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Surface pretreated low-temperature aluminum–aluminum wafer bonding

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Abstract Aluminum–aluminum wafer bonding is becoming increasingly important in the production of CMOS microelectromechanical systems. So far, successful bonding has required extreme processing temperatures of 450 °C or more, because the chemically highly stable oxide layer acts as a diffusion barrier between the two aluminum metallization layers. By using the 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 150 °C. The bonded interfaces were characterized using C-mode scanning acoustic microscopy and transmission electron microscopy, and featured areas of oxide-free, atomic contact.

1 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). Compared to other established materials, aluminum has a number of benefits: low price, high thermal and electrical conductivities and relatively high electromigration resistivity (if small concentrations of copper are added (Lloyd 1999)). These properties, combined with its complementary metal oxide semiconductor (CMOS) compatibility, make aluminum a promising candidate for the fabrication of CMOS-MEMS, in which the actuator part is bonded to the electrical circuit.

However, the chemically highly stable oxide layer acts as a diffusion barrier between the two aluminum metallization layers. Successful Al–Al wafer bonding has thus required extreme processing temperatures so far. Table 1 lists experimental parameters extracted from a number of reports on Al–Al wafer bonding. In established processes, a high pressure—usually several tens of MPa (Yun et al. 2008a; Malik et al. 2014, 2015)—is used to break the oxide in order to establish diffusion channels for Al atoms. As a calculation shows (Rebhan and Hingerl 2015), the elastic energy is much 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 400–550 °C (Yun et al. 2008a; Cakmak et al. 2009; Froemel et al. 2011; Malik et al. 2014, 2015). In recent experiments, Malik et al. were able to reduce the required bonding temperature to about 350 °C by depositing the Al metallization layer onto an intermediate SiO$_2$ layer (Malik et al. 2015). Notably, Akatsu et al. used an ultra-high surface activated bonding set-up (Akatsu et al. 1997) to bond cubes of single crystalline aluminum at room temperature (with a bonding pressure of 40 MPa) (Akatsu et al. 1999). This technique was also used on wafer-level for copper (Kim et al. 2003), but there is no account for surface activated Al–Al wafer-level bonding.

In the present experiments, for the first time successful Al–Al wafer bonding was performed at temperatures as low as 150 °C using the ComBond® surface preparation process.

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Table 1 Comparison of experimental parameters from different reports on successful Al–Al wafer bonding

	Al thickness	Cu content	Bond area	Force	Pressure	Temperature
Yun et al. (2008a)	2 μm	0–4%	600–1200 mm^{2a}	60 kN[a]	50–100 MPa	450 °C
Yun et al. (2008b)	2 μm	2%	n. a.	9–18 kN	n. a.	450 °C
Cakmak et al. (2009)	500 nm	0%	175 cm^2	60 kN	3.4 MPa	400–550 °C
Froemel et al. (2011)	1 μm	n. a.	n. a.	n. a.	4.5 MPa	450 °C
Malik et al. (2014)	1 μm	0%	525 mm^2	18–36 kN	34–69 MPa	400–550 °C
Malik et al. (2015)	1 μm	0%	525 mm^2	36–60 kN	69–114 MPa	300–550 °C

n. a. = not available

[a] Values estimated from description of frame structure

2 Experimental

The substrates used for the present bonding experiments were 200 mm diameter silicon wafers with a 20 nm Ti adhesion/barrier layer on top. metallization layers of 99.5% Al and 0.5% Cu with a thickness of 300 nm were deposited on top of the Ti film using two different techniques: standard sputter deposition and aluminum low pressure seed (ALPS). ALPS differs from the standard deposition mainly in terms of processing pressure and temperature. While the standard deposition was performed at 215 °C with an Ar pressure of 3.3×10^{-3} mbar, the ALPS process was carried out at only 30 °C with an Ar pressure of 5.33×10^{-5} mbar. The surface roughness of the wafers was determined from $2 \, \mu m \times 2 \, \mu m$ atomic force microscopy (AFM) scans recorded in tapping mode.

