Impact of SiO₂ on Al-Al Thermocompression Wafer Bonding

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Abstract

Al-Al thermocompression bonding suitable for wafer level sealing of MEMS devices has been investigated. This paper presents a comparison of thermocompression bonding of Al films deposited on Si with and without a thermal oxide (SiO₂ film). Laminates of diameter 150 mm containing device sealing frames of width 200 µm were realized. The wafers were bonded by applying a bond force of 36 or 60 kN at bonding temperatures ranging from 300–550 °C for bonding times of 15, 30 or 60 minutes. The effects of these process variations on the quality of the bonded laminates have been studied. The bond quality was estimated by measurements of dicing yield, tensile strength, amount of cohesive fracture in Si and interfacial characterization. The mean bond strength of the tested structures ranged from 18–61 MPa. The laminates with an SiO₂ film had higher dicing yield and bond strength than the laminates without SiO₂ for a 400 °C bonding temperature. The bond strength increased with increasing bonding temperature and bond force. The laminates bonded for 30 and 60 minutes at 400 °C and 60 kN had similar bond strength and amount of cohesive fracture in the bulk silicon, while the laminates bonded for 15 minutes had significantly lower bond strength and amount of cohesive fracture in the bulk silicon.

1. Introduction

Micro electromechanical systems (MEMS) often consist of a movable part or a component that is sensitive to the surrounding environment, imposing special requirements on their packaging. Wafer level bonding is widely used in MEMS packaging. It not only provides high stability, but also reduces the die size and fabrication cost [1].

There exists a wide range of wafer bonding techniques, which have their own requirements and limitations. Silicon direct bonding requires ultra-smooth (<10 Å surface roughness) surfaces, while for anodic bonding a high DC voltage (400-1000 V) is employed for bonding of two wafers [2]. Adhesive [3], glass-frit [4] and metal bonding [5] use an intermediate layer for bonding and can be less sensitive to uneven bonding surfaces. Metal bonding is attractive among these techniques as metal seals of a certain width provide hermetic seal for a longer time compared to seals of the same width consisting of non-metals [6]. Metal seals also provide good electrical contacts and high thermal conductivity. Metals such as Au [7], Cu [8] and Al [9] have been demonstrated as suitable intermediate layers for thermocompression bonding of wafers. Fraux and Baron [10] report that STMicroelectronics obtained a die shrinkage ratio of 57 % by replacing glass-frit bonding by Au-Au thermocompression bonding.

Metal thermocompression bonding [6] is a form of solid-state joining of two metal surfaces by the simultaneous application of temperature and pressure to bring the mating surfaces to be bonded into atomic proximity. The applied pressure must be high enough to enable metal-metal contact breaking the surface oxide film, if present and facilitate bonding. The interface is bonded by the interdiffusion of metal atoms across the surfaces. Further reorientation and grain growth in the metal layers transforms the two deposited films into a single metal layer.

Al is an attractive choice of metal due to its CMOS compatibility. Successful Al thermocompression wafer bonding has been reported [9, 11-14]. Martin [9] bonded Al (1 % Cu) seal rings of width 4-90 µm at 445 °C by applying a bond pressure of 30 MPa. A shear strength of 740 grams was reported for 30 µm wide rings, which was

equal to the shear strength of a 150 μm wide glass frit bond. Yun *et al* [11] bonded wafers with 3-150 μm wide rings sputtered with Al having 0-4 % Cu impurity. The yield was slightly higher for pure Al, but the Al with 4 % Cu resulted in the highest shear strength. Dragoi *et al* [12] investigated the effect of varying the bonding temperature (400–550 °C), time (1–4 h) and environment (N_2 and forming gas) for Al thermocompression bonding. Blanket Si wafers with a layer of 500 nm thick Al (1 % Si) were bonded. Neither bonding time nor bonding environment had an effect on the bonded interface quality within the experimental limits, while an increase in the bonding temperature appeared to improve the quality of the bonded interface.

Our group has investigated Al-Al thermocompression bonding of patterned wafers, varying the bonding temperature and the bonding force [13]. The results indicated that strong Al-Al thermocompression bonds can be achieved either at or above a bonding temperature of 450 °C for bond forces of 18 and 36 kN, and at 400 °C for bond forces of 36 and 60 kN. This indicates that an increased bond force was required to compensate for the reduced bonding temperature in the studied temperature regime [13]. In the current study, we continue our investigations by a study on Al-Al thermocompression bonding of patterned wafers, with Al films deposited on Si with and without a thermal oxide (SiO_2 film). The impact of bonding temperature, bond force and bonding time is presented. The bond quality was estimated by measurements of dicing yield, tensile strength, amount of cohesive fracture in Si and interfacial characterization.

2. Experimental

A test wafer containing frame structures suitable for MEMS device packaging was designed. Dies of dimension 6 mm × 6 mm contained frames of outer dimension 3 mm × 3 mm and frame width 200 μm. The frames had rounded corners, as shown in figure 1. There were 54 such dies in the mask design, distributed over the wafer. The design contained other structures as well, so that the total bonding area of the wafer was 525 mm².

Ten laminates were produced by bonding Si wafers with frame structures to flat Si wafers. Ten Si wafers 400 μm thick with <100> orientation were structured by deep reactive ion etching (DRIE) in an AMS 200 I-Prod (Alcatel) with SiO_2 as mask material to realize frame structures that protruded 6 μm. The 7500 Å thick SiO_2 mask material was stripped from six of the wafers, while it was left on the four remaining wafers. Three of the structured wafers where the mask had been removed were thermally wet oxidized to a nominal thickness of 2000 Å SiO_2. In total there were thus three wafers where there was no SiO_2 on the surface. Four flat silicon wafers were oxidized to a nominal thickness of 1500 Å SiO_2, while three flat wafers were oxidized to a nominal thickness of 800 Å SiO_2. Three flat silicon wafers were left un-oxidized, as these were to be paired with the structured wafers with no SiO_2 on the surface. A layer of ~1 μm thick pure Al (99.999 %) was sputter deposited on all the 20 flat or structured wafers. A back sputter etch was included for the wafers without SiO_2 layer to ensure complete removal of native oxide from Si surface.

