High efficiency single wafer cleaning for wafer bonding-based 3D integration applications

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Abstract. Current work describes development, testing and verification of a single wafer megasonic cleaning method utilizing a transducer design that meets the extreme particle neutrality, Particle Removal Efficiency (PRE), and repeatability requirements of production scale wafer bonding and other applications requiring extremely low particles levels.

Introduction

Different microelectronic processes require very clean surfaces in terms of particulate contamination. Among them, Direct wafer bonding has very aggressive requirement in terms of particulate cleanliness. Direct wafer bonding consists of joining together two materials by simply bringing their smooth and clean surfaces into contact (fig. 1). At room pressure and temperature, adhesion will be generated by Van Der Waals forces formed between the molecules/atoms at the surfaces of the two materials. As the two surfaces in contact are rigid, particles trapped between the surfaces generate areas which are not in contact (un-bonded areas or voids) thus decreasing the yield. A particle with a diameter of 1 μm is known to generate a bonding defect (void) with a diameter of ~1 cm! In order to prevent this from happening a typical process step consisting of a single wafer cleaning process is integrated.

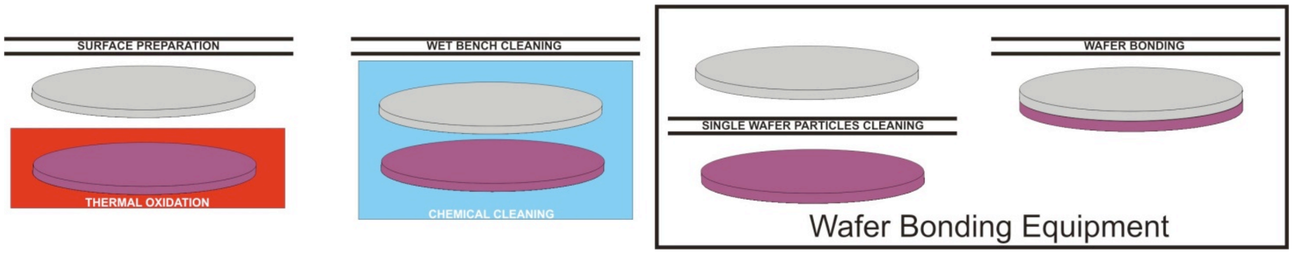
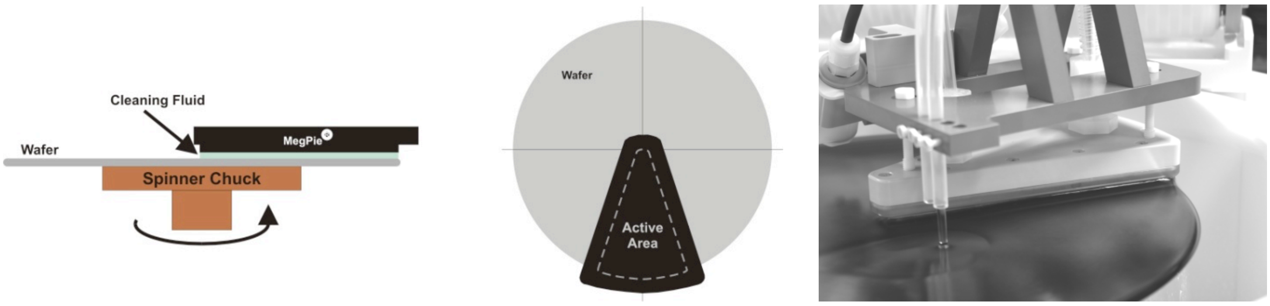


Figure 1. Schematical direct wafer bonding process flow.

For the above reasons, wafer bonding is very strict in terms of substrate cleanliness. If for a post-CMP cleaning process incoming wafers would show particles levels of thousands or tens of thousands that are removed by cleaning process down to hundreds or tens of particles per wafer, in case of direct bonding the particles levels required for successful and reliable wafer bonding are in the range of less than 10 particles per 200 mm or 300 mm diameter wafers (particle size >0.12 μm). With such success criteria the efficiency of this novel cleaning method has to be qualified also by particles neutrality. Studied here as an application for direct wafer bonding, the MegPie® process may also be fine tuned to fulfill the cleaning and throughput requirements of other critical applications (thermo-compression bonding, epitaxy, layer deposition, lithography).

