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Laser-Induced Forward Transfer for Flip-Chip Packaging of Single Dies

--Manuscript Draft--

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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, fine-pitch bumping 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 metals can be printed in a single-step with great flexibility, high speed and accuracy at room temperature. In addition, LIFT enables the bumping and bonding down to chip-scale which is critical for fabricating ultra-miniature circuitry.
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Laser-Induced Forward Transfer for Flip-Chip Packaging of Single Dies

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LIFT, direct-write, flip-chip, interconnects, indium, micro-bumps, thermo-compression, VCSEL

SHORT ABSTRACT:
We demonstrate the use of the Laser-Induced Forward Transfer (LIFT) technique for flip-chip assembly of optoelectronic components. This approach provides a simple, cost-effective, low-temperature, fast and flexible solution for fine-pitch bumping and bonding on chip-scale for achieving high-density circuits for optoelectronic applications.

LONG 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 room temperature. In addition, LIFT enables the bumping and bonding down to chip-scale which is critical for fabricating ultra-miniature circuitry.

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

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 are discussed in the following sections:

1.1 Micro-bumping using LIFT:

1.1.1) 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: 5 x 5 x 0.07 cm^3.

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.

1.1.2) 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.

1.1.3) 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 by using e.g. metallic spacers.

1.1.4) 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 ps laser source of 355 nm wavelength and 12 ps 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.

1.1.5) 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 this experiment measure the surface profile and thickness of the printed bumps 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 the 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.

1.2. Chip to substrate thermo-compression bonding (Figure 4-6):

1.2.1) Use a semiautomatic flip-chip bonder for bonding the optoelectronic chips to the bumped substrates.

1.2.2) 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.

1.2.3) Use a suitable pick-up tool and align it on the centre of the chip. Use a needle-shaped tool as shown in figure 5. Next, pick the chip using this pick-up tool.

1.2.4) Align the chip bond-pads with the corresponding contact pads on the receiver substrate using a camera-alignment system.

1.2.5) Once aligned place the chip on the substrate.

1.2.6) Apply heat (~ 200 ^{0}C) and pressure (12.5 gf/bump) simultaneously to realize chip to substrate electrical and mechanical interconnections.

1. 3: Encapsulation of the bonded assemblies (Figures 4-6):

1.3.1) 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 83H for encapsulating the bonded chips.

1.3.2) Cure the adhesive using a UV lamp for ~ 30 s.

2. Characterization of the bonded vertical-cavity surface-emitting lasers (VCSELs)

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:

2.1) Place the flip-chip bonded device onto a custom-made transparent stage. The stage has a hole drilled in the centre for easy access to the light emitted by the VCSELs.

2.2) Place a photodetector (PD) underneath the transparent stage and align its active area with the bonded chip using a microscope.

2.3) Precisely position the probing needles on the Ni-Au probing pads using a microscope.

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

FIGURE LEGENDS:

Figure 1: Schematic illustrating the principle of the LIFT technique.

Figure 2: Optical micrograph of a LIFT-assisted bumped receiver substrate. The inset shows a magnified image of a printed indium micro-bump.

Figure 3: Typical optical profilometer measurements of the LIFTed micro-bumps.

Figure 4 : Depicts the various steps involved in the thermo-compression flip-chip bonding of OE components.

Figure 5 : Optical micrographs taken at various processing steps.

Figure 6: Optical microscope image of a flip-chip bonded VCSEL chip as viewed from the backside of the receiver glass substrate.

Figure 7: Typical LIV curves recorded for a flip-chip VCSEL assembly prior and post encapsulation. (Modified from [15])

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])

Figure 9: Plot depicting the results of ageing tests performed on the bonded VCSEL chips.

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.

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DISCLOSURES:

The authors have nothing to disclose.