Conventional wafer bonds were produced in a standard thermo-compression wafer bonding system (EVG®520IS). For the low-temperature bonds, the EVG®580 ComBond®, a fully automated, high-vacuum dry surface pretreated wafer bonding system was used. In the ComBond® system, a robot arm transfers the wafers from a central chamber to several modules. This way, a surface preparation step can be performed before the bonding without exposing the wafers to air. The surface treatment is a proprietary EV Group process with special plasma, gas and pressure parameters. It acts as a "mild" oxide removal process, revealing oxide-free surfaces while only negligibly enhancing the sample's surface roughness. Prior to the bonding experiments, Al_2O_3 removal rates of up to 15 nm min^{-1} were confirmed by thickness measurements of atomic layer deposited Al_2O_3 films on Si substrates. The bonding chamber in the ComBond® is practically identical to that of the EVG®520IS. In both set-ups, a bonding force of 60 kN was used. Since all bonded wafer pairs presented in this paper are full area bonds of unstructured wafers (bonding area: 314 cm^2), this force corresponds to a bonding pressure of 1.9 MPa. The interfaces of the bonded wafer pairs were characterized by C-mode scanning acoustic microscopy (C-SAM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

3 Results and discussion

3.1 Wafers

Figure 1 shows AFM images of the surfaces of the two different kinds of wafers. The standard deposited Al developed grains with lateral sizes of 300 nm to 700 nm, while the grains of the ALPS wafers are significantly smaller with 200 nm to 300 nm. The root mean square (RMS) surface roughness was found to be about 1.2 nm for both kinds of wafers. TEM measurements revealed that the grains extend throughout the whole layer for both deposition types. Furthermore, the thickness of the native aluminum oxide is about 3 nm to 4 nm, which is in agreement with typical reported values (Hart 1956; Evertsson et al. 2015).

3.2 Conventional Al–Al wafer bonding

The present attempts to bond two unstructured 200 mm diameter Al wafers on a conventional set-up were unsuccessful. Figure 2 shows a typical C-SAM result of a wafer pair (standard Al deposition) bonded at 550 °C. The image shows many weakly bonded areas. The sound velocity in Al is very close to the sound velocity in aluminum oxide, and factors of 10 to 20 different to the one of voids (air). This is why C-SAM allows to detect defects with layer-to-layer distances even in the sub-micrometer range. The bond quality was found to be extremely sensitive to local pressure variations. The low bonding pressure of only 1.9 MPa (which is the maximum possible with this specific bonding
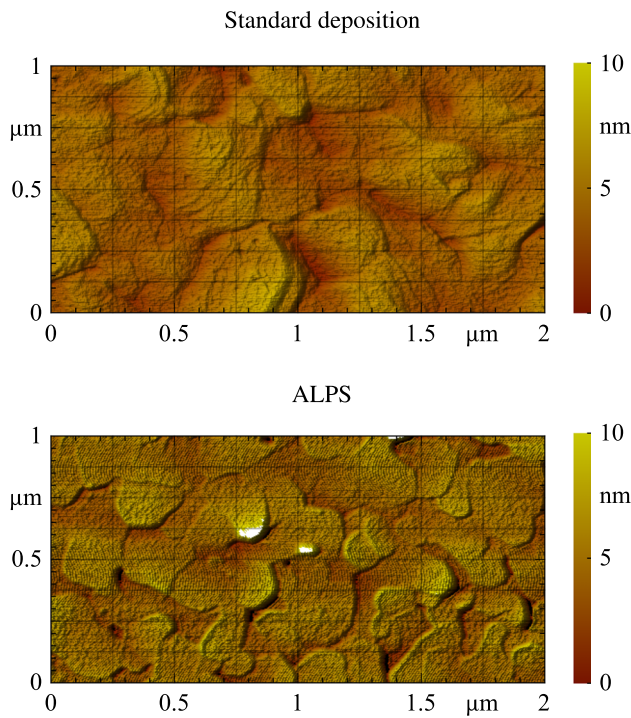
Standard deposition

ALPS

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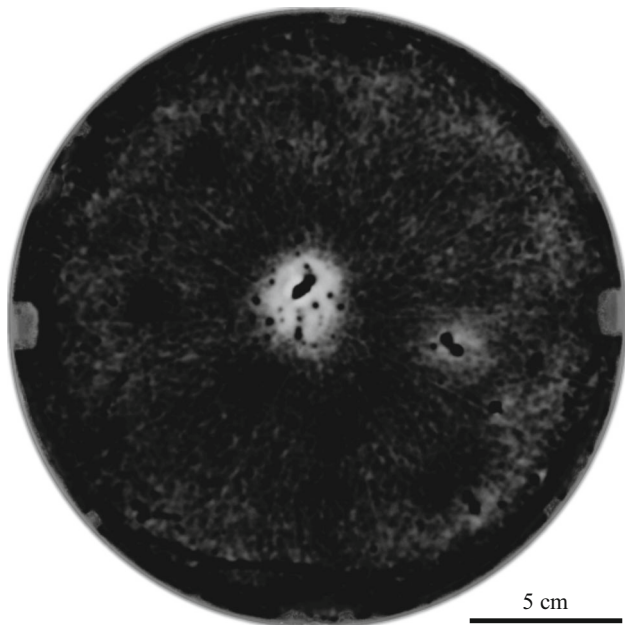

