Low-Temperature Aluminum-Aluminum Wafer Bonding

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Aluminum-aluminum thermo-compression wafer bonding is becoming increasingly important in the production of microelectromechanical systems (MEMS) devices. As the chemically highly stable aluminum oxide layer acts as a diffusion barrier between the two aluminum metallization layers, up to now the process has required bonding temperatures of 300°C or more. By using the EVG®580 ComBond® system, in which a surface treatment and subsequent wafer bonding are both performed in a high vacuum cluster, for the first time successful Al-Al wafer bonding was possible at a temperature of 100°C. The bonded interfaces of blank Al wafers and Al wafers with patterned frames were characterized using C-mode scanning acoustic microscopy (C-SAM) and transmission electron microscopy (TEM) as well as dicing yield and pull tests representative for the bonding strength. The investigations revealed areas of oxide-free, atomic contact at the Al-Al bonded interface.

Introduction

Thermo-compression wafer bonding is a key technology for the wafer-level production of hermetically sealed cavities, which are essential for the functioning of many microelectromechanical systems (MEMS). Aluminum, with its low material price, high thermal and electrical conductivities and its complementary metal oxide semiconductor (CMOS) compatibility, is a promising candidate for the fabrication of CMOS-MEMS, in which the sensor/actuator part is bonded to the electrical circuit.

The highly chemically stable native oxide layer on the Al surface cannot be removed by conventional methods. The thin oxide acts as a diffusion barrier layer between the two aluminum metallization layers, and therefore inhibits successful low temperature Al-Al wafer bonding. So far, effective Al-Al wafer bonding has required processing temperatures of >300°C and high contact pressures. TABLE I summarizes the experimental parameters extracted from a number of reports on Al-Al wafer bonding and the current work. In the referenced processes, a high contact pressure (usually several tens of MPa) (1-3) is used to break the oxide in order to establish diffusion channels for Al atoms. As a calculation shows (4), the elastic energy is too low to influence the bonding between atoms directly, but the applied stress and the resulting strain breaks up the surface layer. The wafers are bonded at high temperatures, usually in the range of 400°C to 550°C (1-3, 5-7). In recent experiments, Malik et al. were able to reduce the required bonding temperature to about 300°C by depositing the Al metallization layer onto an intermediate SiO_2 layer (3).

TABLE I Comparison of experimental parameters from different reports in literature and the present work on successful Al-Al wafer bonding.

First Author	Al Thickn. (μm)	Cu Content (%)	Bond Area (cm^2)	Force (kN)	Pressure (MPa)	Temp. (°C)
Martin (5)	1-2	1	n. a.	n. a.	30-117	450
Yun (8)	2	0-4	6-12[a]	60[a]	50-100	450
Yun (9)	2	2	n. a.	9-18	n. a.	450
Cakmak (6)	0.5	0	175	60	3.4	400-550
Froemel (7)	1	n. a.	n. a.	n. a.	4.5	450
Malik (2)	1	0	5.25	18-36	34-69	400-550
Malik (3)	1	0	5.25	36-60	69-114	300-550
Rebhan	0.3-1	0-0.5	5.25-314	60	1.9-114	100-550

n. a. = not available [a]Values estimated from the description of frame structure

In the references listed in TABLE I, typically temperature of 400°C-550°C led to bonded Al-Al wafers with Al_2O_3 precipitates present at the bonded interface and still with reasonably good bonding quality. In the EVG®580 ComBond® system, the aluminum oxide is first removed physically, followed by bonding of the two metal layers, both performed in a high vacuum cluster. The first Al-Al wafers were successfully bonded at 100°C using EVG®580 ComBond® equipment, which allows for preparation of oxide-free surfaces enhancing atomic contact. Notably, Akatsu et al. used a surface activated bonding set-up (10) to bond cubes of single crystalline aluminum at room temperature (with a bonding pressure of 40 MPa) (11). However, to our knowledge, there is no account for surface activated Al-Al bonding on wafer-level.