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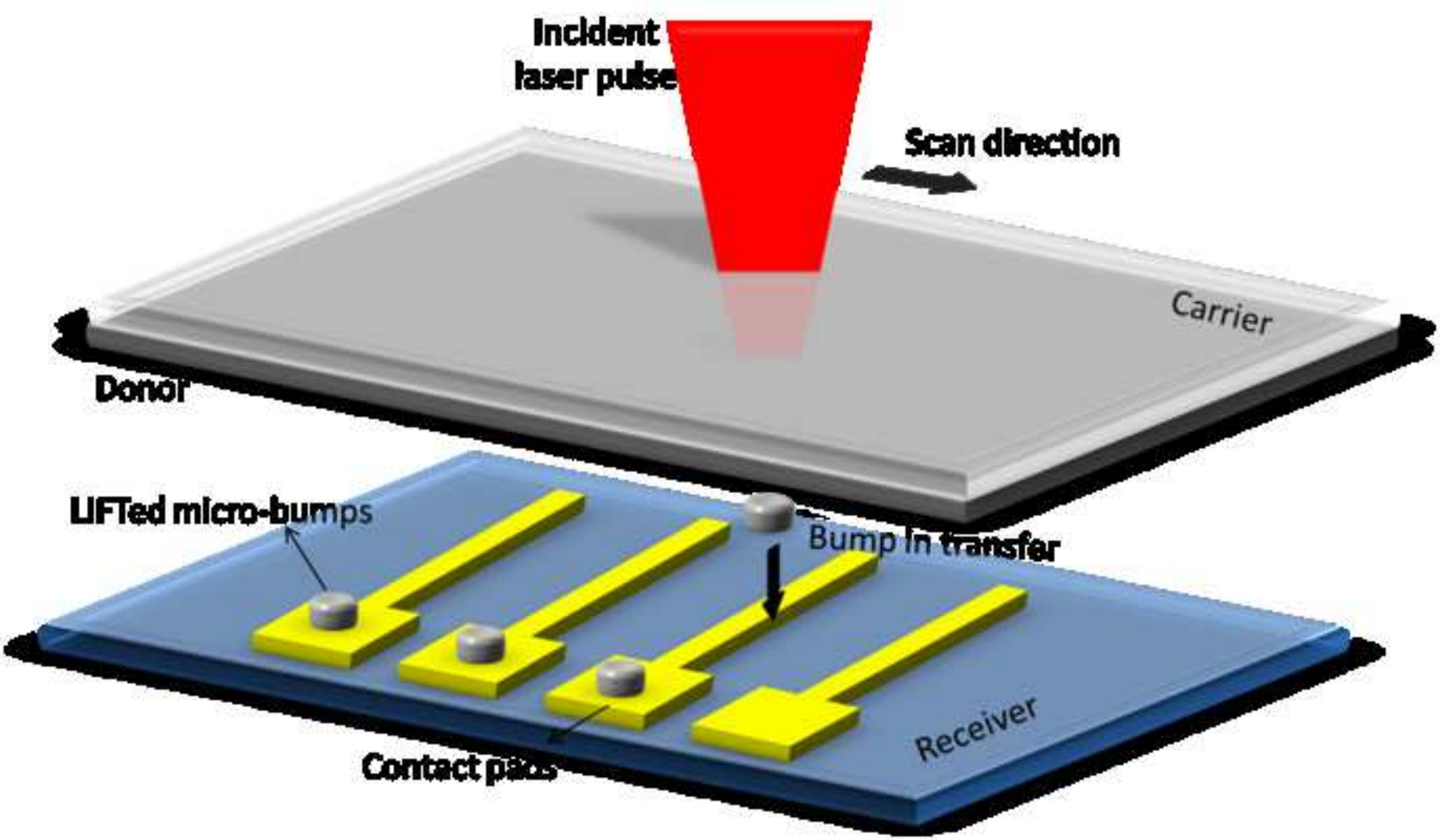

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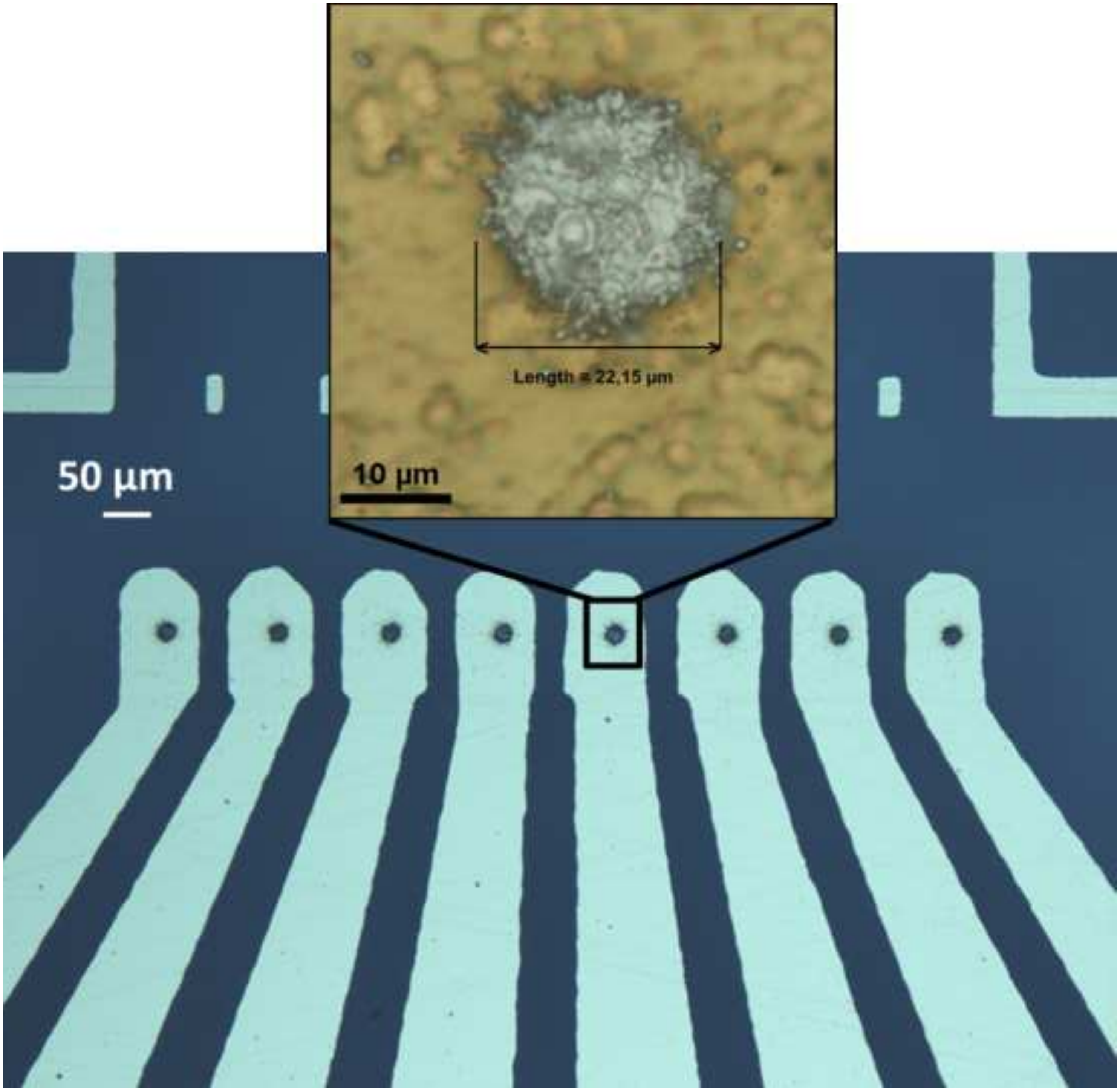