Flat and structured wafers respectively, both having the SiO_2 layer underneath the Al film, were bonded together (called Ox laminates, no discrimination was made between wafers with 7500 or 2000 Å thick SiO_2 layers). Similarly, wafers with Al deposited directly on Si (called Si laminates) were bonded together in an EVG 510 wafer bonder. Sketches showing the cross-sections of the laminates are found in figures 2 and 3. The wafers were aligned and kept in place separated by spacers in the bonder. The ambient pressure inside the bonder was reduced below 1×10^{-3} mbar and the spacers were removed. An initial bond force of 1 kN was applied and the temperature of the bonder was raised to the desired value, after which the specified bond force was applied. The thermocompression bonding was performed by applying a bond force of 36 kN or 60 kN at bonding temperatures of 300 – 550 °C for bonding durations of 15, 30, or 60 minutes. The applied bond forces corresponded to bond pressures of 68.6 MPa and 114.3 MPa. An overview of the bonding parameters of the 10 bonded laminates is given in table 1. During the subsequent cool down, the bond force was reduced to 1 kN and was removed after the bonding tool temperature was below 50 °C.

All the laminates were diced into individual dies by a DAD321 (Disco) dicing saw. The dicing yield, defined as the "percentage of dies that were not delaminated after the dicing process", was recorded. The dies which survived dicing were used for the subsequent tests. The tensile bond strength was measured by pull testing. A random selection of 12 dies from the laminate were glued to flat headed bolts and pull tested using a MiniMat2000 (Rheometric Inc.). The elongation versus applied force was recorded and the force, at which the fracture occurred,

designated as the fracture force, was noted. The bond strength was calculated by dividing the fracture force by the nominal bond area.

Cross-sections of selected dies were prepared by dicing a die into half by using a dicing saw, in order to expose the bonded interface. One half of the die was ion milled to make its rough interfacial surface smooth and visible by microscopy. During ion milling the rough surface of the bonded interface was sputtered by Ar+ ion beam and thinned down by ~200 μm to ensure the removal of dicing induced surface defects. The bonded interface was inspected along the complete length (200 μm) of the ion milled bond frame, see figure3.

The fractured surfaces of the pull-tested dies and cross-sections of the bonded interface were studied and characterized by macro photography (Canon EOS 600D) or scanning electron microscopy (SEM, FEI Quanta FEG 600). The bond frame along the interfacial line was visually inspected. The percentage of voids along the interfacial line and the average size of voids were estimated from SEM images. It was a visual and non-automated process with an estimated uncertainty of 10 %. The average size of voids was calculated from measurements of a minimum of 4 voids. The objective of the interfacial line investigation was merely to semi-quantitatively compare samples. An energy dispersive spectroscopy (EDS, EDAX) was performed on selected areas to determine the materials present at the fractured surface. The percentage of the nominal bonding area having a cohesive fracture in the bulk silicon was estimated for each die, and designated as the cohesive fracture number (CFN). A CFN percentage above 0 % indicates that the strength of the materials and interfaces in the tested structure was equal to or greater than the strength of crystalline Si.

3. Results

Figure 4 shows the dicing yield results for all the bonded laminates. The dicing yield was above 95 % for all laminates having an SiO_2 layer underneath the bonding Al, irrespective of the bond force, bonding temperature and bonding time. The laminates without an SiO_2 layer underneath the bonding Al also had a dicing yield above 95 % when bonded at temperatures of 450 and 550 °C (Si450 and Si550), but the yield of laminate Si400, bonded at 400 °C, was below 34 %. There was no significant effect of bonding time on the dicing yield within the tested range (15-60 min).

The results of the pull test measurements are shown in figure 5. The mean bond strength of laminates Ox300–Ox450 ranged from 18-42 MPa. There was a trend of increasing mean bond strength with increasing bonding temperature for the laminates with SiO_2. The mean bond strength for each bonding temperature was less than 34 MPa for the laminates without SiO_2. The laminates with SiO_2 had lower standard deviation in bond strength than the laminates without SiO_2. The bond strength of laminates with SiO_2 was between 42-61 MPa when bonded with 60 kN at 400 °C (Ox400-15 to Ox400-60). There was a noticeable increase in the bond strength when increasing the bond force from 36 kN to 60 kN at 400 °C, and when increasing the bonding time from 15 minutes to 30 minutes, while no significant further increase in bond strength was observed when increasing the bonding time from 30 to 60 minutes.

A typical fracture surface after pull testing is shown in figure 6. Electron dispersive spectroscopy (EDS) was used to identify that three or four different types of fractures occurred during pull testing. The dark grey colored regions at or near the bond frame represented cohesive fracture in the bulk Si. The white and shiny region corresponded to either adhesive (at the bond interface) or cohesive fracture (inside the Al film) in the Al. The light grey region corresponded to adhesive fracture at the Si-SiO_2 interface. Figure 7 shows SEM images of a fractured surface, identifying the materials present on the surface. The image shows that some Si material was transferred from one wafer to the other during delamination. It also shows a cross-section of the fracture mode across the frame width. As reported in our earlier study, no adhesive fracture was observed at the Al-Si interface of dies from laminates Si400 – Si550 [13]. Laminates Ox300 - Ox450 and Ox400-15 - Ox400-60, which all had an intermediate SiO_2 layer, had some fracture at the SiO_2-Si interface in most of the dies, while there was no adhesive fracture observed at the Al-SiO_2 interface.

