Use of Laser Direct-Write in Microelectronics Assembly

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The use of a laser-based direct-write (LDW) process is presented for the transfer of unpackaged semiconductor bare die for microelectronics assembly applications. Previous work using LDW techniques at the Naval Research Laboratory had been aimed towards demonstrating the use of a laser-based microfabrication process for direct-writing the materials required for the fabrication of microelectronic components such as interconnects, passives, antennas, sensors and power sources. Recently, we have applied the LDW process in forward-transfer mode to the release and transfer of single devices, such as semiconductor bare die, inside a pocket or recess in a substrate, thus performing the same function as pick-and-place machines used in circuit board assembly. The use of this technique is ideally suited for the assembly of microelectronic components and systems while allowing the overall circuit design and layout to be easily modified or adapted to any specific application or form factor. This paper presents examples of how the LDW process can be used as an effective laser die transfer tool and analysis of the laser-driven release process as applied to various types of silicon bare dies.

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1. Introduction

The development of embedded electronic circuits comprising surface mount devices, interconnects, IC's and power sources promises to make possible levels of miniaturization well beyond the capabilities of current circuit 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. 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 of embedded bare dies need to be considered. Presently, each singulated bare die has to be handled by pick-and-place tools or by hand in order to be placed in the required pocket where is then embedded. These approaches are ineffective when handling small (< 0.2 mm^2) or very thin (~ 50 μm) dies, or for high throughput applications.

The use of laser-based die transfer processes as an alternative to conventional pick-and-place might be the best approach for the embedding of bare dies. The concept is simple in principle: have each component mounted on a laser transparent support using an intermediate polymer sacrificial layer. Upon exposure to one or several laser pulses, the sacrificial layer is ablated, and the generated vapors release and propel the component away from the support. Assembly is achieved by aligning the supported device over the pocket where it is to be embedded. This process can be carried out at great speeds (~ 1 ms/device) with great lateral precision (< 50 μm) for short travel distances away from the support.

The use of laser-based transfer processes for the release and assembly of structures or devices was first studied by Holmes et al. [1,2]. In their work, the authors demonstrated for the first time, the use of laser-transfer processes for the batch assembly of MEMS structures. Despite the success obtained with MEMS structures, the application of this process to the transfer of functional semiconductor bare die has yet to be reported. It is important to distinguish the laser-based transfer process from the well established laser lift-off technique, which can be used to release functional bare die devices such as individual GaN *pn*-diodes without degrading their performance [3]. In laser lift-off, the devices are separated from a bonded structure, due to the laser-induced melting of an intermediate layer. However, in this technique, the devices are never transferred across a gap. More recently, Karlitskaya et al. proposed a thermal model for the laser-release process of relatively small Si die (200 μm x 200 μm) [4]. Their model showed that the release threshold is below the thermal damage threshold for the reverse side of the die (< 673 K), based on heat diffusion of the absorbed laser pulse through the Si substrate. In their work, the backside of the die was exposed to the laser pulse, thus protecting the front patterned side from damage due to excessive heating. However, the authors do not discuss whether or not the dies are functional after transfer. This configuration is not very practical for embedding individual devices, due to the difficulties in establishing the electrical connections to the pads on the patterned side of the die, which end up facing the bottom of the pocket in which the device has been embedded. A better approach is to transfer the die with its patterned or active side facing up, enabling direct-write approaches to print the electrical interconnects to each pad on the die. The challenge, however, is to be able to illuminate the active region of the die with the laser release/transfer pulse without damaging it.

In this paper, we demonstrate that utilizing the right type and amount of sacrificial polymer it is possible to laser transfer front facing semiconductor bare dies without damaging them. The process was demonstrated to efficiently transfer devices with sizes ranging from 0.1 to over 6 mm^2 in area. These results show that the LDW technique can be used effectively as a laser-based device transfer tool for the embedding of semiconductor bare die IC's under the surface of circuit boards and other plastic substrates.

