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# Rapid Prototyping of Embedded Microelectronics by Laser Direct-Write

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## 1. Introduction

For commercial, aerospace and military applications, miniaturization and functionality are key factors. In all these applications, the driving force is the need to achieve higher functionality in increasingly smaller volumes. As a result, traditionally packaged electronic components such as integrated circuits (ICs) and surface mount devices (SMDs) are reaching the point where their individual packaged size is too large to achieve the required device density on the available circuit board surface. There are various ways to address these limitations: for instance, application-specific ICs or ASICs, which eliminate the need for individual components, can be designed to replace an entire microelectronic circuit board. With ASICs, the entire circuit is fabricated in one fell swoop, and then packaged. However, development of these single-chip designs is costly and time consuming, and once their designs are completed, very difficult to change. In other words, none of the solutions currently available are capable of rapid prototyping customized circuits at a reasonable cost and in a limited amount of time.

A better solution is to be able to place unpackaged devices and components inside the circuit board in order to achieve higher component densities. This approach, known as embedding, is used in some applications with passive devices, but has had limited success when applied to unpackaged or bare die semiconductor devices. This is because bare dies are very fragile and tend to be easily damaged by the robotic systems, known as "pick-and-place" tools, used to mount the devices on a circuit board. Furthermore, pick-and-place tools are ineffective when handling small or very thin ( $< 50 \mu\text{m}$  thick) dies, or for high throughput applications ( $> 10$  devices/sec). Therefore, the implementation of embedded electronic circuits comprising SMDs, interconnects and IC's in bare die form promises to make possible levels of miniaturization well beyond the capabilities of current circuit manufacturing techniques. By burying or embedding the various circuit elements under the surface, significant reduction in weight and volume can be achieved for a given circuit board design. Embedded semiconductor bare dies are a good example of the advantages provided by this approach, since an embedded die occupies a fraction of the volume required by the same IC when packaged and wired using surface mount techniques. In order to realize these gains, novel approaches to the assembly and interconnection of embedded bare dies need to be considered.

Laser direct-write processes and techniques, also known as LDW offer numerous advantages to the rapid prototyping of embedded microelectronic circuits (Piqué & Chrissey, 2002a). Laser

direct-write encompasses several laser-based processes that can create patterns directly on substrates without lithography or masks (Arnold & Piqué, 2007a). These non-lithographic processes can add or subtract materials, modify the materials themselves, and transfer or print complete devices or parts. Laser direct-write processes can for example be used to first laser micromachine a pocket or recess on a substrate, then to laser transfer a device or component inside the pocket without damaging the device's functionality, and finally laser print the metallic electrical interconnects required by each device in order to complete the circuit.

In particular, laser-based device-transfer processes are a novel alternative to conventional mechanically driven pick-and-place methods for placement and embedding millimeter-to micrometer-sized structures such as semiconductor bare dies, surface-mount devices, optoelectronic devices, sensors, actuators and MEMS onto any surface. The concept for this process, which is referred to as "lase-and-place" is simple and could in principle revolutionize the way embedded electronic circuits are currently fabricated. The lase-and-place process is a contactless technique and thus allows the transfer of very small and very thin devices that would easily be damaged by mechanical pick-and-place tools. Application of this technique to various types of semiconductor bare die has shown that it is possible to transfer complete devices with the active surface facing the laser pulse without damage. Hence the devices are embedded with their contact pads facing up, which greatly facilitates the next required step, which is the fabrication of the metallic patterns that allow the device to be interconnected to the rest of the circuit. Another LDW technique, known as laser decal transfer, can then be used to literally print planar interconnects thus replacing traditional wire bonding processes. As these examples demonstrate, the use of LDW techniques would allow the rapid prototyping of embedded microelectronics, which is not possible using present circuit fabrication tools.

This chapter presents an introduction to the rapid prototyping of embedded microelectronics using laser-based techniques such as laser decal transfer and lase-and-place. The chapter discusses the mechanisms driving each of the various LDW processes and how they have evolved. It then describes how these techniques can be used to create an effective laser-based tool for the fabrication of embedded circuits and discusses the laser-driven transfer process as applied to various types of materials and functional devices. Finally this chapter concludes with a discussion of laser based transfer processes for the digital microfabrication of next generation microelectronics whose design and geometry can be customized and quickly prototyped in less time and at lower cost than with any other currently available circuit fabrication technique.

## **2. Digital microfabrication with laser direct-write**

From the perspective of rapid prototyping applications, the development of embedded microelectronics presents considerable challenges since the materials requirements for building an electronic device, much less a complete circuit, cannot be satisfied by using one single type of material system in the prototype fabrication. Given the wide range of materials required, traditional additive manufacturing approaches such as selective laser sintering (SLS), stereolithography and fused deposition modeling (FDM) are not compatible with the goal of rapid prototyping of embedded electronic circuits. However the need for such capability grows larger and larger with time.

## 2.1 Digital microfabrication

The advent of computer aided manufacture (CAM) techniques and tools made possible the fabrication of mechanical parts in digital fashion, i.e. from computer design to final product without the need for intermediate steps to verify the compatibility and fit of a part relative to the rest of the design. In general, the term digital fabrication describes any process that allows the generation of patterns or structures from their design directly under computer control. Digital fabrication using CAM tools, although revolutionary on its own, was far from ideal since it could only be used to remove material through machining steps. Additive digital fabrication had to wait until the development of solid freeform fabrication techniques such as selective laser sintering and laser stereolithography. These processes, although capable of digitally generating three dimensional prototypes accurate in form from computer designs, are still limited to the early design stages within the manufacture cycle, given the limited functionality of the generated parts. Over the last decade, however, new applications in areas beyond large-scale manufacture of mechanical parts have surfaced, requiring the rapid prototyping of designs comprising multiple types of materials and feature sizes down to a few microns. These applications, mainly in the electronics, optoelectronics, sensor and biomedical industries are in need of novel microfabrication techniques beyond lithography and other traditional semiconductor manufacturing processes. Non-lithographic techniques such as digital microfabrication offer great promise for applications requiring processing on plastic or flexible substrates, production of small batch sizes, customization and prototype redesign. Gao and Sonin were the first to use the concept of digital microfabrication for fabricating three-dimensional structures by precisely dispensing microdrops of molten wax, with each microdrop serving as a 3-D pixel or voxel of the final three-dimensional design (Gao & Sonin, 1994). The use of a rapid solidifying wax allowed the printing of 3-D microstructures in a digital fashion. However, as a material, wax had limited functionality and offered little if no practical application.

Of the direct-write techniques mentioned already, LDW is ideally suited for digital microfabrication applications. As mentioned in the Introduction, LDW systems are capable of operating in various modes from additive (laser forward transfer), subtractive (laser micromachining) and modifying (laser sintering, laser annealing, etc.) (Arnold *et al.*, 2007b). What makes LDW unique is its ability to laser transfer such a wide variety of materials with relatively high resolution conformal to the surface. As will be described later in this chapter, the laser transfer process does not have a deleterious effect on the electrical, chemical and even biological properties of the voxels of material forming the digital pattern. The ability of LDW to laser transfer functional materials and then process them or modify them in order to achieve the required properties and behavior is unique and offers the best opportunity to realize the advantages that digital microfabrication has to offer.

## 2.2 Embedded electronics

For a given circuit layout, in order to accommodate the various components in the most effective way and at the highest possible density, it is necessary to place them inside the circuit board. These electronic circuits, comprised of interconnected embedded components, promise to advance the manufacture of miniaturized electronics. Embedding components leads to significant reductions in weight and volume of a circuit. It also results in circuit designs with shorter interconnects and reduced parasitic inductance, thereby enhancing their electrical performance. Embedding passive components, such as resistors and capacitors, inside a circuit board is not a new technology. However, embedding active semiconductor

components has been demonstrated only for specialized applications due to two current challenges in manipulating and interconnecting the unpackaged semiconductor device, known as bare die, with the rest of the circuit. The first challenge is due to the fact that bare semiconductor die are very fragile and tend to be damaged easily by the robotic systems designed to handle them. The pick-and-place tools, are not well suited to insert bare die devices inside pockets on a circuit board. Furthermore, pick-and-place tools are ineffective when handling small (less than 1 mm square) or very thin (less than 50  $\mu\text{m}$  thick) dies, or for high throughput applications (more than 10 devices/sec). The second challenge is due to the lack of techniques capable of generating high density interconnects from an embedded die and the surrounding components. Traditional approaches such as wire bonding are not capable of making connections between separate components placed at arbitrary distances from each other. In order to avoid these limitations, new approaches to placing and interconnecting embedded bare dies are required.

### 2.3 Laser direct-write

Since the initial reports of laser transferred copper metal patterns by Bohandy, et al. over 25 years ago (Bohandy *et al.*, 1986), the use and development of laser forward transfer techniques has grown steadily. These simple yet powerful techniques employ a pulsed laser to locally transfer material from a source film onto a substrate in close proximity or in contact with the film, thus achieving the non-lithographic processing or laser direct-write of patterns on a given surface. The source is typically a coated laser-transparent substrate, referred to as the target, donor, or ribbon. Laser pulses propagate through the transparent ribbon and are absorbed by the film. Above an incident laser energy threshold, material is ejected from the film and propelled toward the acceptor or receiving substrate. Translation of the source and receiving substrate, or scanning and modulation of the laser beam, enables complex pattern formation in three dimensions with speed typically limited by the laser repetition rate. Commercially available, computer-controlled translation stages and/or galvanometric scanning mirrors enable rapid motion and high-resolution patterns from the individually written voxels, i.e. 3D volumetric pixels that result from the laser transfer process. A schematic showing the basic components of a laser direct-write system is shown in Figure 1. The fact that the laser transfer process does not require the use of vacuum or cleanroom equipment greatly contributes to the technique's great simplicity and compatibility with virtually any type of material and substrate.