The CFN results of the dies from laminates with and without SiO_2 are shown in figure 8. There was no cohesive silicon fracture in dies from laminates Ox300 and Ox350. For samples bonded at similar bond force and temperature, there was no significant difference in CFN between laminates with and without SiO_2. For both laminates with and without SiO_2, the CFN increased with increasing bonding temperature. There was a noticeable increase in mean CFN when increasing the bonding force from 36 kN to 60 kN at 400 °C and when increasing the

bonding time from 15 to 30 minutes at 400 °C for 60 kN bond force, but no significant further increase in CFN when increasing the bonding time from 30 to 60 minutes for a bond force of 60 kN.

SEM cross-sectional images of the ion-milled bonded interfaces from five different laminates are shown in figure 9. Estimates of void percentage, height and length from SEM cross-sectional images are given in table 2. Several voids were observed at the bonding interface of laminate Ox400. The average length of the voids was 0.76 µm and the average observed void height (gap between two opposing Al surfaces) was 0.024 µm. Inspection of the ion-milled region (seen in figure 3) showed that ~70 % of the interface in the studied ion-milled region had voids. On the other hand, for laminate Ox450, a similar inspection showed that only 40 % of the studied interface had voids and their average height was 0.017 µm and their average length was 0.60 µm. The voids observed for laminate Ox450 were smaller in size than voids observed for laminate Ox400. An almost complete bonded interface with only ~10 % of the ion milled interfacial area having voids was estimated from SEM analysis of cross sections on laminate Ox400-60. For laminate Si400, voids in ~70 % of the ion milled interfacial area were observed. These voids had an average length of 0.63 µm and an average height of 0.045 µm, and the aluminum cross-sectional surface seemed to have large pits (See figure 9 (a)). The pits had a size comparable to the Al thickness and had a pronounced different appearance than the voids; the pit mostly had an irregular shape in the bulk of the bonding material but a straight edge at the position of the original bond line. Laminate Si450 had voids in 60 % of the ion milled interfacial area, which had an average length of 0.62 µm and an average height of 0.026 µm. No pits were observed along the inspected interface of laminate Si450. The average size of voids was small for laminates with SiO_2 compared to laminates without SiO_2, bonded using similar parameters.

4. Discussion

The results presented in the current paper show that the presence of a SiO_2 film underneath the bonding aluminum has a large impact on the bonding results, in particular on the indicators of bonding quality used here as dicing yield, bonding strength and the CFN of the fractured surface. We will first restate the difference in the results and the parameter space over which it has been observed. We then go onto discussing the trends of variations in results with bonding variables and point out the differences between the case with and without SiO_2. The trends we discuss are changes in the observed bonding quality by varying bonding temperature, bonding pressure, and bonding time respectively. The results obtained on laminates Si400–Si550 (without SiO2) have been previously reported by our group [13] and are included in the current work for comparison purposes. After the comparisons we discuss the observations of pit formation in the Al film cross-sections. Finally we address the reasons for the differences in results with and without SiO_2.

The results presented in the current paper show that the presence of an SiO_2 film underneath the bonding aluminum has a large impact on the bonding results. At 400 °C bonding temperature, the dicing yield was 33 % for laminate Si400, but 98 % on laminate Ox400. Hence, the presence of the SiO_2 film seemed to cause an increase in the dicing yield. At 450 °C, the dicing yield of laminate Si450 was 100 %, hence no positive impact on the dicing yield could be observed. The mean bond strength, shown in figure 5, was also improved by the presence of the SiO_2 film: both for 400 °C and 450 °C bonding temperatures, the mean bond strength of the dies was increased by more than 20 % by the presence of the SiO_2 film. The dicing yield results at 400 °C and the bond strength results indicate that laminates with SiO_2 layer underneath bonding Al had stronger bonds than laminates without SiO_2. When comparing the bond strength of Ox300 and Si400, it should be noted that in case of laminate Si400 there was a pre selection of dies during the dicing. Only the 34 % dies surviving the dicing were pull tested so there was a high probability of the surviving dies to be strongly bonded. However, no significant difference in CFN results was observed for laminates with and without SiO_2.

The results shown in figures 5 and 8 indicate that the bonding temperature had an impact on both the bond strength and CFN. For the laminates with SiO_2 underneath the bonding Al, no impact on temperature was observed in our selected temperature regime. A dicing yield above 95% was obtained for all laminates. The variation between 95% and 100% dicing yield was caused by delamination of 1 − 2 dies, thought to be stochastic, random variations. For laminates Ox300–Ox450, a trend of increasing mean bond strength with increasing bonding temperature was observed, from 18 MPa at 300 °C to 42 MPa at 450 °C. The mean CFN results in figure 8 also show an increase in CFN with increasing bonding temperature. Dies bonded at 300 and 350 °C had 0 % CFN, increasing to 12 % CFN at 400 °C and 49 % CFN at 450 °C. The CFN gives an indication of the crack propagation mechanism in the structure. A high CFN indicates that the strength of Al–Al bond surfaces is stronger than the strength of the crystalline Si in

the structure, while a low CFN indicates that this Si is not the weakest material in the structure that is pull tested. A low CFN is not necessarily an indication of the low bond strength; presence of a multilayer structure can introduce a different energetically favorable crack propagation path other than in the crystalline Si, e.g. as a cohesive fracture inside the thin silicon oxide or Al layers. The cross-sections in figure 9 clearly show a difference in the bonding interface of laminates bonded at 400 °C and 450 °C. The void percentage decreased from 70 % with pits on laminate Si-400 to 40 % without pits on laminate Si-450, and from 70 % on laminate Ox-400 to 60 % on Ox-450, see table 2. An improvement in the interface quality was thus observed with an increase in bonding temperature. Our observation is in agreement with the results reported by Dragoi *et al* [12], who found that increasing bonding temperature improved the bonded interface quality. We think that the temperature dependence of Al diffusion is the main reason for the overall trend in bonding quality versus bonding temperature. An enhanced diffusion of the Al atoms in the interface region will promote bonding. Increasing the temperature also softens the Al material, which can increase the area where the surfaces to be bonded are in atomic contact. Higher temperature also helps in the deformation of Al which may assist in breaking of the Al native oxide. These effects are likely to cause the observed increase in bond strength and decrease in interfacial voids at the bonding interface with increasing bonding temperature from 400 to 450 °C. Even if we have observed that the added SiO_2 layer improved bonding quality, there is no need to infer a drastic difference in the bonding mechanisms based upon the discussed temperature dependence. The results could be explained by a change in degree of diffusion by factors we will discuss further in the last paragraph of the discussion.