2. Laser-based direct-write processes

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 [5]. 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 (ablation). The later is better known as laser micromachining and allows the generation of the pockets where the devices are to be embedded inside the substrate. Subtractive LDW can generate patterns by either moving the substrate or scanning the laser beam or a combination of both. In additive mode, the LDW technique behaves effectively as a "functional materials printer". In this mode, the system utilizes a laser-forward transfer process for the deposition of metals, oxides, polymers and composites under ambient conditions onto virtually any type of surface. This laser printing process has been used with great success in the fabrication of sensors, microbatteries, interconnects, antennae and solar cells [6,7,8,9]. More recently, LDW techniques have been utilized in the fabrication of embedded electronic devices and circuits, were interconnects were laser-printed onto the contact pads of bare die without damaging the thin metal layers [10,11]. It is also possible to use the LDW technique to transfer entire single devices such as the semiconductor bare die embedded in our previous work, inside a pocket or recess in a substrate, thus performing the same function of pick-and-place machines used in circuit board assembly, as described in this paper. In principle this means that using a single LDW system it is possible to print, transfer or assemble all the components required to make a fully functional microelectronic circuit.

3. Experimental

Bare die were first loaded onto a low adhesion, "die transfer tape". The die transfer tape was fixed on a glass microscope slide using "double stick" tape. A thin layer of FSC-L surface coating (Microposit, Inc.) was spin-coated on a quartz wafer at 1,400 rpm for 15 seconds. The slide containing the devices was pressed, device side down, onto the wet FSC-L layer. A small weight (20 grams) was placed onto the assembly, which was then dried at 100°C for 30 minutes. The glass side with the transfer tape was then removed, leaving the devices glued to the quartz wafer by a thin layer of dried FSC-L surface coating. The quartz wafer was then rinsed for 2 to 4 minutes in methanol to remove unwanted FSC-L. This resulted in an array of devices glued to the quartz wafer on small "pedestals" of FSC-L.

The quartz wafer was then mounted, device side down, onto a cantilever extending from an X-Y translation stage. The wafer was positioned in the system (shown schematically in figure 1) under the objective and in the field of view of the camera, such that the devices could be exposed to a UV laser pulse and imaged simultaneously.

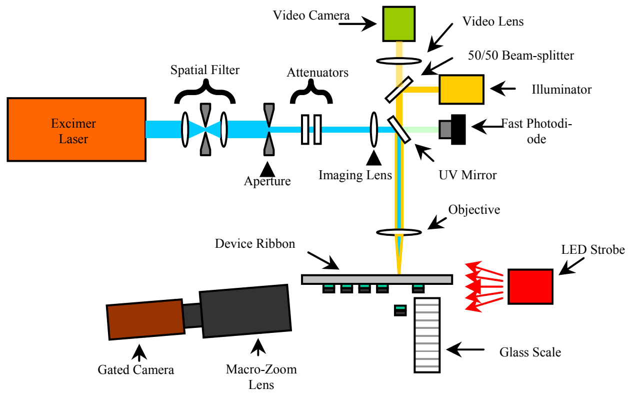

Fig. 1 Schematic of die transfer imaging apparatus.

The transfer and strobe imaging of a device is controlled with a Stanford Research, DG535 Digital Delay/Pulse Generator. The DG535 is manually triggered, and generates two pulses, designated AB and CD. The AB pulse is coincident with the manual trigger and triggers a Pixelink PL-A781, Firewire camera to acquire a single frame. The Pixelink camera requires approximately 12 msec to clear the image buffer, reset, and begin integrating the subsequent image frame. The CD pulse from the DG535 is therefore delayed by 12.5 msec, to ensure that the entire event is captured by the camera. The CD pulse triggers the firing of a single laser pulse from a Lambda Physik, LPX300 Excimer Laser (248 nm). The delay between the rising edge of the CD pulse and the arrival of the laser pulse at the die was measured to be less than 2 µsec. The CD pulse is also routed to a HP, 214B Pulse Generator. The 214B is operated in a gated mode, such that it generates a series of 1 µsec pulses at variable frequency. The 214B pulses trigger a Stoker-Yale, 3000SD LED strobe driver. The LED strobe outputs 1µsec, optical pulses (660 nm) which illuminates the device "in flight". By changing the duration of the CD pulse from the DG535 and the frequency of the 214B, the LED strobe can be programmed to emit an arbitrary number of flashes, with an arbitrary delay between flashes. For this work, we used 4 or 5 flashes with delays from 140 to 450 µsec between flashes.