These laser transfer techniques, known as laser direct-write or LDW, belong to a class of processes capable of generating high-resolution patterns without the need for lithographic processes afterwards (Arnold & Piqué, 2007a; Piqué & Chrisey, 2002a). To better understand the applicability and potential new uses of laser direct-write and associated laser transfer techniques for digital microfabrication, it is useful to compare and contrast them with other well-established digital microfabrication processes such as ink-jet. Similarly to ink-jet, laser transfer techniques are capable of precisely depositing or direct writing many types of functional materials (or their precursors) over virtually any type of surface or substrate in a conformal fashion. Unlike ink-jet, laser transfer techniques are not constrained to deliver the material through a nozzle, making them impervious to clogging problems. Moreover, laser transfer can deposit fluid materials ranging from very low viscosity inks to high viscosity pastes, making it immune to ink-surface wetting issues, and even transfer solids and entire devices. Furthermore, these techniques offer the added benefit of laser processing,



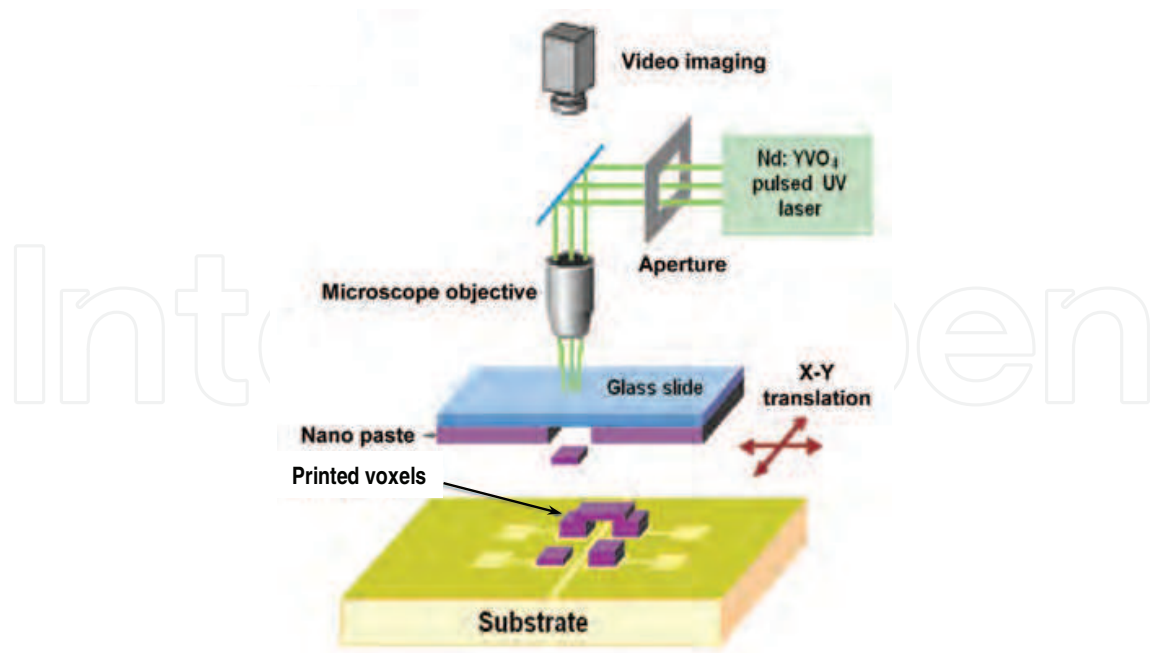


Fig. 1. Schematic diagram illustrating the basic elements of a laser direct-write system.

such as micromachining, for material removal (not possible with ink-jet) and laser materials modification, for *in-situ* annealing, curing or sintering, all with the same tool.

What makes LDW unique is its ability to laser transfer such a wide range of materials with relatively high resolution conformal to the surface. As will be described later in this chapter, the laser transfer process does not have a deleterious effect on the properties of the voxels of material forming the digital pattern. The ability of LDW to laser transfer functional materials and then process them or modify them in order to achieve the required properties and behavior is unique and offers the best opportunity to realize the advantages that digital microfabrication has to offer for rapid prototyping applications.

### 3. Understanding the laser transfer process

Lasers are uniquely suited for digital microfabrication processes requiring the forward transfer of functional materials given that their energy output is monochromatic and pulsed in nature. The monochromatic light generated by lasers allows for the direct-write process to be carried out via a specific excitation path characteristic of a given wavelength while minimizing or eliminating other reaction channels. Meanwhile, the ability to generate very short pulses ( $< 10^{-8}$  sec) of laser radiation allows the interaction of the laser pulse with the functional material to take place with minimal thermal effects. By directing single wavelength, very short laser pulses of sufficient intensity through a transparent substrate coated at the opposite end with a thin layer of material, discrete (or digital) material transfer in the forward laser direction can be achieved. The transferred material can be collected on a separate substrate facing the thin layer. The straightforwardness of this approach led to many groups to try it with different types of materials as the following sections will show. Despite its inherent simplicity, laser forward transfer exists in many different variations, is compatible with virtually any type of material, and takes place under ambient atmospheric conditions, thus making it one of the most versatile digital microfabrication techniques developed to date.

The earliest report of laser-induced transfer of material across an air gap can be found in the work performed by Levene *et al.* back in 1970 (Levene *et al.*, 1970). The material transferred consisted of black ink from a polyethylene backed typewriter ribbon and colored dies from a Mylar substrate across gaps up to  $100\mu\text{m}$  wide using a Nd:YAG laser ( $\lambda = 1.06\mu\text{m}$ ). Although the authors motivation was to develop a laser-based printing or marking process (the authors referred to it as "recording"), their work was prescient in highlighting the simplicity and high writing speed of the technique, while proposing a simple model based on the melting and vaporization of the transferred material as a function of the laser pulse energy. Unfortunately the authors did not apply their technique to any other types of materials and their work went unnoticed until the late 90's when their article began being cited within the printing and image science community. Fifteen years later, the laser forward transfer process was rediscovered, this time with metals. In 1986 Bohandy, *et al.* reported the deposition of copper metal patterns via laser forward transfer inside a vacuum chamber (Bohandy *et al.*, 1986). Excimer laser pulses ( $\lambda = 193\text{ nm}$ , 15 ns) were focused with a cylindrical lens to a 25 mm long by  $50\mu\text{m}$  wide line on a source substrate containing a thin copper film. The Cu was transferred to silicon and fused silica substrates, where further examination revealed resistivities ranging between 3 to 50 times the value for bulk copper with adhesion behavior that passed the "tape test". Bohandy's group coined the term laser-induced forward transfer or LIFT to denote the process and proposed a model more detailed but similar to Levene's to describe the process. According to this model; (1) the laser pulse heats the interface of the film at the source substrate; (2) a resulting melt front propagates through the film until it reaches the free surface; (3) at about this time, the material at the interface is superheated beyond its boiling point until, (4) the resulting vapor induced pressure at the interface propels the molten film forward towards the acceptor substrate (Adrian *et al.*, 1987). Figure 2 shows a schematic illustrating the phases of this model. The same group then demonstrated that this process could be carried out in air, i.e. under atmospheric conditions, without the need for a vacuum (Bohandy *et al.*, 1988).

The LIFT technique gained acceptance in a short time and was used successfully for a wide variety of single element materials, mainly metals such as copper (Bohandy *et al.*, 1988), vanadium (Mogyorósi *et al.*, 1989), gold (Baseman *et al.*, 1990; Bohandy *et al.*, 1988), aluminum (Schultze & Wagner, 1991), tungsten (Kántor *et al.*, 1994; Tóth *et al.*, 1993), chromium (Zergioti *et al.*, 1998a), nickel (Sano *et al.*, 2002) and Ge/Se thin film structures (Tóth & Szörényi, 1991). Reports of LIFT for oxide compounds such as  $\text{Al}_2\text{O}_3$  (Greer & Parker, 1988),  $\text{In}_2\text{O}_3$  (Zergioti *et al.*, 1998b),  $\text{V}_2\text{O}_5$  (Chakraborty *et al.*, 2007) and  $\text{YBa}_2\text{Cu}_3\text{O}_7$  high temperature superconductors (Fogarassy *et al.*, 1989) are worth mentioning, although the quality of the transferred ceramics was not as good as those deposited by traditional film growth techniques. In a variation to the basic process, polycrystalline silicon films can be deposited using a hydrogen assisted LIFT technique (Toet *et al.*, 1999). More recent examples include transfers of  $\text{TiO}_2$ -Au nanocomposite films (Sakata *et al.*, 2005), carbon nanotubes for field emitter applications (Chang-Jian *et al.*, 2006; Cheng *et al.*, 2007), conducting polymers such as Poly(3,4-ethylenedioxythiophene) (PEDOT) (Thomas *et al.*, 2007) and semiconducting  $\beta\text{-FeSi}_2$  crystalline phases (Narazaki *et al.*, 2008). Repetitive transfers from the ribbon over the same area can be used to increase the thickness of the transferred film on the acceptor substrate. In a similar way, by changing the type of ribbon material, multilayer structures can be generated. The success of any digital microfabrication technique depends on its ability to direct-write a wide variety of materials over many different types of surfaces. It is the ability to precisely control the intensity and nature of the interaction of the laser pulse at the interface between the

