Video Article

Laser-induced Forward Transfer for Flip-chip Packaging of Single Dies

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URL: https://www.jove.com/video/52623
DOI: doi:10.3791/52623

Keywords: Physics, Issue 97, LIFT, direct-write, flip-chip, interconnects, indium, micro-bumps, thermo-compression, VCSEL

Date Published: 3/20/2015

Citation: Kaur, K.S., Van Steenberge, G. Laser-induced Forward Transfer for Flip-chip Packaging of Single Dies. *J. Vis. Exp.* (97), e52623, doi:10.3791/52623 (2015).

Abstract

Flip-chip (FC) packaging is a key technology for realizing high performance, ultra-miniaturized and high-density circuits in the micro-electronics industry. In this technique the chip and/or the substrate is bumped and the two are bonded via these conductive bumps. Many bumping techniques have been developed and intensively investigated since the introduction of the FC technology in 1960[1] such as stencil printing, stud bumping, evaporation and electroless/electroplating[2]. Despite the progress that these methods have made they all suffer from one or more than one drawbacks that need to be addressed such as cost, complex processing steps, high processing temperatures, manufacturing time and most importantly the lack of flexibility. In this paper, we demonstrate a simple and cost-effective laser-based bump forming technique known as Laser-induced Forward Transfer (LIFT)[3]. Using the LIFT technique a wide range of bump materials can be printed in a single-step with great flexibility, high speed and accuracy at RT. In addition, LIFT enables the bumping and bonding down to chip-scale, which is critical for fabricating ultra-miniature circuitry.

Video Link

The video component of this article can be found at https://www.jove.com/video/52623/

Introduction

Laser-induced Forward Transfer (LIFT) is a versatile direct-write additive manufacturing method for single-step pattern definition and material transfer with micron and sub-micron-resolution. In this paper, we report the use of LIFT as a bumping technique for flip-chip packaging of vertical-cavity surface-emitting lasers (VCSELs) on a chip-scale. Flip-chip is a key technology in system packaging and integration of electronic and optoelectronic (OE) components. In order to achieve dense integration of components fine pitch bonding is essential. Although fine pitch bonding has been demonstrated by some of the standard techniques but there is a void in terms of combining together the other important features such as flexibility, cost-effectiveness, speed, accuracy and low processing temperature. In order to meet these requirements we demonstrate LIFT-assisted thermo-compression bonding method for fine pitch bonding of OE components.

In LIFT, a thin film of the material to be printed (referred to as the *donor*) is deposited onto one face of a laser-transparent support substrate (referred to as the *carrier*). **Figure 1** depicts the basic principle of this technique. An incident laser pulse of sufficient intensity is then focused at the carrier-donor interface that provides the propelling force required to forward transfer the donor pixel from the irradiated zone onto another substrate (referred to as the *receiver*) placed in close proximity.

LIFT was first reported in 1986 by Bohandy as a technique to print micron-sized copper lines for repairing damaged photo-masks[3]. Since its first demonstration this technique has gained significant interest as a micro-nano fabrication technology for controlled patterning and printing of a wide range of materials such as ceramics[4], CNTs[5], QDs[6], living cells[7], graphene[8], for diverse applications such as bio-sensors[9], OLEDs[10], optoelectronic components [11], plasmonic sensors[12], organic-electronics[13] and flip-chip bonding[14,15].

LIFT offers several advantages over the existing flip-chip bumping and bonding techniques such as simplicity, speed, flexibility, cost-effectiveness, high-resolution and accuracy for flip-chip packaging of OE components.

Protocol

1. LIFT-assisted Flip-chip Bonding

NOTE: There are three stages involved in realizing the LIFT-assisted flip-chip assemblies, namely-micro-bumping of the substrates using the LIFT technique, attaching the optoelectronic chips to the bumped substrates using thermo-compression flip-chip bonding method, and finally encapsulation of the bonded assemblies. Each of these stages is discussed in the following sections:

1. Micro-bumping using LIFT:

1. For donor preparation, deposit a thin film of the donor material onto a laser-transparent carrier substrate. For this experiment, evaporate a 200 nm thick film of indium metal on top of glass carrier substrate with dimensions: 2 inch diameter x 0.05 cm thickness.
   NOTE: Donor preparation method depends on the phase of the donor material, *e.g.,* use evaporation and sputtering for solid phase donor materials and spin-coating and doctor-blading for liquid-phase donors.
2. For receiver preparation, use glass substrates with dimensions of 5 x 5 x 0.07 cm^3 as the receivers. Pattern these substrates with the metallic contact pads for bonding the OE chip and fan-out probing structures using photolithography. For this experiment, pattern 4 µm thick Ni-Au bond pads and fan-out probing tracks onto glass receiver substrates.
3. Next, place the donor in contact with the receiver and mount the donor-receiver assembly onto a computer controlled X-Y translation stage.
   NOTE: Depending on the phase of the donor material (*e.g.,* solid (indium) or liquid (ink/paste)) and its thickness, the donor and the receiver substrates are placed at an optimum separation that can be easily controlled (*e.g.,* by using metallic spacers).
4. Focus the incident laser beam at the carrier-donor interface employing an objective lens of 160 mm focal length and scan the beam (20 µm spot size) across the donor substrate for transferring donor micro-bumps onto the receiver bond-pads. Use a picosecond laser source of 355 nm wavelength and 12 psec pulse duration to LIFT indium bumps onto the receiver bond-pads at a fluence of 270 mJ/cm^2.
   NOTE: The laser properties such as energy, no. of pulses, objective lens height, coordinates of the precise location on the receiver substrate for printing donor micro-bumps and the desired pattern to be transferred are accurately controlled by a computer program. Key experimental parameters (*e.g.,* transfer fluence) need to be optimized in case of using another laser source.
5. For thicker bumps move the donor to a fresh area and repeat step 1.1.4 several times. For example, repeat step 1.1.4 six times to get a stack of 6 indium bumps printed on top of each other for this experiment. The final LIFTed bumps have an average height of ~ 1.5 µm and a diameter of 20 µm (**Figure 2**).
   NOTE: For these experiments the surface profile and thickness of the bumps were measured using an optical profilometer. It was examined that the bumps had a convex/dome morphology with an average thickness of 1.5 µm, averaged over the bump diameter (as marked yellow in **Figure 3**). The reason for this is attributed to the fact that the donor melted in the laser irradiated zone and the transferred pellet then re-solidified upon reaching the receiver surface (Indium has a low melting point). The advantage of this is that it results in good adhesion of the printed bump to the VCSEL contact pads.

2. Chip to substrate thermo-compression bonding (**Figures 4-6**):
   1. Use a semiautomatic flip-chip bonder for bonding the optoelectronic chips to the bumped substrates.
   2. Load the bumped receiver and the chip to be bonded onto their respective vacuum plates of the bonder. Place the chip in a flipped position, *i.e.,* with its active area facing down.
   3. Use a suitable pick-up tool and align it on the center of the chip. Use a needle-shaped tool as shown in **Figure 5**. Next, pick the chip using this pick-up tool.
   4. Align the chip bond-pads with the corresponding contact pads on the receiver substrate using a camera-alignment system.
   5. Once aligned place the chip on the substrate.
   6. Apply heat (~ 200 °C) and pressure (12.5 gf/bump) simultaneously to realize chip to substrate electrical and mechanical interconnections.

3. Encapsulation of the bonded assemblies (**Figures 4-6**):
   1. Dispense an optically transparent adhesive around the edges of the bonded assembly using a syringe needle. The encapsulation increases the mechanical reliability of the bonded assemblies. Use a single component UV curable adhesive such as NOA 86 for encapsulating the bonded chips.
   2. Cure the adhesive using a UV lamp for ~ 30 sec.

2. Characterization of the Bonded Vertical-cavity Surface-emitting Lasers (VCSELs)

NOTE: After fabrication the next step is to evaluate the electro-optical performance of the bonded assemblies. The light-current-voltage (LIV) curves of the devices are recorded post-bonding using a probe station. The following steps are involved for the testing:

1. Place the flip-chip bonded device onto a custom-made transparent stage. The stage has a hole drilled in the center for easy access to the light emitted by the VCSELs.
2. Place a photodetector (PD) underneath the transparent stage and align its active area with the bonded chip using a microscope.
3. Precisely position the probing needles on the Ni-Au probing pads using a microscope.
4. Inject up to 10 mA of current and measure the voltage drop across the VCSEL and the light emitted by it using a current/voltage source-meter unit and a power meter respectively.

Representative Results

Figure 7 shows a typical LIV curve that was recorded from one of the many flip-chip bonded VCSEL chips. A good match between the measured optical power to the supplier quoted values indicated successful functioning of the bonded devices post-bonding. The curves were also recorded prior- and post-encapsulation and upon comparison it was verified that the encapsulant had no affect on the chip functionality (as shown in **Figure 7**). Also, a comparison between the I-V curves recorded for the flip-chip bonded VCSELs and those recorded from a bare die resulted in a good match thereby, suggesting negligible additional resistance incurred due to the LIFTed bumps (**Figure 8**).

The mechanical ruggedness of the bonded assemblies was tested using a Dage 4000 series machine. The encapsulated chips did not detach from the substrate without getting damaged when a die-shear force was applied to them, thereby, testifying a very good mechanical reliability. The stability over time of the bonded and encapsulated chips was evaluated by performing the standard 8585 (85 °C and 85% relative humidity) accelerated ageing tests. During these tests the chips were kept under controlled temperature and humidity in a climate chamber for a total of

400 hr. The chips were monitored electrically and optically at regular intervals. The performance and functionality of the chips did not degrade even after 400 hr in the climate chamber as is clear from **Figure 9**.