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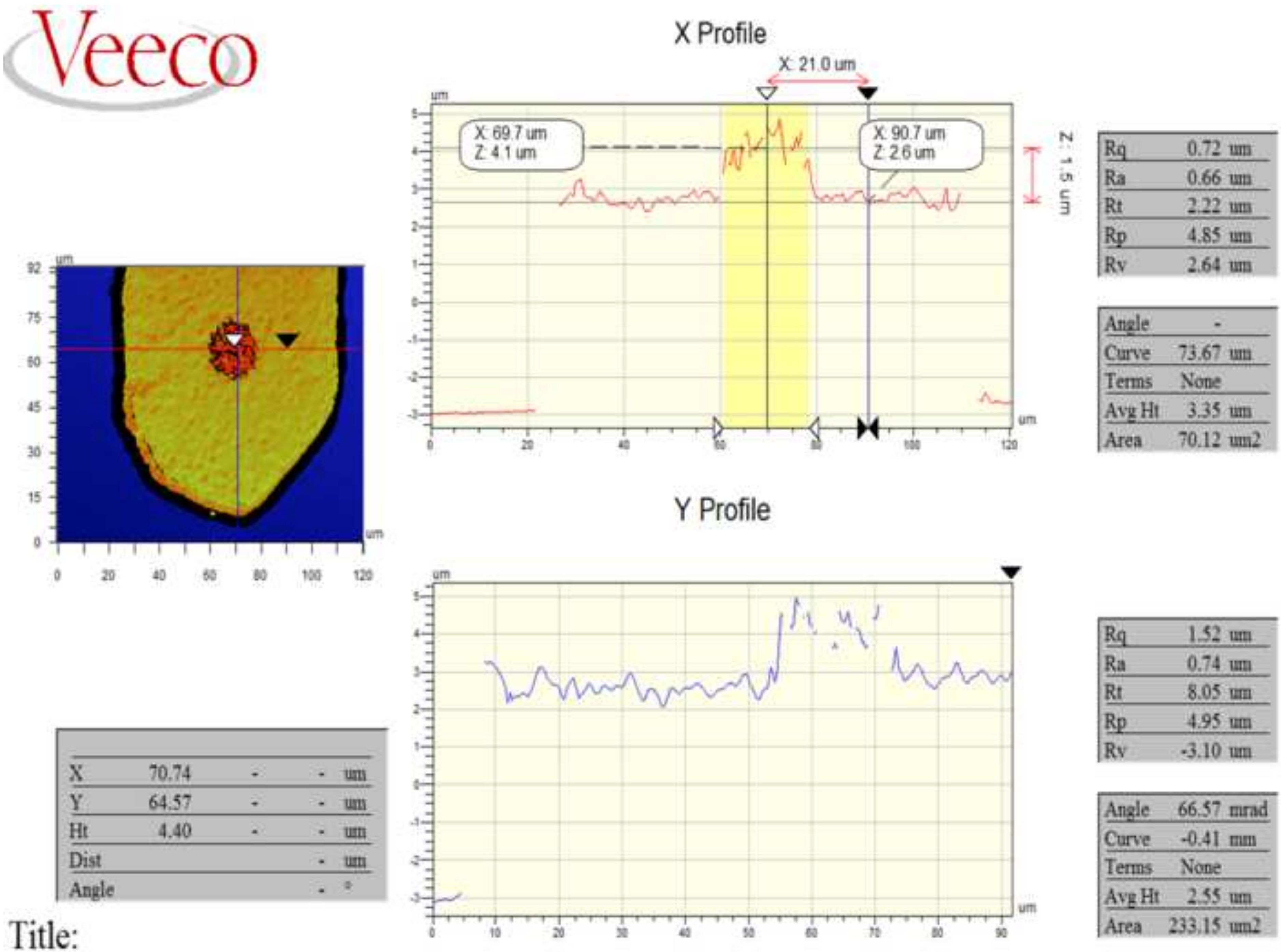

