Assembly of Thin Micro-Chiplets using Laser-Induced Forward Transfer

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Abstract

Precise assembly and handling of thin micro-chiplets (i.e., thickness <100 µm) during heterogenous integration is quite challenging with very demanding requirements. Advanced packaging techniques are continuously been developed to cope up with the continuously increasing demands of semiconductor industries. Broadly, two techniques are commonly explored for mass transfer of micro-chiplets. First, the in-contact transfer printing which is quite mature technology and second, the non-contact laser-based mass transfer technique which is in its embryonic stage. These laser-based mass transfer techniques have added advantages of being non-contact, very selective and flexible with respect to the micro-chiplet's dimensions and shape in addition to high transfer rates. In this research work, laser induced forward transfer (LIFT) of very thin micro-chiplets are presented. Additionally, the present study reports the effect of micro-chiplet's edge chipping obtained by the conventional dicing process, and laser beam spot's alignment on the transfer accuracy of micro-chiplets during LIFT printing for heterogeneous integration applications.

Introduction

Today's world is rapidly moving towards digitalization and high-speed connectivity mainly driven by semiconductor technologies like consumer electronics, 5G network, automotive & mobility, healthcare & wellbeing, internet-of-things, and high-performance computing [1]. The plateauing of Moore's law has resulted in tremendous developments in 3D heterogeneous integration technologies for micro-chiplets in system-in-package applications. The importance of the heterogeneous integration can be analyzed by the fact that international technology roadmap for semiconductors (ITRS), which was successfully guiding our semiconductor industry for so long, was put to an end in 2015 followed by heterogeneous integration roadmap (HIR). The HIR provides direction to the industries, professionals as well as governments to target on the crucial technological challenges so that the electronics market can grow continuously. The market size forecast for the semiconductor devices in various market applications are estimated to be $615 bn by 2025 [2]. Meanwhile, according to the Yole group the chiplet market size is expected to be $135 bn and higher than $205 bn by 2027 and 2032, respectively, with the chiplet packaging market share increasing from 24% to 39% from 2021 to 2027, respectively [3]. These forecasts clearly call for novel developments in heterogeneous integration techniques to achieve faster and low-cost handling of thinner micro-chiplets.

Heterogeneous integration simply refers to the assembly of batch fabricated individual components and/or devices on a higher level arrangement to achieve cost-effective improved functionality and operating characteristics with higher throughputs. These separately fabricated individual components and devices are commonly referred to as chiplets, which are designed and fabricated in a cost-effective and optimized way to perform a specifically dedicated function. Multiple chiplets with different functionalities are then assembled together to yield system-in-package (SiP) which can outperform the system-on-a-chip (SoC) in terms of lower time-to-market, higher throughputs, improved form factor, and eventually cost [4]. In order to achieve this, advanced packaging of these chiplets are critically important and which consequently requires handling and assembly of these chiplets. Corresponding to various applications and requirements the chiplet's size can vary from few millimeters to hundreds and tens of micrometers.

Integration of conventionally thicker micro-chiplets mainly relies on pick and place, however, thinner micro-chiplets (10-100 µm) possess very challenging and demanding handling requirements during the assembly process. Different mass transfer techniques have been developed for precise assembly of micro-chiplets, like kinetically controlled in-contact technique, which is a quite mature technology, however, laser-based mass transfer technique is still in its research and development phase. For thin micro-chiplets (i.e., < 100 µm), laser-induced forward transfer (LIFT) printing is a promising mass transfer technique as it offers added advantages like very high transfer rate, being truly selective for known good dies (KGDs), non-contact, and exhibiting extreme flexibility in micro-chiplets dimensions, shape and materials [5].