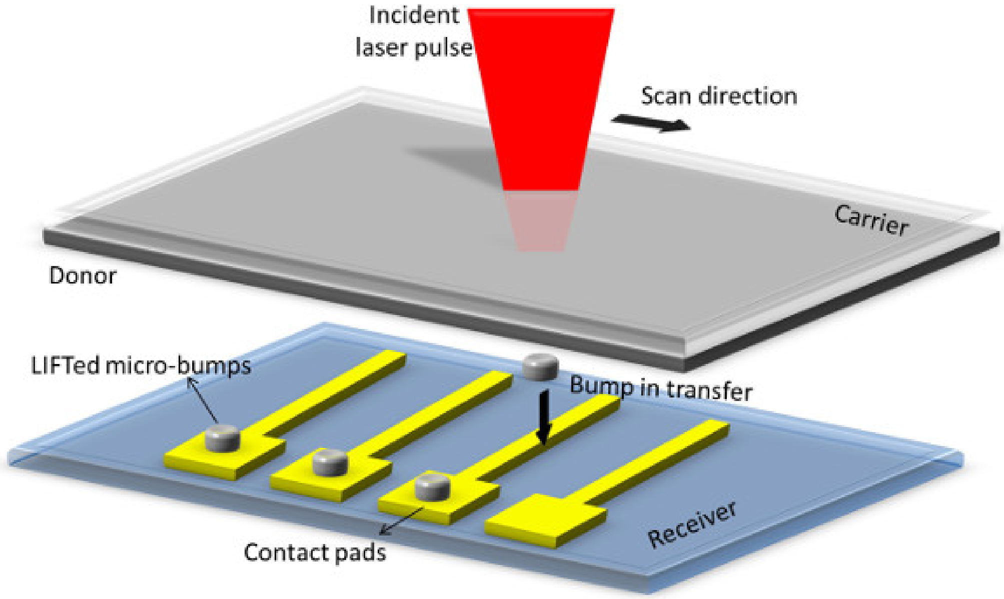

Figure 1. Schematic illustrating the principle of the LIFT technique. Please click here to view a larger version of this figure.

