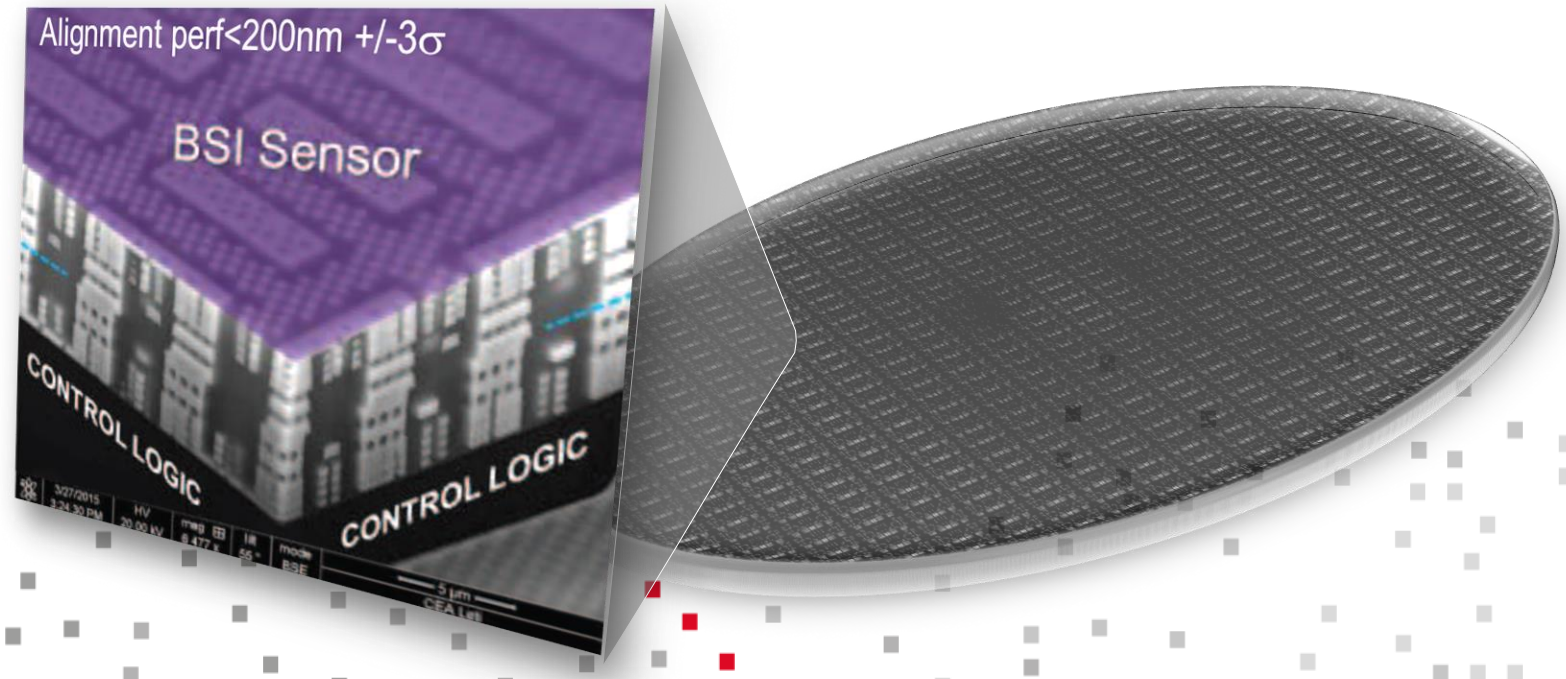
Alternative metrology for CMP performances measurement in 3D hybrid bonding

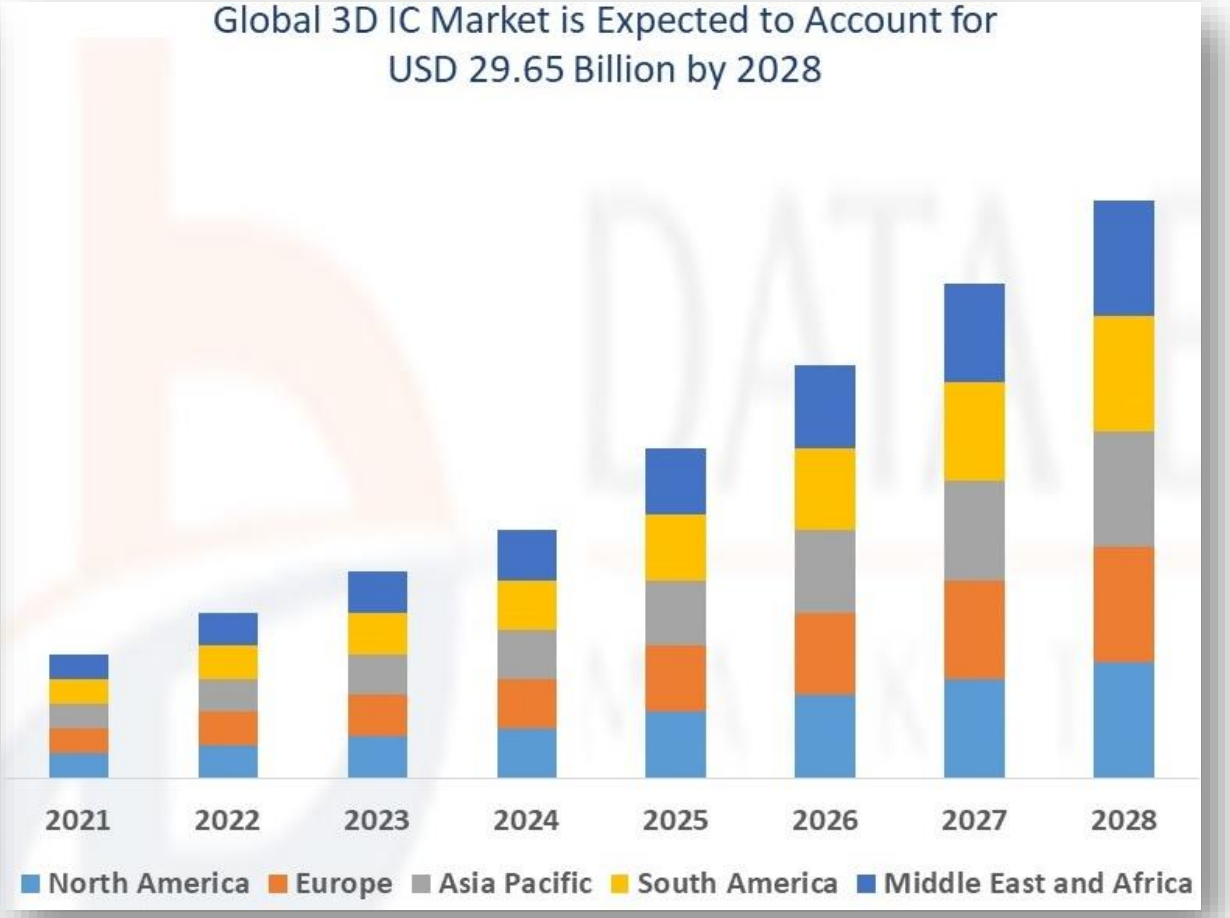
Viorel Balan, Yorrick Exbrayat, Daniel Scevola



