Advanced overlay metrology for CIS bonding applications

Florent Dettoni
STMicroelectronics
Crolles, France
florent.dettoni@st.com

Emilie Deloffre
STMicroelectronics
Crolles, France
emilie.deloffre@st.com

Yoav Grauer
KLA
Migdal HaEmek, Israel
yoav.grauer@kla.com

Shlomo Eisenbach
KLA
Migdal HaEmek, Israel
shlomo.eisenback@kla.com

Motti Penia
KLA
Migdal HaEmek, Israel
motti.penia@kla.com

Arkady Simkin
KLA
Migdal HaEmek, Israel
arkadi.simkin@kla.com

Dror Elka
KLA
Migdal HaEmek, Israel
dror.elka@kla.com

Avner Safrani
KLA
Migdal HaEmek, Israel
avner.safrani@kla.com

Marco Polli
KLA
Concorrezzo, Italy
marco.polli@kla.com

Francesco De Paola
KLA
Concorrezzo, Italy
francesco.depaola@kla.com

***Abstract*— On-product overlay (OPO) control is becoming more and more critical to successful 3D heterogeneous process integration which includes wafer-to-wafer (W2W) bonding. In this work, we will present novel overlay (OVL) methods and experimental metrology results on an advanced CMOS Image Sensor (CIS) W2W process. We will discuss metrology challenges such as thick wafer measurement, target design, precision, and accuracy. Different target designs will be presented and evaluated with the irArcher® 007 from KLA. We will demonstrate Total Measurement Uncertainty (TMU) of 1 nm on production wafers, with Tool-Induced Shift (TIS) values comparable to the current best-in-class metrology tool for single wafer OVL measurement and suitable throughput for High-Volume Manufacturing (HVM). We will highlight the importance of such precise OVL metrology tools to address the sub-50 nm OVL challenge in sub-micron pitch, wafer-to-wafer bonding applications. Inter-field and intra-field terms will be presented. Unexpected intra-field signatures will be discussed. Finally, the impact of bonding OVL on back-side lithography steps will be introduced opening interest for Advanced Process Control (APC) loops.**

Keywords—metrology, overlay (OVL), bonding, On Product Overlay (OPO), 3D Heterogeneous Integration, Wafer to Wafer (W2W), CMOS Image Sensor (CIS), More than Moore (MtM), Total Measurement Uncertainty (TMU), inter-field overlay, intra-field overlay

I. INTRODUCTION

3D heterogeneous integration is an evolving segment in integrated circuit development and advanced packaging to drive More than Moore (MtM) chip scaling [1]. Heterogeneous integration allows IC manufacturers to stack and integrate more silicon devices in a single package, increasing the transistor density and product performance.

As 3D technologies have evolved, copper micro-bumps have provided the required vertical metal device-to-device interconnections into a single, integrated product. While traditional copper micro-bumps will continue to be used, new technologies are also being developed to continue to drive the I/O density roadmap. This is where hybrid bonding technology is needed and emerging as a preferred packaging technology for high-end heterogeneous integration applications where the interconnect pitch is 10 µm and below [2].

Hybrid bonding is the process to create a permanent bond of the heterogeneous die using tiny copper pad connections to increase interconnect density and functionality in advanced 3D device stacking. The key steps include preparing and creating the pre-bonding layers, the bonding process itself, the post-bond anneal, and the associated inspection and metrology at each of the steps to ensure a successful bond. There are two primary ways in which hybrid bonding can be accomplished: wafer-to-wafer (W2W) and die-to-wafer (D2W). For each, the wafers are first manufactured in a semiconductor fab before a hybrid bonding process is utilized to stack the chips vertically.

In the W2W process, a wafer bonder is used to align and bond two whole wafers. The bonded wafers are then cut up into stacked chips using a dicing process and undergo testing and further packaging. To enable hybrid bonding to successfully transition to high volume manufacturing (HVM) with high yield, process control is critical. To successfully bond these two surfaces with a very small pitch, tight control of the bond pad alignment is required to make sure the copper pads to be bonded line up perfectly, driving an increased need for overlay (OVL) metrology precision and die-bonder control [3]. Indeed, recent studies highlighted a solid path to submicron hybrid bonding pitch and demonstrated 50 nm OVL accuracy for W2W bonding empowering the need for advanced OVL metrology for bonding applications [4]-[5].