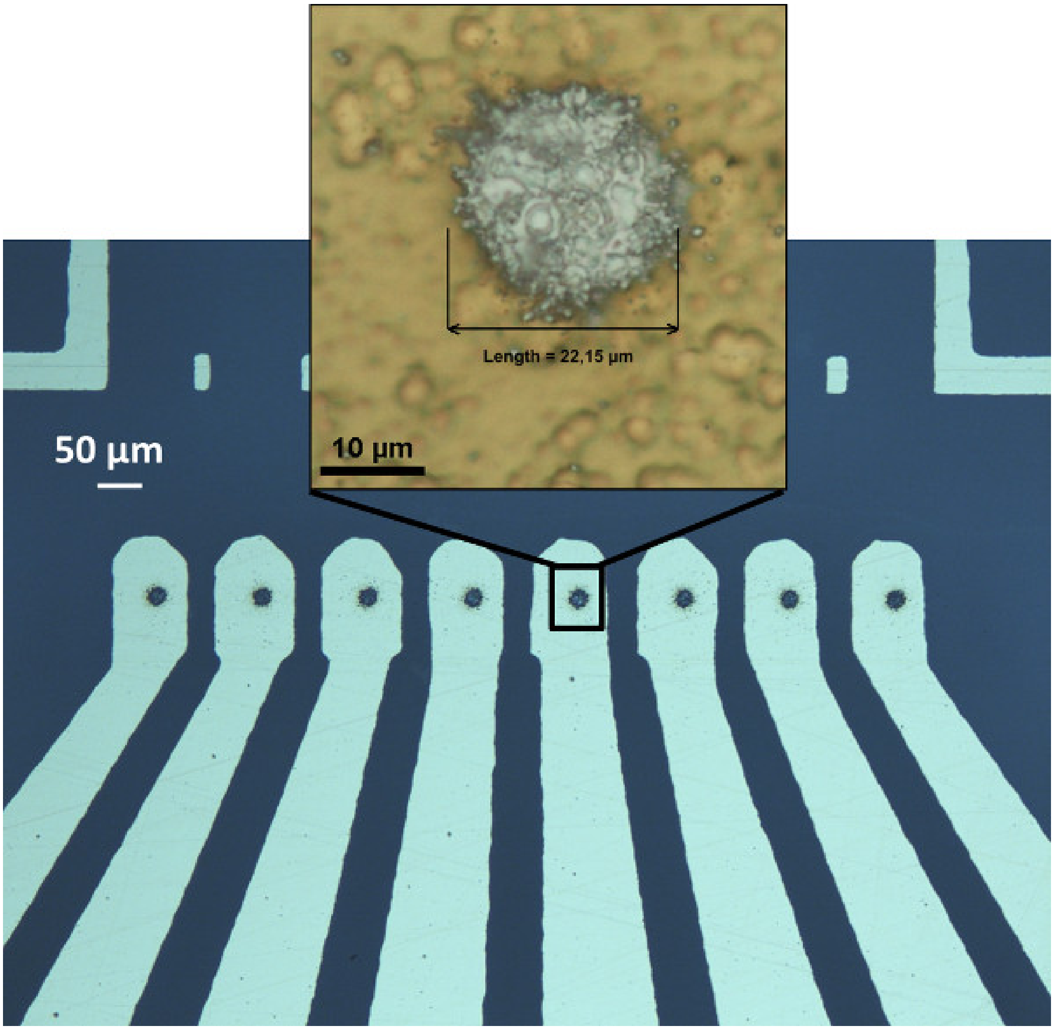

Figure 2. Optical micrograph of a LIFT-assisted bumped receiver substrate. The inset shows a magnified image of a printed indium micro-bump. Please click here to view a larger version of this figure.

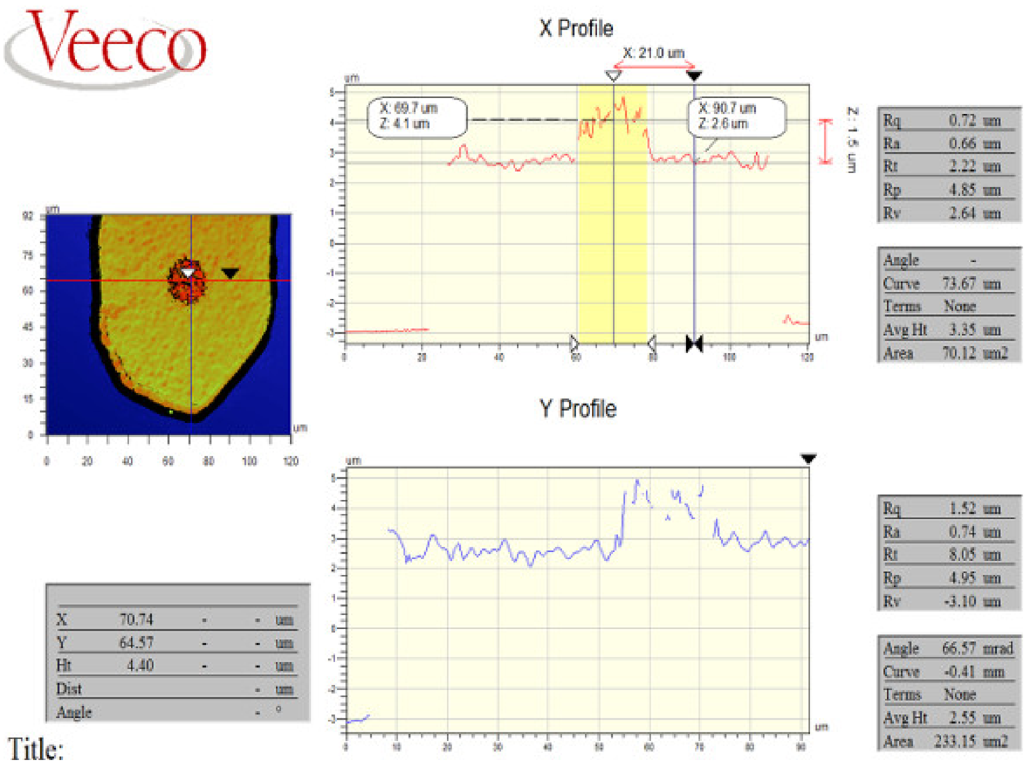

Figure 3. Typical optical profilometer measurements of the LIFTed micro-bumps. Please click here to view a larger version of this figure.