In the present work, Al-Al bonding of blank layers bonded in the EVG®580 ComBond® equipment was compared to Al-Al wafers bonded conventionally in an EVG®520IS equipment. The microstructure of the aluminum films on the silicon substrates was characterized by atomic force microscopy (AFM) and transmission electron microscopy (TEM). C-mode scanning acoustic microscopy (C-SAM), TEM and energy dispersive x-ray spectroscopy (EDXS) interface studies of the Al-Al interfaces bonded with this novel method revealed oxide-free, atomic contact and grain growth across the original interface. Further, the bond strength was characterized based on dicing yield and pull tests of bonded Al-Al wafers with patterned frame structures.

Experimental

An overview of the samples processed in this work is shown in TABLE II. All wafers were bonded with a bonding force of 60 kN at 100-550°C for 1 h, if not otherwise mentioned.

TABLE II Experimental parameters for each used bonding equipment.

Sample type	Metal	Sputtering	Equipment	Temperature
1	Blank Al+0,5% Cu	Standard	EVG®520	150-550°C
2	Blank Al+0,5% Cu	Standard	ComBond®	150-550°C
3	Blank Al+0,5% Cu	ALPS	EVG®520	150-550°C
4	Blank Al+0,5% Cu	ALPS	ComBond®	150-550°C
5	Patterned pure Al	Standard	ComBond®	100-150°C

The first types of substrates used for the bonding experiments were non-patterned 200 mm diameter silicon wafers. Within this work, they are referred to as “blank wafers”. First, a

20 nm Ti adhesion layer/diffusion barrier was deposited on the Si wafers, followed by full-sheet metallization layers of 99.5% Al with 0.5% Cu concentration and a thickness of 300 nm. Two different techniques – standard sputtering deposition and aluminum low pressure seed (ALPS) – were used. ALPS wafers differ from the standard deposition mainly in terms of processing pressure and temperature. While the standard deposition was performed at 215°C with an argon pressure of 3.3×10^{-3} mbar, the ALPS process was carried out at only 30°C with an argon pressure of 5.33×10^{-5} mbar. The surface roughness of the wafers was determined from atomic force microscopy (AFM) scans recorded in tapping mode on areas of 2x2 μm^2.

Figure 1 shows AFM measurements of the surfaces of the ALPS and standard sputtered Al films. The standard sputtered Al layer developed grains with lateral size ranging from 300 nm to 700 nm, while the grains of the ALPS wafers were significantly smaller, ranging from 200 nm to 300 nm grain size. The root mean square (RMS) surface roughness was found to be about 1.2 nm for both films.

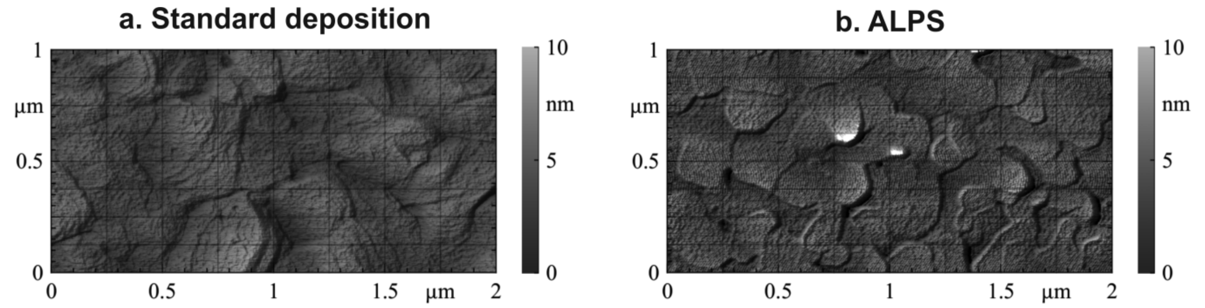

Figure 1. AFM measurements of the blank Al wafer surfaces. The different processing conditions result in larger grains for the standard deposition and smaller grains for the ALPS wafers.