In this work, we will discuss OVL metrology challenges to enable tight and fast on-product OVL (OPO) control for the next CIS generation product development. Dedicated metrology needs such as light source, resolution, and focus will be presented. We will evaluate, different target designs and the various metrics of W2W OPO metrology, including Total

2377-5726/23/$31.00 ©2023 IEEE
DOI 10.1109/ECTC51909.2023.00278

Measurement Uncertainty (TMU), Tool Induced Shift (TIS), accuracy, and Move-Acquire-Measure (MAM) time. Intra-wafer and intra-field OVL induced by the bonding process will also be discussed.

II. METROLOGY CHALLENGES

A. Technical tool selection

The first challenge is to measure through thick silicon, corresponding to two whole 300 mm wafers (~1550 µm) with tight OVL error specification. OVL error specification or Total Measurement Uncertainty (TMU), is usually defined to be 10% of the OVL budget which leads to a TMU target below 5 nm.

Image Based OVL technique (IBO) is preferred to the Diffraction Based OVL technique (DBO) because of the measurability challenges, pitch size involved (not small enough for robust diffraction signal), target height (i.e., inner to outer target Z distance particular to wafer plane), potential high OVL values and design rule incompatibility not discussed in this paper. Thick silicon measurability is addressed using illumination and collection channels optimized to short wavelength infrared (SWIR). The reflection technique (brightfield) is chosen versus the transmission technique (darkfield) to avoid blind wafer areas that could become critical limitations to troubleshooting OVL issues with a very tight OPO requirement. Finally, to reach below the 5 nm TMU target, a high-resolution (small field of view) tool is selected. It is assumed that a high-resolution tool should provide sufficient depth of focus regarding the target height involved in our CIS W2W applications.

B. Tool description

The IBO metrology tool selected for use in this study is an irArcher 007 from KLA. The dedicated W2W post-bonding (pre-grinding) dedicated OVL metrology tool is a reflection-based microscope using SWIR with multiple spectral bands between 1.1-1.6 µm. The tool provides high accuracy via Tool Induced Shift (TIS) control per site, tight Total Measurement Uncertainty (TMU), flexibility to measure different OVL target types (as described hereinafter), robustness to process variation (PV) via different KPIs and all at high productivity.

C. Target designs

Three target designs are evaluated in this work, Bonder Tool Alignment (BTA) target, Bar in Bar (BiB) target, and the Advanced Imaging Metrology (AIM™) target (Fig. 1). Corresponding target sizes are 60 µm, 30 µm, and 30 µm.

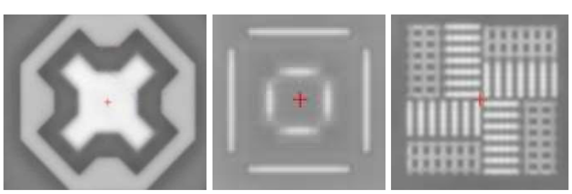

Fig. 1. Contrast pictures of targets used. BTA target (left), BiB target (middle), and AIM target (right)

These three targets are resolved and measurable via the high-resolution tool and narrow field of view. BTA and BiB targets have a higher target height than AIM targets because they are designed at the last metal levels of each wafer. On the other hand, the AIM target is designed with the bonding pad levels of each wafer which leads to a smaller target height. Indeed, due to their sizes and designs, BTA and BiB targets will lead to big empty areas on each wafer (before bonding) which, if designed with bonding pad layers, may create dishing areas leading to bonding voids. On the other hand, because of their designs, these two targets allow high OVL values reading. AIM target with its smaller size and dedicated dummy features (3 perpendicular lines by quadrant) provides suitable bonding pad density to avoid dishing areas and bonding voids. Three different pitch values are used for the AIM target, 2.2 µm, 2 µm and 1.8 µm.

III. RESULTS

A. Target designs evaluation

In this section, we will evaluate the five target designs described in the previous section, 1 BTA, 1 BiB, and 3 AIM with 3 different pitches using 2 wafers from 1 CIS W2W product, 17 fields by wafer, and 1 site-by-field.