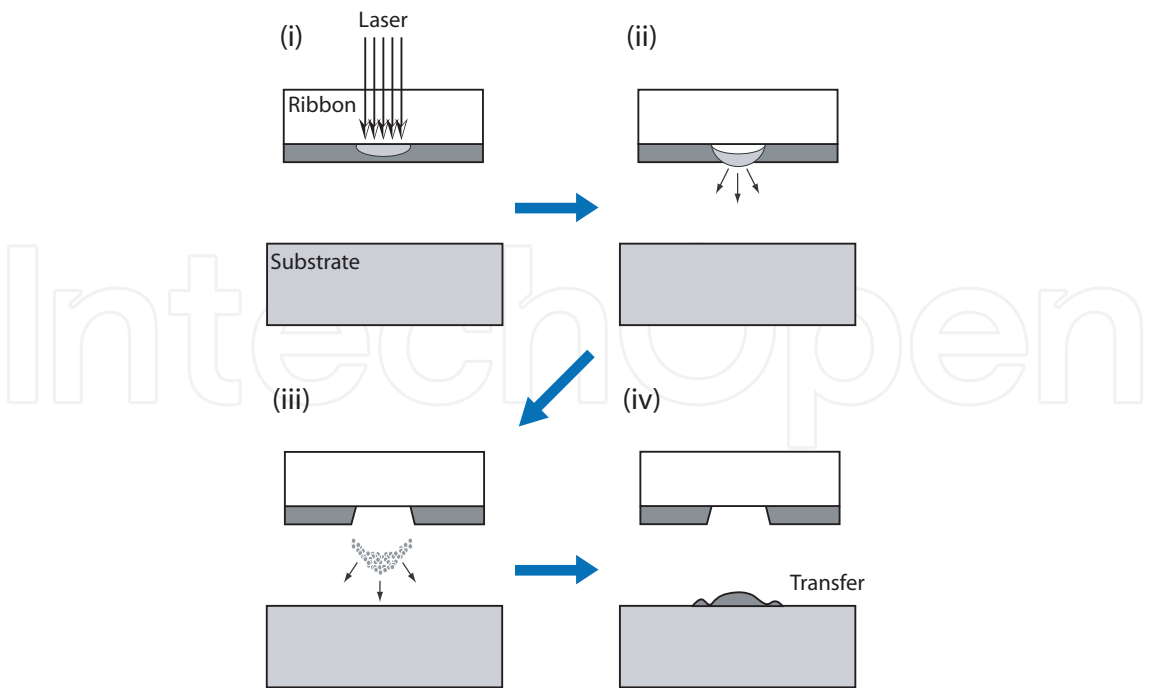


Fig. 2. Schematic representation of the LIFT process. (i) The laser pulse is absorbed and heats a thin solid film at the ribbon interface. (ii) The melted film is pushed away from the ribbon by the confined superheated vapor. (iii) Both melted and vaporized film are ejected away from the donor substrate towards the receiving substrate. (iv) The ejected material is collected on the receiving substrate.

laser transparent substrate and the coating in the donor substrate or ribbon that gives LIFT its unique advantages. This interaction can be modified in many different ways allowing many variations of the basic laser forward transfer technique, some of which are compatible with a wide range of materials. Obviously one way to achieve these variations is by varying laser parameters such as wavelength and pulse length. However, as the following section will show, most of the variations of the basic LIFT technique have resulted from taking advantage of the unique role that the donor substrate plays in the laser transfer process.

3.1 The role of the donor substrate

Despite its successful application to the deposition of thin metal layers, the actual uses of the LIFT process are limited due to several shortcomings. In LIFT, metal films are required to be deposited on the ribbon by conventional vapor deposition techniques that require vacuum deposition and other expensive processes. Since these metal films tend to be very thin (a few hundred nanometers), the individual layers deposited by LIFT are similarly thin, thus limiting its application to lithographic mask repair and other niche areas. During LIFT, the melting and solidification of the transferred material results in the formation of interfaces between adjacent voxels, which can have deleterious effects in the electrical transport properties of the patterned structure being fabricated. Furthermore, the melting of the transferred material becomes a serious issue when LIFT is performed under atmospheric conditions, because most metals are easily oxidized when melted in air. Moreover, the rapid quenching of the metal voxels once ejected can result in high intrinsic stresses between the transferred metal and the substrate, ultimately leading to poor adhesion and delamination of the transferred layers. Finally, LIFT is not suited for the transfer of ceramics and other inorganic phases given the



irreversible phase changes and decomposition that tend to be exhibited by these materials upon melting and solidification.

The main source of the above-mentioned limitations derives from the reliance of the basic LIFT technique on phase transformations of the material undergoing laser transfer. Obviously, its very difficult, if not impossible, for these transformations to take place with no changes to the material once the transfer is completed. Clearly, for the LIFT process to be truly compatible with the widest possible range of materials, it is necessary that the laser induced forward transfer takes place with minimal or no change or modification of the starting material to be deposited from the donor substrate. This is very critical since many types of materials, in particular complex multicomponent and multiphase systems will undergo irreversible changes upon melting or vaporization, which will degrade their desirable properties such as composition, phase, structure, homogeneity, electrical behavior or chemical and biological activity.

It is obvious that the nature of the donor substrate is key to the successful application of the laser forward transfer process. The ribbon of a typewriter provides a good analogy to the role of the donor substrate in this process. The resulting transfer of material from the donor to the acceptor substrate upon illumination with a laser pulse reminds us of a typewriter key striking the ribbon and transferring ink onto a piece of paper. Furthermore, transferring different materials from different donor substrates is analogous to printing different colors by changing the pigment of the ink in the ribbon. Clearly without the ribbon the typewriter is useless and similarly without the appropriate donor substrates, LIFT will not work. It is with this in mind that some groups refer to the donor substrate as the "ribbon". Throughout this chapter, the terms donor substrate and ribbon will be used interchangeably.

The main benefits provided by the ribbon to the LIFT process reside in the fact that the ribbon is both independent of the source of transfer energy and the target, i.e. the laser and the receiving substrate. As such it can easily be modified without requiring complex adjustments to the basic setup and components and it can be adapted to a specific material or application. Furthermore, since it is a totally independent part of the process, issues such as minimizing cross-contamination with the acceptor substrate, change of transferred material and removal of the donor substrate to allow direct interaction of the laser with the surface of the acceptor substrate are all easily achieved. Finally, since the type and form of the material in the ribbon can easily be changed, ranging from heterogenous multilayers, composites and entire devices, to liquid dispersions and complex fluids, the nature of the laser interaction with the material from the ribbon can be adjusted almost endlessly. It is this wide range of adjustment in the properties of the material present in the donor substrate that explain the large number of material systems successfully printed with the laser transfer process.

### **3.2 Laser transfer of complex systems**

The use of LDW for the deposition of high quality electronic materials requires the generation of structures comprising of multiple voxels, adjacent or on top of each other, that readily merge to form a single, continuous pattern. Electrical interconnects provide a perfect example of this requirement as heterogeneous interfaces between voxels can degrade the overall conductivity. By enabling the transferred material to remain fluid, adjacent voxels on the receiving substrate will merge into one continuous segment. Figure 3 shows a simple schematic illustrating the basic steps on the laser direct-write of rheological systems.

In reality, the LDW process is very different from prior LIFT experiments as functional materials are deposited without direct vaporization, which could affect their desirable

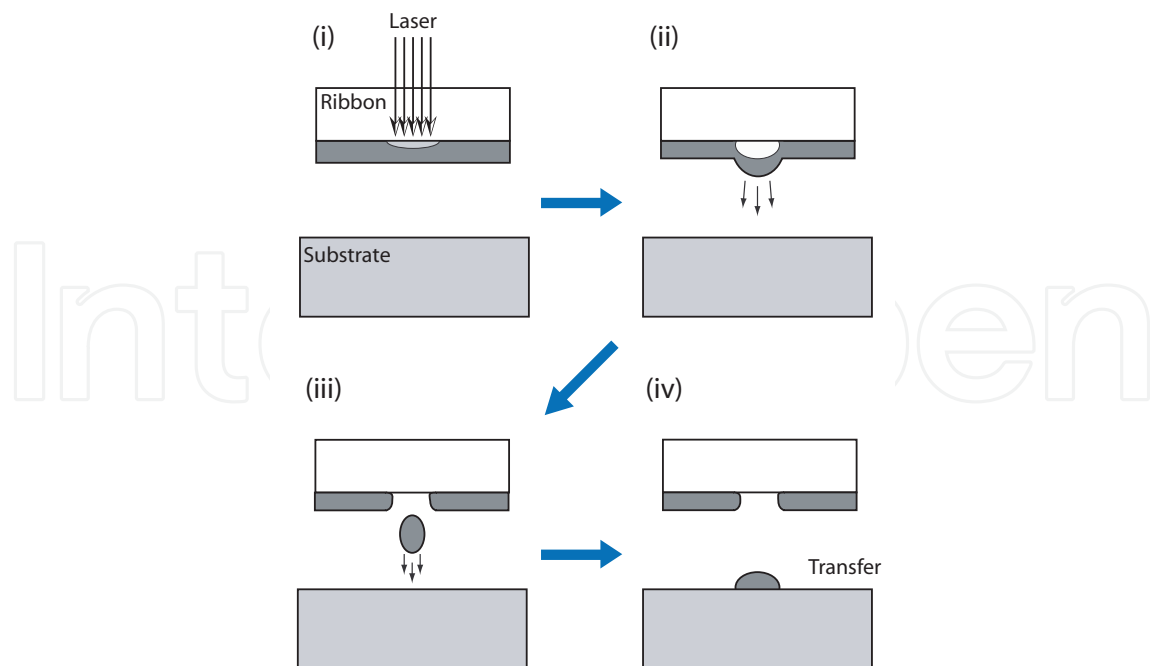


Fig. 3. Schematic representation of the steps involved in the forward transfer of viscous rheological systems during the LDW process. (i) The laser pulse is absorbed by the paste or ink layer at the interface. (ii) The absorption of the laser pulse heats and vaporizes a small fraction of the ink. (iii) A droplet or voxel of ink is ejected away from the donor substrate towards the receiving substrate. (iv) The ejected material is collected on the receiving substrate with little or no surrounding debris.