The results in figures 5 and 8 also show that the bond force had an effect on the bond strength and the CFN. When increasing the bond force from 36 kN (Ox400) to 60 kN (Ox400-60), the mean bond strength increased from 32 to 60 MPa and the CFN increased from 12 % to 49 %. As the dicing yield was 98 % for Ox400, no significant increase in dicing yield could be observed. The cross-sections in figure 9 show that 70 % of the interface had voids in laminate Ox400, while only 10 % voids were observed at the interface of laminate Ox400-60. Hence, a bond force of 60 kN gave stronger bonds, higher CFN, and less voids than 36 kN. There can be several factors contributing to these tendencies. A high bond force assists in bringing the opposing surfaces into intimate contact, by plastic deformation of the asperities thereby increasing the contact area. A high bond force may also assist in breaking the native Al oxide. Al forms an oxide layer in 10^{-4} s on its surface after exposure to the atmosphere. The thickness of this oxide film is usually 5-20 nm [15], and it is physically very strong and chemically inert. The observed trends of bonding quality with increasing bonding pressure is in agreement with the common assumption that the native Al oxide on the surface of the bonding aluminum imposes a limitation on direct contact of the two opposing Al surfaces; removal of this native oxide might facilitate the bonding process [12].

The impact of bonding time when bonding at 400 °C applying 60 kN bond force can be seen in figures 5 and 8. There was a significant increase in both bond strength and CFN when increasing the bond time from 15 to 30 minutes. However, there were no significant differences in the mean bond strength or CFN when further increasing the time from 30 to 60 minutes. As the dicing yield was above 98 % for all three laminates, no differences in dicing yield could be observed. The larger standard deviation observed for laminate Ox400-60 is thought to reflect the stochastic nature of the applied experimental procedure. The results suggest that the first 30 minutes are most important in the Al-Al thermocompression bonding process at 400 °C when applying 60 kN bond force. It seems that increasing the bonding time above 30 minutes does not improve the bond strength.

One striking feature shown in figure 9 is the pits observed in the cross-sectional surface of Al. These pits were observed for laminate Si400 (without SiO_2), while no pits were observed in the Al at the interface of laminate Ox400 (with SiO_2). The observation of the pits has limited statistics: they were observed for two out of two cross-sections for laminate Si400 along a 200 µm long interface line. The cross-sections having pits in figure 9 appeared like the Al had been pulled out of the surface. We think that the pits were not created during the bonding process but created during the dicing process for making the SEM cross section. We consider that the creation of a pit can be conveniently broken down into two physical processes: i) transfer of force from the dicing blade to the Al grain, ii) detachment of the grain from the film by breaking its bonds from the surroundings. We can imagine that both of these processes can depend upon the grain size and the grain structure, which will both depend upon the bonding parameters. This can explain qualitatively that a large difference in pit formation was observed. The efficiency of the force transfer might depend upon grain size through the resulting variation in moment. From figure 9 we see that the pits always occurred where there was a void at the interface. This location in the film might have given the force a leverage, but perhaps more important, the grain would have had no bonds across the original interface, making it weakly bonded. However, according to our observations, the occurrence of interfacial voids was not a sufficient

condition for the creation of pits during dicing, as we observed no pits on laminate Ox400 (with SiO2) while that laminate showed interfacial voids: Almost 70 % of the studied ion-milled region had voids for both Si400 and Ox400, Laminate Si450 had voids in 70 % while laminate Ox450 had voids in 40 % of the ion-milled region. There were no pits observed in the Al at the interface of neither laminate Si450 nor laminate Ox450. This difference between laminates with and without SiO_2 could be related to difference in grain size and structure. A detailed study of the grain structure might reveal if this is the case. Another, more direct reason for the difference, might be the bonding between the Al film and its substrate which is either SiO_2 or Si respectively. From figure 9 we cannot decide if the missing grain spanned the whole Al film close to the surface before ion milling the cross section. If it spanned the whole film thickness it is relevant to consider the difference in bonding between Al and Si on one hand and Al and SiO_2 on the other. It is known from general chemical trends that Al-O bonds are stronger than Al-Si bonds. The interaction of Al with SiO_2 has been studied by many authors [16]. Zeng reported that when Al is interacting with SiO2, an oxidation-reduction reaction occurs between Al and SiO_2. A thin bonding layer (~5 nm thick) forms at the Al/SiO_2 interface. Our results in figure 8 also indicate that the adhesion between Al and Si was weak after bonding at 400 °C, but that the adhesion increased with increasing temperature, as CFN increased from 12 % on Si400 to 49 % on Si450.

The reasons for the different bonding results observed for wafers with an SiO_2 film underneath the bonding aluminum and for wafers without such an SiO_2 film are not yet fully understood, but are important and should therefore be addressed. The practical benefit could be an improvement in bonding quality or lowering of the bonding temperature. We do not have enough experimental clues to draw a conclusion and can only point out likely possibilities. We have indications of different mechanisms that can play an important role. We believe that the microscopic topography of the Al film (characterized by the so-called RMS value, the Ra value, and also by the spatial frequency distribution) is important and have therefore planned a detailed systematic study of the effect of variations in Al surface roughness at different temperatures. The microscopic topography of the Al film at the onset of bonding is expected to be a key parameter. The topography is linked to the grain structure of the film, which is related to heat treatments of the as-deposited Al film and its grain structure. The original grain structure typically varies with the substrate in addition to vary with sputtering parameters due to different surface mobility of deposited atoms on different substrates [17]. We believe that surface roughness of Al can play an important role in breaking of the Al native oxide, thus improving the bonding. The presence of SiO_2 underneath the Al can also have an effect on the grain size distribution and thereby the surface topography and can thus have a large effect on the bonding. The evolution of the grain structure during bonding may also depend locally on whether the mating Al surfaces have made physical contact early in the bonding process. For strength and fracture of the bonded laminates other factors may play a role, like the chemical bonding of the Al to Si versus Al to SiO_2.