Mean TIS, TIS 3σ, precision, and TMU are used as evaluation criteria for proposed target designs. TIS defines the misregistration measurement error caused by tool optical imperfections. TIS can be quantified by doing two OVL measurements at 0 (OVL_0) and 180 (OVL_{180}) degrees and is defined as:

$$TIS = \frac{OVL_0 + OV\ \ _{180}}{2} \quad (1)$$

Mean TIS corresponds to the average value of all TIS values over the wafer and TIS 3σ to three times the standard deviation of all TIS values over the wafer. TMU is defined as:

$$TMU = \sqrt{Mean\ TIS^2 + TIS\ 3\sigma^2 + Precision^2} \quad (2)$$

where Precision (repeatability) is defined as:

$$Precision = 3\sqrt{\frac{\sum_{i=1}^{i=n}(\sigma_i)^2}{n}} \quad (3)$$

$$\sigma_i = \sqrt{\frac{\sum_{j=1}^{j=m}(OVL_i - \overline{OVL})^2}{m-1}} \quad (4)$$

with *n* the number of sites, *i* the site number, *m* the number of iterations, *j* the iteration number, σ_i the standard deviation for site *i* and OVL_i OVL results for iteration *i*. The number of iterations is 5.

By design, irArcher 007 measures TIS for all sites, and since TIS is measured, the tool can provide TIS-corrected OVL values (i.e., calibrated OVL). This tool operational mode in essence means that tool TMU=Precision and TIS / TIS 3σ are mostly used to monitor PV and/or tool intrinsic performance.

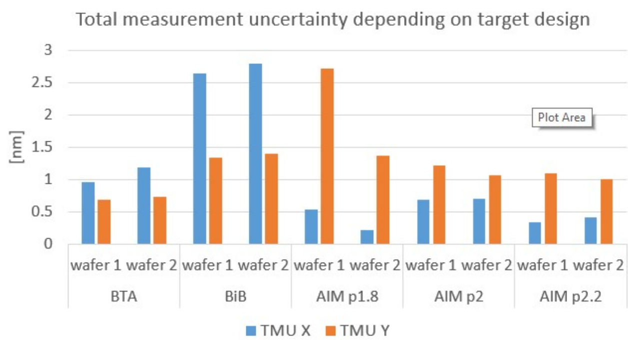

Fig. 2. Total measurement uncertainty depending on target design

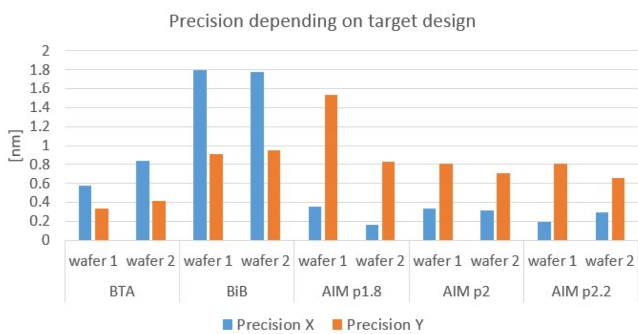

Fig. 3. Precision depending on the target design

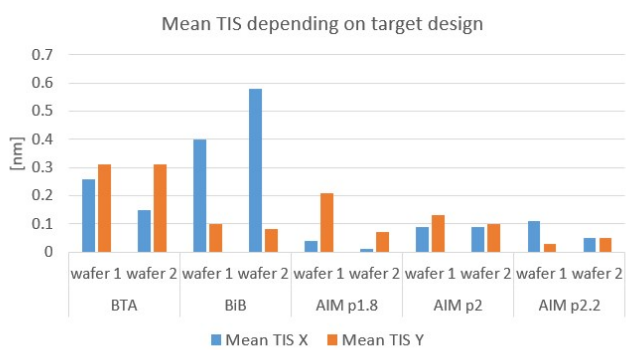

Fig. 4. Mean TIS depending on the target design

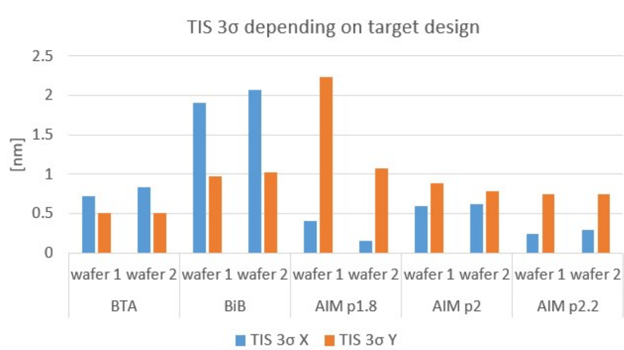

Fig. 5. TIS 3σ depending on the target design

Fig. 2 shows TMU values well below the targeted specification of 5 nm whatever the target design used. Most of the targets can reach a TMU value of 1 nm even in the worst direction. As expected, we observe the interest in AIM design allowing it to have a very good TMU value associated with a small target footprint of 30 µm compared to the 60 µm BTA target.

