Local tentative bonding method to maintain alignment accuracy in bonding process using resin as an adhesive material

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Abstract: The authors proposed a novel method to maintain the alignment accuracy in the wafer-bonding process, which uses a resin as an adhesive material. Recently, the resin has received attention as an adhesive material for wafer bonding in microelectromechanical system device fabrication because of its multiple advantageous material properties. However, because of its inherent material viscosity, the alignment accuracy cannot be easily maintained, particularly when two wafers are bonded with a thick resin after alignment. To solve this problem, they proposed a local tentative bonding method. After aligning the two wafers, they irradiated the adhesive resin layer between the wafers using a near-infrared (NIR) spotlight (wavelength = 1020 nm), which is transparent to Si wafers. Using several NIR irradiation spots aimed at the resin layer after aligning the wafers, the resin layer was bonded locally and tentatively, which was sufficiently secure to avoid wafer shifting in the subsequent process. The local tentative bonded areas acted as anchors, which held the wafers during the bonding process. They performed experiments to demonstrate the effectiveness of their method using resins, such as polyimide, benzocyclobutene and SU-8. Consequently, they achieved an alignment accuracy <5 µm, which is a significant improvement compared with the typical bonding results.

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1 Introduction

A wafer-bonding technique using resin as an adhesive material has multiple advantages in terms of the process temperature and tolerance. The temperature in a wafer-bonding process using a resin adhesive is relatively low, typically lower than 400°C. Moreover, a resin adhesive layer is not severely affected by wafer-surface roughness and is tolerable to particle contamination on the wafer surface. In other words, the intermediate resin layer can incorporate contaminated particles within itself if their diameters are smaller than the resin-layer thickness. Furthermore, a resin-bonding layer has multiple advantageous physical properties, such as isotropic dielectric constants, good thermal stability, low Young's modulus and good adhesion to different substrates, which are also desirable in various application fields [1]. In particular, the above-mentioned advantages are highly valuable to microelectromechanical system (MEMS) devices fabrication, which uses various wafer-bonding processes and substrate types. For the integration of MEMS devices fabricated on different types of substrates or using different technologies, various methods have been proposed [2]. Similarly, to integrate MEMS devices with CMOS electronics, each fabricated on different substrates, a number of novel ideas have been also proposed [3]; however, these methods are complicated to implement or only applicable to specific cases. As a simple and universal method for three-dimensional stacking heterogeneous integration, we considered that the bonding technology using a resin adhesive layer would be one of the promising candidates. A bonding technology using resin is also applicable to the wafer-level packaging in MEMS devices, which results in low manufacturing costs [1, 4–7] because of the low material cost and less need to invest in processing tools.

On the other hand, there is a disadvantage in the bonding technology using a resin adhesive layer. Owing to the liquid-like soft state of the resin, it is difficult to maintain the initially obtained good alignment accuracy between wafers when applying temperature and load during bonding. In other words, when pressing the wafers together using the commercially available bonding equipment, it is practically inevitable that shear forces occur, which the coated resin cannot counteract. Because of the shear forces during the adhesive bonding process, the wafers move relative to each other and become misaligned. For the commercially available bonding equipment, the achievable alignment accuracy deteriorates to 10–15 µm although the typically attainable pre-bond wafer alignment accuracy is 2–5 µm [8].

To improve the alignment precision during the adhesive bonding process with resin, several methods have been proposed. One of them, a method using a dummy structure on the wafer surfaces to provide areas of solid-state material contact between the two wafers during the process, is remarkable [8]. The method uses a prepared metal pattern on the wafer surface for the adhesive bonding process. This pattern increases the friction forces between the wafers, which prevents them from shifting relative to each other while the intermediate adhesive resin is in a liquid-like soft state. With the aid of solid-state material contact, they could have improved the relatively poor alignment accuracy in the bonding process when 2-µm-thick benzocyclobutene (BCB) was used as the adhesive resin layer. However, to ensure metal contact on a wafer, an additional fabrication process would be needed for the dummy structure and the wafer area for device fabrication would be decreased, both of which would lead to an increased production cost. Moreover, the metal pattern thickness should be at least as thick as the adhesive resin layer to obtain sufficient friction force. If a thick adhesive resin layer is necessary, their method is not applicable because fabrication of the thick metal pattern is not easy.

