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Laser-assisted ultrathin die packaging: Insights from a process study

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ABSTRACT

Laser-assisted assembly of ultrathin, ultrasmall bare dice holds promise for enabling a new class of very low cost flexible electronic devices with applications in many areas. But this advanced packaging technology will be of little use if two important parameters are not considered – transfer rate and precision/accuracy of die placement. Both parameters depend on the laser process parameters and the properties of the consumable materials used. Reported are results from a process study designed to investigate the effects of the laser pulse parameters, the adhesive layer properties, and the method of wafer dicing on the transfer rate and placement precision/accuracy when transferring ultrathin (50-μm thick) silicon dice using the thermo-mechanical selective laser-assisted die transfer (SLADT) technique developed by this team and reported in prior publications. It is shown that, when properly controlled, SLADT can transfer ultrathin bare dice with precision and accuracy compatible with those achievable by the conventional die placement methods but at a much higher transfer rate.

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1. Introduction

1.1. Ultrathin semiconductor dice

Conformal, wearable and, in some cases, disposable microelectronic devices assembled on flexible substrates are revolutionizing the way technology integrates into our lives. These devices have the potential to enhance our security, make commerce more efficient, enable new capabilities in healthcare and potentially will provide consumer electronics users the opportunity to integrate computing into their daily lives like never before. All this will be made possible by the ability of the flexible electronic devices to bend, roll, and fold into complex geometries.

The traditional IC package is nothing but a small piece of silicon, a bare die, encapsulated in a plastic encasement with bonding wires or balls and a metal lead system for connecting the die circuit to the external world. These additional elements of the IC package serve to protect the die and facilitate the assembly process but they are not essential to the functions of the chip itself. Miniaturization requires the size of the electronic components to be as small as possible. To reduce its footprint, the IC package has to shed all these nonessential elements, ultimately leading to what is known in the industry as a wafer-level package. The transition from a plastic to wafer-level IC package reduces the footprint but this may not be enough to have a flexible electronic device. The flexible substrate requires not only small but also flexible bare dice. This can be achieved only if the thickness of the silicon is reduced to 50 μm or less [1,2] thus adding flexibility to the intrinsically fragile bare dice. For example, the allowable bend radius for a 25-μm thick silicon wafer is as small as 1 cm [3]. The reasons for the acquired flexibility are quite simple – the maximum tensile and compression stresses in a plate subjected to bending develop on the outer and inner surface of the plate and are proportional to the plate thickness. If this thickness is small enough, as in the ultrathin dice, the bending stresses are below the fracture limit, turning the intrinsically brittle and rigid monocrystalline silicon into a flexible material. Obviously, the thinner the die the more flexible it becomes. At 10 μm and less silicon acquires an excellent flexibility and unconditional mechanical stability [4].

The amount of literature published in the past decade indicates a strong interest in the ultrathin die technology. The critical points in this technology are the front-end-processed wafer thinning, dicing, handling, and especially, ultrathin die placement and assembly. Various back-end methods have been developed to successfully solve most of these problems except the latter. The conventional methods are designed for wafers with thicknesses of 200 μm or more. They can be modified and adapted for packaging thin wafers (<200 μm) on flexible substrates but this is not a trivial task. For example, it was shown that 200-μm diameter wafers thinner than 200 μm cannot be handled by the standard equipment [5]. The problems become even more complicated if the wafer thickness is reduced to 50 μm or less. Handling and processing of such ultrathin wafers requires unique and unconventional methods [5,6].