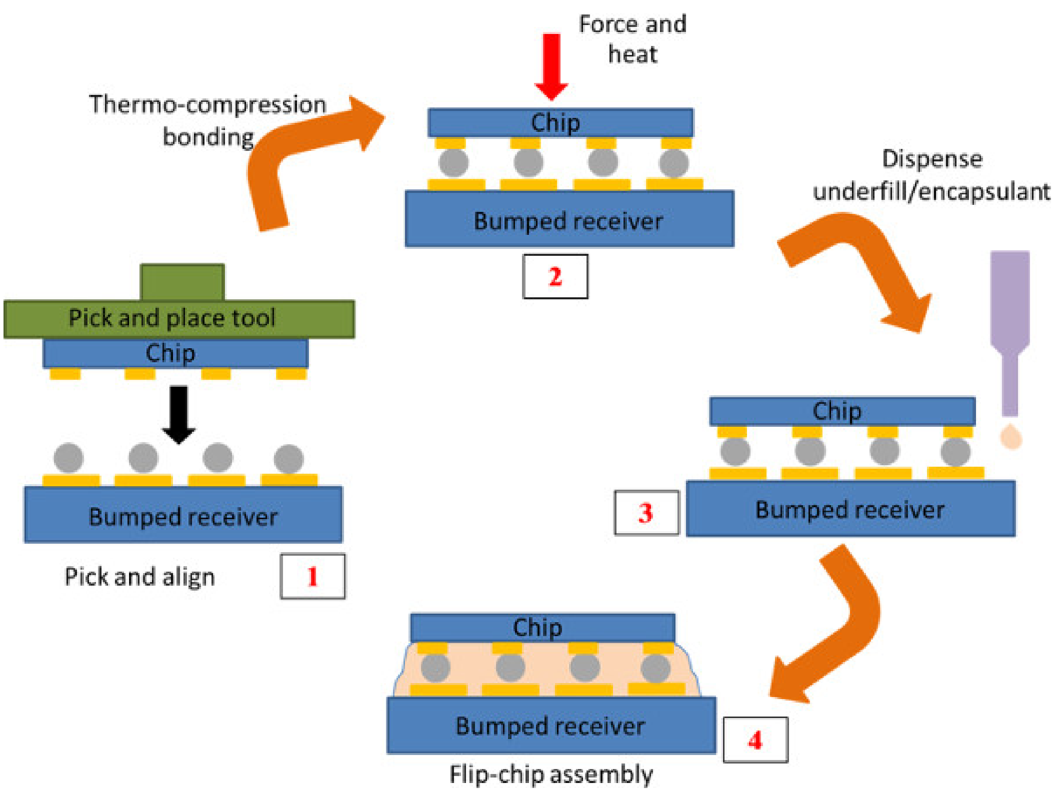

Figure 4. Depicts the various steps involved in the thermo-compression flip-chip bonding of OE components. Please click here to view a larger version of this figure.

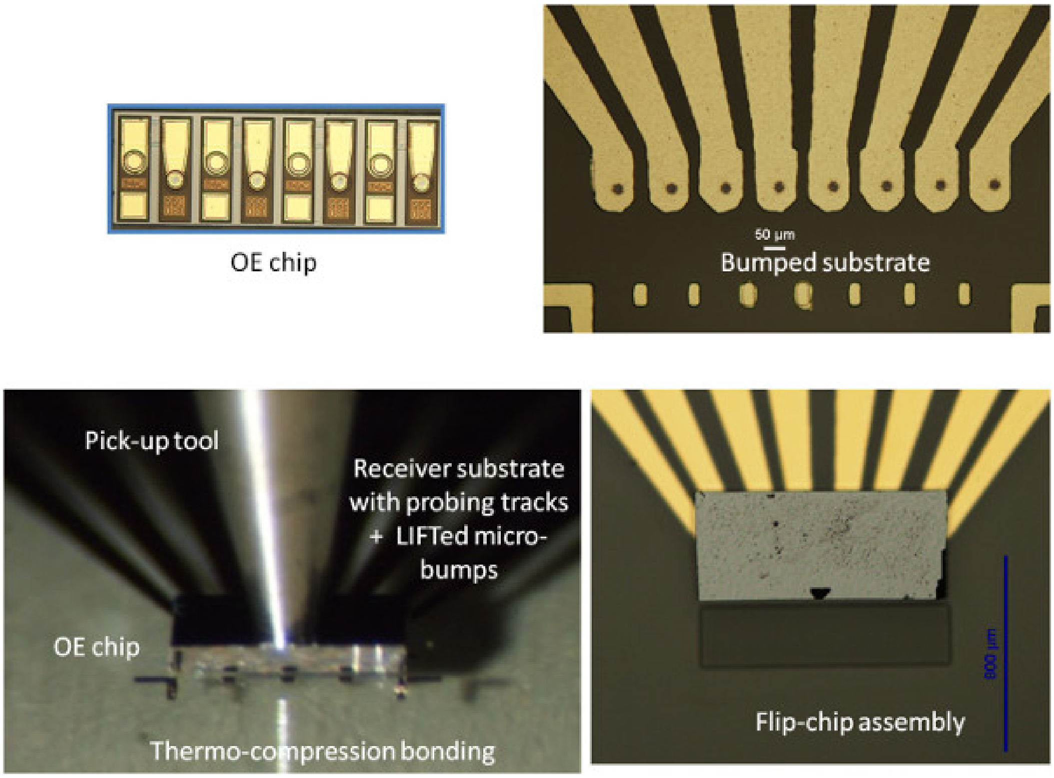

Figure 5. Optical micrographs taken at various processing steps. Please click here to view a larger version of this figure.