The cross-section TEM investigation revealed that the grains extended throughout the entire Al layer thickness for both deposition types. As an example, the cross-section of a standard sputtered Al layer is shown in Fig. 2. In XTEM high-resolution mode, the thickness of the native aluminum oxide was determined as ~3.5 nm, which is in agreement with typical values reported in literature (12, 13).

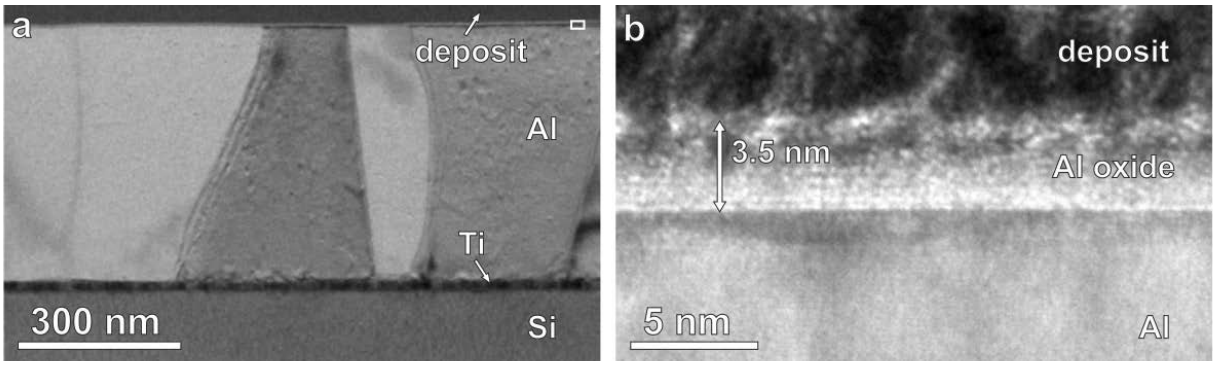

Figure 2. XTEM measurements after “standard deposition” of the Al layer. In (b) the marked inset of (a) at the top right demonstrates the Al surface and its native oxide layer with high magnification.

While the conventional bonds were performed in a standard thermo-compression wafer bonding system (EVG®520IS), the low-temperature bonds were performed in the EVG®580 ComBond®, a fully automated, high-vacuum wafer bonding system. In the latter system, the wafers are transferred from a central chamber to several modules. This way, a surface preparation step can be performed prior to bonding without exposing the wafers to an oxidizing atmosphere.

The proprietary ComBond® surface preparation process can be tuned to perform an oxide removal while only negligibly changing the sample's surface roughness. Prior to the bonding experiments, aluminum oxide removal rates of up to 15 nm/min were confirmed by thickness measurements of Al_2O_3 films on Si substrates. The bonding chamber in the EVG®580 ComBond® equipment is identical in functionality to that of the EVG®520IS used for standard bonds, the major difference is that in this equipment the wafers are handled between the ComBond® surface preparation chamber and the bond chamber under high vacuum environment and not at ambient conditions. In both setups, a bonding force of 60 kN was used. Since these bonded wafer pairs are full area bonds of non-patterned wafers (bonding area: 314 cm^2), the applied force corresponds to a bonding pressure of 1.9 MPa.

MEMS devices often consist of a cavity produced by etching in one or both substrates and closed by a wafer bonding process. Therefore, besides bonding substrates with blank Al layers, two wafers with patterned Al bond frames were bonded to flat wafers in the EVG®580 ComBond® system. Within this paper these wafers are referred to as "frame wafers". These wafers are patterned with MEMS-relevant size dummy dies with bonding frames having a line width of 100 µm, 200 µm, or 400 µm, with straight corners, named F100, F200 and F400, as well as 200 µm wide frames with rounded corners, named F200R, respectively (see Fig. 3 and (3)). The outer dimension of all frames was 3x3 mm^2. Two 400 µm thick Si wafers (150 mm diameter) with (100) orientation were patterned by deep reactive ion etching (AMS 200 I-Prod, Alcatel) to realize 6 µm high frames. All four wafers were thermally wet oxidized to a nominal thickness of 150 nm SiO_2. Subsequently an adhesion layer of 100 nm Ti was sputtered on the oxide surfaces. Without breaking the vacuum between the deposition steps, an approximately 1.2 µm thick layer of pure Al (99.999%) was deposited in the same sputtering chamber. In order to allow for optimum bonding conditions, chemical mechanical polishing (CMP) of the wafers was performed, resulting in a final Al layer thickness of 1 µm.