In this paper, we propose a novel method to prevent the wafers from shifting relative to each other during the adhesive wafer-bonding process when a thick adhesive resin layer is used. After aligning and mechanically fixing the wafers, we irradiate the adhesive resin layer using a near-infrared (NIR) spotlight with a wavelength 1020 nm. NIR is transparent to silicon, which enables our method to be widely applied in MEMS and microelectronics device fabrication. The NIR radiation strikes areas of the patterned adhesive resin layer surrounding each previously fabricated device on the wafer, which are locally heated and tentatively bonded. The tentatively bonded areas serve as anchors, and we can, therefore, prevent the wafers from shifting relative to each other during the bonding process. In our method, additional complicated fabrication processes are not necessary and the wafer area for device fabrication is not decreased. We performed experiments to demonstrate the effectiveness of our method. As a result, we were able to maintain alignment accuracy during the adhesive wafer-bonding process using commercially available bonding equipment.

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2 Experimental process

In order to prevent the wafers from shifting relative to each other occurring while temperature and load were applied during the adhesive wafer-bonding process with resin as the adhesive material, we applied NIR spot irradiation onto the wafer surface after alignment. The intermediate adhesive resin layer between the wafers was heated and hardened around the irradiated spot areas by the NIR transmitted through the Si wafers. The hardened resin served as an anchor, which kept the wafers from shifting. The wavelength of the NIR spotlight was around 1020 nm. This was transparent to a Si wafer, which is the most popular substrate in microelectronics, including MEMS. Other irradiation sources, for instance, lasers, can be also be used to harden the resin. A high-power diode laser with a wavelength of 970 nm has been used in MEMS packaging for the local heating of an 8-μm-thick BCB adhesive layer to reduce the bonding time [9]. However, in the case of a much thicker adhesive resin layer, it takes much more time for sufficient heating by a laser, which may cause wafer damage by local overheating or even breakage of the wafer in the worst case. Therefore, our method is suitable for Si wafer bonding, particularly when a thick adhesive resin layer is used.

To verify our method, we performed experiments with photosensitive adhesive resin layers such as polyimide, BCB and SU-8. Our experimental process is shown in detail in Fig. 1.

In the experiment, we used 150-mm Si wafers as the substrate. Between the two Si wafers, an adhesive resin layer was formed as an intermediate layer. One Si wafer represented the device wafer, on which MEMS or microelectronics devices may be fabricated. Another Si wafer represented the capping wafer for encapsulation of devices. First, as a preparation of the substrates, we performed baking of the Si wafers on a hotplate for dehydration purposes. Moreover, alignment marks were formed with Al on the two Si wafers (Fig. 1*a*). Then, we spin coated photosensitive adhesive resins such as polyimide, BCB or SU-8 on each Si wafer (Fig. 1*b*). The thicknesses of resins are well controlled by the rotation speed of spin coater. After soft baking of the resin-coated wafers, photosensitive adhesive resin layers were patterned using a lithographic process. Consequently, we obtained lattice-like resin patterns with a width of 250 μm (Fig. 1*c*). The area surrounded by the adhesive resin pattern, which would have been used for fabricated devices, was empty in this experiment. Although we patterned the adhesive resin layer even on the capping wafer, it is not necessary for a real fabrication process. Coating and patterning on the capping wafer are only for obtaining a thick adhesive resin layer overall. Next, we aligned the two wafers using a conventional wafer aligner (Fig. 1*d*). In the alignment process, since the alignment marks faced inward to each other, we employed an IR camera on both sides of the polished Si wafers to confirm them. The next experimental step was the most important process in our experiment. In order to implement local tentative bonding, we used a halogen lamp emitting NIR radiation to irradiate the intermediate adhesive resin layer of the aligned wafers (Fig. 1*e*).

