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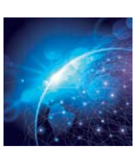

FUSION BONDING AND INTEGRATED METROLOGY – TECHNOLOGY EXPANSION OF SUSS MICROTEC'S PRODUCT RANGE

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With the introduction of the XBS200 bond cluster platform in 2017, SUSS MicroTec has celebrated its reentry into the automated permanent bonding market. The new cluster for up to 200 mm wafers was developed to target metal bonding applications (mainly eutectic bonding and metal diffusion bonding) within the MEMS market, while also being capable of serving anodic bonding, glass frit bonding or temporary bonding requirements.
Looking back on a long tradition in permanent wafer bonding, SUSS MicroTec not only intended to resume its line of automated bonding platforms from the past, but to break new ground in automated permanent wafer bonding.
Therefore, SUSS MicroTec introduced distinct novel features, which provide a worldwide unique selling proposition, mainly fixture-less wafer handling and laser pre-bond.
The technological trends and numerous market requests however also made clear that low temperature fusion bonding as a mayor bonding technique still plays an important role in the market with the demand even increasing with respect to 2.5D and 3D packaging and the rise of RF MEMS.
SUSS MicroTec has therefore invested a great deal of effort to meet this demand by extending the XBS200 process capability to high-precision fusion bonding.

1. INTRODUCTION

Fusion or direct bonding is a long established bonding technique in the semiconductor and MEMS industry [1]. Joining two silicon wafers without any additional intermediate layer can achieve a weak bond if the surfaces are sufficiently flat and clean. In order to establish a permanent bond a subsequent annealing step is generally carried out to strengthen the bond. Traditionally fusion bonding made use of rather high temperatures (in the case of hydrophilic silicon at >1000 °C).
Especially with the rise of SOI (silicon on insulator) in the late 90s, fusion bonding has gained interest for the semiconductor industry besides MEMS and still remains to be one of the major manufacturing techniques for SOI wafers.
However, with respect to other semiconductor applications high temperatures can cause doping broadening by diffusion, metal degradation, thermal stress, defect introduction and even contamination. Post-metallization bonding or the presence of CMOS circuitry in particular therefore require significantly reduced annealing temperature profiles that can be achieved by wafer surface activation (either by exposing the wafer to specific wet-chemical solutions (e.g. RCA) [2] or by treating the wafers with a dedicated plasma process) [3].

Figure 1 XBS200 permanent wafer bonding platform

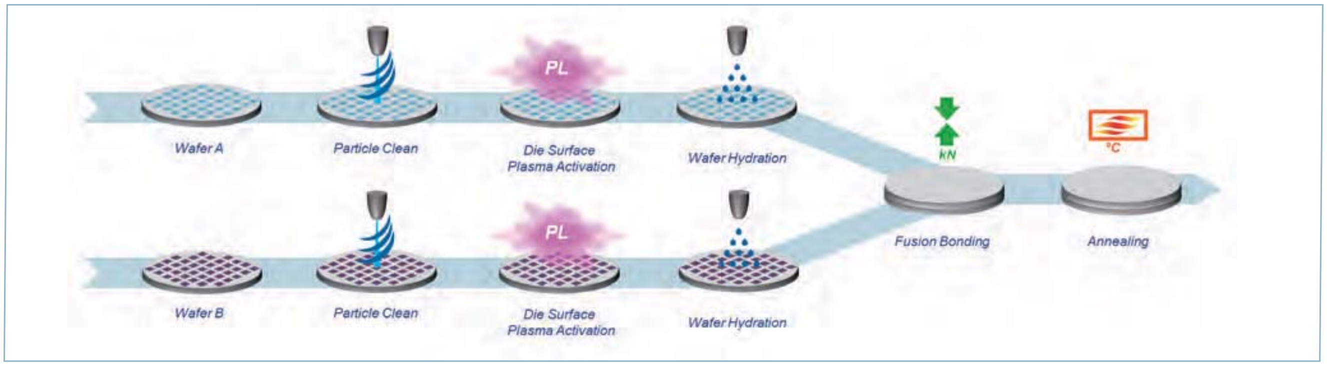

Figure 2 *Typical process flow for low temperature wafer fusion bonding (with plasma activation)*

Wafer surface activation has since allowed for a dramatic drop of the annealing temperatures at fusion bonding down to <450 °C, typically the max. thermal budget for CMOS wafers, while still achieving high bond strengths, sometimes even exceeding the bulk fracture strength of silicon (2.47 J/m²).