The following sections briefly outline some of the issues related to back-end processing of ultrathin wafers. An excellent in-depth discussion on the ultrathin chip technology and applications is provided by Burghartz and co-authors in a recent publication [4].
1.2. Wafer thinning

The major processing steps in wafer fabrication include slicing the silicon ingot into wafers with thicknesses from 0.50 to 1 mm, depending on the desired diameter of the wafer, followed by coarse-grit and fine-grit mechanical grinding. The formation of high-density integrated circuits is impossible without having a layer on the wafer surface free of detrimental surface and crystal-line defects (also called the denuded zone). Reiche and Wagner [7], for example, have provided evidence for a complex structure of about 1–2 μm deep surface cracks oriented parallel to the (111) direction in silicon wafers after mechanical grinding. Chen and De Wolf [8] reported evidence of warpage in the wafer due to stress induced by backgrinding and showed that the stress can be mitigated by dry etching. The damage in the Si wafers caused by mechanical grinding has been also investigated by many other research groups (see, for example, Ref. [9–12]). Therefore, finishing steps will be required to achieve a surface with exceptional flatness and mirror-like finish and to remove the structurally damaged layer and the residual stresses left after the mechanical grinding step. Techniques such as dry plasma etching, wet chemical etching, and chemical mechanical polishing are commonly used as a follow-up operation after grinding. The wafer thickness at this point is between 275 μm for 2-in. wafers and 775 μm for the current high volume 300-mm diameter wafers.

The use of ultrathin dice requires additional wafer thinning at the back end of the IC fabrication process, i.e., after the circuitry has already been formed on the wafer. This can be achieved by mechanical grinding on the wafer backside. Some of the finishing methods mentioned above can be also used to further reduce the wafer thickness to less than 50 μm and down to 10 μm or less, which is otherwise impractical or even impossible to achieve with mechanical grinding. For example, Pinel and co-workers [13], among others, have suggested the use of reactive ion etching (RIE) as a finishing step in order to reduce the wafer thickness to 10 μm. Various techniques for wafer thinning as applied to ultrathin dice are discussed in details in Refs. [4,14].

1.3. Wafer dicing

The dicing of the ultrathin wafer is best accomplished by laser dicing or plasma etching. The conventional method for wafer dicing using a diamond-coated circular saw is not applicable to ultrathin wafers because of problems with mechanical damage such as chipping and cracking. Laser dicing introduces only a limited amount of mechanical stress in the ultrathin wafer due to the large temperature gradients in the heat affected zone. The structural damage, however, is confined only to the heat affected zone and is of a minor concern considering the fact that the streets between the chips on the wafer are much wider than the laser kerf. More significant is the problem with the debris produced in laser dicing that may deposit on the die bumps and as a result affect the reliability of the package. Figs. 1a, b show a part of a laser diced silicon wafer where the extensive accumulation of debris along the laser cut streets is clearly evident.

Plasma etching, on the other hand, eliminates most of the problems with the mechanical sawing and laser dicing. As seen in Fig 1c, the RIE-etched sidewalls show no signs of mechanical damage, the edge of the die is much cleaner and well-defined compared to the laser-cut die. Particular issues with this process include low material removal rate and the difficulty in controlling the flatness of the surface and the thickness uniformity. Also, plasma etching may have a negative effect on the surface roughness but this process will reduce the stress concentrations in the wafer resulting in a much better fracture strength [15].

The conventional methods for wafer handling throughout the back-end operations of backgrinding/lapping, dicing, and component placement are intended for rigid wafers. Even then appropriate support mechanisms are required to minimize the gravity-induced sagging effects, especially in large diameter wafers. In the process the wafers are transferred, bonded, and debonded between and to various rigid and flexible carrier substrates. However, the methods for thick wafer handling cannot be mechanically applied to ultrathin wafers that are fragile and tend to warp, making the use of automated robot handling difficult if possible at all [6]. The acquired flexibility of the ultrathin wafers presents unique problems and requires unorthodox solutions. Only methods for ultrathin wafer processing that require limited transfers between the wafer carriers can provide reliable operations with high throughput at low production cost. Consequently, a process called “Dicing-By-Grinding” or “Dicing-Before-Grinding” was suggested [4,16–19] in which half-cut dicing is carried out on the wafer’s front side before thinning. After bonding to a handle wafer or backgrinding tape, the half-diced wafer is thinned by backgrinding until trenches are opened and dice separated.