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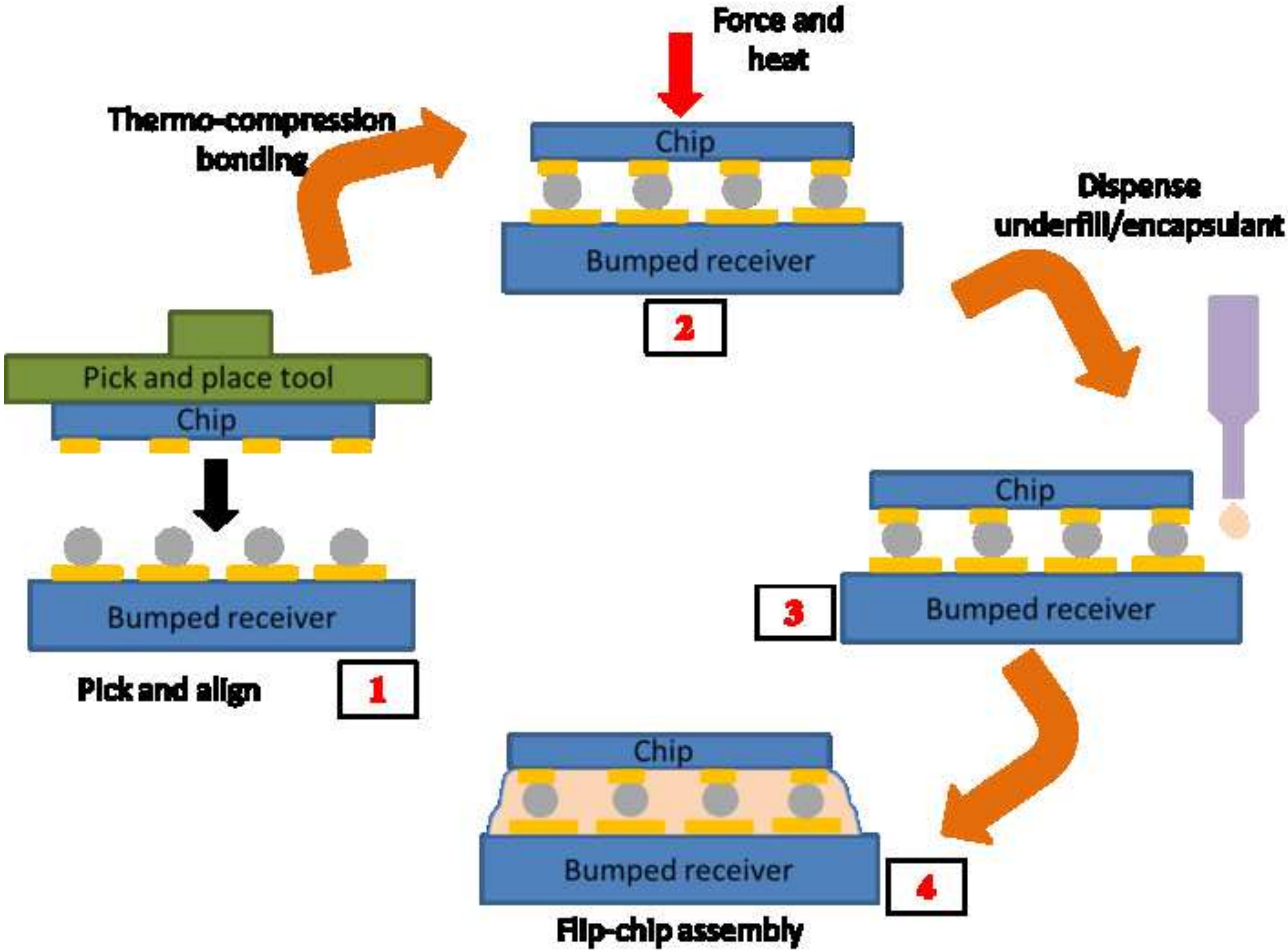

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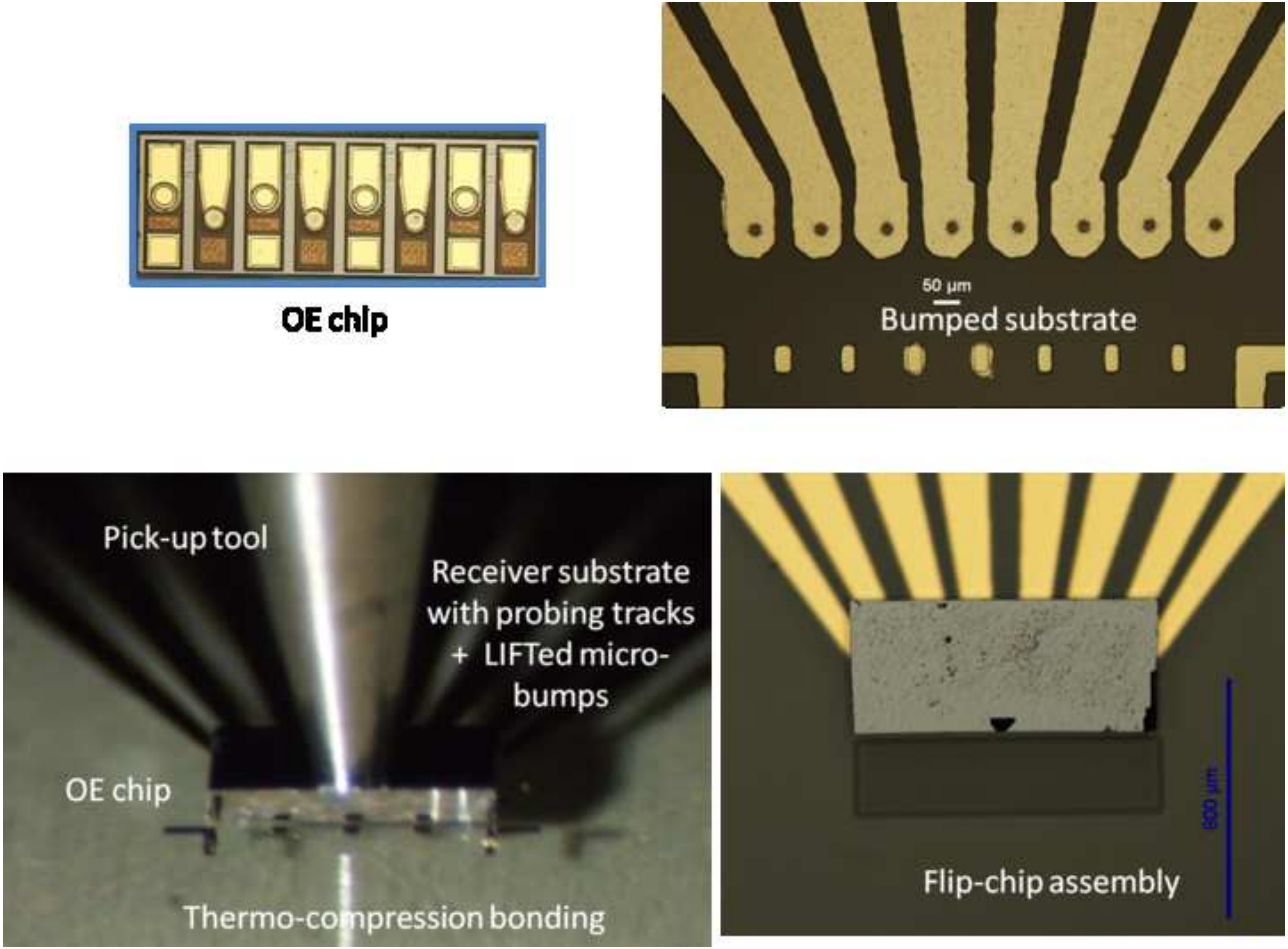