LIFT was initially demonstrated by Bohandy *et al.* to transfer metals from a donor substrate to receiver substrate in a non-contact way [6]. This process utilized the thermal energy of the laser beam for localized melting and hence transferring the molten material. Since then, LIFT has been investigated to transfer a variety of materials like metals, polymers, inorganic inks, pastes, bio-molecules, cells, as well as 3D micro-structures in different domains like electronic, biological and mechanical applications [7]–[10]. There are mainly two mechanisms of LIFT, first, by direct interaction, where the laser pulse energy is directly absorbed by the material to be transferred from donor to receiver substrate. However, in this case, sensitive materials cannot be transferred and thus the second mechanism kicks in where an additional dynamic release layer (DRL) is introduced between the donor substrate and the material. The DRL absorbs the laser pulse energy and depending upon the DRL material and laser wavelength, DRL material either gets ablated or forms blister with nozzle throttling the evaporated DRL material to detach and transfer the desired material in a systematically controlled way. Detailed LIFT mechanisms and their detailed descriptions can be found elsewhere [11].

Depending upon the mechanism used and materials to be transferred, different transfer accuracies can be achieved with higher throughput. In this study, handling and transfer of thin micro-chiplets (<50 µm) using LIFT technology is demonstrated. Additionally, the influence of micro-chiplet's edge chipping and laser beam spot alignment with respect to the micro-chiplet's center of mass axis on transfer accuracy during LIFT printing is presented.

Experimental details

In the present study, the micro-chiplets were fabricated using the similar technology previously reported by Kannojia *et al.* [12], however with some improvements. Alignment marks were incorporated (Fig. 1) to evaluate the transfer accuracy more precisely since the micro-chiplet's edges showed high degree of chipping. Mechanical stainless-steel based spacers used in previous study were replaced by in-house customized poly-ethylene-terephthalat (PET) foil-based spacers to facilitate donor-receiver alignment and restrict any relative movement between donor and receiver substrates during sample movement involved in between donor-receiver alignment, LIFT experiments and inspection steps.

Alignment marks were fabricated by using a sputter deposited 150 nm thick TiW layer on single-side polished 4-inch Si-wafers, 2-inch donor glass substrates, and 2-inch receiver glass substrates. The TiW layer was patterned lithographically (SET MG1410 Mask aligner) to form complimentary alignment marks. The wafers were then spin-coated with S1818 photoresist to protect the top surface of the Si micro-chiplets during dicing and grooving steps. Thereafter, 16x16 mm^2 Si chips were diced out from the 4" Si wafer using Disco's DAD322 dicer. Shallow grooving was carried-out in multiple 16x16 mm^2 Si chips with two different dicing saws, i.e., low grade #2000 (saw 1) and high grade #4500 (saw 2), respectively. The lateral pitch and dicing blade depth during grooving step were 130 µm and 50 µm, respectively. This resulted in 100x100 μm^2 micro-chiplets since the dicing street width was 30 µm. Afterwards, the protective photoresist layer was stripped in acetone, followed by thorough cleaning of Si chips in isopropyl alcohol (IPA) and deionized (DI) water with N_2 blow drying. The chipping length was measured with respect to micro-chiplet's edges in order to quantitatively characterize the level of chipping. Grooved Si chips were bonded to the 2-inch donor glass substrates having spin-coated dynamic release layer (DRL), followed by dicing-by-thinning process to get individual 19±2 µm thick micro-chiplets. Detailed description of the fabrication process flow can be found elsewhere [12].

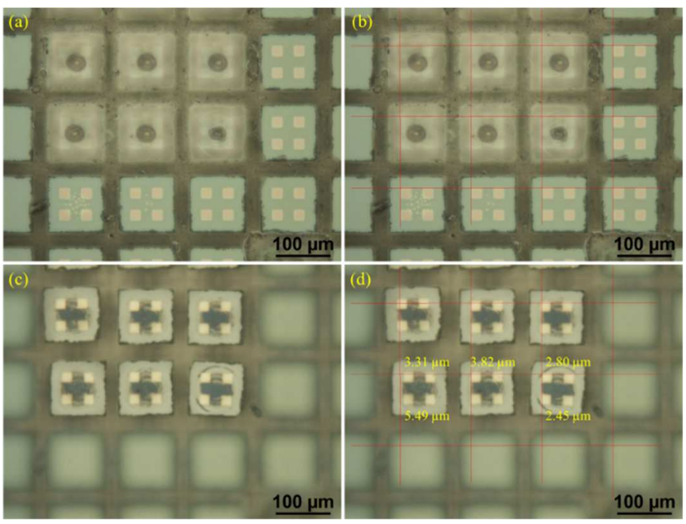

Fig. 1: LIFT accuracy measurement using alignment marks. (a) Micro-chiplets on donor in focus, (b) reference lines drawn using alignment marks, (c) LIFT printed micro-chiplets in focus, and (d) superimposed reference lines to measure transfer accuracy.