physical or chemical properties such as electrical conductivity, dielectric properties or electrochemical activity. As shown schematically in Figure 3, a small region of the laser absorbing ink interacts with a low fluence ( $< 100 \text{ mJ/cm}^2$ ) laser pulse causing a small amount of the ink to evaporate. As the resulting vapor expands, it generates shear forces that result in the ejection of a droplet from the film towards the receiving substrate, where it is deposited with its original rheological properties intact. The results obtained with transfers of extremely laser sensitive systems, such as buffer solutions containing biomaterials, proteins and living cells (Wu *et al.*, 2001), or electrochemically sensitive materials (Arnold *et al.*, 2002b; 2004b) confirm that most if not all of the transferred fluid does not interact with the laser pulse.

The uniqueness of the laser transfer of rheological systems resides in the fact that it represents a totally new approach to LIFT based on the non-phase transforming forward transfer of complex suspensions, inks or pastes. This is made possible by the reduced shear forces required to dislodge and release the portion of the coating in the donor substrate illuminated by a laser pulse, allowing the use of lower laser energy fluences, thus resulting in virtually no ablation of the transferred material. Given the diverse nature and large number of parameters affecting the laser transfer process for rheological systems, a simple description as the one provided in the previous paragraph cannot be expected to completely explain its behavior. For instance, it is known that laser parameters such as fluence, pulse duration and wavelength, laser beam dimensions and gap or distance between donor and acceptor substrates play an important role in the laser transfer of complex fluids or inks. Additionally, parameters such as the composition of the ink in the ribbon, its thickness, viscosity, solids content, solids particle size, and the surface chemistry and morphology of the receiving substrate greatly affect the

ability to transfer a particular fluid and the resulting morphology of the transferred voxels. The use of fast imaging techniques in order to be able to determine the timing and shape of the transfer front can provide a better understanding of the laser transfer of rheological systems.

### 3.3 Laser decal transfer

A shortcoming of the laser transfer of fluids or inks is the generation of satellite droplets during transfer that result in debris formation on the donor substrate with deleterious effects to the achievable resolution. The use of ribbons thinly coated ( $\leq 1\mu\text{m}$ ) with high viscosity ( $> 10,000$  cps) nanoinks or nanopastes has been shown to mitigate this problem (Auyeung *et al.*, 2007). This process, which has been termed laser decal transfer, offers the possibility for the laser transfer of patterns with feature fidelity and thickness uniformity comparable to lithographically patterned thin films (Piqué *et al.*, 2008a;b). This new approach represents a significant advance in LIFT-based direct-write processes given the improved spatial resolution (down to 2 microns), increased thickness uniformity (within 50 nm), sharper edge features and minimal surrounding debris compared to previous laser transfer processes. Figure 4 shows some examples of the types of features generated with laser decal transfer. The AFM image in Fig. 4(b) demonstrates the sharp edges and extreme thickness uniformity of the transferred voxels with their surface precisely matching the area of the transfer laser pulse. This unique capability to faithfully reproduce the size and shape of the laser spot by the laser-transferred nano-suspension relies in the use of thin and highly viscous nanoink layers in the ribbon. This nanoink can in turn be sheared away from the transparent donor substrate at very low laser fluences, usually below  $200\text{ mJ}/\text{cm}^2$ , without noticeable deformation or fragmentation of the released voxel.

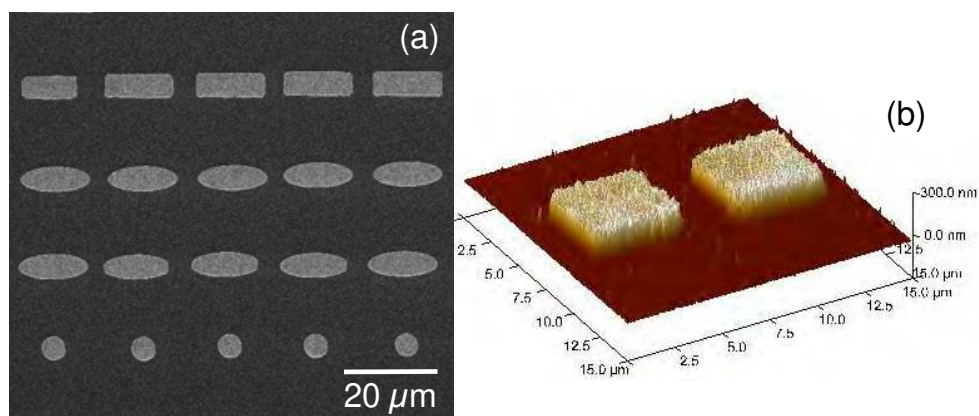


Fig. 4. Types of patterns and structures deposited using laser decal transfer of a silver nano-paste. (a) SEM image showing rows of patterns generated with different laser apertures. (b) AFM image showing in detail two square voxels transferred on a Si substrate.

The laser decal transfer process has great potential since it can minimize the time it takes for the digital microfabrication of a pattern or design by allowing the size and profile of the transferred voxel to be varied without loss in resolution. This means that with laser decal transfer it is now possible to generate the patterns required to digitally microfabricate interconnects, transmission lines, circuit repairs and even complete devices in considerably fewer steps (Piqué *et al.*, 2008b). This is possible since the shape and size of each "bit", i.e. voxel, required for the digital microfabrication of a pattern or design, can be changed

at will without loss of resolution during the laser decal transfer process (Auyeung *et al.*, 2011). One of the early applications of the laser decal transfer process was for additive repair of defective metal patterns in LCD displays (Piqué *et al.*, 2008b). Fabrication of arrays comprising of individual voxels with a specific geometry such as a split ring has also been demonstrated for applications requiring the rapid prototyping of resonators to operate at a particular band of the electromagnetic spectrum for metamaterial applications (Kim *et al.*, 2010a). More recently, the laser decal transfer process has also been applied to the fabrication of free-standing structures such as cantilevers and microbridges without the use of sacrificial layers (Auyeung *et al.*, 2009; Birnbaum *et al.*, 2010a). It is worth noting that lithographic techniques are not capable of generating free-standing structures without the use of sacrificial layers. Similarly, multilayer structures (Birnbaum *et al.*, 2010b) and cavity sealing membranes (Birnbaum *et al.*, 2011) have also been demonstrated via laser decal transfer. Such capabilities are unique among traditional direct-write or digital microfabrication processes.

### 3.4 Laser transfer of functional devices

The use of LIFT processes for the transfer and placement of prefabricated parts or components onto a receiving substrate was first reported by Holmes *et al.* (Holmes & Saidam, 1989). In their work, the authors describe the laser-driven release of Si-based microstructures from a UV-transparent substrate with an intermediate polymer sacrificial layer. Upon irradiation with an excimer laser pulse, a thin fraction of the sacrificial layer is vaporized, releasing the microstructure. This technique was later used to demonstrate the laser-assisted assembly of microelectromechanical devices from parts fabricated on separate substrates (Holmes, 2002). These initial results showed how to use the laser transfer process as an alternative to conventional pick-and-place approaches for the placement of electronic components such as passives and semiconductor bare dies. The basic concept relies in the use of a laser absorbing sacrificial release layer. In essence, it requires a sacrificial layer such as the polymer layer used by Holmes to attach the individual components to a UV-transparent support. A laser pulse then ablates the sacrificial layer generating gases that release and propel the component towards a receiving substrate placed in close proximity. This laser device-transfer process is contact-less and thus allows the transfer of very small and very thin components, which could easily be damaged by pick-and-place tools.

Recently, this concept has been applied to the laser transfer of semiconductor bare dies. Karlitskaya and coworkers have developed a simple model that predicts the fluence threshold for the release of  $200 \times 200 \mu\text{m}^2$  by  $150 \mu\text{m}$  thick Si dies held with a polyvinyl chloride (PVC) sacrificial layer (Karlitskaya *et al.*, 2004; 2006). The model shows that the release laser fluence is below the thermal damage threshold for the reverse side of the die ( $< 673 \text{ K}$ ) based on heat diffusion of the absorbed laser pulse through the Si substrate. In this case the authors applied the laser transfer process to devices with the active region facing opposite to the laser pulse. This configuration is not very practical since in order to establish the electrical connections between the pads on the transferred die and the acceptor substrate, extremely precise alignment is required. A better solution is to transfer the die with its active surface facing up enabling wire bonding tools or direct-write approaches to interconnect the device with the acceptor substrate. The challenge however, is to be able to illuminate the active region of the die with the transfer laser pulse without damaging it.