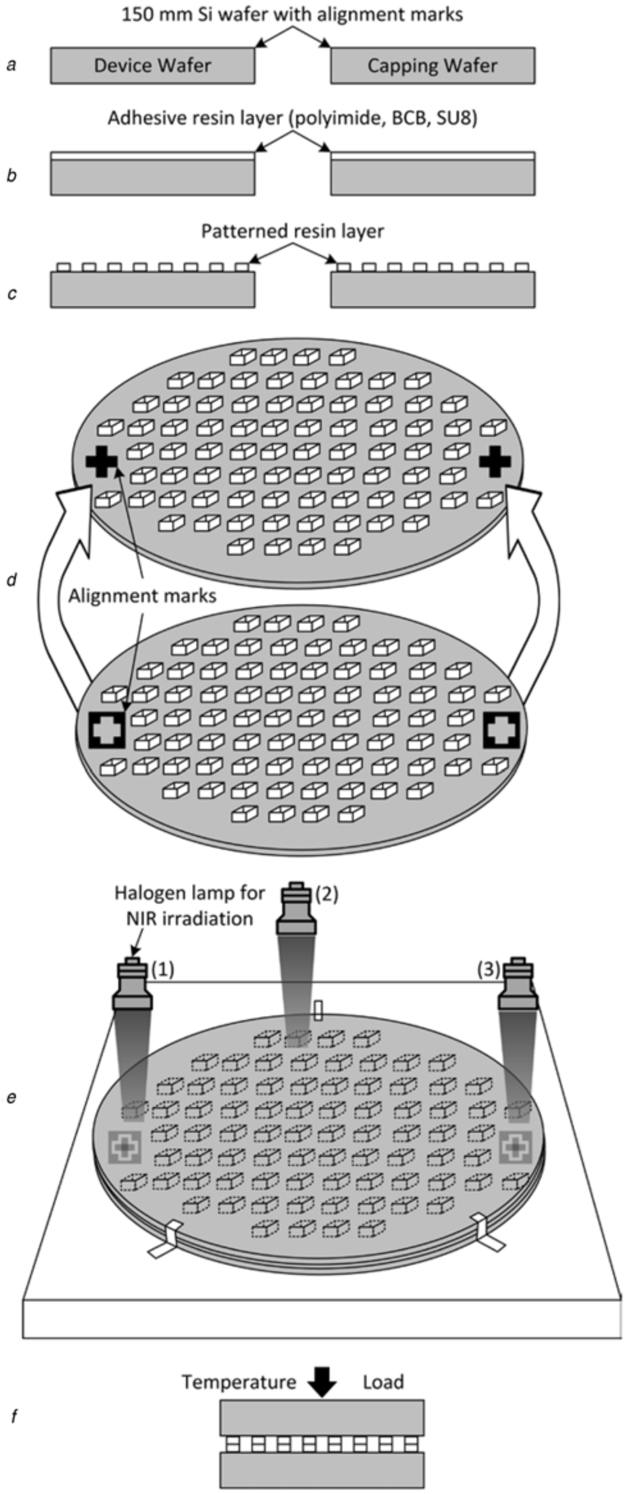

Fig. 1 *Experimental process*
a Preparation of wafers
b Adhesive resin-layer coating
c Patterning of the adhesive resin layer
d Alignment and clamping
e Local tentative bonding
f Adhesive wafer bonding

The detailed experimental setup for NIR irradiation is shown in Fig. 2. It was made in house. A set of aligned wafers is located on the wafer holder, which we irradiated using an NIR radiation emitted from a halogen lamp. The irradiation time could be controlled by a controller, which was set to 90 s, e.g. when the adhesive resin was polyimide or BCB. Moreover, the intensity of the halogen lamp could be also controllable by changing the electrical current applied to the controller. The central wavelength of the halogen lamp (heater) luminescence was 1020 nm, which was achieved by applying an electrical current of 14 A, which was used in all of our experiments. The typical NIR spot diameter on the wafer surface was ∼2 mm. Moreover, we fixed the distance between the halogen lamp and aligned wafers at 30 mm for all of the experiments. In the experiments, we generally irradiated the aligned wafers at three spots. The first time, e.g. we irradiated the aligned wafers with the halogen lamp at location (1) in Fig. 1*e* for a predefined time. After that, we rotated the aligned wafers and irradiated them by turns at locations (2) and (3) in Fig. 1*e*, for the same predefined time. Owing to NIR irradiation that was transparent to Si wafers, the heat emitted from the halogen lamp was transferred