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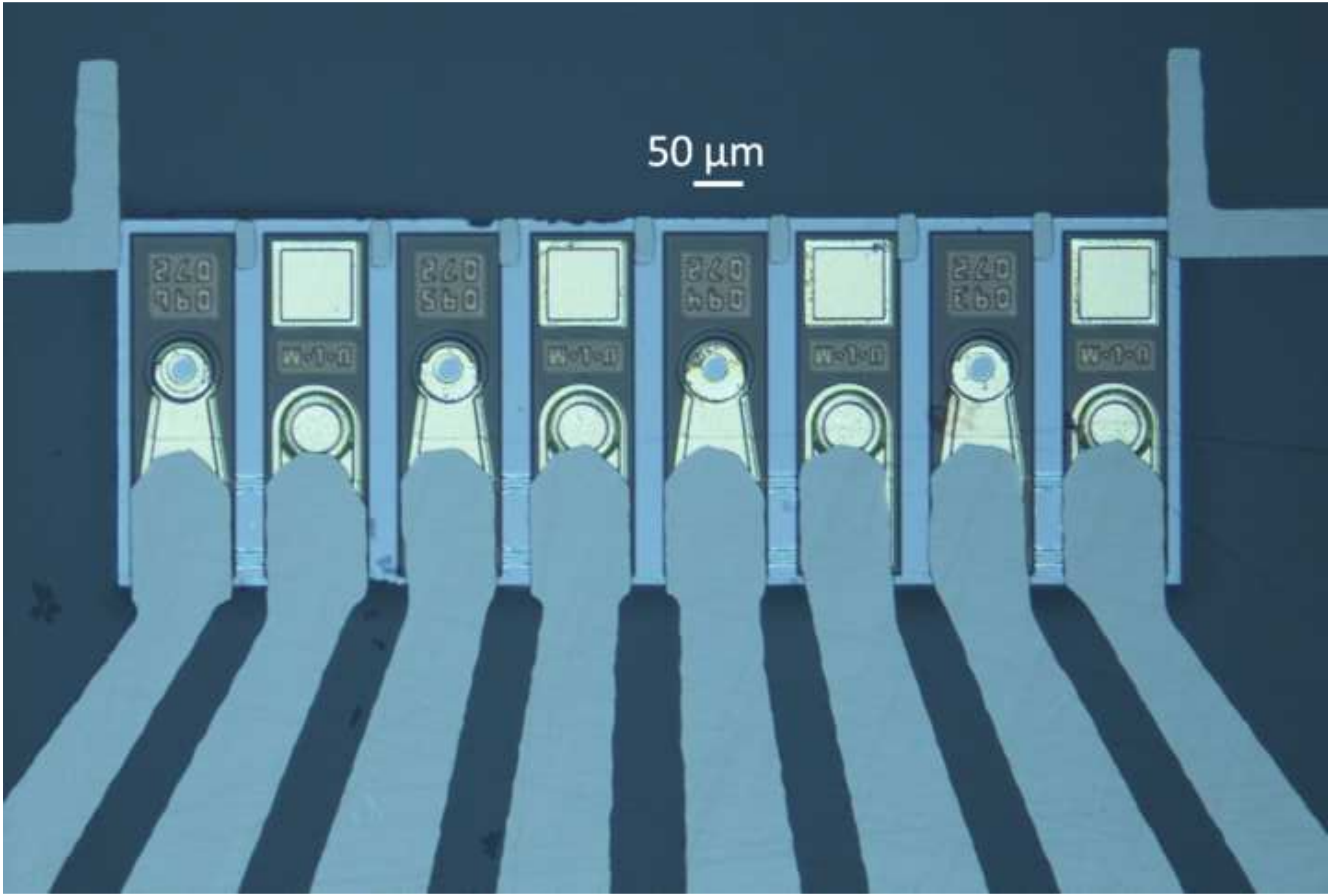