At the U.S. Naval Research Laboratory, this capability was demonstrated for the laser forward transfer of individual InGaN LED semiconductor substrates ( $250 \times 350 \mu\text{m}^2$ ) in bare die form, i.e. unpackaged, using a series of low fluence ( $\approx 150 - 200 \text{ mJ/cm}^2$ ) 10 ns pulses from either

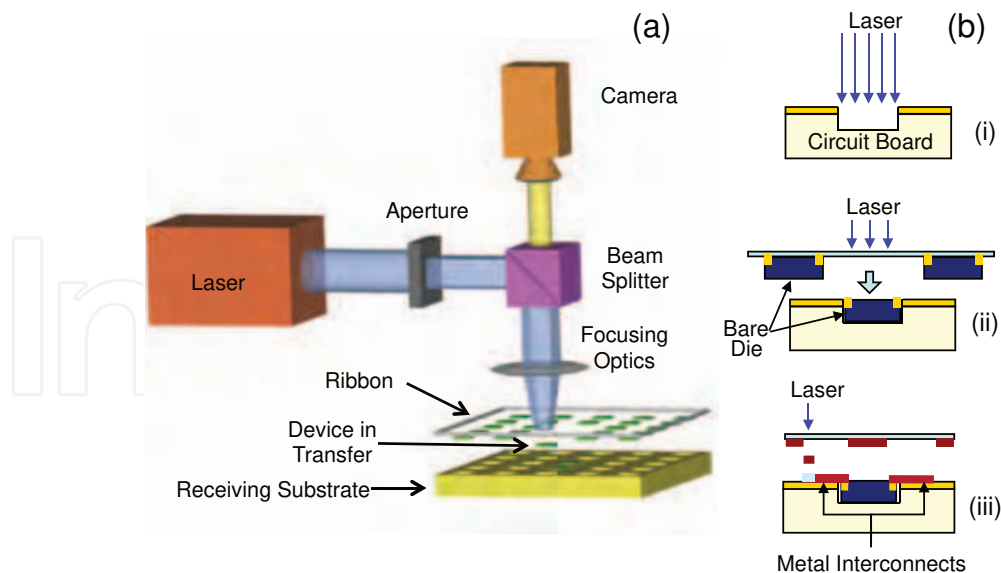


Fig. 5. Schematic diagrams showing: (a) the apparatus used for laser-and-place, and (b) the steps required to embed electronic components inside a substrate. The steps are: (i) laser micromachine the pocket on the substrate; (ii) transfer of the device using laser-and-place; (iii) laser printing of the interconnects to complete the circuit.

excimer (248 nm) or YAG (355 nm) lasers (Mathews *et al.*, 2007a). Once laser transferred, the LED's were electrically tested and their operation verified. This laser-driven pick-and-place of electronic devices has been named "laser-and-place" and is shown schematically in Figure 5. Figure 5(a) shows how a modified ribbon containing the devices to be transferred instead of an ink or paste is used in the laser-and-place process, while figure 5(b) shows the steps required to embed and interconnect an electronic device inside a substrate. The fact that the devices are not damaged upon laser illumination of their active surface and subsequent transfer demonstrates that a uniquely versatile laser-based component placement and interconnecting process can be developed by combining laser-and-place with laser printing of metallic inks. The laser-and-place technique has been used successfully to laser transfer a wide variety of components such as surface mount devices and semiconductor integrated circuits ranging in size from 0.1 to over 6 mm<sup>2</sup> in area (Piqué *et al.*, 2007a). This technique has also been shown to be compatible with the transfer of extremely thin ( $\approx 10 \mu\text{m}$ ) silicon substrates, which despite their fragility can be deposited by laser-and-place with extreme precision on the surface of an acceptor substrate without being damaged or fractured (Mathews *et al.*, 2007b; Piqué *et al.*, 2007b).

#### 4. Laser direct-write of devices and circuits

The continuing evolution of the laser direct-write process, as demonstrated by the numerous variants to the basic laser forward transfer techniques described in the previous sections, has been driven by the wide range of applications ready to benefit from the use of digital microfabrication processes. In fact, in most cases, a specific application has led to the development of new laser transfer techniques derived from the original approach. In the following sections, examples of the use of laser direct-write techniques for the rapid prototyping of embedded electronic devices and circuits are presented to illustrate the versatility and great potential of these laser-based digital microfabrication techniques.



#### 4.1 LDW of embedded passives

The capability offered by the various laser direct-write processes to conformally transfer viscous fluids, pastes or inks has been used with great success for the fabrication of metal interconnects, vias and antenna structures (Piqué *et al.*, 2003a; 2005). In fact, LDW processes have been used to deposit metallic screen printable inks over complex 3-D surfaces, which has always been extremely difficult, if not impossible, using traditional lithographic processes. Typically, a commercially available screen printable silver paste is used for the ink. The laser spot size is adjusted depending on the required line-width of the metal lines. Once the transfers are completed, the acceptor substrate (usually printed circuit board) is baked at 100 - 150°C to obtain the final metallic silver patterns. The electrical resistivity of these patterns ranges between 3 to 50 times higher than that of bulk silver depending on the silver ink used and the baking temperature. The adhesion and mechanical properties of patterns made by LDW are very good, as indicated by tape and flexing tests (Piqué *et al.*, 2003a). Overall, the ability to deposit conformal metal patterns on substrates at low temperatures allows for the fabrication of novel types of electronic designs such as conformal GPS antennas (Auyeung *et al.*, 2004) on polymer radomes. By adjusting the viscosity of the silver ink is also possible to achieve patterns with resolutions compatible with the requirements for electrodes in organic thin film transistors. In these applications, deleterious effects due to wetting issues between ink and substrate limit the resolution and gaps between the source and drain electrodes achievable with other direct-write processes such as inkjet (Kim *et al.*, 2009; 2010b). Similarly, LDW of thick film polymer or ceramic pastes has been used to fabricate passive electronic components such as resistors (Modi *et al.*, 2001) and interdigitated capacitors (Young *et al.*, 2001). The use of LDW to fabricate simple electronic circuits comprising of several passive components and their interconnects has been demonstrated as in the case of a simple chemoselective gas sensor circuit (Piqué *et al.*, 2002b) and RF filter test structures (Zhang *et al.*, 2003).

#### 4.2 LDW of embedded sensors

Digital microfabrication of embedded sensors using laser direct-write is another example of the capabilities of these non-lithographic techniques for the rapid prototyping of entire functional circuits. The first type of sensor devices made by LDW were chemical vapor sensors that relied on the ability of chemoselective polymers loaded with graphite particles to reversibly change its volume in the presence of vapors from a solvent (Piqué *et al.*, 1999a,b). Upon exposure, the chemoselective polymer (polyepichlorohydrin or PECH) expands increasing the average distance between its graphite particles and thus exhibiting an increase in its electrical resistance. Figure 6(a) shows a photograph of a chemiresistor sensor element (black portion) laser printed across a set of silver interdigitated electrodes also fabricated by LDW (Piqué *et al.*, 2003b). Figure 6(b) displays the change in resistance as a function of time for this sensor element as it is challenged with vapors containing various concentrations of solvents (acetone in this case). Note that this simple laser printed sensors is capable of detecting vapor traces down to the parts per million (ppm) range.

Figure 7 shows an image of a fully operational chemiresistor sensor circuit with a chemiresistor sensor element, Ag metal interconnects and polymer thick film (PTF) resistors all made by LDW (Piqué *et al.*, 2003c,d). The 4-Quad comparator device chip and the surface mount LED components were soldered to the silver interconnects and power to the circuit was provided by an external battery. In the presence of organic vapors, the resistance change across the chemiresistor sensor caused the 4-Quad comparator to sequentially light up individual

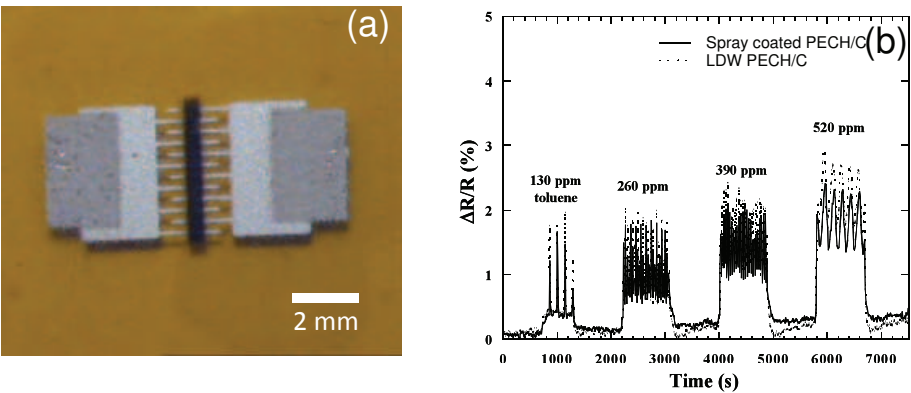


Fig. 6. Example of an embedded chemical sensor fabricated using laser direct-write. (a) Chemiresistor gas sensor element (black stripe) and associated interdigitated silver metal electrodes (grey) on a polyimide substrate. (b) Change in resistivity vs. time for a typical laser printed chemoselective sensors when exposed to toluene.