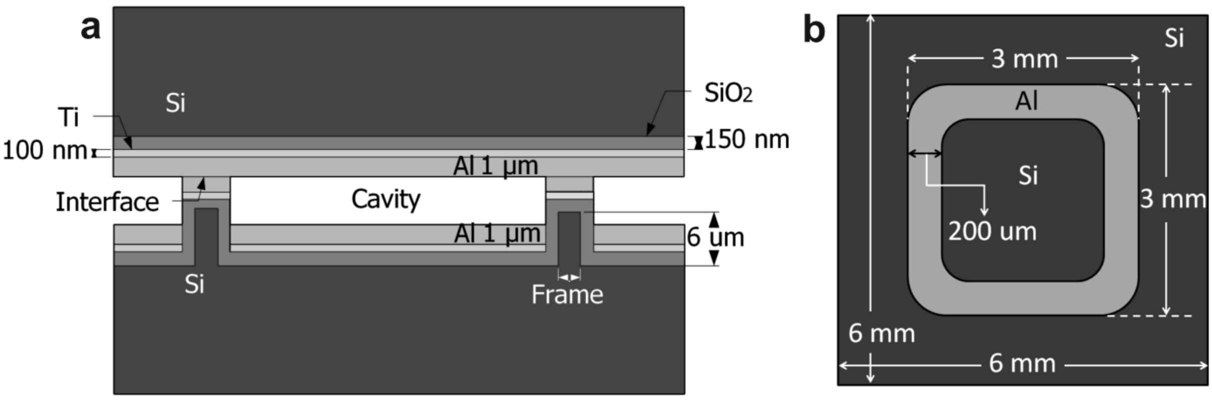

Figure 3. (a) Schematic cross-section and (b) top view of a single F200R bond frame.

A wafer with frames was bonded to a flat wafer in the ComBond® system applying a bonding force of 60 kN and a bonding temperature of 100°C or 150°C. The applied bonding force corresponded to a bonding pressure of 114.3 MPa. The bonded wafer pairs were diced into individual dies using a DAD321 (Disco) saw. The dicing yield, defined as the percentage of dies that were not delaminated after the dicing process, was recorded. A random selection of 12 non-delaminated dies of frame type F200R was made from each bonded pair, glued to flat headed bolts and pull tested using a MiniMat2000 equipment (Rheometric Inc.). During pull testing, displacement versus applied force was recorded and the maximum force, at which the fracture occurred, designated as the fracture force, was determined. The bond strength was calculated by dividing the fracture force by the bonding area.

Results and Discussion

The discussion of the experimental results is split into three sections, each corresponding to a bonding type (materials and processes used):

- conventional Al-Al wafer bonding with blank wafers
- low-temperature surface pre-treated Al-Al wafer bonding with blank wafers
- low-temperature surface pre-treated Al-Al wafer bonding with frame wafers

Conventional Al-Al Wafer Bonding: Blank Wafers

The attempts to bond two wafers with blank Al films in an EVG®520IS resulted in a bonded interface of low quality at bonding temperatures between 400°C-550°C. In Fig. 4 a typical C-SAM result of a wafer pair (standard Al deposition) bonded at 550°C. The different tones of gray in the C-SAM image represent areas which are weakly bonded or even unbonded areas. The bond quality was found to be highly sensitive to local pressure variations. The relatively low bonding pressure of 1.9 MPa (this was the maximum available for this setup) was not enough to reproduce the results of Cakmak et al., who were able to bond non-patterned 150 mm diameter wafers (6) with a higher pressure of 3.4 MPa. The root cause for this difference might be explained by differences in the Al film properties (4,14) or by the bonding pressure difference.