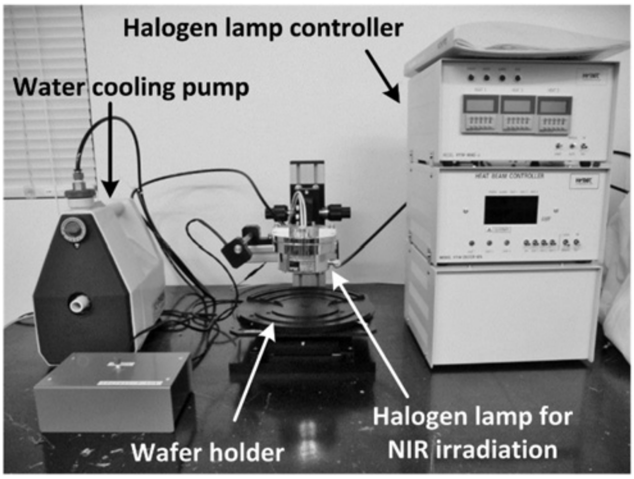

Fig. 2 *Photograph of our experimental setup for local tentative bonding. It comprises a halogen lamp for NIR irradiation, a halogen lamp controller, a water-cooling pump and a wafer holder*

directly to the adhesive resin layer. Consequently, the adhesive resin layer around locations (1)–(3) in Fig. 1*e* was hardened by the NIR heating and played the role of an anchor. During the adhesive bonding process, the hardened anchors could hold the aligned wafers, which were prevented from shifting relative to each other by shear forces.

In the experiments, the halogen lamp was cooled by water that was circulated around it using a pump, which is shown in Fig. 2. This was necessary because when a current of 14 A was applied to the halogen lamp, its temperature reached 2846 K.

The irradiation time and applied current to halogen lamp were determined by investigation of the temperature dependency of the hardness of the adhesive resin layer. The temperature profiles caused by halogen lamp radiation on the top and bottom surfaces of the aligned wafers are shown in Fig. 3. The temperature measured by thermocouples on the top (T_t) and bottom (T_b) wafer surfaces reached around 930 and 560°C, respectively.

Finally, we performed the adhesive bonding process with the aligned wafers (Fig. 1*f*). In the experiments, a commercially available conventional bonder (Ys400CTH, Yamanaka Hutech Corp.) was employed. With this bonder, by applying temperature and load, we achieved adhesive bonding of the aligned wafers. The typical adhesive bonding temperature and load were 350°C and 14.7 kN, respectively, for 150-mm Si wafers. The application time was 15 min.

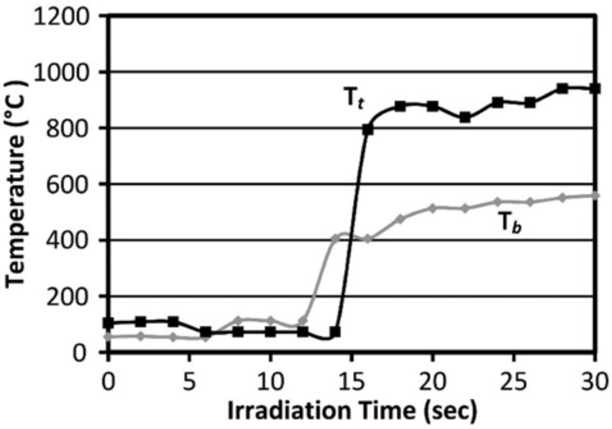

Fig. 3 *Temperature profiles used in the experiment. The temperatures are measured on the top surface of the capping wafer and on the bottom surface of the device wafer at the same time during NIR irradiation, representing* T_t *and* T_b*, respectively*

3 Experimental results and discussion

In the experiments, to verify the effects of local tentative bonding, we used photosensitive polyimide, BCB and SU-8 as the adhesive resin layer.