ALTERNATIVE METROLOGY FOR CMP PERFORMANCES MEASUREMENT IN 3D HYBRID BONDING

CAMP2021 | V. BALAN, Y.EXBRAYAT, D.SCEVOLA

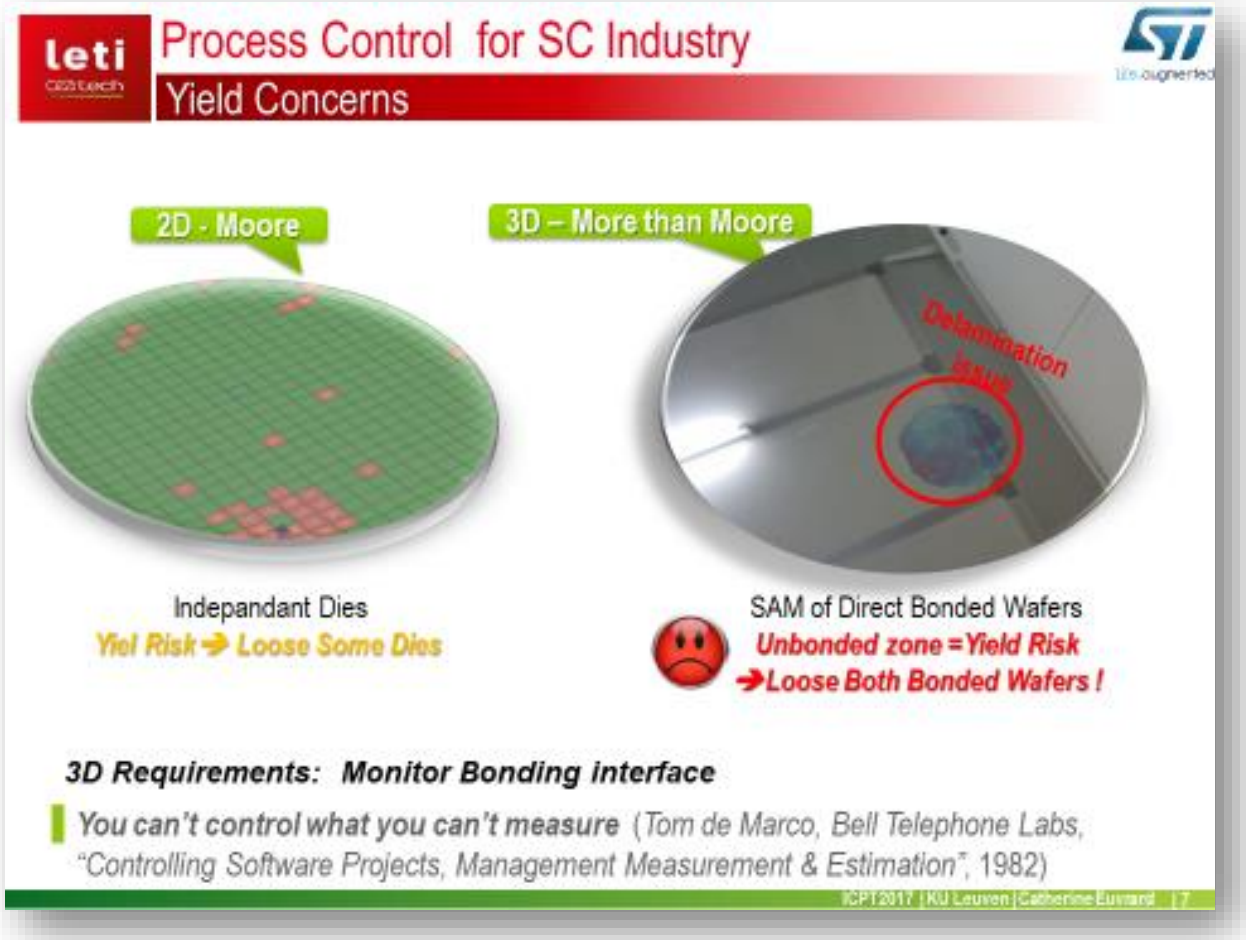
Intro



- Paradigm Evolution: from Scaling to Stacking through Hybrid Bonding, a CMP – enabled process
- Data Bridge Market Research analyses that the 3D IC market will exhibit a CAGR of 33% for the forecast period of 2021-2028.

Intro

- While BEOL CMP is a mature process, CMP for 3D hybrid bonding is much more challenging: Cu pad size is bigger while topography constraints are much more aggressive in order to avoid critical bonding voids