Fig. 3 - Fig. 5 report the same trends for precision, mean TIS and, TIS 3σ. Precision for the AIM target is approximately 0.8 nm except for Y direction on wafer 1 and 1.8 µm pitch AIM target, Mean TIS is approximately 0.1 nm, and TIS 3σ below 1 nm except for wafer 1 and 1.8 µm pitch AIM. These values are comparable to the ones coming from the IBO tool dedicated to single-wafer OVL measurement. Furthermore, for precision values on AIM targets, we can see a direction dependency pointing out an important potential for improvement if the root cause can be found and solved. Such direction dependency could be explained by process direction dependency (due to lithography illumination) or by neighbor impact and can be both addressed by dedicated design modifications.

Fig. 6 focuses on the Qmerit value depending on the target design. Qmerit is an indication of any asymmetry in the target structure that may influence the OVL misregistration value [6]. A zero Qmerit value means that there is no asymmetry in the specified target part and thus no induced OVL. Fig. 6 indicates that AIM target designs present lower Qmerit values, nevertheless, it is complicated to conclude about target design impact since AIM targets are manufactured at the bonding interface while BTA and BiB targets are designed on previous metal layers of each wafer.

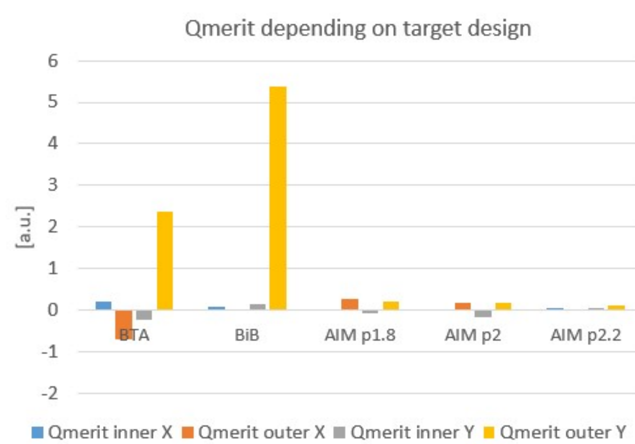

Fig. 6. QMerit depending on target design

Fig. 7 represents normalized MAM times depending on target type and Adaptative Noise Reduction Algorithm (ANRA) values. The noise subtraction is related to the number of image frames taken for each target measurement and is reported as an ANRA value. ANRA value is an important recipe parameter allowing us to easily choose the correct balance between precision and throughput. It can be noticed that ANRA values are included between 2 and 19 leading to a MAM time difference of 27%. BTA and BiB targets seem to require high ANRA values nevertheless they cannot be directly linked to the target design. Indeed, BTA and BiB targets are not designed at the same level as the AIM targets and the target height impact hypothesis is the privileged one to explain such differences.

Finally, AIM targets low ANRA values to provide an additional precision improvement path if needed and if the MAM time penalty is acceptable.

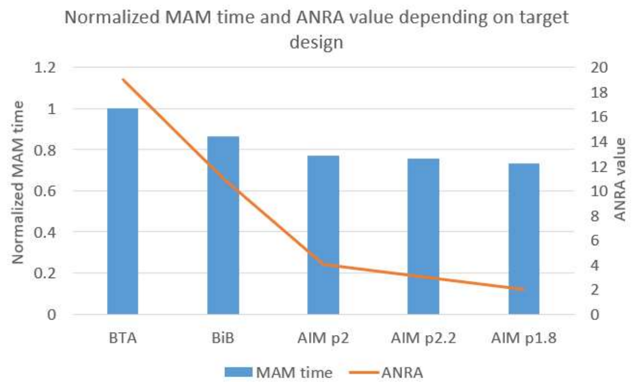

Fig. 7. Normalized MAM time and ANRA value depending on target design

Previous results highlight that OVL metrology is available for 50 nm, wafer-to-wafer, hybrid bonding OVL challenge not only to address TMU specification requirements but also to provide acceptable target footprint and high-volume manufacturing throughput compatibility. The importance of target design has been highlighted. Furthermore, the combination of a small target footprint and high throughput enables intra-field OVL metrology capability for high-volume manufacturing. Indeed, even if intra-field OVL for wafer-to-wafer bonding application is not widely addressed - either from a metrology point of view or from a bonding tool correction capability - it will be interesting to investigate intra-field OVL signature to better understand bonding behavior.