5. Conclusion

Our results show that the presence of a SiO_2 film underneath the bonding aluminum is beneficial for reduction of bonding temperature and better bond quality for Al-Al thermocompression bonding. The SiO_2 film resulted in an increase in dicing yield at 400 °C, and an increase in mean bond strength at both 400 °C and 450 °C bonding temperature. The amount of cohesive fracture in the bulk silicon during pull testing, named the cohesive fracture number (CFN), was not affected by the presence of a SiO_2 film. The bond strength and CFN increased with increasing the bond force and bonding temperature. The bond strength and CFN were similar for bonding times of 30 and 60 minutes, while significantly lower values were observed for 15 minutes bonding time. Introduction of thermal oxide (SiO_2) underneath the bonding Al, and increase in bonding temperature and pressure, were found to reduce the size and occurrence of voids at the Al-Al bonded interface. Al-Al bonding for 30 minutes at 400 °C, applying 60 kN results in bonds with mean strength 55 MPa, mean CFN of 45 % and a dicing yield of 98 %, which is thought to be suitable for industrial applications.

Acknowledgements

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Table 1. Bonding parameters and SiO_2 thickness of all 10 bonded laminates, detailing the bond force, bonding temperature and bonding time.

Laminate ID	Bond Force (kN)	Bonding Temperature (°C)	Bonding Time (minutes)	Thickness of SiO_2 Layer on Patterned Wafer (Å)	Thickness of SiO_2 Layer on Flat Wafer (Å)
Ox300	36	300	60	7500	1500
Ox350	36	350	60	7500	1500
Ox400	36	400	60	7500	1500
Ox450	36	450	60	7500	1500
Ox400-15	60	400	15	2000	800
Ox400-30	60	400	30	2000	800
Ox400-60	60	400	60	2000	800
Si400	36	400	60	No	No
Si450	36	450	60	No	No
Si550	36	550	60	No	No

Table 2. Percentage of bond frame area having voids, void length and void height of 5 bonded dies estimated from SEM cross-sectional images.

Laminate ID	Inspected bond frame area having voids (%)	Average void length (µm)	Average void height (µm)
Ox400	70	0.76	0.024
Ox450	40	0.60	0.017
Ox400-60	10	–	–
Si400	70	0.63 [904*]	0.045 [750*]
Si450	60	0.62	0.026

*length and height of the pits observed in the Al for laminate Si400.
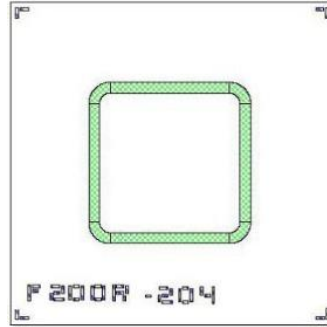
**Figure 1.** Top view of the layout of the die with 200 µm wide bond frame with rounded corners.
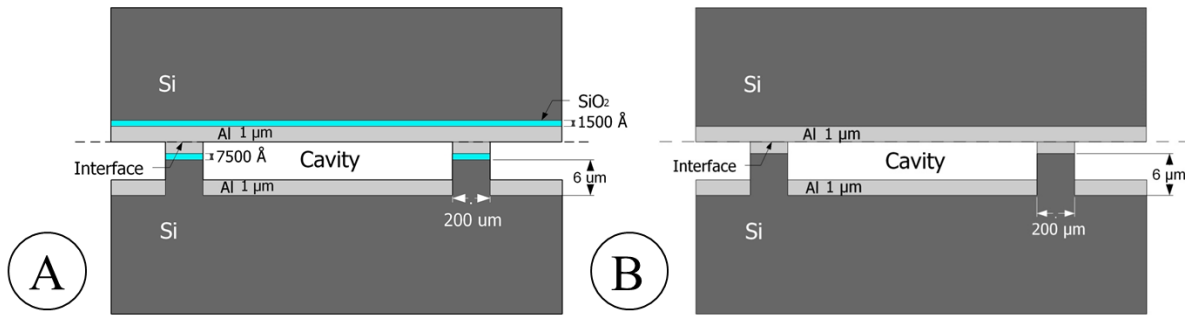
Figure 2. Cross-sectional sketches of the bonded die. The bonded interface is indicated by a dashed line. The top wafer is a flat Si wafer whereas the bottom wafer is the structured Si wafer with the bond frame design. (A) Top and bottom wafer have a SiO_2 layer underneath bonding Al. The sketch represents the cross-section of a die from bonded laminates Ox300, Ox350, Ox400 and Ox450. (B) Top and bottom wafer have a bonding Al layer deposited directly on Si. The sketch represents the cross-section of a die from bonded laminates Si400, Si450 and Si550.
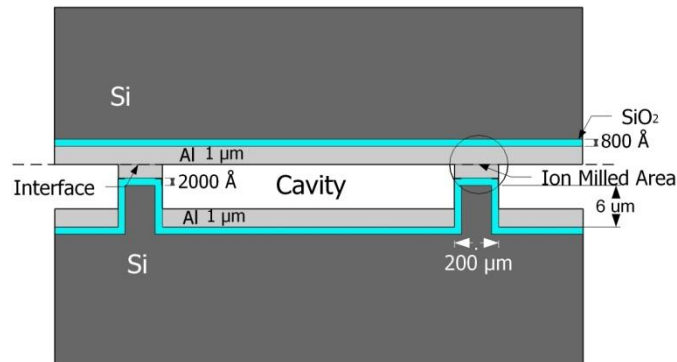