Experimental

Apparatus. Two different models of a radially uniform area megasonic transducer, the MegPie®, were used in these experiments (fig. 2). This transducer couples acoustic energy into a fluid filled gap formed by the substrate and the transducer face. The form and resonator design assure uniform acoustic dosage over the entire surface of the rotating substrate without scanning motion. Constant monitoring of forward and reflected RF power as well as PZT crystal temperatures, assures consistent and repeatable acoustic processing conditions.



a. b.

Figure 2. Single wafer cleaning system based on MegPie® transducer: a. schematical setup, and b. example of a V3 MegPie® model integrated on a production wafer bonder.

Initial testing was performed using a V2 MegPie® with a Teflon® PFA (perflouralkoxy) coated resonator. PFA coating is meant to provide a metal-free surface while assuring compatibility with the various chemical solutions used in wafer cleaning and etching. The PFA coated V2 MegPie® had been adopted for post CMP and other high particle count cleaning steps that had previously been accomplished with conventional brush or nozzle devices.

While the PRE achieved with the V2 MegPie met the requirements of high particle count cleans, testing to the very demanding particle level and size specifications of direct wafer bonding exposed some issues with PFA coated resonators. It was found that PFA material is not particle neutral when megasonic energy is applied, and PFA coating itself was actually found to generate sub 100 nm particulate, therefore not acceptable for this pre-bond cleaning application. The PFA coated resonator was also proven to be very sensitive in that it could be scored or breached easily through contact with a hard substance, for example a broken wafer fragment. A score or breach of the material will, in best case, provide a source of additional particulate, and in worst case expose the underlying metal resonator to the process fluid.

In order to meet the direct wafer bonding cleaning requirements, alternative resonator materials were investigated. Quartz was eliminated due to restricted chemical compatibility and limited lifetime in a proximity system (erosion and pitting). Due to excellent physical robustness and chemical resistance, single crystal sapphire was ultimately selected for the resonator of the V3 model MegPie®. With a controlled resonator thickness and crystal orientation, monocrystalline sapphire is also a high efficiency acoustic waves conductor. Sapphire is also compatible with the eutectic PZT to resonator bond method, eliminating the need for epoxy/adhesive bonding. The final results presented herein are based on the sapphire resonator V3 model MegPie®.

A MegPie® large area megasonic transducer (fig. 2.b.) was integrated in the pre-bond cleaning station of an automated bonding system (EVG®850LT).

Particles neutrality testing. Testing was carried out using new prime-grade 200 mm diameter silicon wafers. Measurements were performed using a KLA Tencor SP-2 system at a threshold of 90 nm. Process conditions ranged from 0 to 3 W/cm^2 with both NH_4OH solutions and de-ionized water (DIW). Testing series was initiated with a V2 MegPie® with PFA coated resonator. Although particle removal efficiency (PRE) results were showing good values for standard applications, experimental data showed the generation of sub 100 nm particulate. The source of such particle generation was found to be the PFA coating. The transducer was changed to the V3 MegPie® model with monocrystalline sapphire resonator and testing re-initiated. The V3 Sapphire MegPie® proved to be particle neutral at power densities ranging from 0 to 3 W/cm^2 and spin speeds ranging from 5 to 100 RPM (cf. Table 1). The final results presented herein are based on the sapphire resonator V3 model MegPie®.

Table 1: MegPie® cleaning of blank Silicon wafers.

Test No.	Particles Number		
	Incoming	After MegPie®	Difference
1	14	4	-10
2	12	5	-7
3	13	3	-10
4	3	4	1
5	9	4	-5
6	3	5	2
7	4	3	-1
8	12	9	-3
9	25	18	-7
10	11	9	-2
11	23	33	10
12	13	15	2
13	8	7	-1

Test No.	Particles Number		
	Incoming	After MegPie®	Difference
14	11	1	4
15	10	12	2
16	6	6	0
17	8	13	5
18	16	9	-7
19	5	5	0
20	18	18	0
21	13	12	-1
22	12	11	-1
23	30	17	-13
24	14	14	0
25	7	12	5

The two measurements highlighted in table 1 (#11 and #25) correspond to reference wafers without Megpie® process: these wafers were only handled same as the test wafers but no cleaning process was performed. Considering the reference values it can be observed that at such low particles levels wafers transfer between different process stations (e.g. cassettes, cleaning stations, particles counter) can induce some particles contamination which is not related to cleaning efficiency.