A typical process flow for fusion bonding is depicted in figure 2. The incoming bond partners (wafers A and B) are particle-cleaned via megasonic DIW cleaning in an initial step (which is optional, depending on the cleanliness of the wafers). This step is followed by plasma activation and subsequently hydration of the wafer surface via DIW rinse in order to provide OH-groups to form silanol groups at the wafer surface. The pre-treated wafers are then typically aligned to each other using a bond aligner, followed by bonding either in vacuum or at room temperature by bringing the wafer surfaces into contact (using very little or no force at all).

2. NEW MODULES

In order to enable this process flow the XBS200 cluster modules had to be extended by three dedicated process modules: AC200 for wafer cleaning, PL200 for plasma activation and MM200 for integrated in-line metrology. While cleaning and plasma modules in general have been part of previous bond clusters from SUSS MicroTec, the MM200 is an entirely new dedicated metrology platform.

2.1 AQUEOUS CLEANING MODULE AC200

The new cleaning module AC200 builds up on the experience gained at SUSS MicroTec from existing semi-automated and automated wet-processing systems. It offers single wafer cleaning with puddle and megasonic DIW rinsing.

The cleaning module allows for diluted chemistries (e.g. < 2 % NH_4OH). Organic removal functionality (SC1) is available on request.

The module also allows for optional backside rinsing and N_2 assisted spin-drying.

Different wafer chucks (e.g. edge-handling capability for perforated wafers) are optionally available.

Figure 3 *Aqueous cleaning module AC200*

2.2 PLASMA MODULE PL200

The plasma module PL200 offers controlled and efficient plasma treatment and provides highest process flexibility/repeatability for plasma-based wafer surface activation.
Various process gases such as Ar, O_2, N_2 etc. and mixed chemistries can be used and are controlled via mass flow controllers (MFCs). Gate-valve loading of the PL200 is key for high-throughput handling. In general, the PL200 can also be used for plasma cleaning of polymer residues and for effective metal oxide reduction.

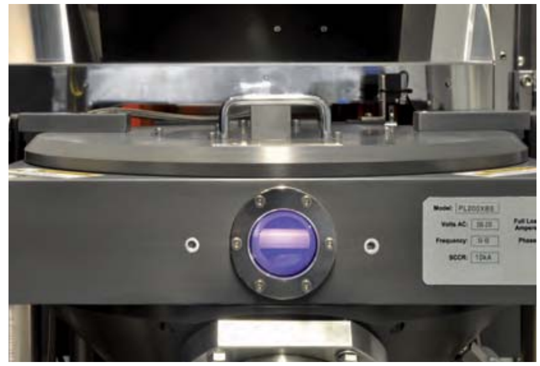

Figure 4 Plasma module PL200

2.3 METROLOGY MODULE MM200

Integrated in-line metrology functionality allows for fast process feedback and therefore short intervention times. The novel MM200 module therefore can play an essential role for increased process control and yield improvement.
With the absence of intermediate layers at the fusion bonding surface, particle cleanliness is crucial to obtain void-free bond interfaces. In addition to this, the verification of the post-bond alignment quality (overlay) requires quick response times in high-volume manufacturing. This is in particular the case when the overlay requirements are sub-micrometer (e.g. for wafer-to-wafer (W2W) hybrid bonding).
For this reason the MM200 module can be configured for full-field infrared (IR) void inspection and/or high precision IR overlay measurement (reflective and transmissive modes are available) including multi-site measurement capability.
The throughput- and footprint-optimized MM200 can detect voids down to 0.5 mm size and offers automatic classification and localization logging. In case of overlay measurement, the metrology system provides both high repeatability (figure 7) and high measurement resolution to serve demanding overlay requirements of <50 nm.