1.4. Contact methods for ultrathin die packaging

The next major step after wafer dicing is the component placement. The pick-and-place equipment conventionally used for direct chip attachment cannot satisfactorily handle ultrathin and small dice [12,18]. One of the reasons is that these dice are very fragile and tend to be easily damaged. Also, the die warpage can impede the shape recognition by the image-recognition system of the pick-and-place equipment. Currently, the industry relies on prototype equipment optimized to handle thin silicon, e.g., flip chip die bonders with adapted tooling and special release tapes [6,20–22]. Temporary carriers may be used to support the thinned dice during assembly [23]. In some instances, the ultrathin chips were assembled using a mask aligner [24].

Regardless of the method, it is obvious that the equipment that can handle ultrathin bare dice is unique and costly [25] and the

![Fig. 1.](https://example.com/fig1.png) (a) An SEM picture of a part of silicon wafer after laser dicing, showing the accumulation of debris around the 20-μm wide streets; (b) a close-up view of a street ablated using a Nd:YVO4 HIPPO laser; (d) a close-up view of an RIE-etched street.
packing rates are low. Placement accuracy and rate for the pick-and-place machines are inversely correlated. According to Gilleo [26], the most advanced single nozzle placement machines are capable of 4000 placement accuracies of ±15 μm at a rate of 2000 components per hour (cph). Multiple nozzle placement machines are capable of up to 100,000 cph but with the 4x placement accuracy degraded to ±100 μm. Though a single nozzle placement machine may have the precision to place extremely fine pitch components, its inability to place ultrathin dice [18] and similar components at a rate sufficient for high throughput assembly (>10 components/s) has led to the pursuit of other techniques.

In summary, although capabilities exist both for placement of ultrathin dice as well as placement of regular size dice at high rates, there is an unfulfilled gap when both capabilities are required simultaneously.

1.5. Thermo-mechanical Selective Laser Assisted Die Transfer

The contactless laser-induced forward transfer technologies, modified for die assembly in order to solve the problems with the contact methods, are receiving increasing attention in the industry. Existing technologies, such as those reported by Holmes [27,28], Karlitskaya et al. [29,30] and Pique et al. [12,31–34], however, suffer from significant drawbacks which limit their applicability. Among them are the precision and accuracy of die placement. The ablative releasing method in which a sacrificial layer is vaporized as it is heated by a laser has been found to provide highly unpredictable component transfers. By the nature of gas dynamics, the use of a relatively low density gas to push a higher density component, such as a semiconductor die, results in a process which is highly sensitive to initial conditions. Small variations in the heat absorption mechanism, irregularities in the sacrificial layer thickness and homogeneity, presence of contamination as well as variations in the intensity profile of the laser beam used for ablating the sacrificial layer all contribute to the ablative release process being very unstable and the results highly unpredictable. The gradual thermal release technique suggested by Karlitskaya et al. [30] is intended to address the transfer volatility and unpredictability observed in the ablative transfer process. The problem with the thermal releasing mechanism is the need to precisely control the process and the release material properties in order to achieve the desired effect. Also, in the case of small area, ultrathin dice, because of their small mass, the gravitational force acting on the die may not be sufficient to overcome the interface forces of attraction and the die may not separate from the adhesive layer and transfer over the gap.

The thermo-mechanical Selective Laser-Assisted Die Transfer (tmSLADT) process developed at North Dakota State University in Fargo, North Dakota, overcomes the problems with the ablative and thermal release processes. The basic concept of this method, illustrated in Fig. 2a, includes using a dual dynamic release layer (DRL) to attach the dice, to be transferred, to a laser-transparent carrier.