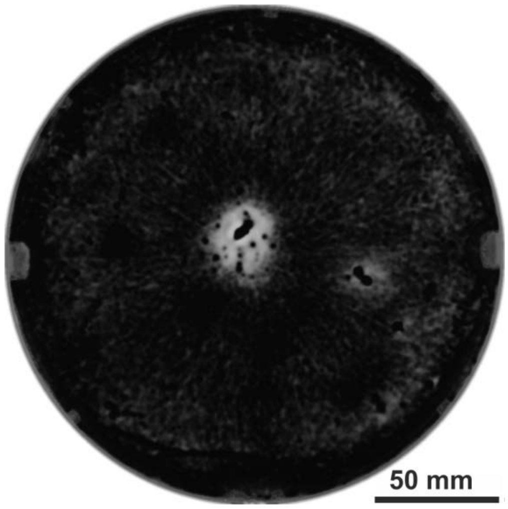

Figure 4. Typical C-SAM result of 200 mm diameter (standard deposition) Al wafers bonded in an EVG®520IS at 550°C for 3 h with 60 kN.

The aluminum oxide properties (e.g. thickness, chemistry) seem to be crucial for the bonding process. Between the two aluminum layers, non-damaged Al oxide was visible in the SEM cross section images, and Al oxide was also detectable by Auger electron spectroscopy (AES). Figure 5 shows the depth profile of the bonded interface for the wafers with ALPS deposited films at a position with relatively good bonding quality; this corresponds to one of the dark areas in Fig. 4. Close to the bonded interface the metallic Al concentration drops. At the same time, the signal for Al oxide increases. It was assumed that the oxide layer obstructs diffusion of Al atoms between the two Al metal layers, hence preventing significant grain growth across the initial wafer interface. The results of wafers with standard sputtered Al layers were showing similar aspect (not shown here).

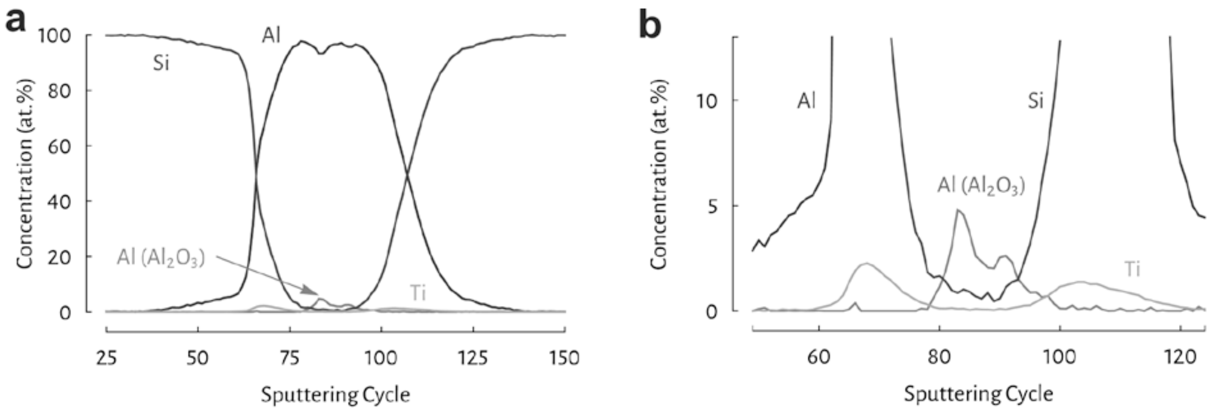

Figure 5. AES depth profile of bonded 300 nm thick Al ALPS wafer pair showing the wafer surface structure (Si-Ti-Al) as well as the presence of aluminum oxide at the interface. In (b) a closer view of the sputtering cycles around the bonding interface is presented.