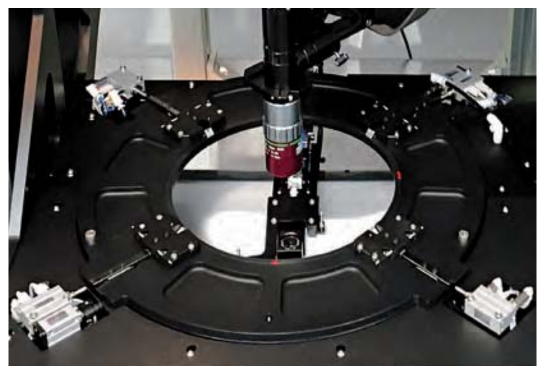

Figure 5 Integrated metrology module MM200

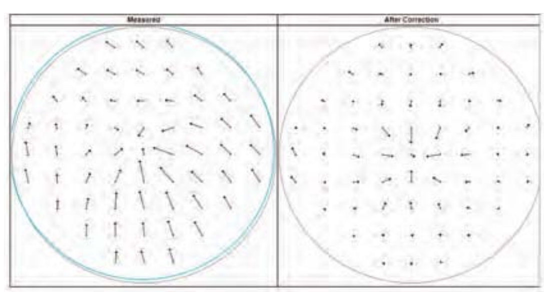

Figure 6 Vector plot of overlay results showing the MM200 measurement results (left) and calculated bond (right) using correction values derived from the measurement.

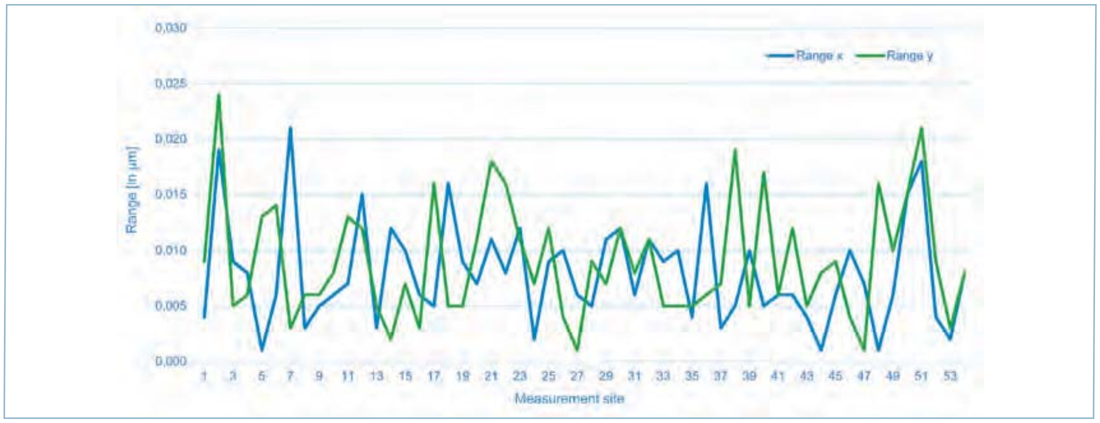

Figure 7 *Repeatability of overlay results of 53 measurement sites over 10 cycles*

In case the XBS200 is used for temporary bonding or other applications comprising adhesive layers (e.g. collective die-to-wafer bonding (D2W)[5]), the MM200 can be extended with total thickness variation (TTV) measurement functionality. Here the adhesive thickness underneath populated dies can be measured with high precision. Such data can provide valuable process information on the die-height variation on populated wafers.

Since alignment verification and defect inspection are essential for all bonding schemes, the MM200 will thus also play an important role for non-fusion bond configurations of the XBS200 in the future.

In order to improve and optimize the wafer alignment results, the MM200 provides a closed-loop feedback to the bond aligner for offset calibration and wafer run-out compensation.

Last but not least, it should be noted that due to the flexibility of the wafer handling system (6-axis handling robot) of the XBS200 platform the MM200 could be effectively designed to not occupy valuable process module footprint. The new metrology station can also be field-upgraded into existing XBS200 systems.

3. UPGRADE OF EXISTING MODULES

Since the available process modules of the current XBS200 platform had to be adapted in order to enable the fusion bonding concept, they will also be mentioned in the following.

3.1 HIGH-FORCE BOND CHAMBER XB200

The XB200 bond chamber is the cluster process module version of the stand-alone XB8 bonder. It offers a wide parameter window and is therefore ideal for all kinds of bonding schemes including metal-diffusion, eutectic, glass-frit, adhesive, anodic and fusion bonding processes.

Figure 8 *XB200 high-force bond chamber*

Reproducible bonding results from wafer to wafer are essential for achieving consistently high product quality. The XB200 bond chamber consists of a closed process chamber with a gate valve for loading and unloading. During wafer transfer, the chamber is purged with nitrogen to ensure optimum cleanliness.