The DRL comprises both a blistering layer and an adhesive layer. During the process of laser transfer, the DRL is irradiated by a laser pulse through the laser-transparent carrier. In contrast to the other laser-induced forward transfer mechanisms, tmSLADT does not rely on the kinetic energy of a plume of vaporized material from the DRL or solely on the gravitational force to transfer the dice. Instead, the laser pulse creates a blister in the DRL, thus confining the vaporized material within the blister (Fig. 2b). The DRL, with a blistering layer that is thicker than its laser absorption depth, is subjected to only a limited non-penetrating ablation, which creates vapors to form a blister, without rupturing it. The force exerted by the blister, in addition to the gravitational force of the die, initiates the transfer over the gap. More details about tmSLADT are available elsewhere [35–37].

To reiterate, regardless of how sophisticated the die placement technique might be, it will be of little use if two important parameters are not considered – transfer rate and precision/accuracy of die placement. Both parameters depend on the nature of the laser transfer process – ablative, thermal, or thermo-mechanical – as well as on the material and process parameters. Very few, if any, experimental results have been reported in the literature relating the outcomes of the laser transfer process to the process factors. Reported here are results from a process study designed to investigate the effects of the laser pulse parameters, the adhesive layer properties, and the method of wafer dicing on the transfer rate and placement precision/accuracy when transferring ultrathin (50-μm thick) silicon dice using the tmSLADT technique.

2. Method

The problems with processing silicon wafers with thicknesses less than or equal to 50 μm outlined in Section 1 can be minimized if some of the operations are consolidated thus reducing the time the ultrathin wafer is transferred from one carrier to another before the component placement step. This minimalist approach to the major operations in the beginning of the back-end processing sequence is illustrated in Fig. 3. The following sections explain in detail the steps in this process, which has been successfully applied to fabricate a prototype passive RFID tag with an embedded ultrathin RFID chip in what would be the first technology demonstration reported in the literature of a functional electronic device packaged using a contactless laser-induced forward transfer method [35].

2.1. Sample preparation

2.1.1. Wafer carrier with DRL

The laser transparent carrier used in these experiments was a 3” × 1/16” fused silica disk (CGQ-0600-10, Chemglass Life Sciences).
The DRL consists of a blister layer of spin-on polyimide (PI-2525, HD Microsystems), followed by an adhesive layer of low molecular weight polyester, formulated in house and designated as PE7. The structure of this material, which is based on fatty dimer diacid and biodiesel, is shown in Fig. 4.

PE7 was synthesized by charging dimer fatty acid (Croda Polymer & Coatings) (0.01 mol, 5.70 g), soy biodiesel (Cargill Inc.) (0.02 mol, 5.54 g), dibutyltin dilaurate (Sigma–Aldrich) (0.05 g), and xylene (20 ml) into a three-necked, round-bottomed flask equipped with a magnetic stirrer, a Dean–Stark trap with a condenser, and a gas inlet and outlet. The mixture was heated to 160 °C for 3 h under nitrogen atmosphere. Xylene and water were removed from the system by distillation. The mixture was then heated to 230 °C for 5 h to obtain yellow, viscous liquid of PE7, with a yield of about 97%. For use in the DRL, PE7 was further diluted in tetrahydrofuran (THF) to concentrations of 5%, 10%, and 25% by weight.

The DRL materials were spin coated on a SUSS RC-8 spin coater. The fused silica disks were first cleaned using THF and dried by spin coating. The spin coating of the PI-2525 polyimide layer was carried out as follows: (1) dispensing and relaxation without spinning, (2) spinning at 500 rpm for 10 s (acceleration 500 rpm/min), followed by spinning at 5000 rpm for 40 s (acceleration 1000 rpm/min). Curing was carried out in an oven under nitrogen atmosphere as follows: (1) ramping to 120 °C and holding at that temperature for 30 min, (2) ramping to 350 °C and holding for 30 min, (3) cooling down gradually to 50 °C or less before exposing to room temperature. This cycle results in an incomplete crosslinking of the PI-2525 polyimide, which was shown to work best in the laser transfer experiments. The thickness of the polyimide film obtained with these spin-coating and curing parameters was 4 μm, which agrees well with the spin curves provided by the material manufacturer. The PE7 material was also dispensed on a static substrate, but unlike the polyimide, the whole fused-silica disk was coated with the starting material prior to spinning. Parameters used for spin coating were 5 s spin at 500 rpm (acceleration 500 rpm/min), followed by a 4500 rpm spin for 40 s (acceleration 1000 rpm/min). The THF solvent evaporated after spin coating leaving varying amounts of PE7 deposited depending on the concentration used.