First, we selected photosensitive polyimide as the adhesive resin because it has gained attention as a good adhesive material with many advantages. Many wafer- or chip-level packaging technologies using polyimide have been proposed and developed for MEMS or microelectronics fabrication [9, 10]. In the case of polyimide, we investigated three thicknesses: 10, 20 and 30 μm. These thicknesses were obtained by coating 5-, 10- and 15-μm-thick polyimide on each wafer, as shown in Fig. 1*b*. Each wafer, after patterning of the polyimide layer by a lithography process (see Fig. 1*c*), was postbaked at 250°C for 30 min to harden. However, the postbaking temperature was less than the thermal cure temperature, which was above 300°C for our polyimide sample. Polyimide is locally hardened by NIR irradiation (see Fig. 1*e*) and it will be completely hardened in the whole wafer by the adhesive bonding process shown in Fig. 1*f*.

A local tentative bonding effect was confirmed by investigation of the degree of alignment accuracy. Alignment accuracy can be obtained by observing the misalignment between before and after the adhesive bonding process. Misalignment was observed by infrared (IR) microscope, and we measured the distance between a target and key alignment marks on the edges by using the length measurement function of the IR microscope. The measured points of the alignment marks are represented in Fig. 4*a* as *x* and *y*. First, we measured distances *x*1 and *y*1 after the alignment of two Si wafers, namely after the experiment step shown in Fig. 1*d*. Then, we measured distances *x*2 and *y*2 after NIR irradiation, namely after the experiment step shown in Fig. 1*e* to distinguish the origin of the misalignment. Finally, we measured distances *x*3 and *y*3 after the adhesive bonding process, namely after the experiment step shown in Fig. 1*f*. As distance measurements in the case of 20-μm-thick polyimide, we obtained the distances *x*1 and *y*1, *x*2 and *y*2 and *x*3 and *y*3 as 50.5 and 56.8 μm, 51.3 and 56.3 μm and 46.6 and 59.2 μm, respectively.

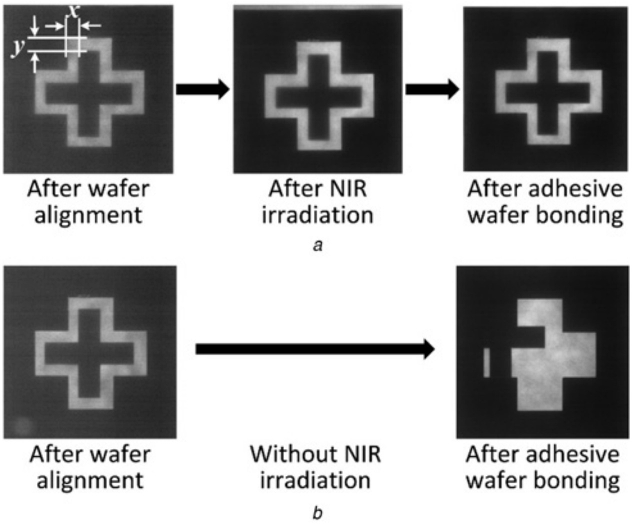

Fig. 4 *Alignment mark observation procedure*
a IR photographs of alignment marks after wafer alignment, after NIR irradiation and after adhesive wafer bonding
b IR photographs of alignment marks in the case without local tentative bonding