In order to have predefined gap between the donor and receiver substrate, spacers with predefined thicknesses were fabricated. Polydimethylsiloxane (PDMS) was spin-coated over 25 µm thick PET foils to obtain 48±4 µm thick spacers. The actual air-gap or the distance which micro-chiplets need to travel during the LIFT experiment was 29±4 µm. The PDMS coated spacers also provided a temporary attachment of the donor substrate over the receiver substrates because of its tackiness. Once donor substrates were placed on top of these tacky spacers on receiver substrates, dynamic movement between the donor and receiver substrates was not possible. The receiver glass substrates were also spin coated with 50±5 µm thick PDMS as soft and tacky layer to avoid bouncing back of Si micro-chiplets during LIFT printing. The donor-receiver substrates arrangement during LIFT experiments using PDMS coated PET based spacers is shown in Fig. 2. Single pulses from Time-Bandwidth Duetto's picosecond laser having wavelength, pulse duration and spot size of 355 nm, 12 ps, and 30 µm, respectively, were used for the LIFT experiments. In this study, pulse energy range of 0.5 – 2.0 µJ was used for the LIFT printing of Si micro-chiplets. Additionally, to investigate the effect of laser beam spot location with respect to the Si micro-chiplet's center of mass, an offset of 2 µm was provided to the laser beam spot in both X- and Y-directions with respect to its geometric center because of symmetric square shape of the micro-chiplets.

LIFT printing of nine (3x3) micro-chiplets were repeated three times to measure the average transfer accuracy of 27 Si micro-chiplets. The transfer accuracy was measured by observing the alignment marks on the LIFT printed Si micro-

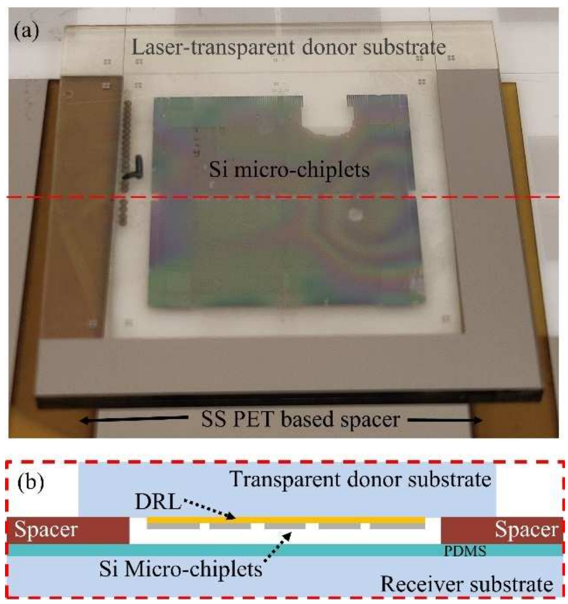

Fig. 2: Donor-receiver substrate arrangement during the LIFT experiments. (a) Donor-receiver substrate with PDMS coated PET based spacer, and (b) schematic cross-sectional view of the set-up.

chiplets with respect to the alignment marks on the Si micro-chiplets still bonded to the donor glass substrate (shown systematically in Fig. 1(a-d)). The LIFT accuracy measurements were performed with high resolution Nikon Optiphot 200 microscope. Non-contact type optical profilometer (Veeco WYKO NT3300) was used to characterize the planarity of the LIFT printed Si micro-chiplets on the receiver glass substrates.