2.1.2. Wafer thinning
Mechanically ground to a 65 μm thickness (100) p-type Si wafers were procured and used in these experiments. The wafer preparation started with sputtering a 0.8-μm thick Cu layer on the front of the wafer, preceded by a 30 nm thick layer of Ti for improved adhesion of the copper layer. The latter was patterned using standard lithographic techniques into squares with 350, 670, and 1000 μm sides to define dice with the corresponding dimensions. The Cu and Ti layers in the streets were then etched away to expose the Si wafer in the streets. Since the objective of this work was to study the laser transfer process parameters, blank silicon tiles without circuitry were used instead of functional dice. When the method described here is used for assembly of functional devices, sputtering and patterning metal films onto the front side of the wafer will not be permissible. In this case, the street pattern can be defined by structuring a photosist layer with a photolithographic process and then using the structured layer as an etching mask, as shown in Fig. 3.
To minimize the possibility for structural damage in the chips, additional wafer thinning from 65 μm down to 50 μm was done using RIE. After etching of the metal layers, the wafers were rinsed and dried and then placed Cu-side down in a Trion Phantom II RIE Plasma Etcher. The parameters used for both wafer thinning and opening the streets in the next step are shown in Table 1.

The measured etch rate resulting from these parameters was 0.25 μm/min. The wafer thickness was measured using a contact profilometer (KLA Tencor P-11) on a separate control piece of Si wafer placed in the etcher adjacent to the processed wafer. After the wafer was thinned to 50 μm, it was manually attached to the DRL spin-coated on a laser transparent fused silica carrier using plastic tweezers. The pre-prepared stack was run through an Optec DPL-24 Laminator to ensure reproducible and evenly distributed bonding pressure between the DRL and the wafer. Lamination was carried out as follows: (1) dwelling in vacuum for 7 min, (2) pressurizing the chamber and (3) dwelling for additional 3 min. The pressure of the laminator used is set at 30 psi and is non-adjustable.

2.1.3. Wafer dicing

After the wafer was bonded to the DRL, it was singulated into individual dice. This was performed utilizing two methods, RIE and laser ablation, thus allowing their respective results to be compared.

The RIE process involved opening the exposed streets using the RIE parameters in Table 1. Half of the sample was protected by a glass slide in order to leave a wafer area for laser singulation and comparison experiments between the RIE-etched and laser singulated dice. A Spectra Physics HIPPO Nd:YVO₄ laser operating at 355 nm was used for dicing the other half of the wafer along the wafer streets. The laser was set to a 50 kHz repetition rate, and used at an average power of 3 W, with pulse energy of approximately 60 μJ. Utilizing a scan speed of 400 mm/s, 20 scans were required to singulate the 50 μm thick wafer.

After laser singulation was complete, the sample was inspected utilizing a backlit optical microscope to ensure complete dicing was achieved. In some cases, nearly complete dicing occurred while small tabs of Si remained intact across the diced streets, which inhibited the transfer process. The desire for full separation must be balanced with the harmful effects of over-scanning during dicing, as laser scanning much beyond that necessary to singulate the wafer affects the properties of the DRL and must be monitored.