Fig. 2 Typical C-SAM result of 200 mm diameter Al wafers (standard deposition) bonded conventionally at 550 °C

set-up) was not enough to reproduce the results of Cakmak et al. (2009), who were able to bond unstructured 150 mm wafers with a pressure of 3.4 MPa. A cross-sectional SEM inspection showed that the high bonding temperature had caused the Ti barrier layer to dissociate into individual,

droplet-like grains. Furthermore, between the two aluminum layers the undamaged Al oxide was visible, which was also detectable by Auger electron spectroscopy depth profiling. The oxide layer obstructs diffusion of Al atoms between the two metallization layers, making grain growth across the original interface impossible. The results with ALPS wafers were similar.

3.3 Low-temperature surface pretreated Al–Al Wafer Bonding

Figure 3 shows a typical C-SAM result of a ComBond® surface pretreated, low-temperature (150 °C) bonded wafer pair. Due to the surface pretreatment, which removes the native Al oxide prior to the bonding process, the wafers can be bonded at temperatures lower than any values reported in literature (see Table 1). The C-SAM image shows only minor interface defects. The larger ones, with a lateral extent of a few millimeters, were mainly caused by particles. While the origin of the smaller defects is still open for discussion, it could be shown that they can be partially cured by an additional thermal annealing step. Figure 4 (top) shows sectors of C-SAM measurements recorded (1) directly after wafer bonding in the ComBond® at 150 °C for 1.5 h, and after subsequent annealing for 1 h at (2) 250 °C, and at (3) 350 °C. To detect areas of weak bonding, the images were binarized at a certain threshold value, leaving only those pixels colored that were originally part of unbonded areas. For better visibility
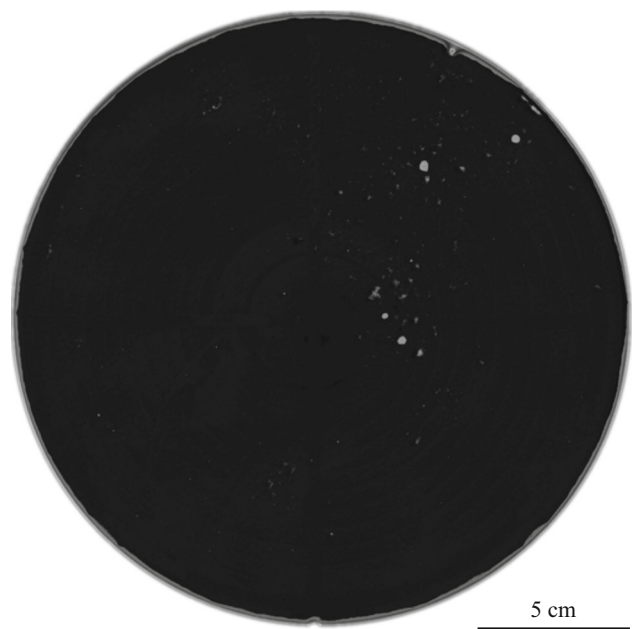