Results and discussion

In this study, successful LIFT printing of Si micro-chiplets were observed for the pulse energy's range of 0.75 µJ to 1.5 µJ, which is lower than the pulse energies reported in the previous study [12]. This is mainly attributed to the lower thickness of the Si micro-chiplets, i.e., 19±2 µm which is much lower than the thickness of the micro-chiplets reported in the previous study (i.e., 99±2 µm) [12]. The threshold pulse energy for successful LIFT printing in this study was 0.75 µJ (Fig. 3(b)) which implies that for given set of experimental conditions, pulse energies ≤0.5 µJ (Fig. 3(a)) didn't result in micro-chiplet transfer from donor to receiver substrates. This is because the force exerted by the blisters formed at lower pulse energies would be lower than the adhesion strength between the micro-chiplet and DRL material and hence insufficient to separate them. However, pulse energies ≥1.75 µJ resulted in the failure of the Si micro-chiplets since they broke physically (Fig. 3(d)). This is due to the rapid formation of blisters in the DRL material which exerts excessive bending stresses in the Si micro-chiplets. Since the blisters exert force at the micro-chiplet's center, the separation initiates and extends gradually towards the micro-chiplet's edges. These stresses would be sufficient enough to break these thin micro-chiplets used in this study. Since thicker micro-chiplets were used in the previous study [12], micro-chiplet's fracture was not observed as relatively much higher pulse energy would be required to break thicker micro-chiplets. Additionally, there is a potential concern that a part of laser's pulse energy is transferred through the DRL material to Si micro-chiplet's to surface which results in the heating of the Si micro-chiplet and in turn facilitating the micro-chiplet's fracture. Highest average transfer accuracies for the given experimental conditions were observed for the pulse energy of 1.0 µJ. A micro-chiplet, fabricated by low grade dicing saw 1, transferred with the pulse energy of 1.0 µJ is shown in Fig. 3(c) for reference.

Confirming the pulse energy for highest average transfer accuracies, 1 µJ was used to investigate the effect of chipping quality on micro-chiplet's transfer accuracy. The edge quality of the grooved Si micro-chiplet in terms of chipping, improved considerably when grooved using higher grade dicing saw. The highest chipping length for micro-chiplets fabricated by dicing saw 1 and 2 were measured to be 15 µm and 5 µm, respectively, as shown in Fig. 4(a-b). This is basically attributed to the finer average grit size comprising smaller abrasive particles in higher grade dicing saws (i.e., saw 2) [13]. Therefore, the micro-chiplets fabricated by the grooving of low-grade dicing saw 1 showed very high chipping than those grooved with high grade dicing saw 2.

The micro-chiplets having non-uniform and irregular edges fabricated by the dicing saw 1, resulted in higher misalignments when compared to the micro-chiplets with uniform and symmetric edges. A comparison of micro-chiplets showing the effect of chipping on the micro-chiplets and their transfer accuracies are presented in Fig. 4(a-b) and Fig. 4(c-d), respectively. The average transfer accuracies along X- and Y-direction for micro-chiplets exhibiting higher chipping was measured to be 4±4 µm with a few outliers having relatively higher misalignments up to ~22 µm due to the random and non-uniform chipping. On the other hand, the micro-chiplets having lower chipping showed the transfer accuracy of 2±2 µm. In this case as well, few outliers with higher misalignments were observed but only as high as 12 µm. Regarding outliers, it is believed that combined effect of various process parameters might result into these outliers. Further detailed investigations into the reasons causing these outliers are ongoing. However, chipping at the micro-chiplet's edges results in the uneven area

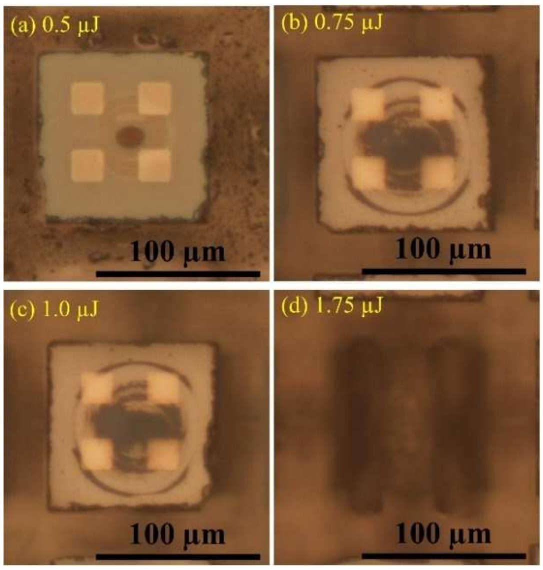

Fig. 3: Si micro-chiplets LIFT printed using pulse energies of (a) 0.5 µJ (no LIFT observed), (b) 0.75 µJ (threshold energy), (c) 1.0 µJ (good LIFT), and (d) 1.75 µJ (micro-chiplets broke).

