Analysis of the interfacial structure and the bonding mechanism of wafer-level direct bonding by using a neutron beam

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1. Introduction

3D stacking technology is one of the key technologies for the 3D integration, and 300-mm-wafer-level bonding is applied for image sensors, memories, and so on[1]. For Wafer-level bonding for devices, fusion bonding using plasma activation have been adopted because of the compatibility with the existing semiconductor manufacturing process and requires the high-yield and high-reliabilities connection. However, fusion bonding requires the precise control of the bonding surfaces. In particular, SiO_2 layer for the bonding surface is very sensitive to water required for the bonding intermediate [3]. Also after bonding, the humidity affects to the bonded interface of SiO_2 layer [2]. Therefore, interfacial structure including water is significant factor for the bonding quality.

Meanwhile, there are several tools for the interfacial analysis, such as transmission electron microscopy (TEM) cross sections, surface acoustic transmission (SAT) microscopy, and so on. These methods are indispensable in the evaluation of the bonded interfaces, therefore, the specimens would be affected by the measurement preparations or circumstances. Generally, SAT images of the interface of the bonded wafers show voids among the interface caused by redundant hydrophilization, and interfacial structure can be observed by cross-sectional TEM. However, the cross-sectional TEM image of the interfacial structure of dioxide was difficult to analyze, because the contrast of the reacted (or water contained) layer is very weak. As the reaction occurs at the interface of substrates and analyzing targets are light elements (H_2O, -OH) and other deuterated substitutes. Therefore, in previous study, we demonstrated the interfacial analysis of wafer-level bonded dioxide wafers by neutron reflectivity (NR), and we confirmed that NR would have possibilities to distinguish conditions of bonded interfaces [4].

2. Experimental Procedures

In this research, 300 mm Si wafers are prepared and they are oxidized by wet thermal oxidation at 90 °C and a 100-nm-thick SiO_2 layer was deposited. Some of SiO_2 wafers were polished by chemical mechanical polishing before introduced to a bonding apparatus, and other wafers were introduced as prepared. In the bonding apparatus, first, wafers were activated by plasma, that plasma activation was optimized as a sequential plasma process same as our previous work [5]. Activated wafers were cleaned with megasonic water, then they were transferred and bonded in relatively high vacuum (20 Pa), or were transferred in N_2 ambient under atomic pressure and bonded in relatively low vacuum (1000 Pa). These wafers were bonded with a 1000 N load. After that, the bonded wafers were annealed at 200 °C for 7 hrs in an infrared (IR) image furnace within 3–5 hrs (0 days) or after c.a. 2 days storage in the air (Fig. 1). For these experiments, wafer bonding was performed with several parameters as shown in Fig. 4.

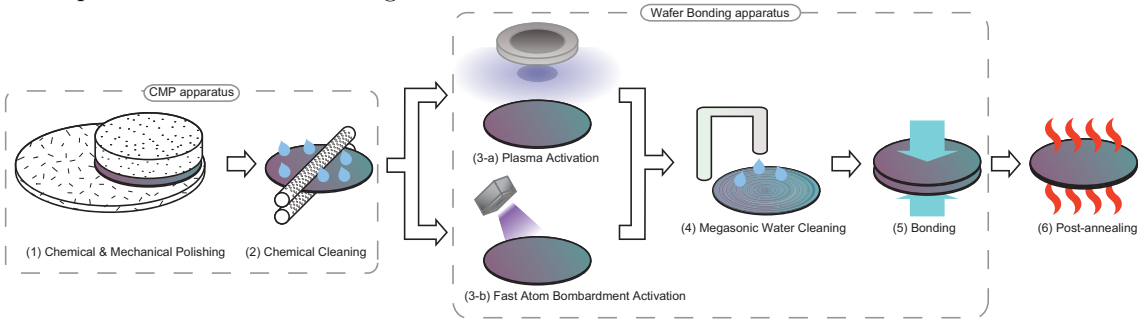

Figure 1. Schematic image of wafer bonding process.

The bonded wafers were evaluated by blade test [6] for bonded strength measurement, scanning acoustic microscopy (SAM), and NR at BL17 SHARAKU. Neutron pulses of 25 Hz were generated with a wavelength band of 0.2 - 0.88 nm. Neutrons penetrated into the bonded interface from the side with incident angles of 0.2°, 0.7° and 1.6°, as shown in Fig. 2. The obtained NR data was analyzed by Motofit program within the IGOR software package and the analytical program developed for NR data to evaluate neutron scattering length density (SLD) profiles in the film thickness direction of interfacial structures.