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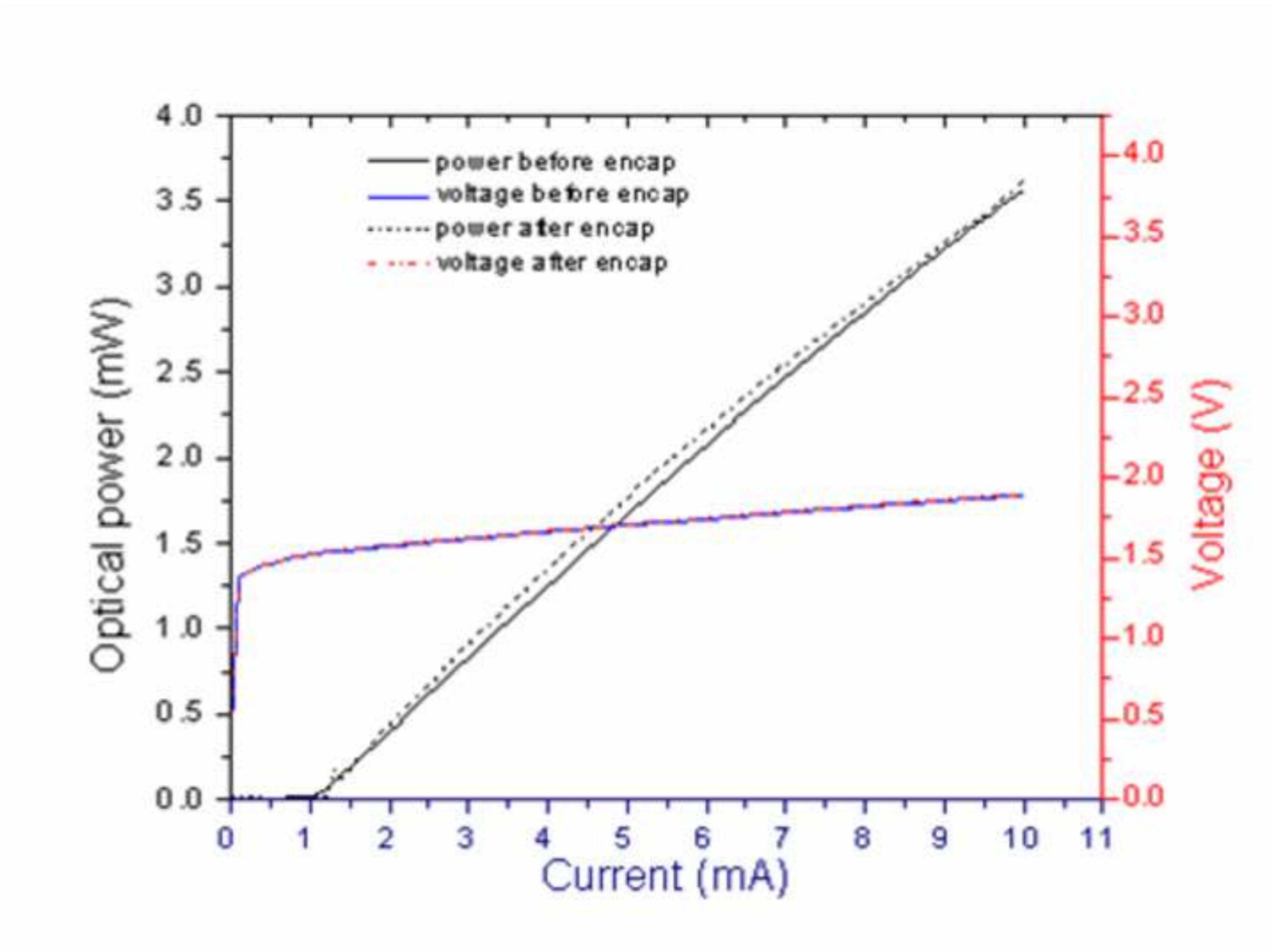

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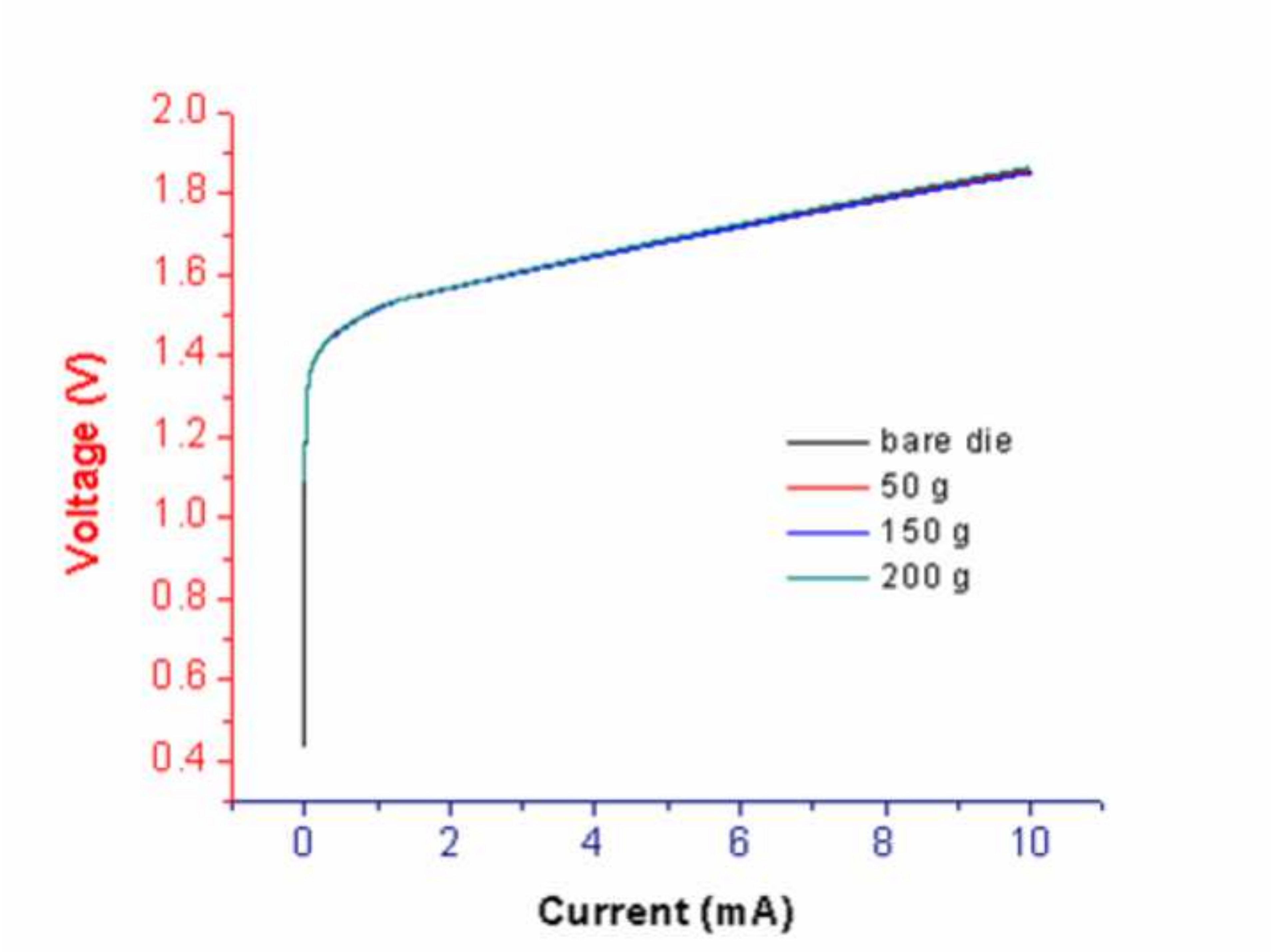