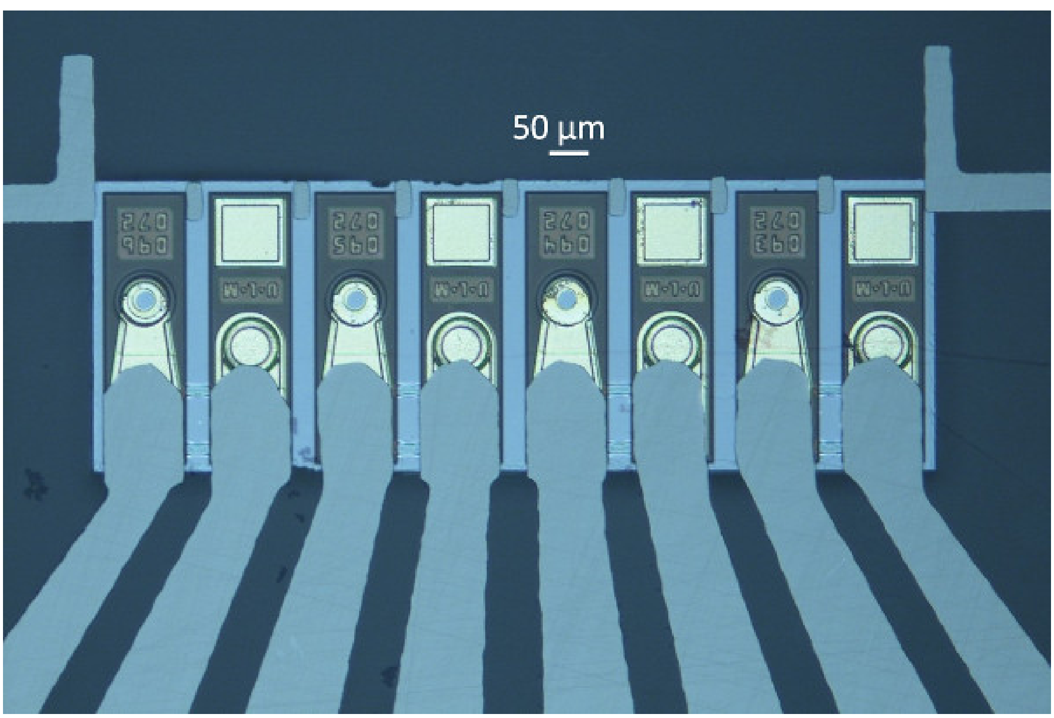

Figure 6. Optical microscope image of a flip-chip bonded VCSEL chip as viewed from the backside of the receiver glass substrate. Please click here to view a larger version of this figure.