Figure 3. Cross-sectional sketch of a bonded die from laminates Ox400-15, Ox400-30 and Ox400-60. Top and bottom wafer have a SiO_2 layer underneath Al. In this sketch the section of the bond frames that was ion milled and studied in SEM is encircled. The bonded interface was studied along the 200 µm long ion milled section. This area is denoted "the studied ion-milled region".
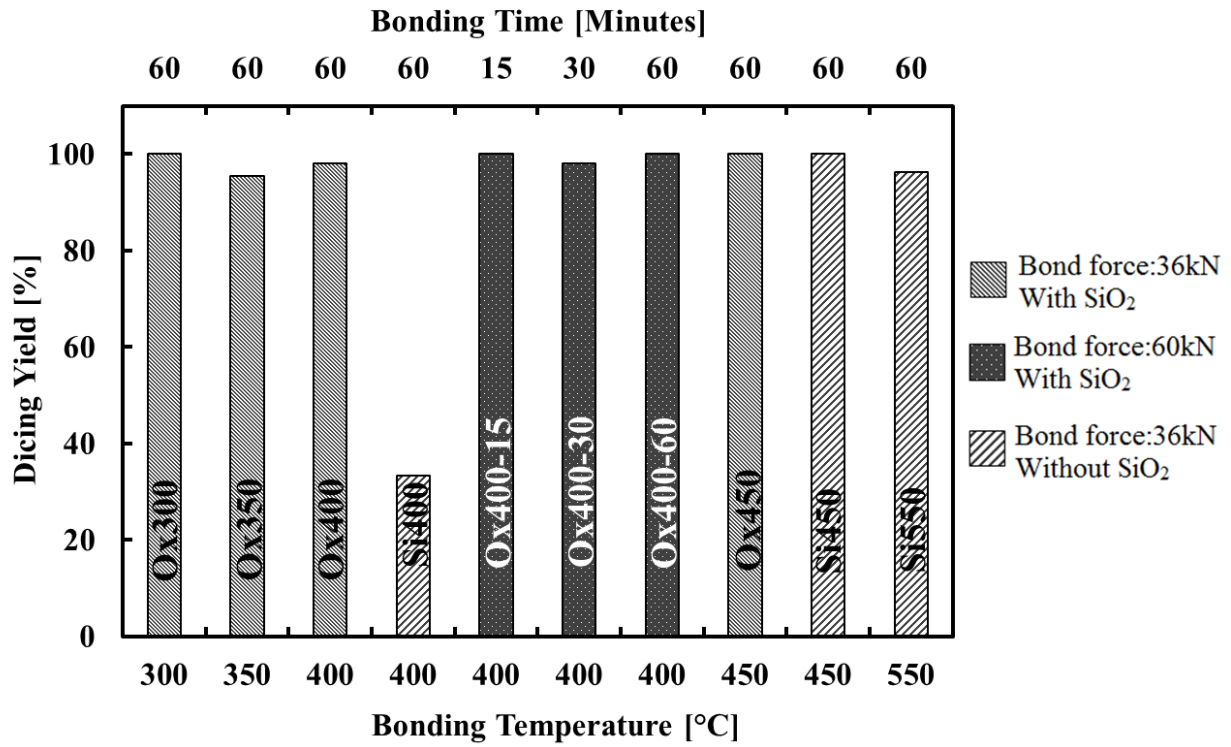
Figure 4. Dicing yield of 54 dies from laminates with and without SiO_2 underneath the bonding Al film (See figure 2). Laminates were bonded at 36 and 60 kN bond force at different temperatures for 15, 30 or 60 minutes.
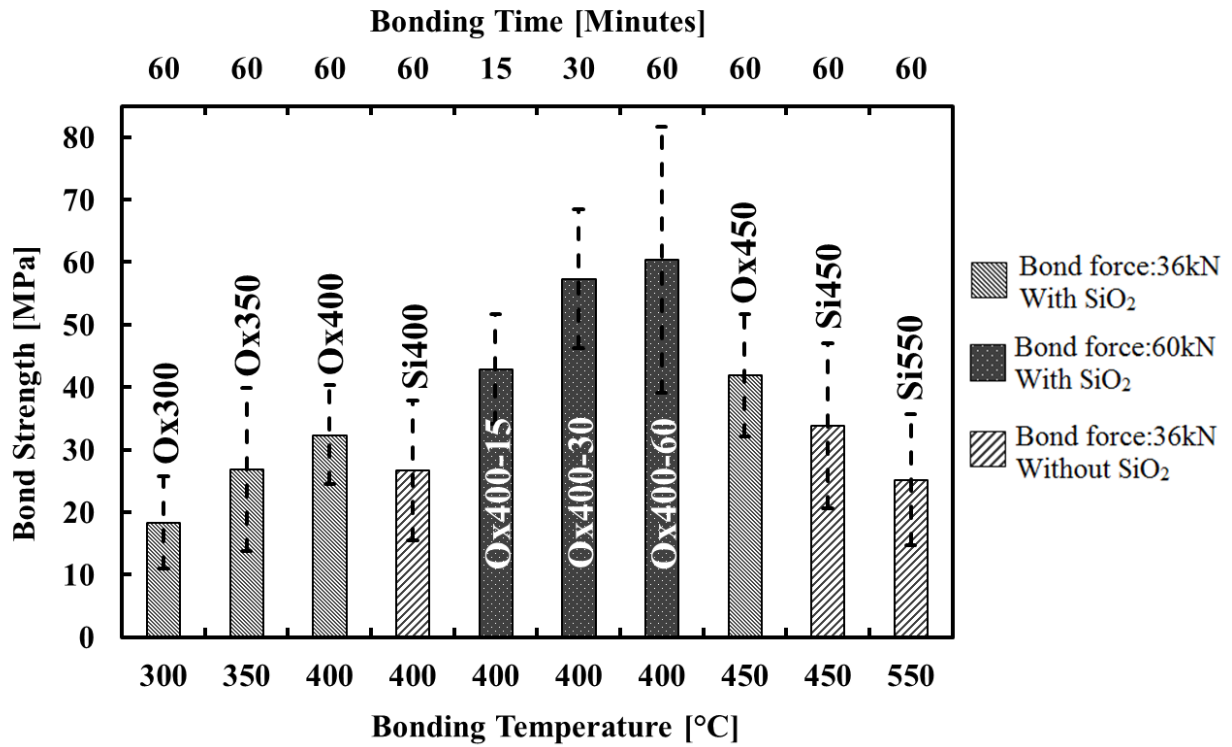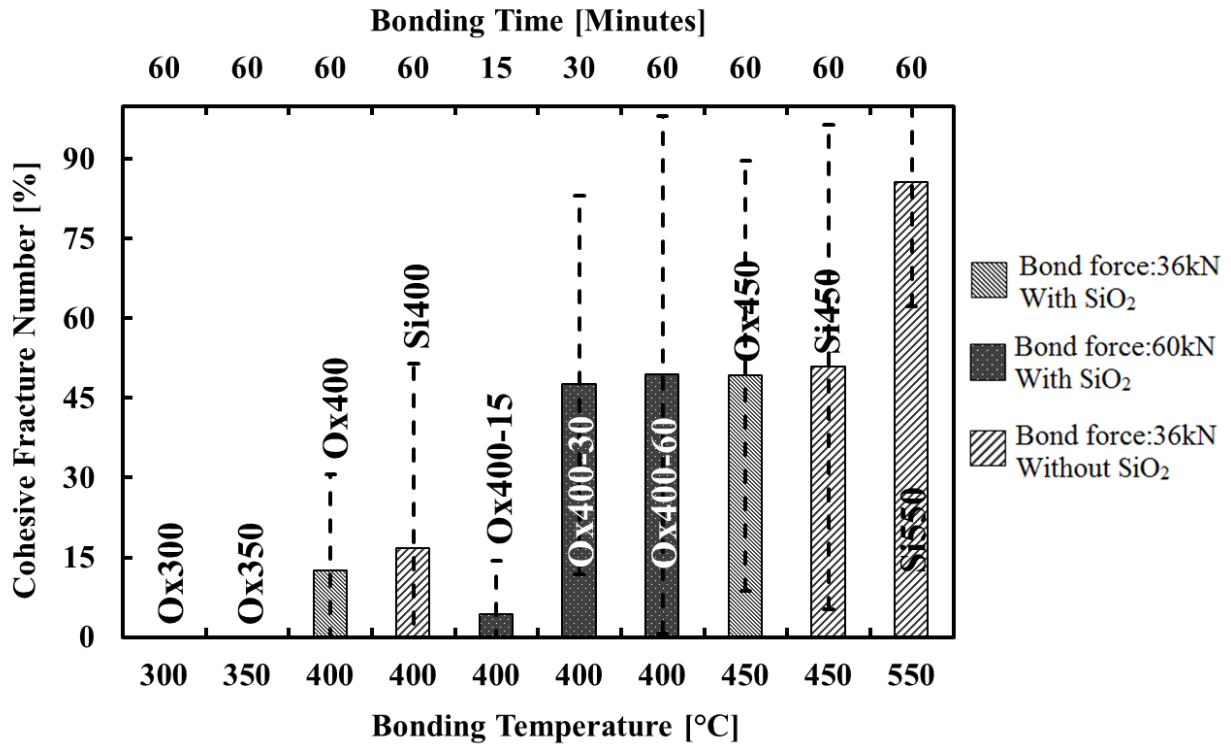
Figure 5. Mean bond strength and standard deviation for laminates with and without SiO_2 underneath bonding Al, calculated for minimum 9 dies. Laminates were bonded at 36 and 60 kN bond force at different temperatures for 15, 30 or 60 minutes.