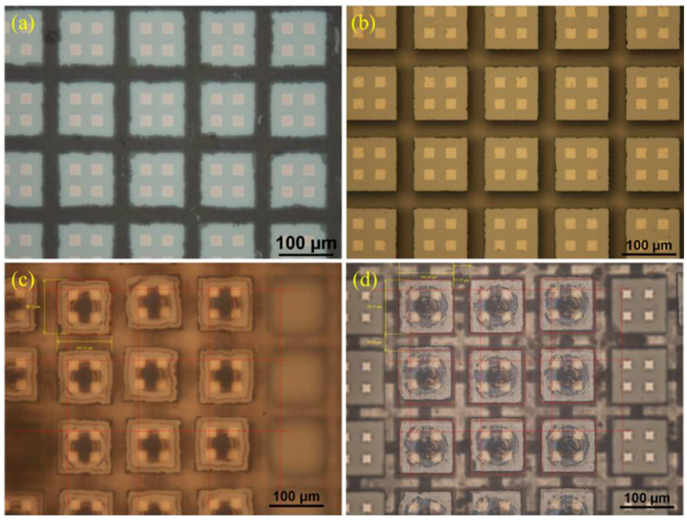

Fig. 4: Effect of chipping on micro-chiplet's edge quality and LIFT accuracy after LIFT printing. Micro-chiplets grooved with dicing (a) saw 1 (low-grade), and (b) saw 2 (high-grade). Transfer accuracies corresponding to dicing (c) saw 1 (lower accuracy), and (d) saw 2 (higher accuracy).

of contact between the micro-chiplets and the donor substrates because of the irregular and non-uniform shape of the micro-chiplets which in turn would result in the uneven adhesive force between them. Therefore, the LIFT printing of chipped micro-misalignments and eventually lower transfer accuracies. Moreover, it was observed that the micro-chiplets were transferred towards the opposite side of the edge exhibiting chipping. This can be attributed to the shift in the micro-chiplet's center of mass because of chipping and resulting in a misalignment between the laser beam spot and the micro-chiplet's center of mass. One of these potential reasons could be variation in the laser spot beam alignment with respect to the micro-chiplet's center of mass.

Since the blister formation and the vaporized DRL material flowing through nozzle guides the micro-chiplet transfer from donor to receiver substrate [14], the laser beam needs to be aligned with the micro-chiplet's center of mass. This would result in blister formation and hence application of separation force at the axis along the micro-chiplet's center of mass, causing uniform separation of the micro-chiplet from the donor substrate and planarized movement towards the receiver without any tilting and/or rotation (Fig. 5(a-b)). Thus, to investigate this effect, intentional offset of 2 µm was provided to the laser beam spot with respect to the micro-chiplet's center of mass and the resulting die shift direction and transfer accuracies were measured. Since the micro-chiplets were square and had symmetric patterned metal alignment marks, the center of mass coincides with the geometrical center of the micro-chiplets.

The offset of the laser beam spot in one direction along an axis was observed to cause a deflection in the LIFT printed micro-chiplets in the opposite direction along the same axis, i.e., an offset in the negative X-direction resulted in the micro-chiplet's shift in the positive X-direction on receiver substrates during LIFT printing (Fig. 5) and vice versa. Corresponding to the offset of 2 µm in X-direction, the micro-chiplets were observed to incur an average misalignment of 4±2 µm in respective opposite directions. However, the average misalignment observed in Y-direction when the offset was