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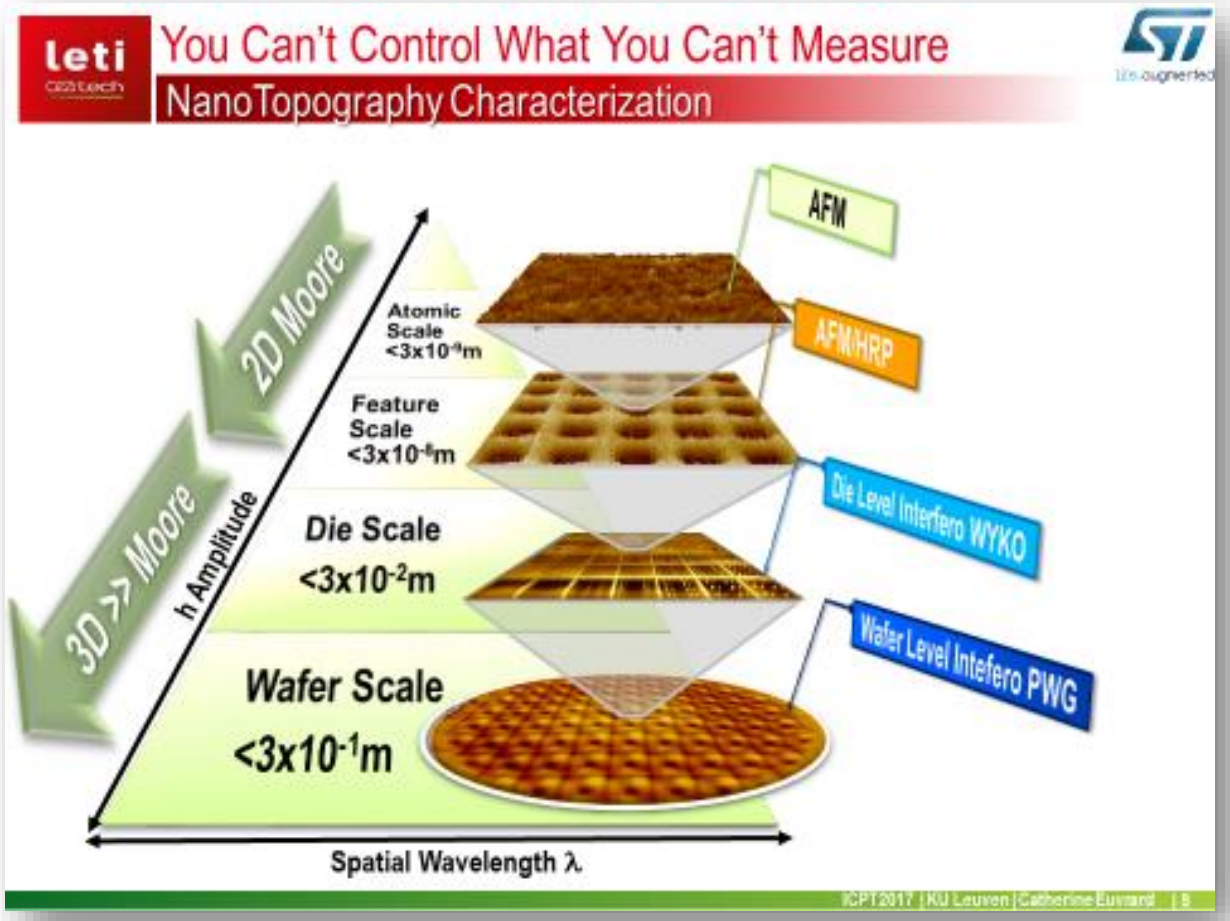
- While BEOL CMP is a mature process, CMP for 3D hybrid bonding is much more challenging: Cu pad size is bigger while topography constraints are much more aggressive in order to avoid critical bonding voids
- Quantifying CMP process performance is done by estimating final topography at different scales, with different metrology techniques



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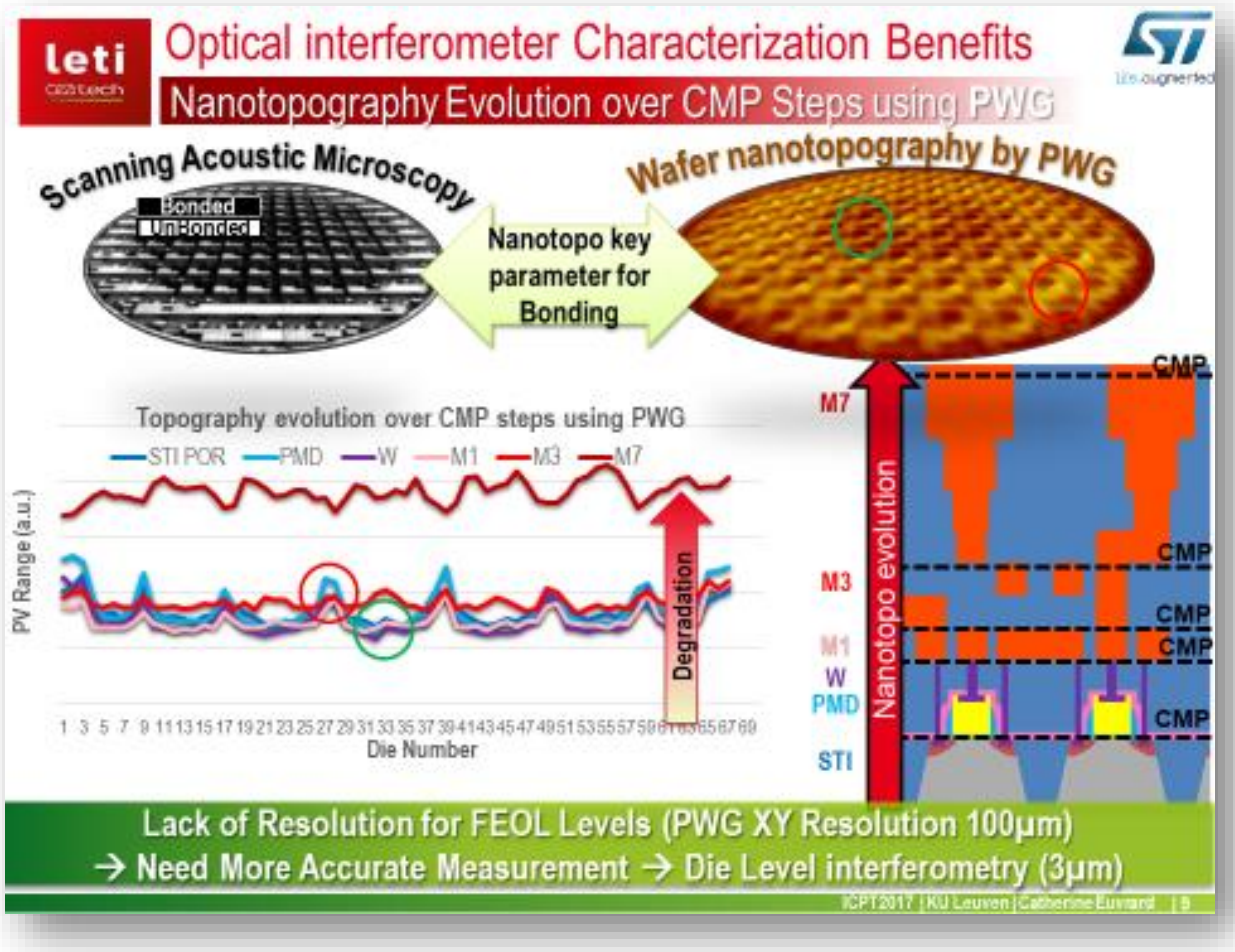
- Quantifying CMP process performance is done by estimating final topography at different scales, with different metrology techniques
- Correlation between topography amplitude and Scanning Acoustic Microscopy (SAM) images is done in order to improve bonding yield



