \mu\text{m}$ laser spots with a fluence of 2 J/cm^2 , $100 \mu\text{m}$ square vias are laser machined to expose the contact pads on the 555 bare die.

In order to evaluate the quality of the contact between the CB-230 electrically conductive paste used to fill the vias and the pads in the bare die, identical sets of vias are laser machined and LDW filled in several Kapton covered gold/silicon substrates. These substrates are called “dummy dies”. Tests are conducted on several of these dummy die samples to characterize the conduction process between the conductive paste and the die surface and the data is analyzed in order to establish that the conduction process is symmetric and ohmic. Four terminal contact resistance measurements are performed with a Keithley 2400 source meter that applies voltages from 0V to 0.01V in the forward and reverse direction and data is collected for corresponding current values. An I-V plot obtained from the test sample is shown in Figure 6. Examination of the plot indicates that the voltage is proportional to the current, is independent of polarity and the constant contact resistance of 1.7Ω demonstrates ohmic behavior.

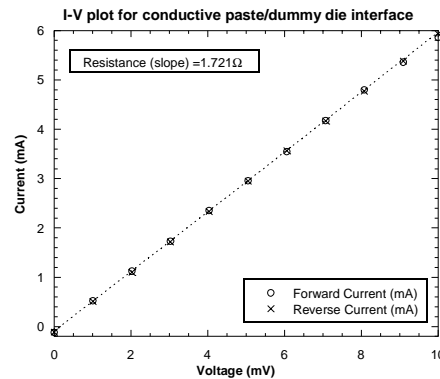


Figure 6. Contact voltage vs. current for conductive paste contact with dummy die test sample. Data is shown for forward and reverse current.

Finally, in order to determine the degree to which the vias are filled with the CB-230 paste and the nature of the interface between the CB-230 and the metal pads, cross sections of the vias and contact pads on the dummy dies are cut and polished for examination under the optical microscope. Figure 9 shows an optical micrograph from one such cross section. The cross section reveals that the contact between the CB-230 and the exposed metal surface is quite uniform and free of voids which agrees with the low contact resistances measured.

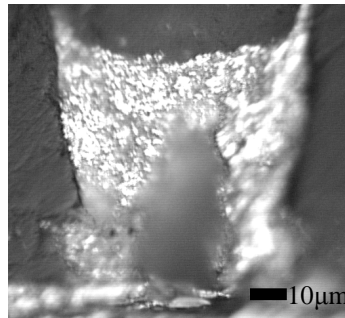


Figure 7. Cross-section optical micrograph of a via laser machined through Kapton exposing the gold surface of an Au coated Si substrate and LDW filled with CB-230 conductive paste.

The resulting functional embedded blinker circuit is shown in Figure 8. Figure 8 (a) shows an optical micrograph of the completed circuit with the 555 bare die at the center of the image and the two LED's in the top row. Two large through holes appear at the bottom, where connections to an external battery are made in order to power the circuit. Figure 8 (b) shows a higher magnification image of the bare die and its interconnects. Notice the proximity to each other of several of the contacts on the bare die. It is worth mentioning that these contacts are designed to be connected using wire bonding. However, using LDW it is possible to achieve planar contacts which occupy much less volume thus allowing the possibility for vertically stacking multiple bare dies. The overall result is a significant reduction in thickness required by each IC. As a result, it is anticipated that the embedded circuits made using the LDW technique will occupy footprints of

about $\frac{1}{4}$ or less and require $\frac{1}{10}$ of the usual thickness of a traditionally printed circuit board designs. These reductions correspond to volume miniaturization factors of 0.1 to 0.02 depending on the type of circuit design.

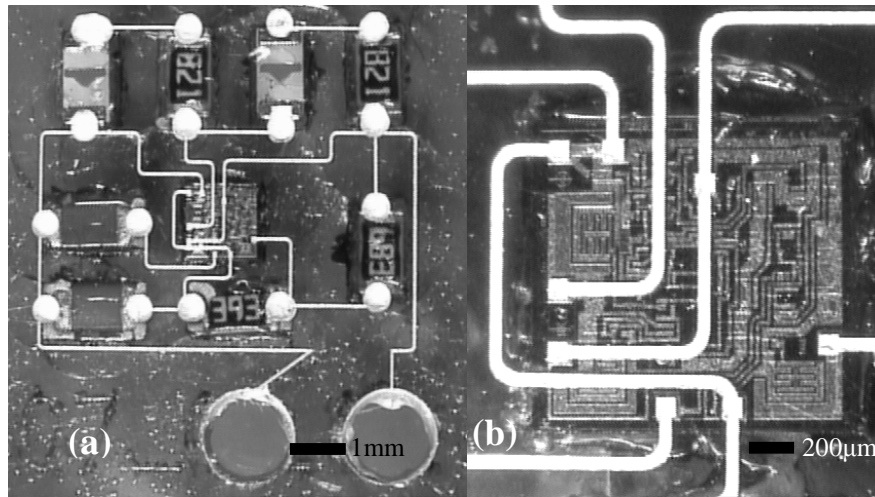


Figure 8. a) Optical micrograph of complete 555 blinker circuit b) detail of interconnects across bare die

4. SUMMARY

Using laser-based direct write techniques for embedding passive components such as surface mount resistors and capacitors, active components such as LED's and bare die IC's, and their required interconnects allows the fabrication of complete circuits with a level of miniaturization beyond what can be achieved with current circuit board manufacturing techniques. LDW processes allow for the rapid implementation of prototype embedded circuits which can be placed under virtually any surface, either planar or conformal, thus making possible the development of circuit layouts compatible with any given form factor. This means that in the future, complete electronic circuits could be buried within any surface, with the surface or substrate serving both as circuit board and packaging.

In this work we have demonstrated how LDW can be used to fabricate a fully operational simple embedded blinker circuit in a plastic substrate at very low processing temperatures. The complete circuit occupies a fraction of the volume required by the same circuit manufactured using traditional printed circuit board techniques. It is envisioned, among many other applications, that embedded circuits could play a key role in the development of so-called functional modules, such as Bluetooth or GPS subsystems. For example, embedded GPS modules comprising of passives, IC's and GPS antennae, occupying a fraction of the volume of current GPS systems, could be designed to fit within any available region in the case of a consumer product. Such flexibility is beyond what can be achieved with current manufacturing techniques given the space and planar form factor required by traditional circuit boards and their surface placed components.

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