B. *Inter-Field overlay*

Inter-field OVL for hybrid bonding is not new but being able to extract OVL values with nanometer precision could help to better characterize inter-field bonder contribution and help to improve or define proper correction strategy.

For this study, we will use a 6-term model (translation X, translation Y, expansion X, expansion Y, rotation, and non-orthogonal rotation) with wafer by wafer as wafer decomposition strategy, and composite field as field decomposition strategy. No data removal is used before applying the model. Values are normalized for confidentiality.

This study is done using 4 different products, 2 lots by product and 7 or 8 wafers by lot. Measurement sampling is 17 fields and 1 site by field.

Fig. 8 through 10 show that whatever the model terms used, significant product-to-product and lot-to-lot variations can be observed. Wafer-to-wafer variations are less pronounced and can be neglected except for some wafers that should require dedicated investigation. Such behaviors can be indicated due to metrology tool precision. Indeed, in the 50 nm OVL specification context for bonding applications, inter-field values and variations should be of the same order of magnitude as measurement errors from the previous OVL metrology tool generation.

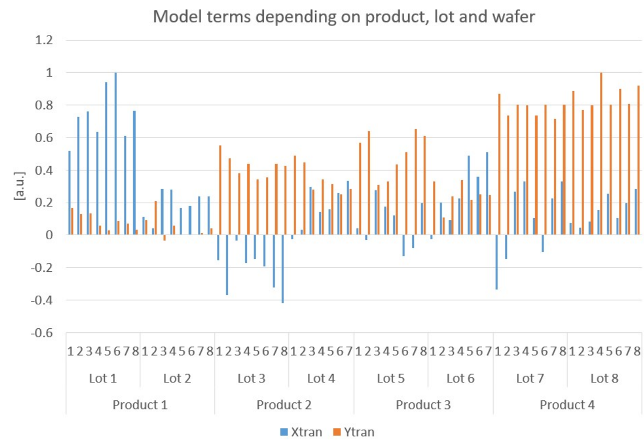

Fig. 8. Model terms translation X and Y depending on product, lot and wafer

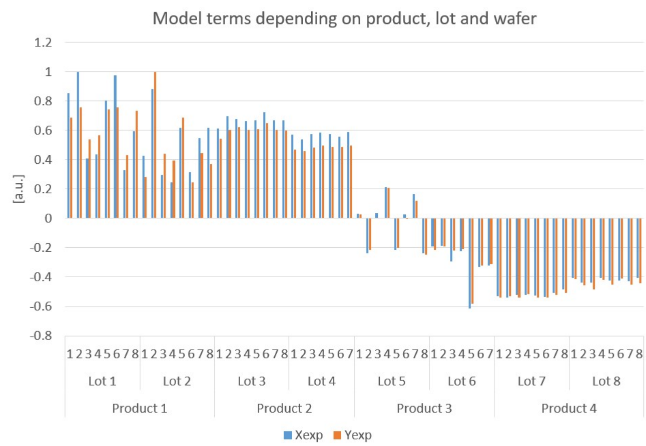

Fig. 9. Model terms expansion X and Y depending on product, lot and wafer

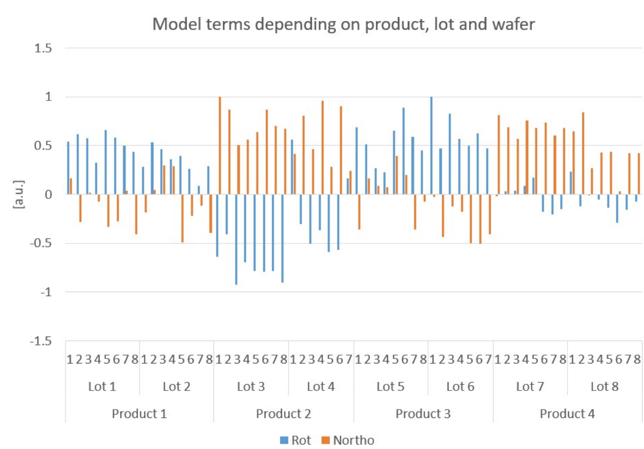

Fig. 10. Model terms rotation and non-orthogonal rotation depending on product, lot and wafer