LED's depending on the magnitude of the change in resistance across the sensor, proportional to the vapor concentration.

At the U.S. Naval Research Laboratory laser-based direct-write techniques have been employed in the fabrication of other types of small size sensor devices such as temperature (Piqué *et al.*, 2003c) and strain sensors on polyimide substrates (Piqué *et al.*, 2003d), and simple electrochemical biosensors for the detection of small concentrations of dopamine on aqueous solutions (Wu *et al.*, 2003). Other groups have used laser transfer techniques for depositing micro patterns of tin oxide layers with various oxygen ratios, which have potential application as gas sensors (Komorita *et al.*, 2003). More recently, a capacitive chemical sensor array was produced using LIFT by laser transferring three different types of polymer materials sensitive to organic solvent vapors. Droplets of each polymer in solution were deposited onto an array of thin silicon membranes to demonstrate a micromechanical capacitive vapor sensor (Boutopoulos *et al.*, 2008).

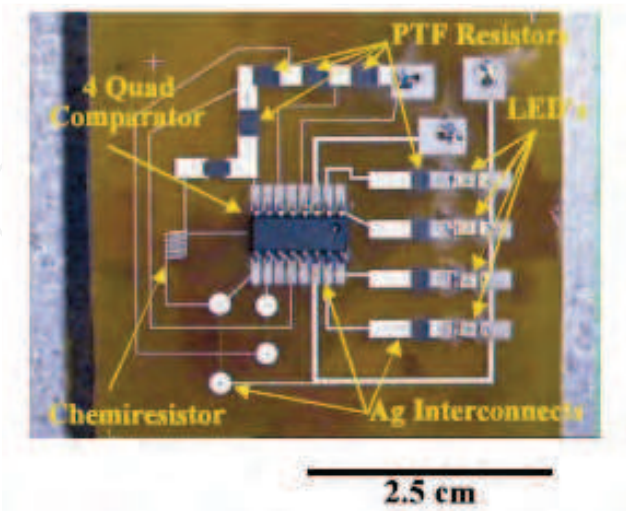


Fig. 7. Fully functional gas sensor circuit with chemiresistor sensing element and LED flashing indicators.

### 4.3 LDW of embedded microbatteries

Laser direct-write has been applied with great success to the laser printing of materials present in electrochemical micropower sources, such as ultracapacitors, batteries, and dye sensitized solar cells (Arnold *et al.*, 2002a;b; 2003; Kim *et al.*, 2004). These micropower sources require the use of materials with a large degree of structural complexity, such as nanocomposites, solid-state polymers, liquids, or mesoporous mixtures of electrochemically active materials. Any technique designed for the fabrication of electrochemical micropower sources must be able to deposit the above types of materials while maintaining their electrochemical activity and structural integrity. This in turn limits significantly the type of direct-write process that can be used.

One of the important attributes of laser printing in the context of electrochemical systems is that it allows for the deposition of highly porous, multicomponent materials without modifying their properties. In all cases, the technique results in uniform transfer of the structurally complex materials with a porous structure that allows for good electrolyte penetration. Another key advantage of LDW in constructing electrochemical cells is the flexibility in the design of operating geometries. The two main approaches include placing the anode and cathode adjacent to each other in the same plane (planar), or layering the anode and cathode on top of one another (stacked). For instance, in the case of stacked geometries, one can obtain higher area densities and lower resistances owing to the relatively thin separator layer, but this layer must be structurally stable enough to support the anode/cathode/current collectors. Furthermore, by combining LDW with laser ablation to micromachine the substrates, it is possible to reduce packaging difficulties by embedding the electrochemical components directly within a substrate, further reducing the packaged size of an entire microdevice while allowing its geometry to be adapted to fit virtually any form factor.

Planar alkaline microbatteries can be constructed with electrodes formed from different materials such as Zn for the anode and  $\text{Ag}_2\text{O}_3$  for the cathode (Piqué *et al.*, 2004a;b). The laser transfer process can include the KOH electrolyte in the complex suspensions or inks and thus generate various planar geometries such as parallel, interdigitated, or ring structures ready for operation. Laser micromachining can be used afterwards to maintain electronic isolation between the electrodes and overall sharp interfaces across the device structures. In this manner, 1.5 V alkaline microbatteries with an energy density of more than  $0.6 \text{ mW h/cm}^2$  and specific energy of more than  $160 \text{ mW h/g}$  have been demonstrated (Arnold *et al.*, 2004a).

Although planar structures are relatively easy to construct, stacking the electrodes can provide a greater interface area for the microbattery structures and reduced contact resistance. One approach taken is to laser print the electrodes on separate current collectors and then manually assemble the layers (Wartena *et al.*, 2004). A better approach is to LDW a nanocomposite solid polymer ionic liquid between the electrodes to directly generate stacked structures that are rigid enough to support the upper layers without compromising their electrochemical performance. The nanocomposite polymer ionic system serves as the separator and solid electrolyte simultaneously, since this material has high ionic conductivity yet it is chemically and structurally stable (Ollinger *et al.*, 2006a;b). LDW has been used to deposit sequential layers of the cathode material ( $\text{LiCoO}_2$  or  $\text{LiMnO}_4$ ), nanocomposite polymer, and the anode (carbon) into a laser-micromachined pocket on a thin polyimide substrate for embedded Li-ion microbatteries. These layered structures are significantly thicker ( $30\text{--}50 \text{ }\mu\text{m}$ ) than a typical sputter-deposited thin-film microbattery structure ( $1\text{--}5 \text{ }\mu\text{m}$ ) yet thin enough to remain entirely embedded in the substrate. These batteries are shown to be rechargeable for more

than 100 cycles with an energy density of more than  $1.3 \text{ mW h/cm}^2$  (or  $0.4 \text{ mW h/cm}^3$  based on volume) (Sutto *et al.*, 2006). Figure 8(a) shows a photograph of two packaged Li-ion thick film microbatteries made by LDW designed to be embedded inside the laser machined pockets on the printed circuit boards shown next to the cells. The microbattery on the top shows the copper current collector corresponding to the anode side (–), while the bottom microbattery is shown embedded with the aluminum current collector, i.e. cathode (+) side, facing up. A SEM cross section from one of these microbatteries, showing each of the above described layers, is displayed in Fig. 8(b).

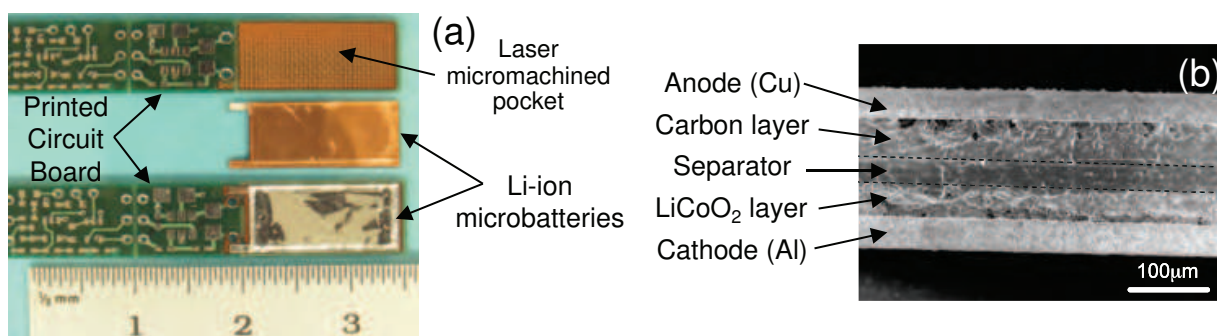


Fig. 8. (a) Optical micrograph showing two sealed Li-ion microbatteries made by LDW, with the bottom microbattery shown embedded inside a printed circuit board. (b) Cross-section SEM image clearly showing each layer from one such microbattery.

Li-ion microbatteries made by LDW with thicker cathodes and anodes (each over  $100 \mu\text{m}$  thick) have been demonstrated for embedded electronics applications (Kim *et al.*, 2007). The high porosity of the laser transferred active electrode layers allowed their thickness to be increased without sacrificing their performance. State-of-the-art sputter-deposited thin-film Li-ion microbatteries cannot be made thicker than a few microns before losses due to their very high internal resistance compromise their performance. LiCoO<sub>2</sub> cathodes up to  $115 \mu\text{m}$  and carbon anodes up to  $130 \mu\text{m}$  in thickness were laser transferred to demonstrate Li-ion microbatteries with maximum power densities of near  $40 \text{ mW/cm}^2$  at current densities of  $10 \text{ mA/cm}^2$  (Kim *et al.*, 2007). For lower current densities ( $100 \mu\text{A/cm}^2$ ), discharge capacities in excess of  $2500 \mu\text{Ah/cm}^2$  have also been demonstrated with these thick-film microbatteries (Kim *et al.*, 2007). These discharge capacities are over an order of magnitude higher than what has been achieved with sputter-deposited Li-ion microbatteries ( $\approx 160 \mu\text{Ah/cm}^2$ ) (Bates *et al.*, 2000).