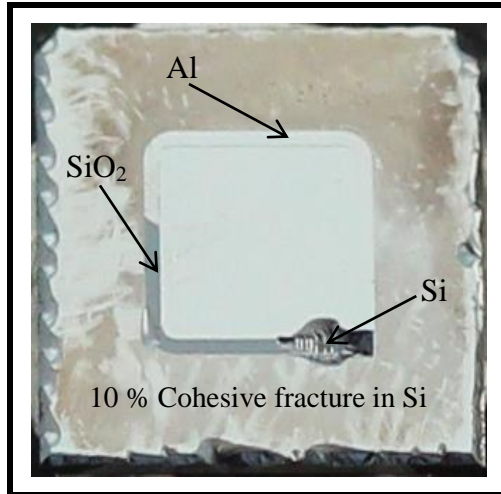
Figure 6. Typical fracture surfaces after pull testing of the bond frame structure. The dark grey region on and near the frame is a cohesive fracture in Si. The shiny white region is Al and the light grey region is SiO_2. The light grey region is adhesive fracture at Si-SiO_2 interface.
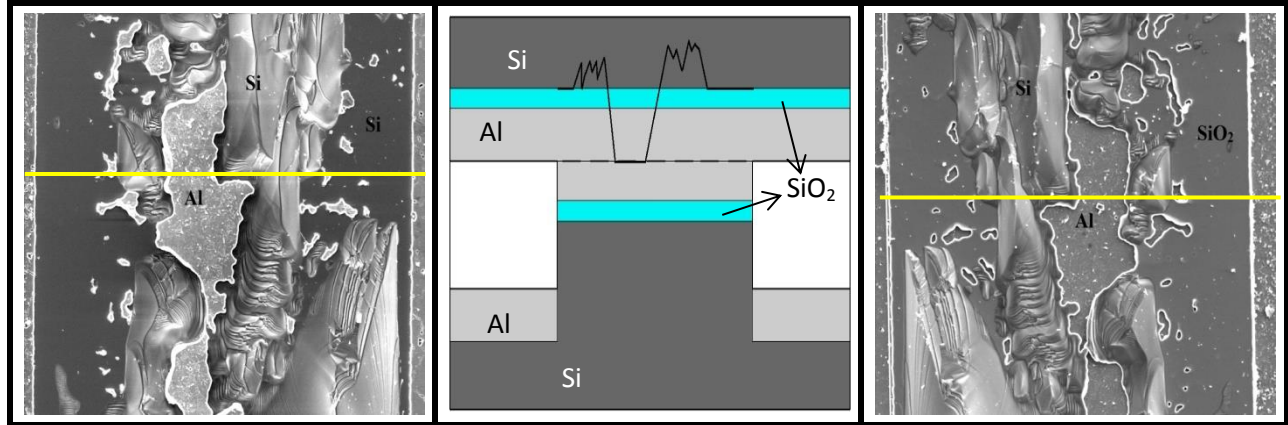
Figure 7. SEM images showing the two parts of a fractured die after pull test. On the left is the flat wafer while on the right is the structured wafer. The materials present on the surface were found by EDS analysis and showed that the fracture contained adhesive or cohesive fracture in Al, cohesive fracture in Si, and adhesive fracture at the Si-SiO_2 interface. The schematic in the center represents a probable fracture mode of the cross-section across the line on the frame width shown in SEM images.