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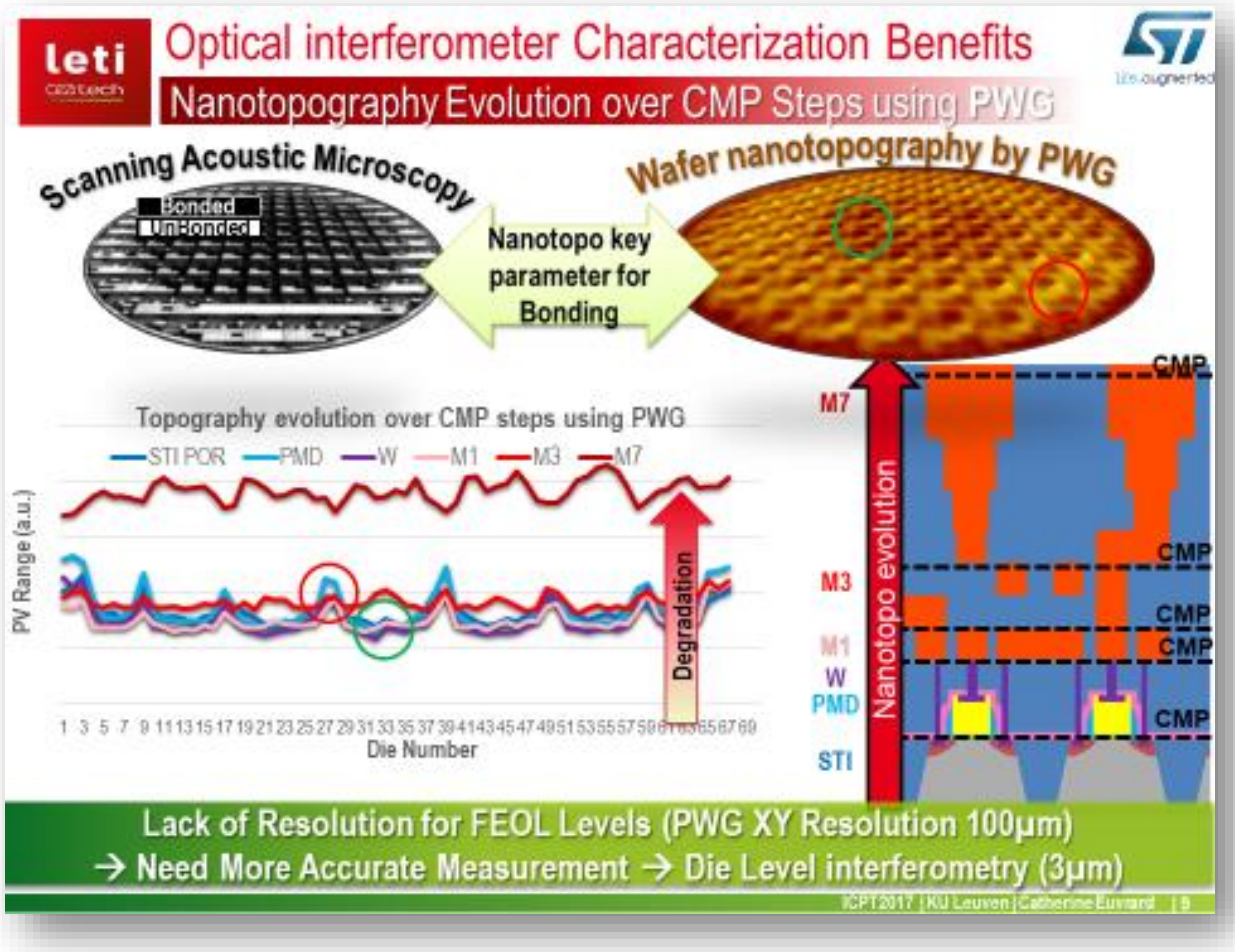
- Quantifying CMP process performance is done by estimating final topography at different scales, with different metrology techniques
- Correlation between topography amplitude and Scanning Acoustic Microscopy (SAM) images is done in order to improve bonding yield
- In this work, we developed a image analysis method in order to **have a direct quantification of the bonding yield** from SAM images and propose best CMP process