2.2. Laser transfer

After dicing, the wafer with the fused silica carrier (releasing substrate) was mounted in a fixture used for laser transfer. The releasing substrate was placed on top of the receiving substrate with the DRL and singulated wafer facing down. Prior to mounting, the receiving substrate was spincoated with a pressure sensitive adhesive (PSA) and cured in order to provide a means for catching the transferred dice. Shims of 260 μm thickness were used to space the receiving and releasing substrates from each other. Since the average thickness of the wafer used in these samples was 50 μm thick, the transfer gap was about 210 μm. In a typical electronics packaging application, the receiving substrates would include rigid or flexible printed circuit boards, or other substrates, that provide a means for interconnecting the transferred dice to the rest of the circuitry.

Once the substrates were mounted, the fixture was positioned under the scanhead of the Spectra Physics HIPPO Nd:YVO₄ laser for transfer (details about the laser system are available elsewhere [36]). The laser parameters used for activating the DRL are critical to optimize the transfer rate, and minimize the lateral or rotational displacement of the die during transfer. Operating with pulse energies just below the rupture threshold of the configured transfer setup ensures maximum blister height while still containing the hot gas generated by the vaporized blistering layer material.

The laser transfers were accomplished by scanning the DRL beneath the die to be transferred with a circular laser scanning pattern at 15 kHz repetition rate and a scan speed of 300 mm/s appropriate to create a continuous blister, which was based on the results of previous work [36,37]. For this study, a series of three concentric circles was used with diameters of 200, 400, and 600 μm for a 670 × 670 μm die size. The pattern starts with the smallest circle first, and works its way outward with a line connecting each circle. This pattern is shown in Fig. 2b.

The third harmonic of the laser at 355 nm was used, which is absorbed within a 0.2–0.5 μm depth in the typically 4 μm thick polyimide layer of the DRL. The beam was focused to a spot size of less than 20 μm in diameter. Many transfer trials were needed to determine the laser settings needed to optimize the die transfer rate, precision, and accuracy. The power needed to transfer depends greatly on the DRL characteristics, namely, the thickness and elastic modulus of the polyimide layer, the adhesion strength of the adhesion layer, and the die thickness (die mass). The average power of the laser was varied from approximately 50–400 mW during the trials. The lowest power did not activate the blister sufficiently to overcome the adhesion of the die to the DRL. The highest power caused complete rupture of the blister, which often caused extreme displacements. Average power settings of 150–250 mW provided the best results for this DRL, adhesive layer formulation, and die thickness. These parameters resulted in pulse energies ranging from 10 to 17 μJ/pulse, usually sufficient to avoid bursting the blister material. In some cases though, rupturing of the blister did occur. However, it was not clear if the rupturing occurred because of the excessive laser energy or because the die took away small pieces of the DRL upon transfer. Fig. 5 illustrates a typical result from the laser transfer process, showing a series of dice which have been transferred in a checkered pattern onto a receiving substrate.

Each processed wafer contained 350, 670, and 1000 μm square dice, which, as mentioned in Section 2.1.3, were singulated using the laser and reactive ion etching. This set of experiments focused on the 670 μm square dice, since they closely represented an active RFID device die used in other experiments. For direct comparison, 200 mW average power was used to transfer both the RIE and laser singulated dice. After setup trials, several sets of transfers were completed with RIE and laser singulated dice. Of the RIE singulated dice, a set of 33 dice were chosen for measurements. After inspection with the optical microscope, data for two dice were deleted because of poor DRL quality in that area. Of the laser singulated dice, a set of 21 dice were chosen for measurements. Data for other dice were deleted after inspection showed that they were not singulated completely.

### Table 1

<table>
<thead>
<tr>
<th>Dry Etch (RIE) Parameters for Si.</th>
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<td><strong>Parameter</strong></td>
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<td>SF₆, sccm</td>
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3. Results and discussion

Transfer precision, accuracy, and rate were studied using samples prepared with 5% PE7 in THF following the procedures described in Section 2.1. Pictures were captured of the transferred dice with an optical microscope to evaluate placement accuracy and precision. The position precision and rotational displacement were measured from the photographs using imaging software.