Particles removal efficiency testing. Clean wafers were contaminated with nitride particles with size ranging between 50 nm and 200 nm. The wafers were then loaded to a the single wafer cleaning station and were processed using following sequence: 2 minutes MegPie® process at 1 W/cm^2 power density at 30 RPM followed by a diluted NH_4OH (<2%) cleaning solution rinse and DIW rinse followed by spin drying. Minimum particle size measured in this experiment was 0.09 µm. Subsequent SP2 analysis showed uniform removal and PRE values >95%, often >100% (cf. Table 2).

Table 2 : MegPie® cleaning of intentionally contaminated blank Silicon wafers.

Test no.	Start Wafer	Contaminated Wafer	After MegPie® Cleaning	PRE	%PRE
1	274	5709	237	-5472	100.68%
2	95	3068	127	-2941	98.92%
3	118	4468	578	-3890	89.43%
4	57	2918	316	-2602	90.95%
5	61	2839	68	-2771	99.75%
6	68	2991	197	-2794	95.59%
7	61	2952	51	-2901	100.35%
8	84	3069	61	-3008	100.77%
9	128	4642	122	-4520	100.13%

Figure 3 shows particles size distribution of an intentionally contaminated Silicon blank wafer.

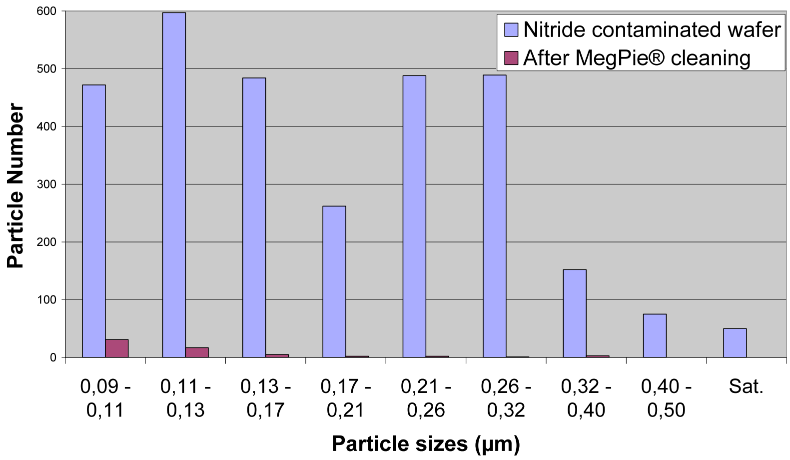


Figure 1. Particle size distribution before and after the MegPie® cleaning of a Silicon wafer intentionally contaminated with nitride particles.

It can be observed the significant removal rate particularly for the large size particles which are responsible for wafer bonding defects.

Conclusions

Among many critical cleaning steps, wafer scale bonding requires a particle free surface for defect free bonds. This requirement dictates a final single wafer cleaning step directly before the bond process step that has the capability to remove the remaining few particles while at the same time not adding any additional particles or metal ions contamination.

The final cleaning step was performed in the past by brush scrubbing, megasonic nozzles or rectangular-shape megasonic area transducers. The use of these standard cleaning methods may not be sufficient for bonding applications due to the risk of wafer-to-wafer cross-contamination or touching the active surface, the relatively poor uniformity (nozzles cleaning involve wafer scanning with a water stream of few mm diameter) or even induce subsurface defects due to non-uniform exposure to acoustic waves (e.g. for rectangular-shaped transducers).

The large area V3 MegPie® with single crystal sapphire resonator, was implemented in a single wafer pre-bond clean station provides for high particle removal efficiency, combined with no particle addition (particle-neutrality). The proprietary design of this transducer ensures a non-contact cleaning with very high radial uniformity of acoustic energy across the wafer.

The use of cleaning chemistries (e.g. diluted NH_4OH) may enhance cleaning results. The MegPie® transducer was proven to be particle neutral and able to show high PRE results.

Acknowledgements

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