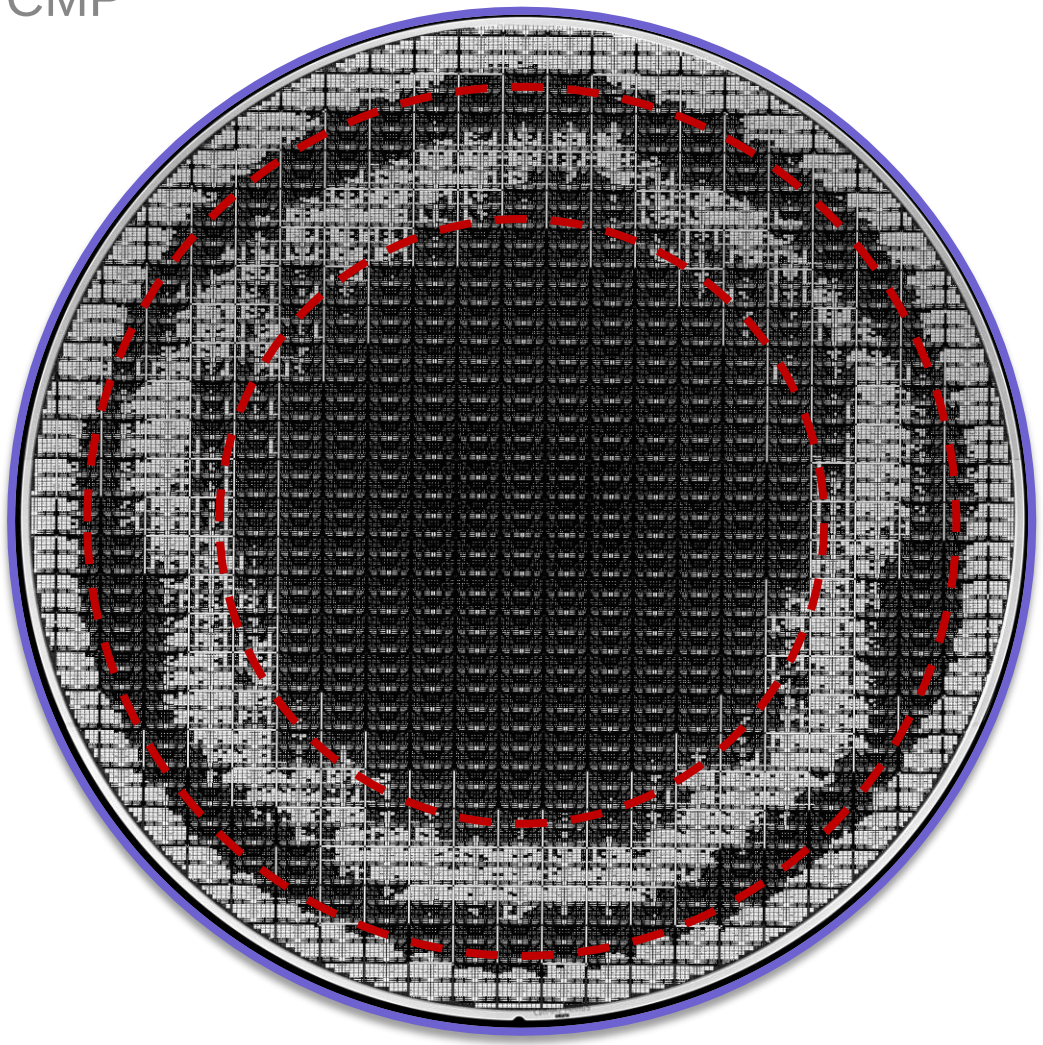
What we will talk about

- Improve a CMP process for Hybrid Bonding → Quantify Bonding Performance
- CMP Process performances are investigated through High-Resolution Scanning Acoustic Microscopy HR-SAM
  - 3 Cu CMP processes performances were studied : standard, POR process C was compared to new consumables processes C1 & C2
  - 2 Barrier CMP processes performances were investigated: POR process B was compared to process B1
- CMP performances were compared by quantifying bonding yield on 3 different test masks with different design rules:
  - Heterogeneous Mask 1 with pitch and density variations
  - Mask II, with fixed density and pitch variation
  - Mask III, with density variation and fixed pitch
- ***While we will not give precise process conditions, we will talk about a method to quantify bonding yield***

Qualitative Estimation of Bonding Performance

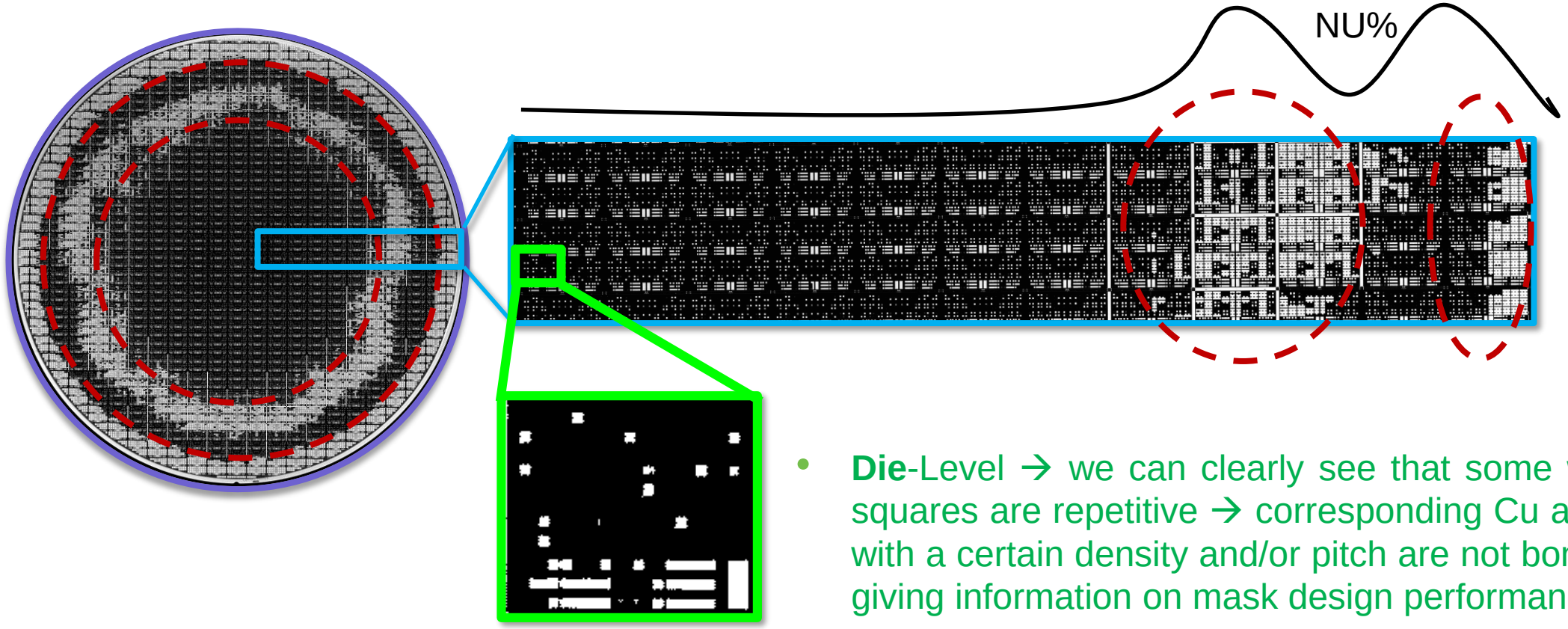
Qualitative Estimation of Bonding Performance

- HR-SAM image of bonded wafers after POR CMP
- **Mask I: pitch & density variation**



Qualitative Estimation of Bonding Performance

- Process signature impact both at
  - **Wafer** level → radial non-uniformity can be seen on the extracted band from the wafer image, indicating CMP process non-uniformity: bonding quality non-uniformity is quantified by white, unbonded zones, giving information on CMP process performance



  - **Die**-Level → we can clearly see that some white squares are repetitive → corresponding Cu arrays with a certain density and/or pitch are not bonded, giving information on mask design performance

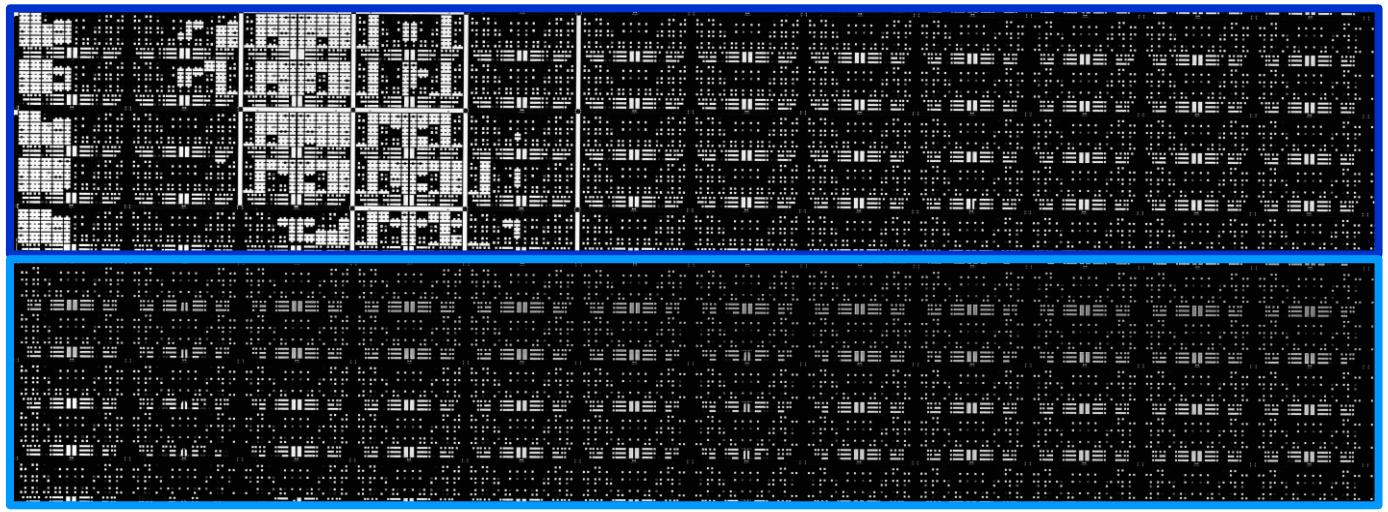
Qualitative Estimation of CMP Process Impact on Bonding Quality