Note that the gap between the target and the key alignment mark was designated as 50 µm. The distances $x2$ and $y2$ were measured to confirm the influence of wafer handling because the aligned wafers were handled with tweezers until the end of local tentative bonding process shown in Fig. 1*e*. However, in our experiment, the differences between $x2$ and $y2$ and $x1$ and $y1$ were less than 1 µm, which is negligible. Therefore, we were able to conclude that the shift of wafers relative to each other was caused mostly during the adhesive wafer-bonding process. We have to focus on the most important experiment results, which are the distance differences between $x1$ and $y1$ and $x3$ and $y3$. We achieved a misalignment <5 µm; therefore, we can conclude that our local tentative bonding method can be an effective method for maintaining alignment accuracy in a wafer-bonding process that uses polyimide as a thick adhesive layer. Moreover, we also performed an experiment without using local tentative bonding in order to compare the results with and our method. Without local tentative bonding, we obtained a large misalignment after adhesive wafer bonding, which would lead to fabrication failure in the case of real device manufacturing. In Fig. 4, the alignment mark observation procedure is illustrated using a 20-µm-thick polyimide case. The observation results are summarised in Fig. 5 including the 10- and 20-µm-thick polyimide cases. Furthermore, we plotted the maximum values of Δx ($\Delta x = |x3 - x1|$) and Δy ($\Delta y = |y3 - y1|$) versus the thickness of polyimide in Fig. 6. The quantities of the alignment shifts in the case without local tentative bonding for 20- and 30-µm-thick polyimides are not represented in Fig. 6 because the misalignments were >50 µm, which is outside the measurement range. It is clear that the thicker the polyimide layer is, the more prominent our proposed local tentative bonding effect becomes.

As an adhesive bonding material, we also examined BCB in our experiment. It has been reported that many packaging technologies also use BCB as an adhesive material [5]. In particular, BCB paid attention in an RFMEMS switch packaging field [11–13]. In the experiments, except for the thickness of the resin, experiment conditions such as the thermal cure condition, NIR irradiation condition, pattern shape (mask) used in the lithographic process and the adhesive wafer-bonding conditions were same as those used for the polyimide. For BCB, we investigated the local tentative bonding effect with a 20-µm-thick BCB layer only. As a result, we were able to obtain an alignment accuracy of <5 µm when NIR irradiation was applied. On the other hand, without NIR irradiation, the alignment was largely shifted after adhesive wafer bonding, which was outside the measurement range. Consequently, we can also conclude that local tentative bonding is also effective for a BCB adhesive layer.

Another interesting adhesive material that is widely used in wafer bonding is SU-8 [14, 15]. In particular, because SU-8 is applicable as a microstructure material, it is widely applied in the microfluidics field. In the experiments, we used SU-8 3000 from MicroChem. In the case of SU-8, we were able to obtain a thick layer and we investigated the effectiveness of our method for 100-µm-thick SU-8. We coated a 50-µm-thick layer of SU-8 on both wafers to obtain a 100-µm thickness of SU-8 in total (Fig. 1*b*). Then, each SU-8-coated wafer was patterned with the same pattern used in the cases of polyimide and BCB and cured at 120°C. Using the NIR irradiation process shown in Fig. 1*e*, we irradiated SU-8 for 15 s, which was shorter than the other adhesive resin cases, but the time was sufficient to harden the SU-8. The bonding temperature in the process shown in Fig. 1*f* was 200°C. In the distance measurement between a target and key alignment marks on the edges, two points P1 and P2 were selected for convenience, as indicated in Fig. 7. As a result, when the local tentative bonding was applied, we were also able to obtain an alignment accuracy of <5 µm. However, without local tentative bonding, the alignment accuracy was not maintained.

In the experiment, although we used metal alignment marks formed by Al to observe any misalignment, the alignment marks could also be formed by the same resin used in the adhesive layer. By doing this, the resin alignment marks could serve as anchors by local tentative bonding and the area for device fabrication would be widened.

As a comprehensive result of our experiment, our proposed method for maintaining alignment accuracy, namely the local tentative bonding method, was effective for adhesive resins such as polyimide, BCB and SU-8.