3.1. Transfer rate

SEM images of laser-singulated and RIE-singulated die sites are shown in Fig. 6. The transfer rates in these experiments were 85.7% (18/21) and 93.5% (29/31) for the laser-singulated and RIE-singulated dice, respectively. With this limited data set, the RIE-singulated dice had a better transfer rate. This is consistent with experimentation with different laser power settings and adhesive formulations. Because of the nature of the RIE process, wider streets are formed between neighboring dice, while the laser-singulated dice have only the kerf-width separating each die. If the dice have been carefully laser-singulated, the DRL is left intact in the streets, while the RIE process removes this layer without negatively affecting the neighboring layer. This effectively de-couples the DRL under each die from its neighbors and may allow for easier transfer. Also, debris and/or recast DRL material can build up in the streets in the laser-singulated dice, which can inhibit die transfer. Finally, the area of the RIE-singulated die that is in contact with the DRL is effectively reduced. This most likely reduces the adhesive force which needs to be overcome by the DRL blister, and results in a higher transfer rate.

3.2. Precision and accuracy of transfer

3.2.1. Effect of the laser parameters

To determine the effect of different laser parameters (power and scan head speed) on DRL blister formation, a simple experiment was performed. The laser was set to 15 kHz repetition rate, and the laser power and scan speed were varied as the laser scanned across the DRL with no die attached. The DRL consisted of the polyimide layer and 5% PE7 in THF. The two laser parameters were set to three different levels, which resulted in 9 different combinations. The laser power was set to 150, 200, and 250 mW, and the scan speed was set to 200, 300, and 400 mm/s. During each run, the laser first scanned a line at high speed to form individual blisters, then scanned a line at the prescribed speed, and finally scanned a circular pattern at the prescribed speed. Selected SEM images of the DRL after scanning with a circular pattern are shown in Fig. 7.

The analysis of the experimental results suggested that the probability for blister rupture increased with the laser power and decreased with the scan speed. The 150 mW blisters were largely intact with a few small ruptures, mostly independent of scan speed. The 200 mW blisters scanned with a low speed were ruptured, whereas the blisters scanned with the same power but at higher speeds were less damaged. All of the 250 mW blisters were badly ruptured, more severely those scanned with a low scan speed.

The use of a multiple-pulse, high-repetition rate laser in our experiments was dictated by the limitations of the available equipment. It may be argued that a single pulse transfer mode in which an individual blister with a size smaller than the size of the transferred die and a shape corresponding to the shape of the die, generated by a single-pulse laser, would provide a better transfer rate and a higher transfer precision. The presumption is that the single blister will push the die uniformly in a single-action fashion as opposed to the current method in which the blister is formed progressively as the beam scans the DRL. In the latter situation, it may be speculated that the transfer is initiated at an off-center point(s) at the beginning of the scan line. If this is the case, the die would travel in an orientation which is not parallel to its initial position, which would eventually result in a deviation from the intended location on the receiving substrate. At this point, the evidence in support of this conclusion is only circumstantial; a
time-resolved study using a high-speed camera, similar to that carried out by Brown and co-authors [38], would help with understanding and optimizing blister formation and die transfer process for a greater precision and transfer rate.

3.2.2. Effect of the adhesive layer properties

To determine the effect of the PE7 concentration on transfer rate and placement precision/accuracy, samples were prepared with 10% and 25% PE7 in THF, in addition to results presented in Sections 3.2.1 and 3.2.3 for 5% PE7 in THF. Laser transfers were performed on RIE-singulated dice. After optimizing the power setting, 30 transfers were attempted with each concentration. For 10% PE7 in THF, the transfer rate was 83.3% (25/30). The power used for transfers was 250 mW. The results for this concentration were similar to those of 5% PE7 in THF, though the displacement appeared to be slightly higher. For 25% PE7 in THF, the transfer rate was 86.7% (26/30). The power used for these transfers was 400 mW. This resulted in much larger displacements, with some of the die moving more than one die width. The reason for this was probably the blister rupturing resulting from the higher laser power (see Fig. 7c) and the subsequent change of the transfer mechanism from thermomechanical to ablative with all the negative consequences of such change as discussed elsewhere [36]. Also, at this power setting, the top side of the dice showed evidence of laser-etching during the transfer process. The 5% PE7 in THF clearly displayed the best transfer rate, and lowest displacement after transfer. These dice were used for further characterization of the transfer process.