Cu CMP (1)

Cu C + Barrier B

POR

Cu C1+ Barrier B



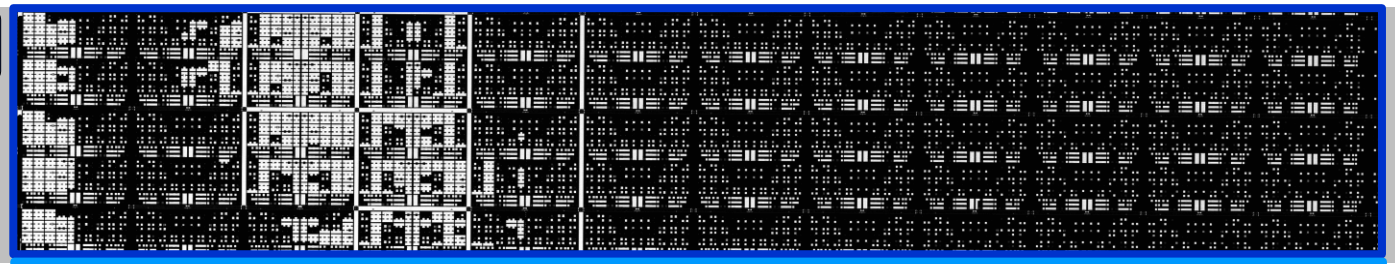
- HR-SAM Images obtained for C1 Cu CMP Process show that white pixels ratio is significantly decreased and, also, their radial distribution on the wafer is significantly improved
- Hybrid bonding quality is highly ameliorated by changing from C Cu CMP process to C1 Cu CMP process and CMP process signature is evidenced
- From mask design perspective, at die scale, white pixels ratio seems reduced for C1 Cu CMP process but is difficult to conclude at this stage

Qualitative Estimation of CMP Process Impact on Bonding Quality

Cu CMP (2)

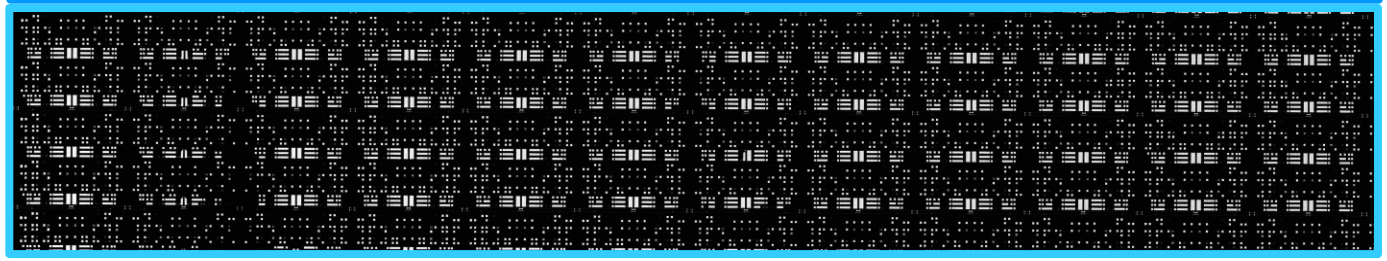
Cu C + Barrier B

POR



Cu C1+ Barrier B

Cu C2 + Barrier B



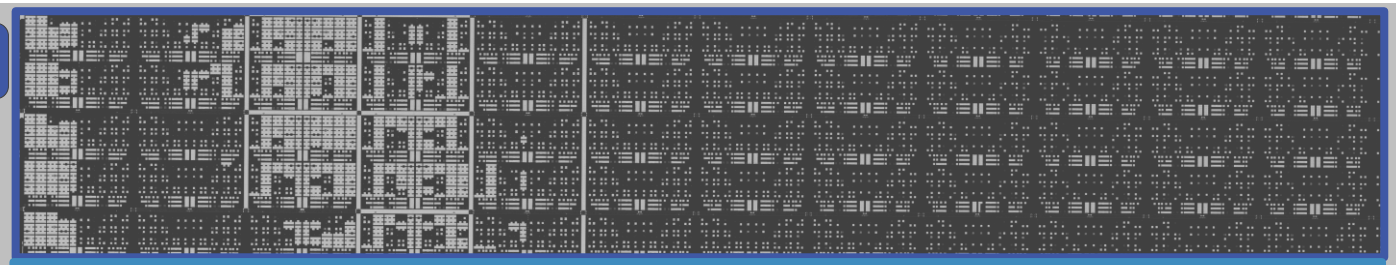
- Changing for another Cu CMP process conditions, Cu C2, the HR-SAM Image show comparable white pixels ratio and distribution: the hybrid bonding quality seems equivalent → choosing the most performant CMP process is difficult in this case

Qualitative Estimation of CMP Process Impact on Bonding Quality

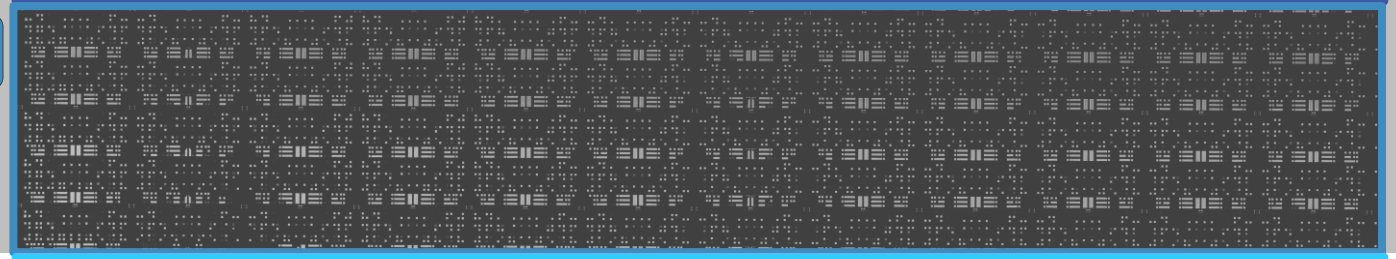
Barrier CMP

Cu A + Barrier B

POR



Cu C1+ Barrier B



Cu C2 + Barrier B

Cu C2 + Barrier B1

- Concerning barrier process conditions, comparing B to B1 is difficult, once again: HR-SAM images show comparable white pixels ratio and distribution so choosing the most performant Barrier CMP process in terms for bonding quality is not obvious