The beam from the LPX300 laser was spatially filtered and directed onto a circular, metal aperture. A 50 cm focal length lens was used to image the aperture, through the objective, onto the device under test. A 10 cm focal length lens was used as an objective, giving a 5-to-1 demagnification of the aperture. This arrangement resulted in a uniform, "flat-top", illumination of a 1.41 mm diameter area at the device. In general, a single laser pulse was sufficient to release each bare die.

A fast photodiode (ThorLabs, DET210) was placed behind the last UV turning mirror. Because the mirror reflects only 97% of the incident UV, the 3% leaking through the mirror can be used to measure the energy of each laser pulse. A Scientech H310 power meter placed parallel to the ribbon after the objective, but beyond the focal plane (to avoid damaging the detector surface) was used to calibrate the photodiode prior to the transfer experiments. Simultaneous readings of the power meter and the photodiode voltage output were taken over the full range of laser energies used for this work. Coarse adjustments of the delivered pulse energy were performed by changing the high voltage settings on the LPX300 laser. Finer adjustments were achieved by placing a series of quartz plates in the beam, between the aperture and the imaging lens. For the present work, the delivered fluence was adjustable and measurable from about 150 to 1400 mJ/cm^2.

An ordinary video camera and visible illuminator were placed in such a way that the device under test could be viewed through the objective. This allowed the operator to position the device at the center of the UV illuminated area and to confirm the transfer of the device.

The Pixelink camera viewed the device under test through a Computar, 35 mm, macro-zoom lens. The LED strobe illuminator was positioned behind the device under test, pointed toward the camera, such that the camera imaged the shadow cast by the device.

A series of device "ribbons" were assembled as described above. They included 0.25 mm by 0.25 mm InGaN LEDs, 1.2 mm by 1.2 mm LM555 bare die, and 2.6 mm by 2.6 mm ASIC bare die. Additionally, several 1 mm by 1 mm "dummy" bare die were cut from a 500 μm thick silicon wafer, in order test the system.

Extensive measurements were performed using these Si "dummy" devices in order to study the effect of laser fluence on the transfer kinetics. Actual bare die devices were tested once the lower laser fluence levels for release were determined, in order to verify that the devices were fully functional after transfer.

4. Discussion

The apparatus shown schematically in figure 1 was used to measure the velocity as a function of laser fluence for a series of 1 mm by 1mm, "dummy", devices.

Figure 2 shows a multiple exposure, shadow image of a device during laser transfer. A glass scale with 1 mm rulings was used to gauge the distance traveled by the device between exposures. The device in Figure 2 is clearly rotating, although the rate of rotation is such that the device turns approximately 90^o in 5 mm. This image is characteristic of most the transfer images acquired in this study.

A 2.6 mm by 2.6 mm ASIC bare die was used to measure the transfer kinetics of a larger device. Figure 3 shows a multiple exposure, shadow image of a 2.6 mm square device during transfer. This device shows more rotation during transfer than the device in figure 2. It is worth noting that under normal conditions the gap between the ribbon and the substrate is only a fraction of a millimeter and for such short distances the rotation of the devices much less than what is shown in figures 2 and 3.