An external force column, consisting of a rigid three-post structure takes up the bond force applied during bonding.

This design offers maximum stiffness to avoid mechanical stress on the actual vacuum chamber, heaters and pressure plates, resulting in minimal post-bond wafer bow. Excellent temperature accuracy and reproducibility are achieved by a thermal decoupling of the heaters from the actual bond chamber. An optionally available multi-zone heater setup furthermore enables advanced temperature uniformity control across the wafer.
Active top and bottom heater cooling ensures symmetric temperature profiles as well as short process cycle-times. Water-based chiller units are used to dissipate the heat from the chamber. The innovative mechanical and thermal design concept used in the XB200 bond chamber enables optimal bonding force and temperature distribution across the wafer to ensure higher yields.

For fusion bonding under defined pressure conditions, a new wafer clamping system was developed for the XB200 bond chamber to enable transfer of aligned wafers from the handling robot without use of a center pin.

Figure 9 *XBA bond aligner*

3.2 BOND ALIGNER XBA

The high precision XBA bond aligner delivers consistent deep-submicron alignment accuracy for transparent or non-transparent wafers by using SUSS MicroTec's proprietary Inter-Substrate Alignment (ISA) technology. Built-in fixed reference targets, global calibration and overlay verification ensure optimum repeatability. Global calibration wafers (GCD) are an integral part of the aligner system and make automated calibration and overlay verification simple and quick.

To allow for highest possible alignment accuracy of aligned wafer pairs independent from potential mechanical distortions of the wafer transfer from bond aligner to bond chamber, the XBA can be provided with a unique laser pre-bond system [4] on request. Inside the bond aligner the aligned wafers can therefore be physically "tacked" at a dedicated location prior to wafer transfer to the XB200 bond chamber.

To meet even the highest requirements in W2W bonding (e.g. for small pitch W2W hybrid bonding of BSI sensors) the alignment capabilities of the XBA have been greatly enhanced. Special attention has been paid to the control of the environmental conditions at the time of bonding, enhanced wafer stage servo system, and the characterization/enhancement of all critical attributes involved in the alignment and bonding process.

The deliberate development process has lately enabled SUSS MicroTec to make a significant leap from <400 nm (3σ) to <100 nm (3σ) alignment accuracy (see figure 10), even allowing for <100 nm overlay results (see figure 11).

The enhanced <100 nm alignment functionality is optionally available and can be integrated in all existing XBS200 platforms.

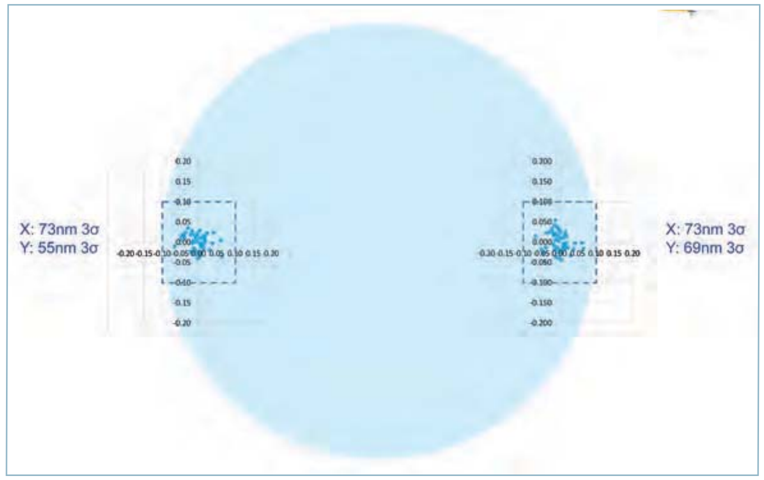

Figure 10 *XBA alignment accuracy over 55 alignment cycles (based on GCD wafers)*