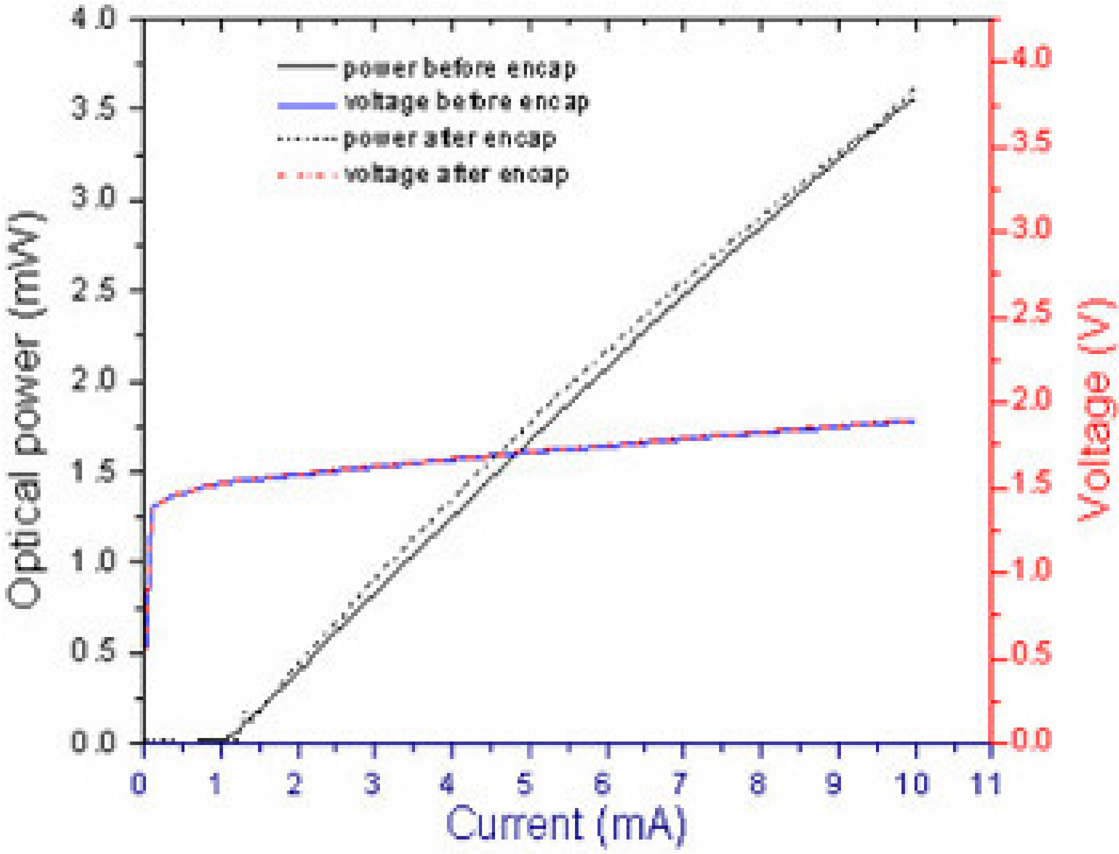

Figure 7. Typical LIV curves recorded for a flip-chip VCSEL assembly prior and post encapsulation. (Modified from [15]) Please click here to view a larger version of this figure.

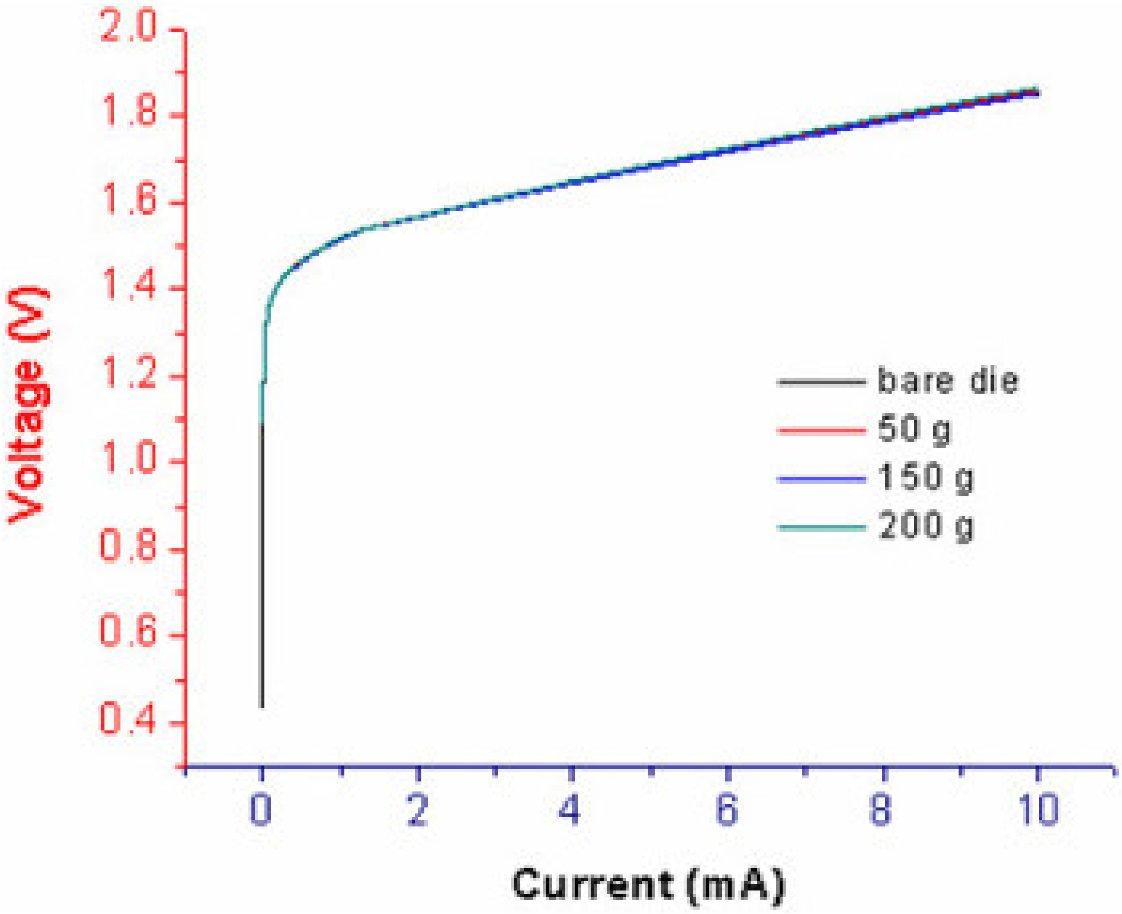

Figure 8. Comparison of I-V curves recorded for flip-chip assemblies bonded using different pressures with those recorded from a bare die. (Modified from [15]) Please click here to view a larger version of this figure.