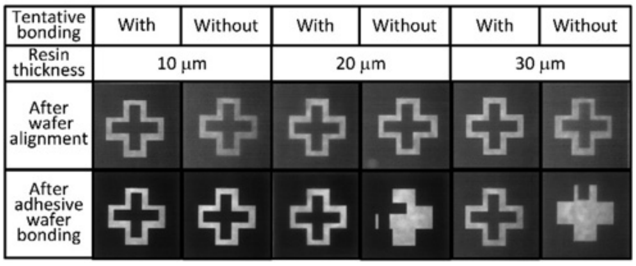

Fig. 5 *Summary of alignment mark observation results obtained using an IR microscope for the polyimide adhesive layer*

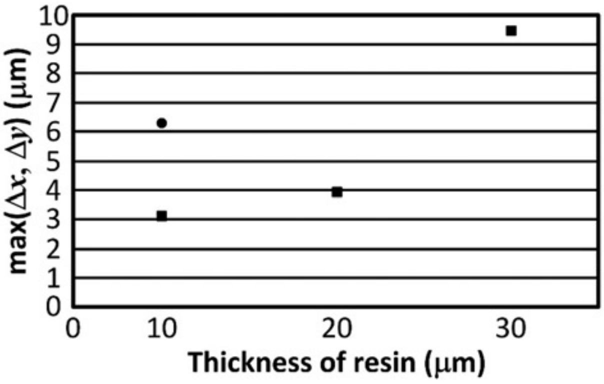

Fig. 6 *Maximum values of misalignment versus the thickness of polyimide. Rectangular points and circular point represent the cases with and without local tentative bonding, respectively*

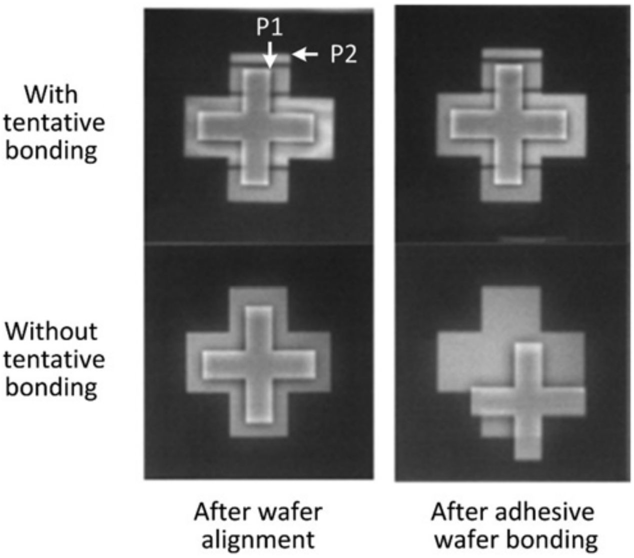

Fig. 7 *Alignment mark observation results by IR microscopy for the 100-µm-thick SU-8 adhesive resin. Misalignment is measured based on the distance difference between P1 and P2*

Many future works also remain for the improvement of our local tentative bonding method. First, the process conditions of the process need to be optimised more precisely for various types of adhesive resins and thicknesses. Especially, the resin layer curing conditions such as the NIR spotted temperatures and irradiation times for various types of adhesive resins must be optimised. Moreover, to achieve more precise alignment results, the optimal area of the resin layer irradiated by NIR for each adhesive resin is also to be investigated. Then, although we used an in-house experiment setup for local tentative bonding, it needs to be improved. Moreover, for the development of packaging and wafer-bonding technology using adhesive resins, reliability has to be guaranteed, and therefore, a shear test and leak test are considered as future works.

4 Conclusions

We proposed a novel method for maintaining alignment accuracy during the wafer-bonding process by using resin as an adhesive material, which uses local tentatively bonding after aligning the wafers with an aligner. Local tentative bonding is achieved by NIR irradiation, which is transparent to a Si wafer.

We performed experiments to confirm our method using our own experiment setup. In this experiment, we used photosensitive polyimide, BCB and SU-8 as resin layers and a halogen lamp as the NIR irradiation source.

As a result of the experiments, we achieved an alignment accuracy of <5 μm because of our local tentative bonding. This means that a local tentative bonding by NIR irradiation is an effective method for maintaining alignment accuracy when a liquid-like resin is used as the adhesive material in wafer bonding, even when it is as thick as 10–30 μm.

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