It is worth concluding this section with a brief discussion of other components required for the development of self-contained and autonomous microelectronics. Such systems would include fully integrated embedded micropower sub-systems capable of harvesting energy from the environment to replenish the limited power stored in their microbatteries and storage devices capable of discharging at very high rates without sustaining damage such as ultracapacitors. For example, combining a micropower generator capable of harvesting solar energy with the various microbatteries previously described (as well as ultracapacitors), would allow the development of truly autonomous microsystems which could operate without interruption and the need of service or maintenance schedules. Towards this end, laser direct-write techniques have been applied to digitally microfabricate prototype nanoparticle TiO<sub>2</sub>-based dye sensitized solar cells with greater than 4% conversion efficiencies (Kim *et al.*, 2004). The use of local laser sintering for the TiO<sub>2</sub> nanoparticles



has also been investigated to develop the ability to process the entire die sensitized solar cell at low-substrate temperatures to enable a large carrier lifetime without destroying the high-surface-area mesoporous structure (Kim *et al.*, 2006).

4.4 Lase-and-place of embedded passives and ICs

The development of embedded surface mount devices (SMDs), semiconductor bare die integrated circuits (ICs), interconnects and power source elements, offers the ability to achieve levels of miniaturization beyond the capabilities of current manufacturing techniques. Given an arbitrary circuit design, significant reductions in volume and overall weight can be achieved by using embedded components. Furthermore, embedded circuits exhibit higher device density and improved electrical performance, resulting in enhanced functionality within a given form factor.

The use of laser direct-write techniques for the fabrication of electronic circuits has been demonstrated for the fabrication of fully functional embedded microelectronics (Piqué *et al.*, 2004a; 2005; 2006). For example, a simple blinker circuit comprised of six passive SMD components (4 resistors and 2 capacitors), two SMD LEDs and one unpackaged IC (LM555 chipset in bare die form) was embedded in ULTEM, a thermoplastic polyetherimide substrate, using LDW as shown in Figure 9. Laser micromachining was used to generate the pockets in the substrate wherein each component was buried. Once in place, the components were planarized with a layer of polyimide. The interconnects required by the circuit were made by laser micromachining blind vias to expose the contact pads on each device. The metal interconnects were then generated by laser printing a conductive silver ink. The resulting embedded circuit occupied a footprint smaller than a single packaged LM555 chip as shown in Figure 9(a). Figure 9(b) shows a close up of the LM555 chip with its laser printed silver interconnects. It is estimated that these LDW embedded circuits can occupy footprints of about 1/4 or less and require less than 1/10 of the thickness of a printed circuit board design, resulting in an overall circuit volume reduction of near two orders of magnitude. This shows that by using LDW processes it is possible to fabricate functional electronic circuits buried under the surface, with the surface or substrate serving both as circuit board and enclosure.

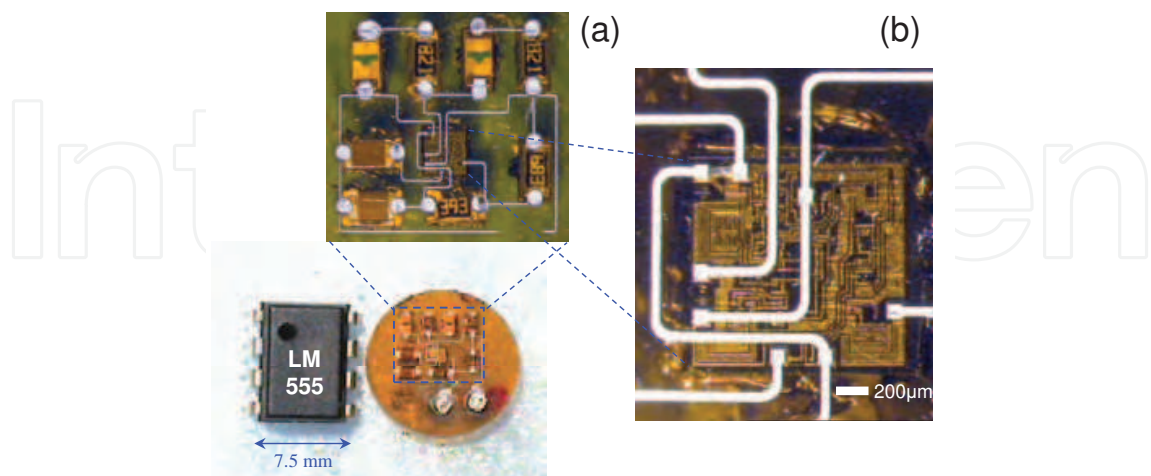


Fig. 9. Embedded circuit made by LDW. (a) Optical micrograph of the embedded circuit with a LM555 timing bare-die semiconductor chip at the center and shown to scale next to a packaged LM555 chip for size comparison. (b) Higher magnification micrograph showing the laser printed interconnects over the LM555 chip.



#### 4.5 Laser decal transfer of free-standing interconnects

Earlier in this chapter, the printing of free-standing structures was discussed using the laser decal transfer process. This capability is highly relevant since continuous microbridges spanning gaps of tens of microns can be deposited without the need for sacrificial layers which have to be etched afterwards. These microbridges are made by laser decal transfer of high viscosity silver nanopastes that once cured at temperatures between 150 to 200°C become metallic (Auyeung *et al.*, 2009). An example of such a free-standing bridge is shown in the SEM image in Figure 10(a). In fact, the shrinkage that takes place during the sintering of the nanoparticles gives rise to microbridges in tension, which keeps them from sagging and therefore, making contact with the bottom of the trench or gap. On the other hand, the adhesion of the silver nanopaste to the substrate has to be very high to avoid de-lamination of the anchor point at both ends of the microbridge. Examining the microbridge shown in Fig. 10(a) reveals very good adhesion of the silver nanopaste to the substrate.

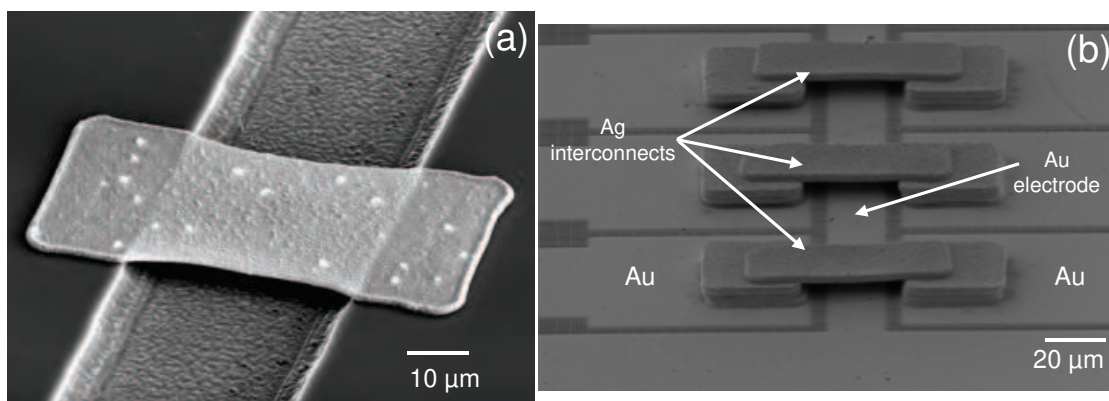


Fig. 10. SEM images showing examples of free-standing structures by laser decal transfer. (a) Free standing silver microbridge laser deposited across a trench on a silicon substrate without the use of sacrificial layers. (b) Posts built by stacking square voxels topped by rectangular voxels to form interconnects over an existing electrical pattern.

The ability to laser decal transfer voxels of material over a surface can also be used to fabricate interconnects over existing patterns on a circuit. As the SEM image in Figure 10(b) reveals, the ability to first stack square voxels on each side of a circuit line to create posts and then print a rectangular voxel spanning the gap between the posts has been demonstrated by laser decal transfer (Piqué *et al.*, 2011). This is very important since it shows the rapid prototyping of free-standing interconnects that can be used to replace traditional wire bonding schemes (Wang *et al.*, 2010). All these capabilities of the laser decal transfer, combined with laser micromachining of a recess on a substrate are demonstrated in Figure 11. In this figure, the steps required in the laser embedding and laser interconnection of a bare die LED device are shown, together with a photograph of the LED in operation demonstrating its functionality. As the figure shows, the laser direct-write techniques here described allow the rapid prototyping of embedded microelectronics with the use of the same laser-driven tool. Such capability is not available with lithography and represents a huge step forward in rapid prototyping as applied to the fabrication of functional embedded microelectronics.