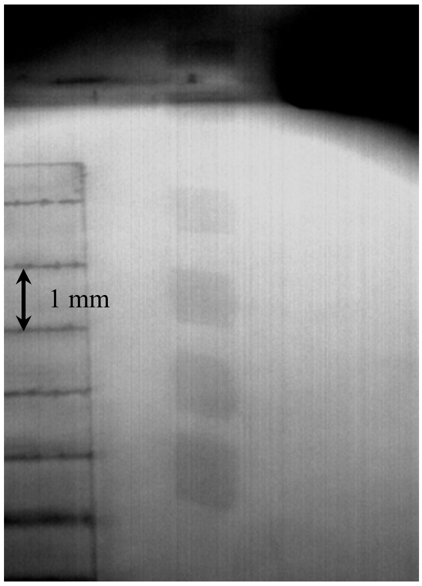

Fig. 2 Multiple exposure optical micrograph of 1 mm by 1mm "dummy" device during transfer.

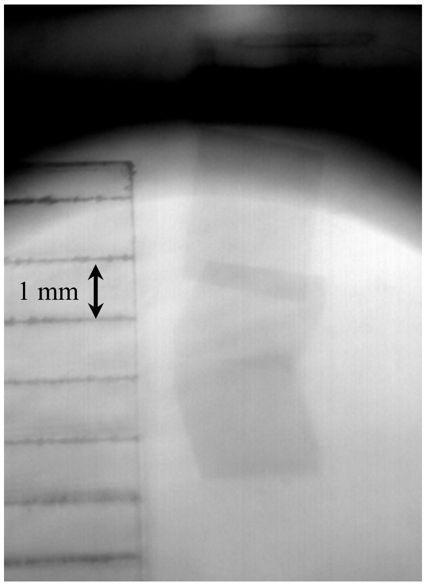

Fig. 3 Multiple exposure optical micrograph of a 2.6 mm by 2.6 mm, ASIC, bare die.

The results obtained from two series of images are summarized in figure 4. The figure shows a plot of device velocity as a function of laser fluence for the 1 mm by 1 mm "dummy" devices and the 2.6 mm by 2.6 mm bare die. It is clear from figure 4 that the larger, heavier devices obtain lower velocities for a given fluence as compared to the smaller, lighter devices. The solid line for the 1 mm by 1 mm devices represents a curve fit based on the formula provided by Holmes *et al.*[2]:

$$v = \sqrt{\frac{2\eta(E - E_T)}{m}}$$

where v is the velocity, η is the fraction of available energy converted into kinetic energy, E is the laser fluence,

E_T is the threshold fluence, and m is the mass per unit area of the device. For the 1 mm by 1 mm devices we found η=0.0826 and E_T=135 mJ/cm^2. The data for the 2.6 mm by 2.6 mm devices predict η=0.036 and E_T=92 mJ/cm2, although the limited number of data points in this series make the computed values somewhat less reliable.

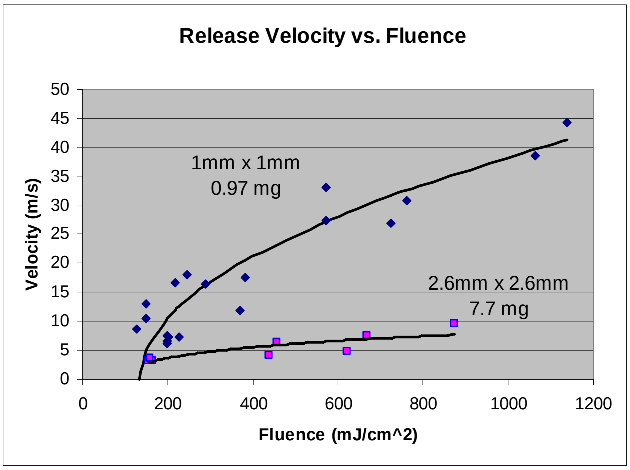

Fig. 4 Plot of velocity vs. fluence for two different sizes of bare dies.