C. *Intra-Field overlay*

Next, we will investigate intra-field OVL signatures. Currently, intra-field OVL for wafer-to-wafer bonding applications is not widely addressed. Indeed, thus far, wafer-to-wafer bonding tools are principally able to address inter-field corrections since OPO for wafer-to-wafer bonding applications is mainly driven by inter-field signatures. On the other hand, until recently, OVL metrology tools especially metrology modules embedded in bonding tools were not able to provide the required throughput to address intra-field OVL. Nevertheless, the last metrology tool generation does provide the required throughput and recent studies pointed out the need for tight OVL specification (50 nm) justifying such work. Further, as back-side device complexity increases, the post-bonding OVL residual impact is becoming critical. In this context, even if intra-field OVL cannot be corrected by the bonding tool, understanding, and monitoring these contributions could be useful for back-side lithography steps. Finally, the growing interest in die-to-wafer technology also empowers previous justifications.

For this study, we will use a 10-term model composed of 6 inter-field terms previously used (translation X, translation Y, expansion X, expansion Y, rotation, and non-orthogonal rotation) and 4 intra-field terms (magnification, asymmetric magnification, rotation, and asymmetric rotation) with wafer by wafer as wafer decomposition strategy, composite field as field decomposition strategy and single pass modeling strategy. No data removal is used before applying the model. Only intra-field terms are presented, and values are normalized for confidentiality.

This study is done using 3 different products, 6 lots and 7 or 8 wafers by lot. Measurement sampling is 17 fields and 4 sites by field.

Fig. 11 and Fig. 12 present reticle magnification, non-orthogonal magnification, rotation, and non-orthogonal rotation intra-field terms for a set of 46 wafers. As already observed, intra-field terms present significant product-to-product and lot-to-lot variations. Wafer-to-wafer variations can be neglected. Respecting the confidentiality policy that required results normalization, we can also share that the order of magnitude of intra-field OVL terms is well higher than expected especially in a 50 nm OVL specification context. This unexpected OVL contribution could become a major issue for back-side devices' reliability.

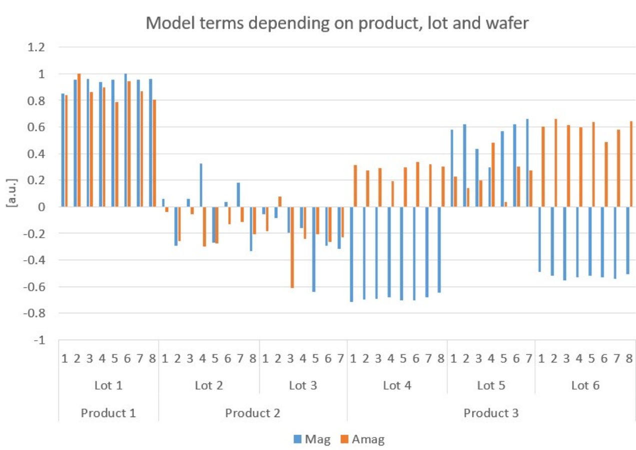

Fig. 11. Model terms reticule magnification and non-orthogonal magnification depending on product, lot and wafer

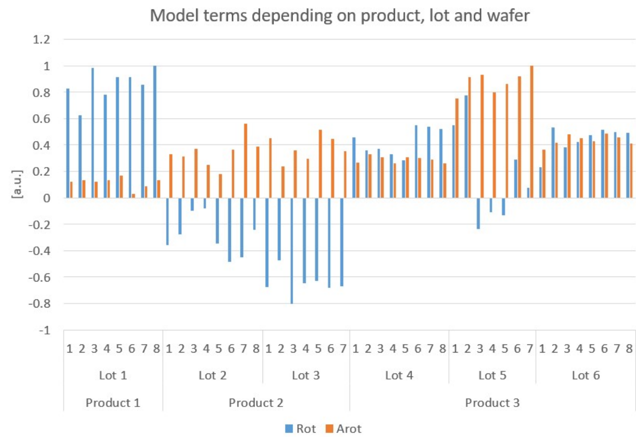

Fig. 12. Model terms reticule rotation and non-orthogonal rotation depending on product, lot and wafer

It can also be observed that intra-field residual signatures show significant trapezoid (k9 or k10) footprints whatever the lot or product (Fig. 13). Unfortunately, 4 measurements by the site do not allow the modeling of such contribution. The trapezoid signature is not easy to correct on lithography tools which can lead to potential issues at back side device lithography steps.