Low-Temperature Surface Pre-treated Al-Al Wafer Bonding: Blank Wafers

Figure 6 shows a comparison of a typical C-SAM result of bonded wafer pairs with ALPS Al films, bonded in an EVG®520IS at 550°C (left) and at 150°C in an EVG®580 ComBond® with surface pre-treatment (right). Both wafers were bonded for 1.5 h using 60 kN piston force. Due to the surface pre-treatment, which removes the native Al oxide prior to the bonding process, the wafers can be bonded at temperatures significantly lower than any values reported in the literature (see TABLE I). Although the bonding pressure was relatively low (1.9 MPa), the C-SAM image shows a high quality bonding interface at almost any position of the wafer pair bonded in the EVG®580 ComBond®.

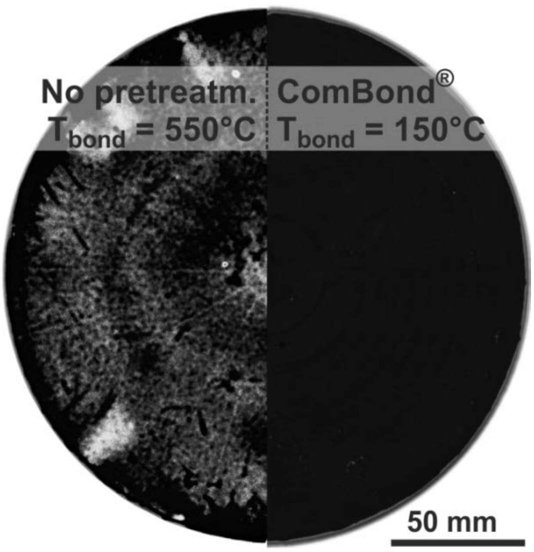

Figure 6. C-SAM images of bonded Al ALPS wafer pairs (left) without pretreatment and (right) with ComBond® surface treatment prior wafer bonding. Both wafer pairs were bonded at 60 kN (1.9 MPa) for 1.5 h.

Compared to bonded ALPS wafer pairs, the samples produced from standard Al-sputtered films had significantly more weakly bonded or larger unbonded areas upon C-SAM inspection. For a qualitative comparison of the bond energy, a razor blade was inserted at the bond interface (15) and the approximate length of the resulting crack was measured with C-SAM. The crack lengths in the samples with standard Al-sputtered films were 5% to 10% longer than the ones in samples with ALPS Al films. The C-SAM and crack length measurement results indicate that the ALPS Al films gave higher bond energy than standard sputtered Al films. The smaller grains observed in the ALPS Al films could be a likely explanation for the observed difference, since smaller grains result in a higher density of grain boundaries, which in turn promotes the diffusion of Al atoms, as the concentration of short-circuit diffusion paths is increased (14, 4).

The bonded interface of the wafer pair with ALPS Al films bonded in the EVG®580 ComBond® system at low temperature (150°C), was inspected by TEM and EDXS. The high resolution TEM image in Fig. 7 (left) shows that no amorphous layer separated the two Al metal films. Similar observations were made by Akatsu et al. (11) for single crystalline samples. The EDXS mapping shown in Fig. 7 (right) revealed no additional oxide near the bonded interface. The oxide signal stemmed exclusively from the native oxide on the surface of the TEM specimen (noise signal), which was exposed to air during the TEM preparation.

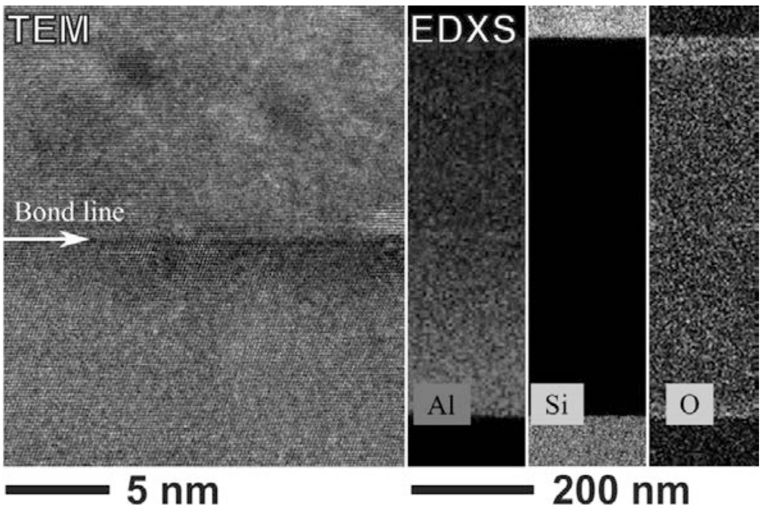

Figure 7. High-resolution TEM image and EDXS mapping of the interface of a ComBond® surface pre-treated, low-temperature bonded Al ALPS wafer pair, showing atomic, oxide-free contact. The wafer pair was bonded at 60 kN (1.9 MPa) and at a temperature of 150°C for 1 h.