Quantification of Bonding Quality

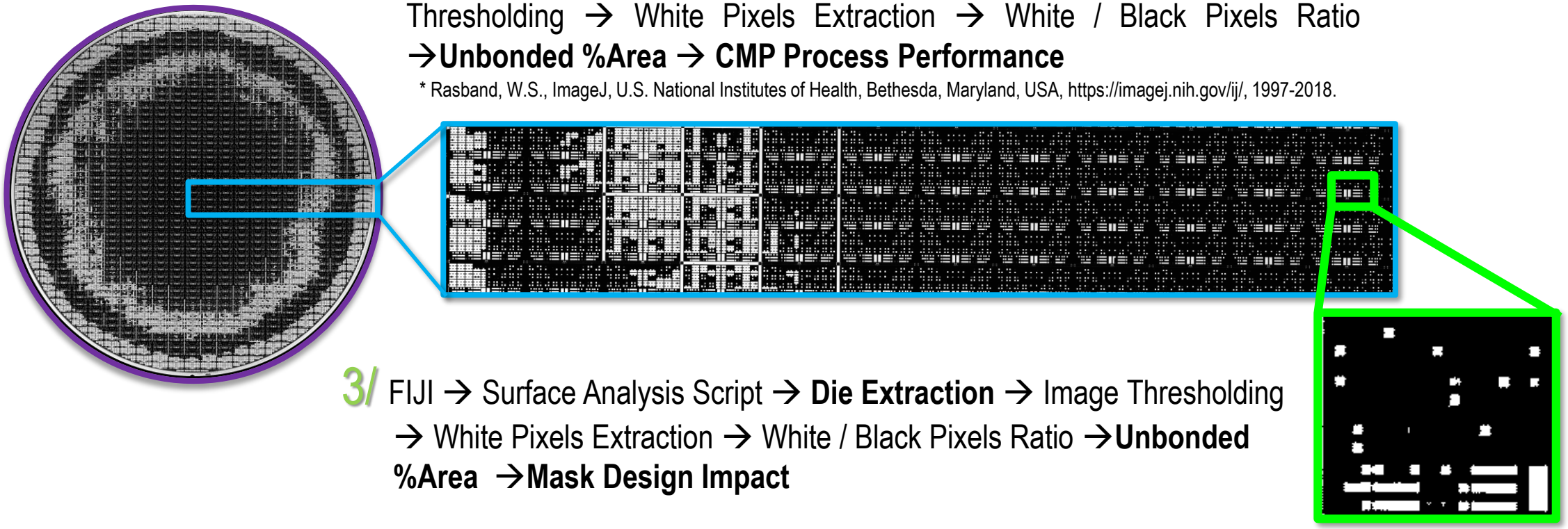
Bonding Quality Quantification Methodology

Unbonded %Area

1/ High Resolution SAM **Image Acquisition**

2/ FIJI* → Surface Analysis Script → **Radius Band Extraction** → Image Thresholding → White Pixels Extraction → White / Black Pixels Ratio →**Unbonded %Area** → **CMP Process Performance**

* Rasband, W.S., ImageJ, U.S. National Institutes of Health, Bethesda, Maryland, USA, https://imagej.nih.gov/ij/, 1997-2018.



3/ FIJI → Surface Analysis Script → **Die Extraction** → Image Thresholding → White Pixels Extraction → White / Black Pixels Ratio →**Unbonded %Area** →**Mask Design Impact**