The plot in Figure 4 shows that at high fluences, the bare die can be released with very high velocities (up to 40 m/s for the 1mm x 1mm dies). It is worth noting, however, that for most laser-based device transfer applications it is anticipated that laser fluences near the release threshold are appropriate to achieve an effective laser-based pick-and-place process.

Several LM555 bare die were transferred using this process. Figures 5a and 5b show optical micrographs of two LM555 bare die, un-transferred and transferred, respectively. After transfer, two LM555 were collected and connected to a simple LED blinker circuit using a probe station. Both devices were functional after transfer.

Several InGaN, bare die LEDs were transferred into pockets laser milled into a receiving substrate. These transfers were accomplished using a frequency tripled, Nd:YAG laser (355 nm). After transfer, these LEDs were connected using a probe station to verify that they were fully functional. Figure 6a shows a bare die LED laser transferred into a pocket, while figure 6b shows that another LED, after transfer, is fully functional.

5. Summary

This work has shown that LDW techniques can be used to release and transfer semiconductor bare dies without affecting their performance. The devices can be directly transferred into pockets using this technique in order to fabricate embedded microelectronic circuits. The fact that the devices are not damaged upon laser illumination of their active surface demonstrates the ability to use LDW processes as effective laser-based pick-and-place systems for die transfer and assembly.

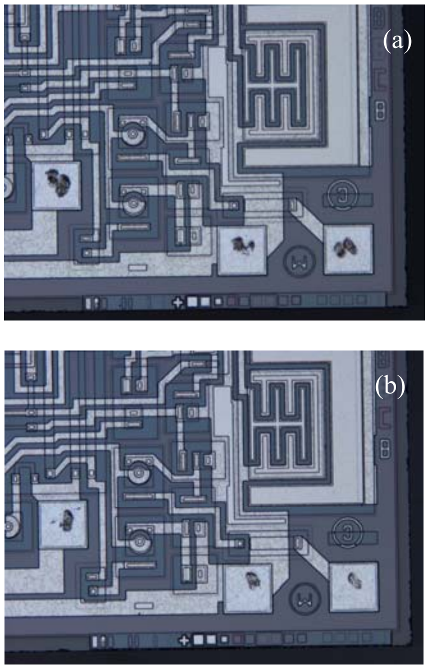

Fig. 5 a) LM555 bare die un-transferred. b) LM555 bare die after transfer.

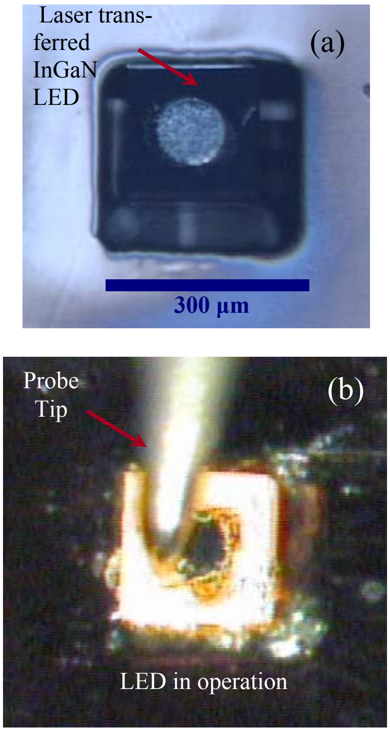

Fig. 6 a) Micrograph of laser transferred InGaN LED inside a receiving pocket. b) When powered, transferred LED emits light.

These results open the door for the development of unique laser-based microelectronics fabrication tools. Such tools would be capable of fabricating, embedding and interconnecting each of the components required for a fully operational microelectronic circuit directly on a substrate, including delicate semiconductor bare die IC's. The advantage of using such a laser-based direct-write system for microelectronics manufacture resides in the fact that the resulting embedded circuits can easily be modified and customized for any given application, while at the same time, the circuit layout can also be reconfigured to fit within a desired form factor. Such a capability would allow the placement of microelectronic systems in places that are inconceivable for current circuit manufacture processes.

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