3. Results and discussion

As shown in Fig. 4, bonding strength has been affected by transfer and bonding circumstances. Bonding in low vacuum circumstances, voids among interfaces were confirmed by SAM, however, there is more possibility to enwind air/N_2 residuals among interface compared to high vacuum conditions. The storage time during bonding and annealing have a little affect to the bonding strength, and CMP process has been less affects to the interfacial conditions.

Also in Fig. 4, reflectivity of neutron beam and calculation in each bonding condition is shown, and reflectivity vs. Q plot of ThOx-01 is shown in Fig. 3 for instance.

As result, bonded interface thickness and SLD have correlation with transfer and bonding circumstances. Therefore, it can be said that the bonding strength would intercorrelate with the bonding interface structure. SLD of interface is around 2.3 $Å^{-2}$ to 2.8 $Å^{-2}$, however, the additional analysis would be required for identifying the layer property.

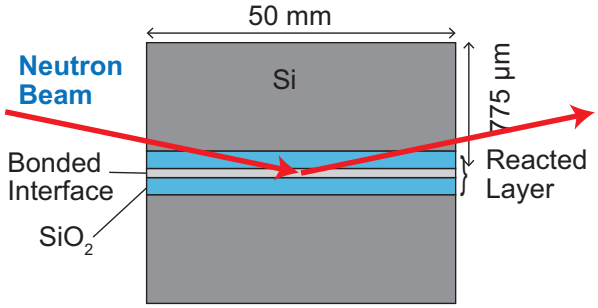

Figure 2. Schematic image of neutron beam line into the bonded interface.

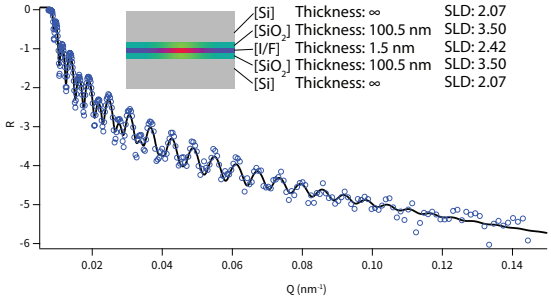

Figure 3. Measured and calculated NR profile of bonded ThOx-01, for instance.

	ThOx-01	ThOx-02	ThOx-03	ThOx-04	ThOx-05	ThOx-06	ThOx-07
CMP	-					▲20-30 nm	
Activation	N_2-plasma 500 W		O_2-pl. 500 W	N_2-plasma 500 W		N_2-pl. 300 W	O_2-pl. 300 W
Transfer	vacuum (∼20 Pa)			N_2 ambient		vacuum (∼20 Pa)	
Bonding	vacuum (∼20 Pa)			1000 Pa		vacuum (∼20 Pa)	
Storage	0 days	2 days	2 days	0 days	2 days	2 days	2 days
C-SAM							
Bonding Strength [J/m²]	0.64	0.83	0.53	1.75	(bulk)	1.02	0.54
I/F thickness [nm]	1.50	1.33		2.24	2.10	1.44	1.42
I/F SLD [Å⁻²]	2.42	2.38		2.79	2.86	2.24	2.25

Figure 4. Experimental parameters and results of bonded thermal oxide wafers.

4. Conclusion

NR has been performed to the bonded interface to detect the reacted interfacial layer during the bonding process. As results, NR could detect the reacted interfacial layer during the bonding process. Moreover, the bonded interfacial structure would have correlation with bonding strength, and these results are useful to improve wafer bonding process.

References

[1] Y. Kagawa, *et al.* "Novel stacked CMOS image sensor with advanced Cu2Cu hybrid bonding ", 2016 IEEE-IEDM, 8.4.1–8.4.4 (2016).

[2] F. Fournel, *et al.* "Water Stress Corrosion in Bonded Structures", *ECS J. Solid State Sci. Technol.* **4** P124–P130, (2015).

[3] J. Desomberg, *et al.* "Influence of water diffusion in deposited silicon oxides on direct bonding of hydrophilic surfaces", *Microsys. Technol.* **24**, 801–808 (2018).

[4] M. Fujino *et al.* WaferBond'19, Helle, Germany, Dec. 2019, p.2–4, p.45.

[5] M. Fujino *et al.* "300 mm wafer-level hybrid bonding for Cu / interlayer-dielectric bonding in vacuum", *Jpn. J. Appl. Phys.*, **59** SBBA02, (2020).

[6] W. P. Maszara *et al.* "Bonding of silicon wafers for silicon - on - insulator", *J. Appl. Phys.*, **64** p.4943–4950, (1988).