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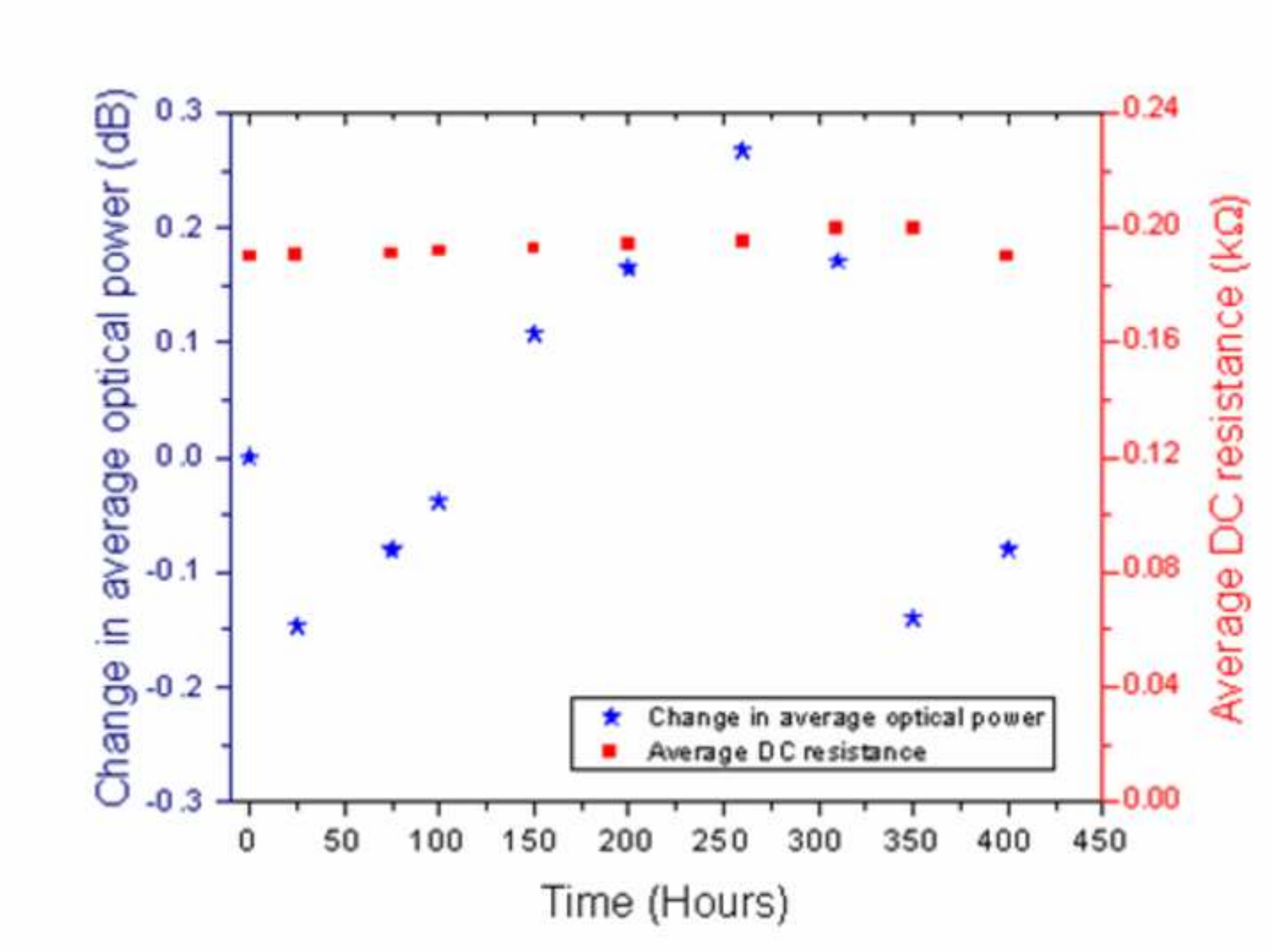

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Source measurement unit	Keithley	2401	
Power meter	Newport	1930	
Underfill	Norlands	NOA 86	
UV lamp	Omnicure	Series 1000 UV	
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Flip-chip bonder	Dr. Tresky	T-320 X	

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Dear Editor,

We would like thank you and the reviewers for the valuable comments on our manuscript titled " Laser-Induced Forward Transfer for Flip-Chip Packaging of Single Dies". We have tried to address all the comments and have modified the manuscript accordingly.