Low-Temperature Surface Pre-treated Al-Al Wafer Bonding: Frame Wafers

Figure 8 shows the C-SAM result of a frame wafer pair, bonded after ComBond® surface pre-treatment at 100°C. The successful bonding of the wafers is shown by the absence of trapped gas, which would have given significant acoustic wave reflections. As the wafers were placed in water during C-SAM inspection and the edge was not sealed, water penetrated from the edge into the unbonded wafer areas, explaining the black irregular pattern close to the wafer edge. The frame wafer pair bonded at 150°C with the same bonding time (1 h) and force showed no difference to the C-SAM result of the 100°C bonded wafer pair.

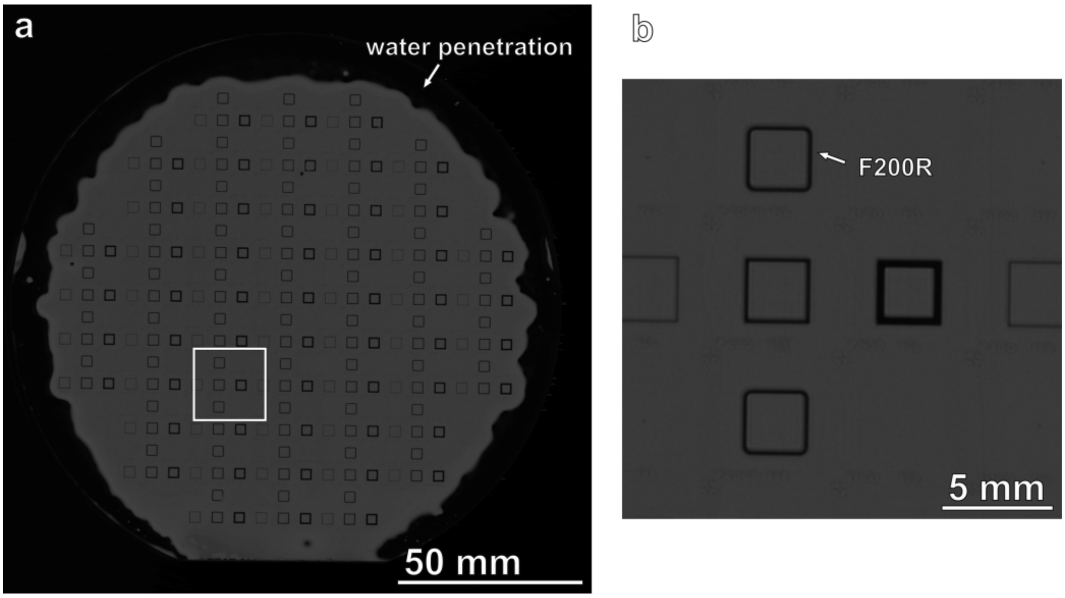

Figure 8. C-SAM measurement of frame wafers after ComBond® surface treatment and subsequent bonding at 100°C for 1 h with 60 kN (114 MPa). In (b) a detailed scan of the bond frames is shown. The dark irregular pattern at the wafer edge in (a) is generated by the water which penetrated into the unbonded wafer areas during the C-SAM measurement.