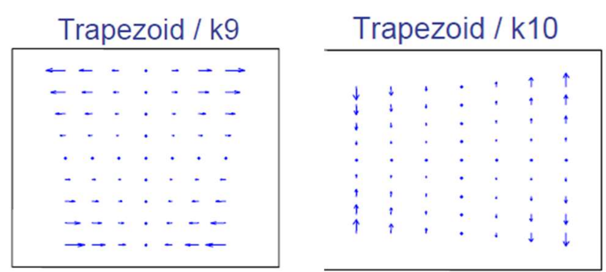

Fig. 13. Trapezoid k9 and k10 intra-field-signatures

Inter-field and intra-field results and discussion are highlighting the need for APC loops not only to monitor and control the bonding tools but also to prevent potential issues during post-bonding lithography steps.

IV. CONCLUSION

High-resolution image-based OVL in reflection mode using an IR light source operating in the SWIR wavelength range is the best metrology tool candidate to reach the 5 nm OVL TMU target for wafer-to-wafer bonding applications. It has been demonstrated that irArcher 007 from KLA can reach 5 nm TMU specification whatever the target design. The AIM target can reach a TMU value of 1 nm with a 0.8 nm precision, mean TIS of approximately 0.1 nm, and a TIS 3σ value below 1 nm. Several paths have been proposed to further improve TMU. We discussed how ANRA value can help choose a good balance between precision and throughput and it has been shown that ANRA values between 2 and 19 can lead to a MAM time difference of 27%. Good OVL metrology precision enables whatever the inter-field model term, significant product-to-product, and lot-to-lot variations can be observed, and model terms values are of the same order of magnitude as measurement error from the previous OVL metrology tool generation. The same behavior has been shown for inter-field terms. The order of magnitude of intra-field OVL terms is well higher than expected and could become a major issue for back-side devices reliability. Trapezoid (k9 and k10) intra-field residual signatures have been noticed. Inter-field and intra-field results and discussions have highlighted the need for APC loops not only to monitor and control the bonding tools but also to prevent potential issues during post-bonding lithography steps.

TABLE I. ACRONYMS DEFINITION TABLE

ACRONYMS DEFINITION	
OPO	On-Product Overlay
W2W	Wafer to Wafer
OVL	Overlay
CIS	CMOS Image Sensor
TMU	Total Measurement Uncertainty
TIS	Tool Induced Shift
HVM	High Volume Manufacturing
APC	Advanced Process Control
MtM	More than Moore
D2W	Die to Wafer
MAM	Move Acquire Measure
IBO	Image Based Overlay
DBO	Diffraction Based Overlay
SWIR	Short Wavelength Infrared
PV	Process Variation
BTA	Bonder Tool Alignment
BiB	Bar in Bar
AIM	Advanced Imaging Metrology
ANRA	Adaptative Noise Reduction Algorithm

REFERENCES

[1] Yole Développement, "Lithography and Bonding equipment for More than Moore 2022", market and technology report 2022

[2] L. Arnaud et al., "Three-dimensional hybrid bonding integration challenges and solutions toward multi-wafer stacking", MRS Communications (2020)

[3] Grauer Yoav et al., "Overlay challenges in 3D heterogeneous integration" Proc. SPIE 12053, Metrology, Inspection, and Process Control XXXVI, 120530D (26 May 2022)

[4] Ayoub Bassel et al., "Sub 1 µm Pitch Achievement for Cu/SiO2 Hybrid Bonding" EPTC 2022 unpublished.

[5] Mitsuishi Hajime et al., "Demonstration of 50 nm Overlay Accuracy for Wafer-to-Wafer Bonding and Further Improvement Study" EPTC 2022 unpublished

[6] Klein Dana et al., "Quality metric for accurate overlay control in <20nm nodes", Proc. SPIE 8681, Metrology, Inspection, and Process Control for Microlithography XXVII, 86811J (2013)