Fig. 3 Typical C-SAM result of 200 mm diameter ALPS wafers bonded in the ComBond® system at 150 °C
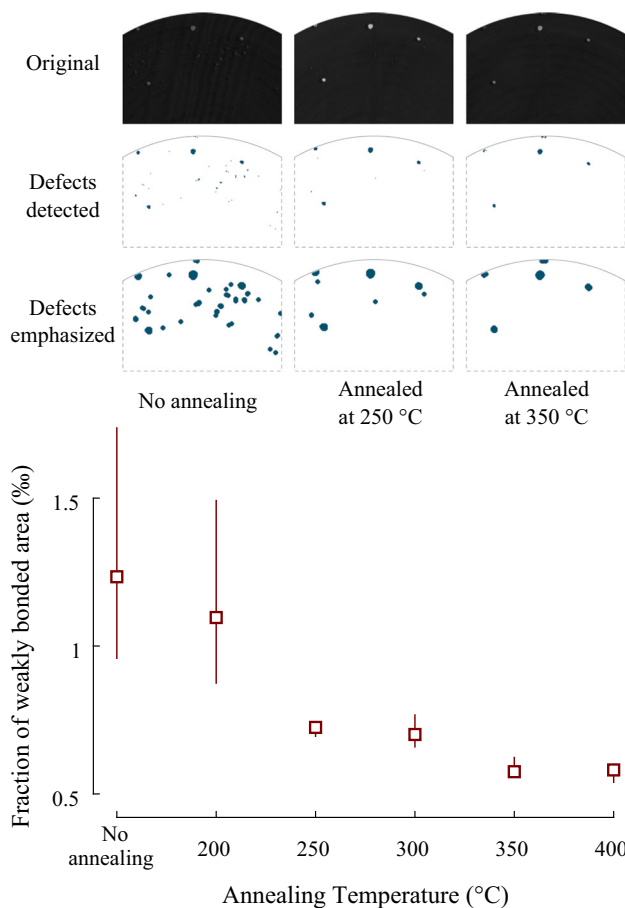
Fig. 4 Top: C-SAM results for a low-temperature wafer bond after thermal annealing at 250 and 350 °C. Bottom: quantitative evaluation of the defect area
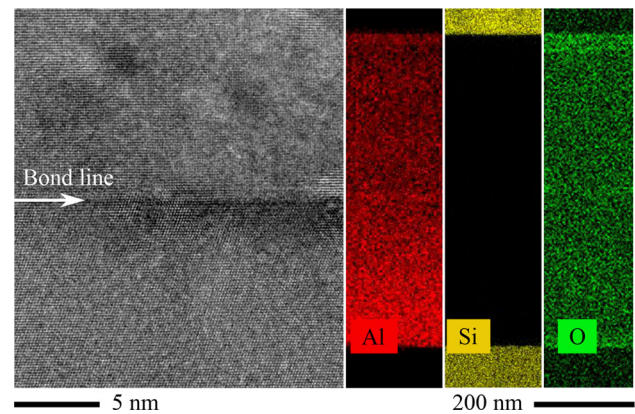

Fig. 5 High-resolution TEM image and EDX mapping of the interface of a ComBond® surface pretreated, low-temperature bonded wafer pair, showing atomic, oxide free contact

(especially of the small defects), Fig. 4 (top) also shows versions of the binarized images with the defects enlarged by dilation. This comparison shows that the defects smaller than a few millimeters vanish after the thermal treatment, more or less leaving only those defects that are caused by particles. A quantitative evaluation of the weakly bonded area shows a drop by a factor of two for annealing temperatures of 200 °C or more (see Fig. 4 bottom). We attribute this effect to the increased self-diffusion and the resulting closing of voids in Al at elevated temperatures (Volin and Balluffi 1968).

Compared to bonded ALPS wafer pairs, the samples produced from standard Al wafers showed significantly more weakly bonded or unbonded areas upon C-SAM inspection. For a qualitative comparison of the bond strength, a razor blade was inserted at the bonded interface (cf. Maszara et al. (1988)) and the approximate length of the resulting crack was measured with C-SAM. The crack length exhibited by the standard Al samples was 5% to 10% larger than that measured for ALPS ones. From the C-SAM measurements and the crack length measurements

it can be concluded that the bonded ALPS wafers revealed higher bond strength than the standard Al wafers. The smaller grains observed in the ALPS wafers might be the reason for this difference. Smaller grains result in a higher density of grain boundaries, which in turn promotes diffusion of Al atoms, as the concentration of short-circuit diffusion paths is increased (Rebhan et al. 2014; Rebhan and Hingerl 2015).

The interfaces of the dry surface pretreated, low-temperature bonded ALPS wafer pairs were characterized by TEM and energy dispersive X-ray spectroscopy (EDX). As the high resolution TEM image in the left part of Fig. 5 shows, no amorphous layer separates the two Al metallization films. Similar observations were made byAkatsu et al. (1999) for single crystalline samples. The EDX mapping shown in the right part of Fig. 5 reveals that no oxide is accumulated near the interface. The oxide signal stems exclusively from the native oxide on the surface of the TEM specimen, which was exposed to air during TEM preparation.

4 Conclusion

Due to the native, chemically highly stable Al oxide layer, which obstructs diffusion of Al atoms between the two metallization layers, conventional Al–Al wafer bonding requires extremely high processing temperatures and pressures. A dry surface pretreatment process, which removes the native oxide, is the key to enable Al–Al wafer bonding at temperatures as low as 150 °C, even with the lowest bonding pressure ever reported. Using the EVG®580 ComBond® system with its surface pretreatment module, low-temperature bonding of unstructured 200 mm aluminum wafer pairs could be demonstrated for the first time. The bonding interface was inspected by C-SAM and

TEM, and featured areas of oxide-free, atomic contact. Most of the voids that were not related to particles could be closed by an additional thermal annealing step (350 °C for 1 h).

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