Figure 8. Mean CFN and standard deviation for laminates with and without SiO_2 underneath bonding Al, calculated for minimum 9 dies. Laminates were bonded at 36 and 60 kN bond force at different temperatures for 15, 30 or 60 minutes.
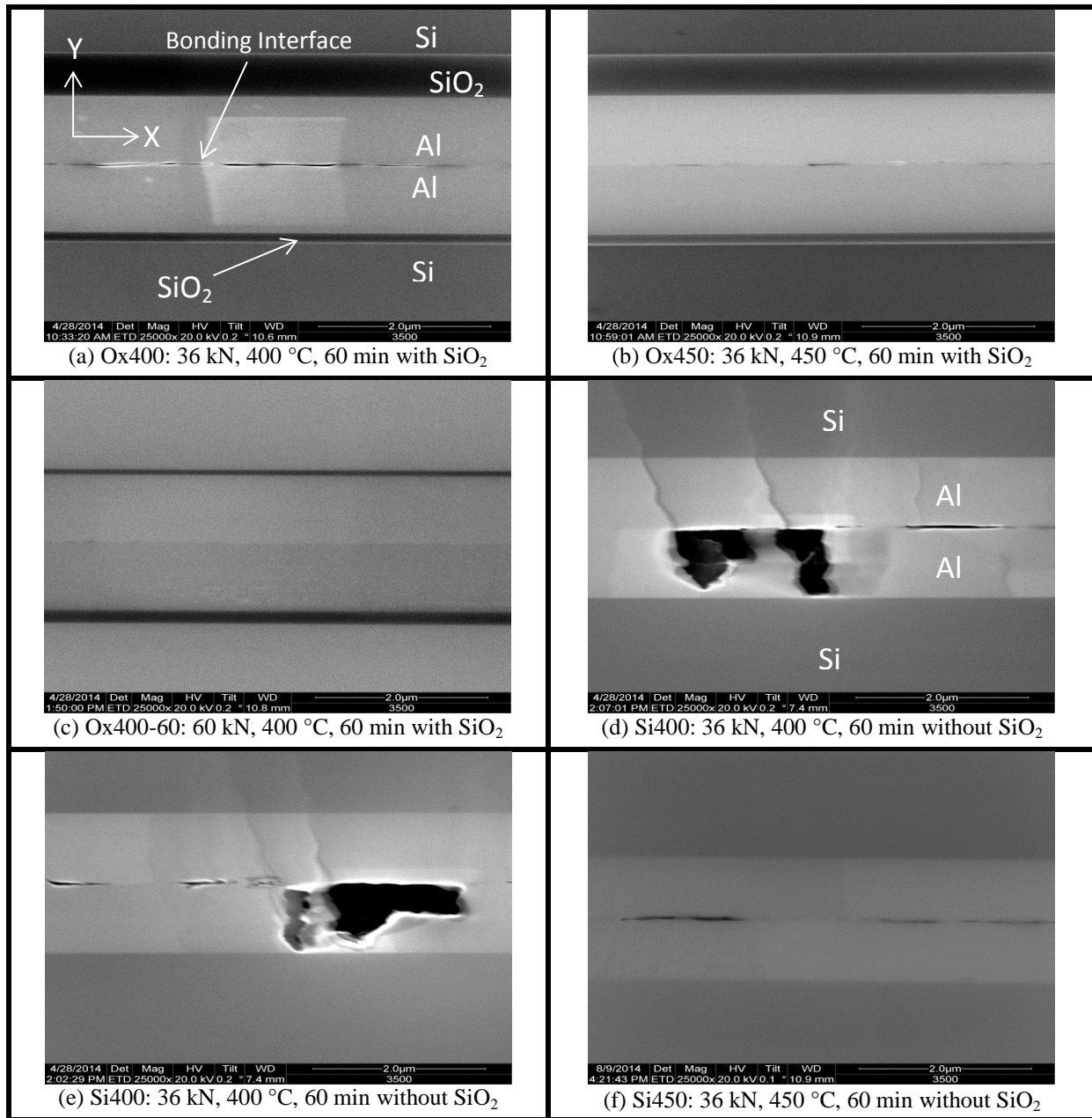
Figure 9. Cross-sectional SEM images of the bonded interfaces from laminates Ox400, Ox450, Ox400-60 with SiO_2 and from laminates Si400 and Si450 without SiO_2. The line pattern as seen in (d) and (e) above the pits was created by the ion beam while sputtering Al during ion milling of the cross-section.