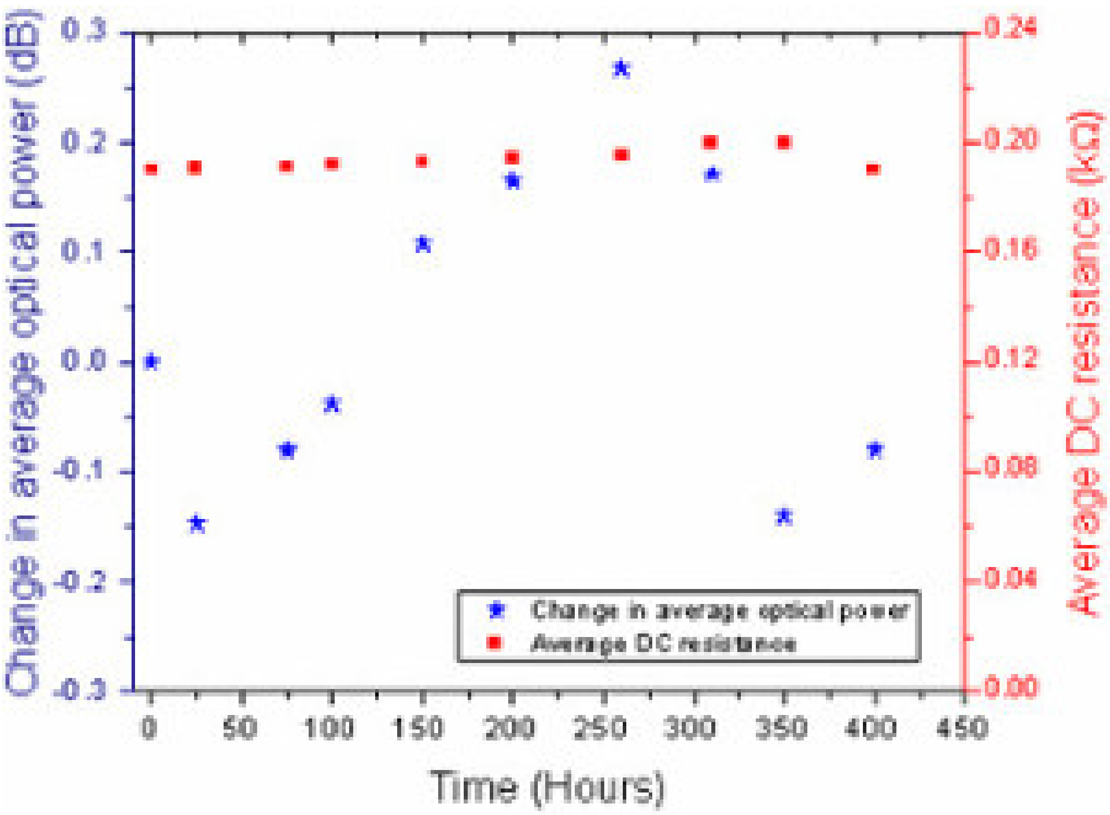

Figure 9. Plot depicting the results of ageing tests performed on the bonded VCSEL chips. Please click here to view a larger version of this figure.

Discussion

In this paper, we have demonstrated thermo-compression flip-chip bonding of single VCSEL chips using a laser based direct-write technique called LIFT. The assembly fabrication steps involved printing of the micro-bumps of indium onto the substrate contact pads using the LIFT technique. This was followed by thermo-compression flip-chip bonding of VCSEL chips to the bumped substrates and finally their encapsulation.

Electrical, optical and mechanical reliability of the LIFT-assisted bonded chips was evaluated by measuring their LIV curves and performing standard 8585 ageing tests. The successful results obtained for optical characterization, mechanical stability, and durability clearly highlight the great potential of the LIFT technique as an interconnect technology.

It should be mentioned that currently LIFT printing is limited to thin films when it comes to solid-phase materials and it is challenging to LIFT thicker films (~ 10 µm). Having said that by pre-processing the donor films such as pre-patterning the donors prior to printing them[16] can make LIFTing of thicker solid materials feasible.

To conclude, LIFT offers a simple, highly accurate and flexible solution to realize chip-level interconnections for applications requiring single-chip bumping, high-accuracy, resolution and fine-pitch for high-density flip-chip applications.

Disclosures

The authors have nothing to disclose.

Acknowledgements

This work was carried out in the framework of the project “MIRAGE,” funded by the European Commission within the FP7 program.

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