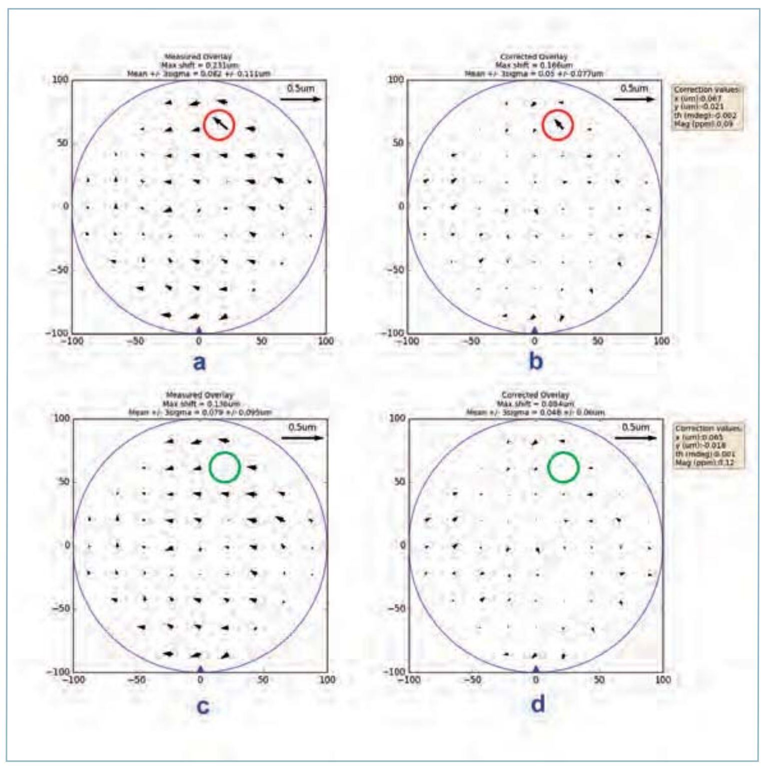

Figure 11 *Vector plot of overlay results from a 200 mm fusion bond, showing the MM200 measurement results (left) and calculated bond (right) using correction values derived from the measurement. The used wafer had a defect at one of the measurement sites, showing its influence on the vector plot*

a) Overlay results:
~80 nm mean alignment, max. overlay error: ~230 nm
b) Calculated overlay:
~50 nm mean alignment, max. overlay error: ~170 nm
c) Overlay results:
~80 nm mean alignment, max. overlay error: ~140 nm
d) Calculated overlay:
<50 nm mean alignment, max. overlay error: ~85 nm

4. CONCLUSIONS

With the new XBS200 permanent bond cluster dedicated for fusion wafer bonding SUSS MicroTec is offering a modular and highly competitive bonding platform with integrated in-line metrology functionality for high-throughput and improved yield requirements.
The system was designed to target MEMS & sensor applications that require fusion bonding (e.g. microfluidics and RF-MEMS). Additionally the greatly enhanced alignment capability can be used to address even more demanding semiconductor application such as CIS, 3D stacked memory and 3D SoC.

The next SUSS Report will therefore cover the extension of the adapted process modules towards 300 mm and highlight results obtained on a dedicated platform for W2W and collective D2W hybrid bonding on 300 mm wafers at SUSS MicroTec.

Thomas Schmidt studied Microsystems Technology at the University of Applied Sciences Kaiserslautern in 2001. In the following years he has held various positions in MEMS/semiconductor processing and has also lectured on advanced lithography as well as on MEMS and CMOS fabrication.

Since 2017 he is Product Manager at SUSS MicroTec with responsibility for the product line "Permanent Wafer Bonding" focusing on automated cluster platforms. This platforms address established bonding techniques for the MEMS/semiconductor industry as well as advanced packaging.

References

[1] *Shimbo, M., et al. "Silicon-to-silicon direct bonding method." Journal of Applied Physics 60.8 (1986): 2987-2989.*

[2] *Tong, Qin-Yi, et al. "Low temperature wafer direct bonding." Journal of Microelectromechanical Systems 3.1 (1994): 29-35.*

[3] *Andreas Plößl and Gertrud Kräuter. "Wafer direct bonding: tailoring adhesion between brittle materials." Materials Science and Engineering: R: Reports 25.1-2 (1999): 1-88.*

[4] *Ishida, Hiroyuki, Tim Griesbach, and Stefan Lutter. "Laser pre-bonding as anovel method for improved post-bond alignment accuracy in silicon-to-silicon metal bonding."*

[5] *Phommahaxay, Alain, et al. "Enabling Ultra-Thin Die to Wafer Hybrid Bonding for Future Heterogeneous Integrated Systems." 2019 IEEE 69th Electronic Components and Technology Conference (ECTC). IEEE, 2019.*