We look forward to hearing from you in due course, but please do not hesitate to contact us should you require any further information.

Yours sincerely,

Kamalpreet Kaur

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Editorial comments:

1.Several steps require additional detail:

a)Steps 1.1.1 and 1.1.2 need references for the procedures described or should be described stepwise.

According to the authors these steps have been described in the simplest possible way. The deposition methods mentioned in this step e.g. evaporation, spin coating, sputtering and photolithography are very commonly used, standard and very well-known processes.

b)Where does step 1.2.6 take place?

At the flip-chip bonder while the chip is placed onto the bumped receiver substrate.

c)Is the wavelength important in step 1.3.2?

No it is not. The adhesive is sensitive over a broad range of UV from 320-380 nm.

2.There are a few minor grammar issues that need to be addressed:

a)1.2.3 "took" should be "tool"
We have made the change in the revised manuscript.

b)2.4 Inject the up to 10 mA..

Changes have been incorporated in the modified script.

3. Please keep the editorial comments from your previous revisions in mind as you revise your manuscript to address peer review comments. For instance, if formatting or other changes were made, commercial language was removed, etc., please maintain these overall manuscript changes.

4. Please take this opportunity to thoroughly proofread your manuscript to ensure that there are no spelling or grammar issues. Your JoVE editor will not copy-edit your manuscript and any errors in your submitted revision may be present in the published version.

5. If your figures and tables are original and not published previously, please ignore this comment. For figures and tables that have been published before, please include phrases such as “Re-print with permission from (reference#)” or “Modified from..” etc. And please send a copy of the re-print permission for JoVE’s record keeping purposes.

Reviewers' comments:

Reviewer #1:
Publishable in present form

Reviewer #2:
Manuscript Summary:
The article "Laser-Induced Forward Transfer for Flip-Chip Packaging of Single Dies" submitted to JoVE Produced Video was published in APPLIED PHYSICS LETTERS 104, 061102 (2014) with title "Flip-chip bonding of vertical-cavity surface-emitting lasers using laser-induced forward transfer". In this paper the use of LIFT as a bumping technique for flip-chip packaging of vertical cavity surface emitting lasers on a chip-scale is presented.

Minor Concerns:
This paper can be presented as video in JoVE, after the authors explain:
1) In the Introduction part (line 74), the article cited [7] is about cells, not bio-materials. The authors should change the word "bio-materials" with "cells" or should give another reference for "bio-materials";

We have made the changes suggested by the reviewer in the revised manuscript.

2) Line 128: please show a "line scan of a bump profile" with the height of 1.5 µm.

We have added the bump profile image (Figure 3) recorded using an optical profilometer in the revised manuscript.

3) Line 107: the authors write that the donor is in contact with the receiver. Please explain how you obtain thicker bumps without changing the target (donor); if the target has to be changed "several times", the bump printing process becomes too slow and rather difficult.

For stacking, first, an indium bump is LIFTed onto the receiver bond pad, then the donor is moved to a fresh area, and another bump is printed on top of the previously printed one. This is repeated six times to achieve a stack of LIFTed dots with an average height of 1.5 µm and 20 µm diameter.

The main reason for using a stack of 6 bumps was due to the fact that the evaporator available in-house is capable of depositing only 200 nm thick films in one run. Deposition of thicker donor films would have required multiple runs and that would have involved breaking the vacuum which is not ideal because of oxidation of the already deposited indium layer. Having said that, in principle it is possible to LIFT thicker indium bumps using e.g. pre-patterned thicker (> 1 µm) donor films (as reported in the following reference).

K.S.Kaur,et al. “Laser-induced forward transfer of focussed ion beam pre-machined donors”, Appl. Surf. Sci. 257 (15) (2011).

However, having a thinner donor also gave the flexibility to test bonding using different bump thicknesses by employing different stacking conditions.

Reviewer #3:
Manuscript Summary:
Review of the manuscript 'Laser-Induced Forward Transfer for Flip-Chip Packaging of Single Dies' by K. Kaur and G. Van Steenberge.
The manuscript describes a new laser-based technique for digital printing of microbumps with high resolution for optoelectronics applications
The manuscript is clear and well-organised. The procedures are well described and the figures illustrate perfectly the different steps of the fabrication process.

Major Concerns:
No

Minor Concerns:
I have few minor comments hereafter
- The point 1.1.4 defines the laser parameters and the irradiation conditions, and the following note explains that the experimental conditions need to be controlled accurately. It could be interesting to mention if these conditions are unique or if similar results could be obtained with other laser source and experimental conditions. There is a mistyping error at the last line of paragraph 1.1.4: flunece instead of fluence

We have addressed these comments and made the changes in the revised script in NOTE of 1.1.4.

- Point 1.1.5: the donor film thickness is 200nm and the thickness of the bumps composed of a stack of six pixels printed on the top of each other is 1500nm. Authors should explain why a stack of six pixels is thicker than six times the maximum thickness of one pixel.

We have addressed the similar point above (please refer to the comment 3 by reviewer # 2). To explain the discrepancy between the sizes of the stacked bump as compared to the addition of thickness of 6 bumps we have added the text explaining the same in the NOTE of 1.1.5.

- Figure 2: a scale should be added in the zoom image too.

We have added the scale in the magnified image.