Brown and co-authors [38] have shown that the presence of a thin layer of material on the surface of the blister layer does not have a significant effect on the size and shape of the blisters which form. Therefore, the observed differences in the transfer rates were due to only the adhesive properties of the different amounts of PE7 adhesive deposited.

3.2.3. Effect of the dicing method

Fig. 8 shows evaluations of the tmSLADT process showing displacement distances in μm for laser-singulated and RIE-singulated dice from their release positions. The circle represents the 6σ region, where σ is the standard deviation; the center of the circle represents the mean radial displacement.

![Fig. 7. SEM images of DRL after scanning with various laser parameters, (a) 150 mW power, 300 mm/s scan speed. The blister formed in the DRL is largely intact, (b) 200 mW power, 400 mm/s scan speed. The blister is partially ruptured, (c) 250 mW power, 300 mm/s scan speed. The blister is completely ruptured. The streaking seen in the SEM images was due to charging of the polyimide, and was not actually present in the layer.

![Fig. 8. XY scatter plots of transferred 670 × 670 μm, 50 μm thick Si dice, showing lateral displacements in μm for laser-singulated and RIE-singulated dice from their release positions. The circle represents the 6σ region, where σ is the standard deviation; the center of the circle represents the mean radial displacement.](image-url)
may not be a result of the selected wafer dicing method. Rather, it was probably due to problems in sample preparation for these experiments. Indeed, the post-experiment inspection revealed evidence of incomplete bonding of the dice to the DRL in some areas of the wafer.

Overall, both types of die had placement accuracy and precision results much better than those from the ablative laser-assisted transfer process and are comparable to the thermal laser-assisted transfer process results described in the literature [29,30]. Karlitskaya et al. [30] argued that in order for the laser-assisted die packaging to be accepted by the industry as an alternative to the conventional pick-and-place robotic assembly, the component placement accuracy should be at least ±35 μm. It is obvious from the results presented in Fig. 8 that the tmSLADT technique not only meets but significantly exceeds this requirement.

4. Conclusions

The presented tmSLADT process is unique in its ability to support high-volume assembly of ultrathin semiconductor bare dice, beneficial in manufacturing the next generation of mass produced high-density miniature electronic devices. The experimental results clearly demonstrate the remarkable transfer precision and accuracy of the tmSLADT process, which are compatible with the capabilities of the conventional die placement methods. No significant difference was observed in the transfer precision of the RIE- and laser-diced samples. The placement precision and accuracy depend mostly on the nature of the transfer process. When the laser transfer process changes from thermo-mechanical to ablative with the increase of laser power, allowing the blister to rupture, both the placement precision and placement accuracy deteriorate significantly. It is envisioned that the placement precision and accuracy can be further improved if a single-pulsed laser is used for the transfers. Additional improvements could be achieved with a more strict control of the wafer bonding step and DRL deposition. Further study and experimental work on the RIE plasma thinning and dicing processes is needed to ensure day-to-day repeatability in wafer thinning and to reduce underetching during street opening for better control of die size. The transfer rate of RIE-singulated dice were better compared to laser-singulated dice. In contrast to the laser dicing process, the RIE process removes completely the DRL layer from the streets between the dice, effectively de-coupling the DRL under each die from its neighbors and allowing for easier transfer. The adhesive properties of the adhesive layer used to bond the wafer to the blister layer in the DRL significantly affect the transfer rates, and indirectly the transfer precision, making this one of the most important material parameters to control in the process.

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