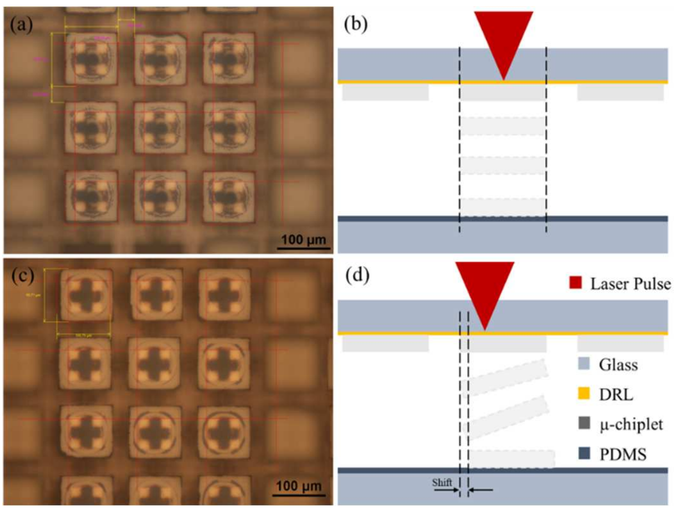

Fig. 5: LIFT printed micro-chiplets and respective LIFT schematics for laser spot aligned (a-b) at center; and (c-d) with slightly displaced in -X direction w.r.t the center of the micro-chiplet.

provided in the X-direction was 2±2 µm, which is same as the average misalignment without any offset. This implies selective and directional misalignments incurred because of the provided offset in the respective specific axis. This was confirmed by similar misalignments in the LIFT printed micro-chiplets corresponding to the offset provided in the negative Y-direction. In this case, an average misalignment of 4.5±2.5 µm was observed in the positive Y-direction. The increased misalignments corresponding to the offset of the laser beam spot clearly infers that it is a critical parameter influencing the transfer accuracy of the Si micro-chiplets in LIFT printing.

The offset in the laser beam spot with respect to the micro-chiplet's center of mass results in the blister formation at a same offset with respect to the micro-chiplet's center of mass. Thus, the separation force by the blister is applied at an offset which in turn causes the closer micro-chiplet's edge to separate first while the farther edge detaches later because of the unequal distance between the opposite edges from the point of separation force application (Fig. 5(c-d)). Thus, the micro-chiplet separates in a tilted position and thereafter approaches towards the receiver substrate in the same orientation. Consequently, the micro-chiplet lands on the receiver substrate in the tilted position where the edge which was closer to the laser beam spot or in turn the blister makes the first contact and then the other side lands on the receiver substrate resulting in added misalignment or shift. This phenomenon is shown schematically in Fig. 5(b,d). The reported higher misalignments correspond to the given set of process parameters used in this study. This increased shift in the misalignment because of the offset in the laser beam spot would also be influenced by the donor-receiver gap which is an ongoing investigation.

Introduction of additional misalignment due to the laser beam spot's offset with respect to the micro-chiplet's center of mass also explains the lower transfer accuracy due to the excessive and non-uniform chipping owing to the low-grade dicing saw as observed in this study. The chipping caused irregular and random material removal from the micro-chiplet's edges resulting in an irregular shift of its center of mass with respect to its geometric center. And since laser beam spot is aligned with respect to the geometric center of the micro-chiplets, there is an offset between the laser beam spot and the micro-chiplet's center of mass. Therefore, higher misalignments were observed for the micro-chiplets having edges with higher degree of chipping.

Conclusions

This study presents a solution for the handling and precise assembly of thin micro-chiplets for heterogeneous integration in different domains. The transfer accuracy for nearly 20 µm thick 100x100 μm^2 Si micro-chiplets is reported to be less than 5 µm. The effect of the laser beam spot's alignment in addition to the micro-chiplet's edge quality in terms of chipping is investigated to achieve highly accurate transfer of thin micro-chiplets. This study shows that the micro-chiplet's center of mass and laser beam spot should be aligned along the same axis to achieve higher transfer accuracy. For higher transfer accuracy, the micro-chiplets needs to have uniform edges i.e., without any irregular or arbitrary chipping which results in shifting the micro-chiplet's center of mass. The micro-chiplet's edge quality can be further improved by utilizing the dry-etching technique to fabricate chipping free and uniform grooves in the Si micro-chiplets. This would lead to improved transfer accuracies with higher throughputs which can be used for high precision heterogeneous integration of electronic and photonic micro-chiplets.

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