#### 5. The future of LDW in rapid prototyping of microelectronics

For commercial, aerospace and military applications, miniaturization and functionality are key aspects where the driving force is the need to achieve enhanced capabilities within

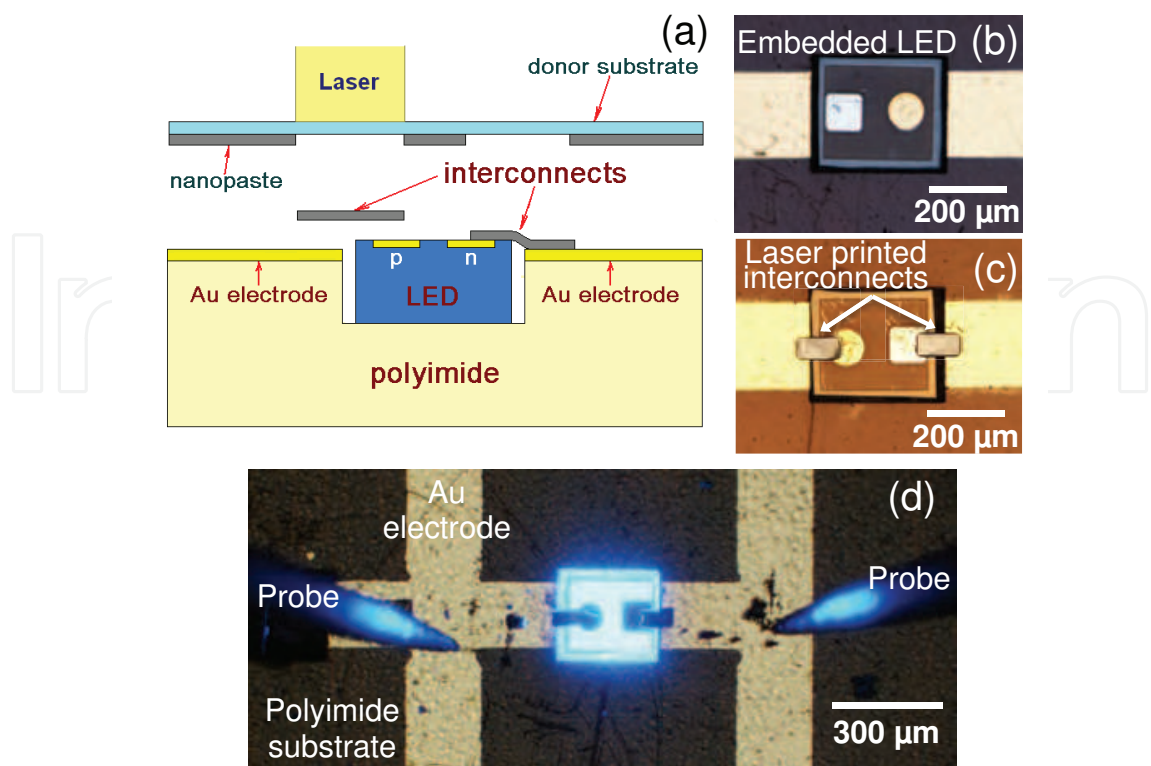


Fig. 11. Use of laser decal transfer for the printing of interconnects. (a) Schematic showing the laser decal transfer of interconnects onto an embedded LED device. (b) Optical micrograph showing a bare die LED embedded inside a polyimide (Kapton) substrate. (c) Optical micrograph of the same LED device after the interconnects were laser decal transferred. (d) Optical micrograph showing the functional LED powered through the probe tips on the sides.

any given form factor. Many times, traditional lithographic fabrication techniques cannot deliver the required solution due to cost, time constraints or process limitations. Digital microfabrication techniques such as laser direct-write can offer a viable alternative in such situations (Piqué *et al.*, 2009).

The benefits of laser direct-write are numerous, particularly in cost reduction for prototyping, customization and production, reduction in processing steps, and greater design freedom due to its geometrical and material versatility. As the previous sections have shown, laser-based transfer techniques offer a wide range of applications with the potential to expand into large volume manufacture. Clearly, LDW is still an emerging technology with developmental challenges remaining to be solved. However, the opportunities for LDW and other digital microfabrication processes are real and how the technique evolves and where it is applied might determine its future success. Given that LDW is a laser materials processing technique which takes advantage of the unique properties offered by the laser radiation that serves as its source of energy, its applications in the field of digital microfabrication should grow and evolve with time. Some of these properties, such as wavelength, intensity and spatial profile of the laser beam combined with control of the width and energy temporal profile of the laser pulse give LDW a clear advantage over other more popular digital microfabrication techniques such as ink-jet.

### 5.1 Comparison with other digital fabrication processes

The application of digital microfabrication technologies and processes span a wide range of industries including microelectronics, opto-electronics, aerospace, military, pharmaceutical, biomedical and medical. This is in part due to the ability of digital microfabrication techniques to process virtually any type of material over a wide range of dimensions ranging from the mm to the submicron scale. One of the best established direct-write process which offers a great potential for digital microfabrication is ink-jet. However, despite the great progress achieved with ink-jet and the large R&D investment made to develop the technology, ink-jet is limited to only additive processes. Furthermore, with ink-jet, the constraints imposed by the narrow nozzles required to achieve finer features limit its applicability to very low viscosity inks. Such inks might not be available for many types of materials, such as those required for the microfabrication of batteries and solar cells. Moreover, for other applications such as electrical interconnects and electrodes, thicker patterns generated from inks or pastes with a heavy solids content might be more effective. For example, high quality gate and source/drain electrodes for organic thin film transistors (OTFTs) made from laser printed silver nano-inks have been demonstrated (Kim *et al.*, 2009; 2010b). When the source and drain electrodes were laser printed on top of the pentacene organic semiconductive layer, the resulting top-contact OTFTs exhibited reduced contact resistance and improved device performance when compared with similar bottom-contact devices. Top-contact OTFTs are very difficult to fabricate by ink-jet because the organic solvents present in the low viscosity metallic inks tend to dissolve or etch the organic layer as soon as they come in contact with it. These are some examples of applications where laser direct-write offers the most opportunities given its capability to remove material, by ablative processes, and through laser forward transfer, to deposit complex solutions or suspensions of a wide range of viscosities, particle size and solids loading. In fact, laser forward transfer remains a leader in the field of digital microfabrication given its great versatility with materials and surfaces.

The benefits of LDW are plentiful, particularly in cost reduction for prototyping and production, manufacture simplification (through the reduction of production steps), and greater design freedom due to its geometrical versatility. As the material is only deposited on-demand, little material is wasted and greater efficiencies and lower environmental impact can be achieved. LDW offers a very wide window of applications ranging from R&D and prototyping to high-throughput production. Many applications have already been identified with many more awaiting development.

Key challenges for laser direct-write techniques are the establishment of design rules, process modeling and optimization, integration of the devices and systems fabricated, metrology and evaluation of the performance of the patterns and devices generated, and long term reliability of the LDW-made parts. Solving these challenges will require a considerable investment in funds, effort and time, but as commercial applications develop and the electronics and aerospace industries embrace laser-based digital microfabrication processes these issues will be addressed in due time. With increasing development and opportunities in micro- and nano-systems combining electronics, optical, fluidics and bioactivity, LDW will play a significant role in the new paradigm offered by digital microfabrication for rapid prototyping applications.

## 6. Summary and outlook

The ability to laser direct-write many types of materials over virtually any surface at room temperature and without the need of a special environment or vacuum conditions

represents a paradigm shift in microfabrication processes for rapid prototyping applications. These LDW techniques are ideally suited for digital microfabrication applications and offer opportunities for the generation of patterns, structures and devices not possible with traditional photolithographic tools. Because they are non-lithographic processes, laser transfer techniques are ideal for rapid prototyping applications, allowing the design, fabrication and testing of a given structure to be completed quickly. As this chapter has shown, LDW techniques can be used for many different types of applications. Some examples of the applications described include metal patterns for interconnects, antennae and circuits, as well as chemical sensors and microbatteries. LDW processes have been used with great success for embedding microbatteries for energy storage, as well as embedded prototype microelectronic circuits. In each case, the ability to transfer complex inks or pastes from a ribbon to an acceptor substrate at room temperature without changing their physical, chemical or biological properties is one of several unique attributes of the LDW process.

The recent development of LDW techniques for the transfer of preformed devices such as semiconductor bare dies, and for embedding microbatteries and simple electronic circuits, opens the door for their use as a unique laser-based microelectronics fabrication tool. Such a tool would be capable of fabricating and embedding electronic circuits with the required power storage and power harvesting components within the same substrate. The resulting fully integrated systems could easily be reconfigured to fit within a desired form factor, thus allowing the placement of electronic systems in places inconceivable today. In fact, the functionality of these digitally microfabricated circuits can be customized for a particular application by choosing the appropriate electronic modules or building blocks from a circuit library available in the LDW tool. Such a laser-based digital microfabrication system does not yet exist, but it is just a matter of time before the various processes described in this chapter are combined into a single rapid prototyping machine capable of making this vision a reality. In fact, based on their success to date, it is most likely that laser direct-write techniques will play a significant role in rapid prototyping of embedded microelectronics sooner rather than later.

## 7. Acknowledgements

The author would like to thank all the members of the laser direct-write group at NRL. Special thanks to Nick Charipar, Kristin Metkus, Heungsoo Kim, Ray Auyeung, Andrew Birnbaum, Jiwen Wang and Scott Mathews. This work was sponsored by the U.S. Office of Naval Research.

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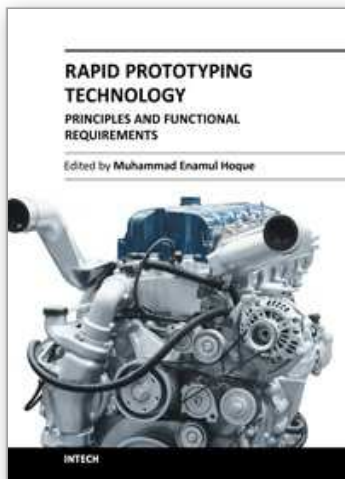
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Edited by Dr. M. Hoque

ISBN 978-953-307-970-7

Hard cover, 392 pages

**Publisher** InTech

**Published online** 26, September, 2011

**Published in print edition** September, 2011

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