The dicing yield results of wafers bonded at temperatures of 100°C and 150°C are shown in Fig. 9a. A dicing yield of 100% was obtained for wafers bonded at both temperatures for all frame types. The dicing yield results showed that the bonds formed with both types of bonds were strong enough to survive the force exerted on them by the dicing saw. The pull test results are shown in Fig. 9b. The average tensile bond strength of chips from the wafer pair bonded at 100°C was 23 MPa, while for the wafer pair bonded at 150°C it was 37 MPa. This shows that the average bond strength increased with increasing bonding temperature from 100°C to 150°C. However, the standard deviation was overlapping.

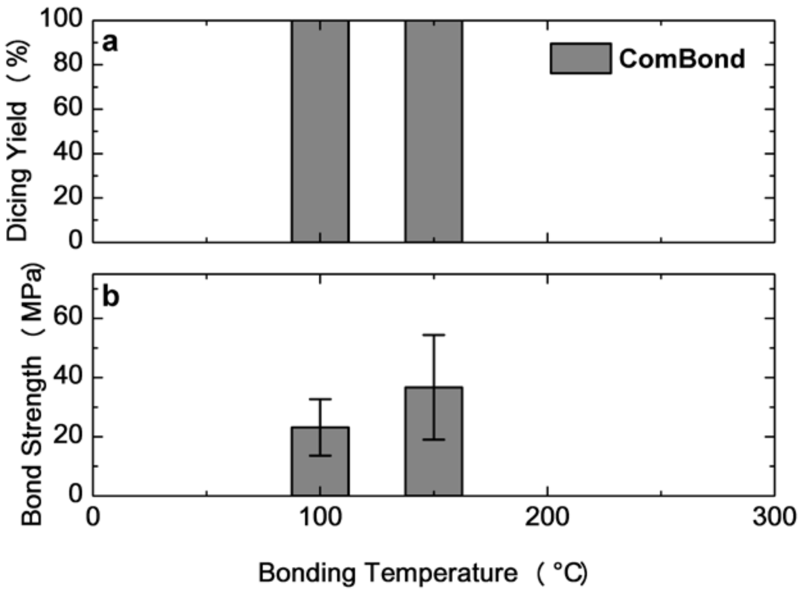

Figure 9. Comparison of (a) dicing yield and (b) tensile bond strength results. Al wafers were bonded with the ComBond® surface activation at 100°C and 150°C for 1 h at 60 kN (114 MPa).

Figure 9 shows that a bond strength which is sufficient for most MEMS applications was obtained with the EVG®580 ComBond® system at only 100°C bonding temperature. The bond strength values obtained at 100°C and 150°C are comparable to bond strength values obtained at temperatures ranging from 300-400°C using an EVG®520IS standard bonder (3). The high tensile bond strength and dicing yield obtained at bonding temperatures of only 100°C indicate that the oxide removal procedure performed using the ComBond® surface preparation has a high impact on the bonding ability of Al films. It is reasonable that the Al_2O_3 removal enables direct contact between the two Al metal surfaces and subsequent bonding by metal diffusion.

Conclusion

Conventional Al-Al wafer bonding requires extremely high processing temperatures and pressures, mainly due to the native chemically-stable Al oxide layer, which obstructs diffusion of Al atoms between the two metal layers. A dry surface pre-treatment process, which removes the native oxide, is crucial to enable Al-Al wafer bonding at low temperatures. It was shown that the bonding temperature could be reduced to as low as 150°C for wafers with blank Al films, and 100°C for wafers with frame Al pattern. The bonding interface of bonded blank wafers was inspected by C-SAM and TEM, and featured areas of oxide-free, atomic contact. The bonding quality was better for Al films deposited by ALPS sputtering than for Al films deposited by standard sputtering, probably due to the smaller grain size of the former films. The more application-relevant frame wafers showed 100% dicing yield for 150°C and 100°C, and high tensile bond strength of 37 MPa and 23 MPa, respectively. In both cases the measured bond strength is sufficient for most MEMS applications. High-quality Al-Al bonded wafer pairs were produced with high, but also with low bonding pressures of 114 MPa and 1.9 MPa, respectively. Compared to Al-Al thermo-compression wafer bonding without *in situ* removal of native oxide, when using the ComBond® pre-treatment, the bonding pressure is no longer a key parameter for successful Al-Al bonding.

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