4/ Unbonded **Arrays Identification** using die layout file → **Design Rules**

Wafer Scale Quantification of Bonding Quality

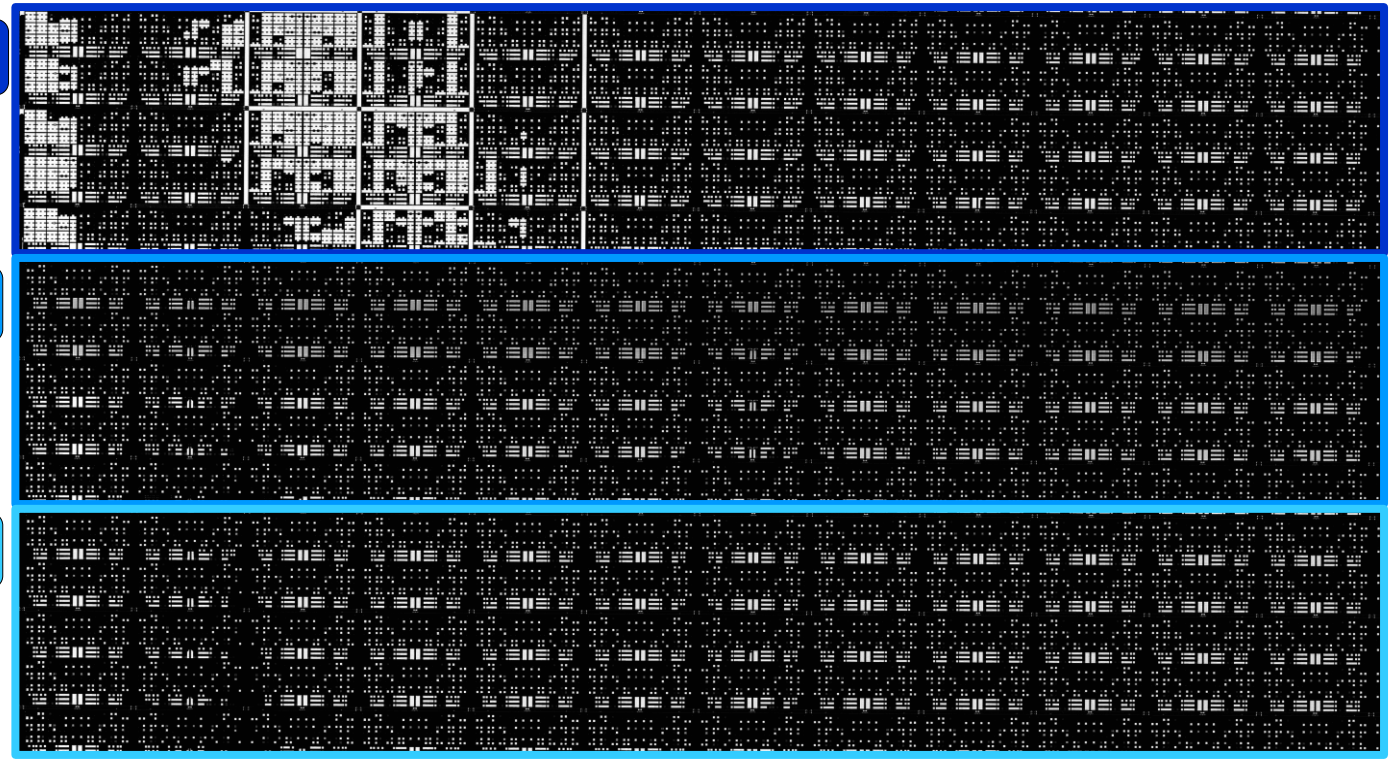
Cu CMP

Cu C + Barrier B

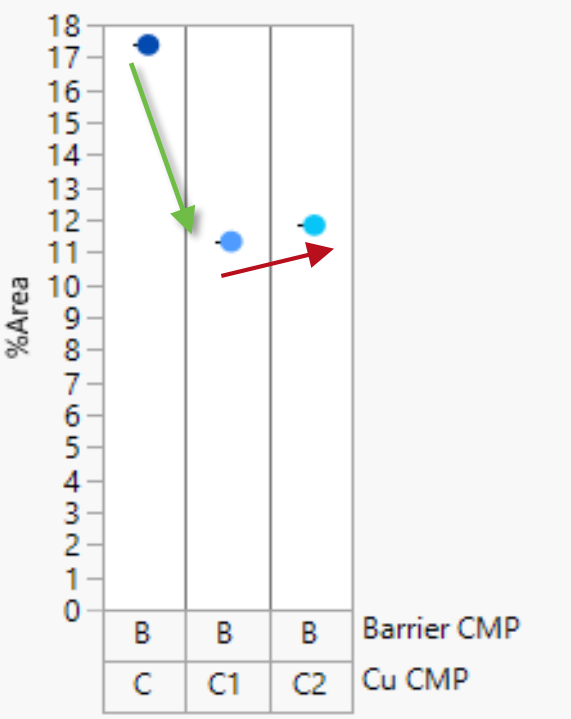
POR

Cu C1+ Barrier B

Cu C2 + Barrier B



Band Unbonded %Area



- While C1 Cu CMP process do show significant reduction of Unbonded %Area, meaning better bonding performance, C2 Cu CMP process lead to slight increase of white, unbonded pixel ratio: bonding performance of C2 process is worse

Wafer Scale Quantification of Bonding Quality

Barrier CMP

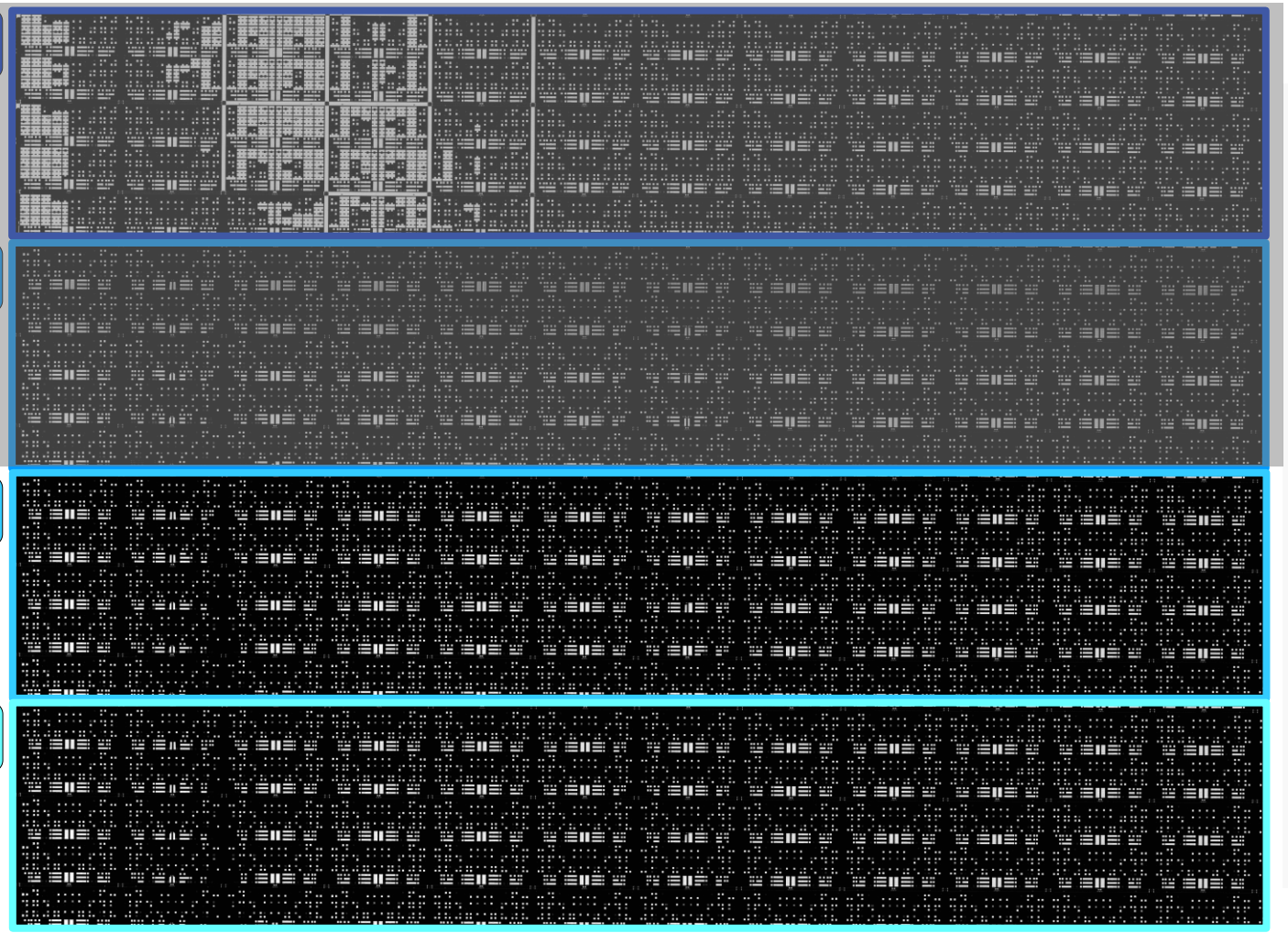
Cu C + Barrier B

POR

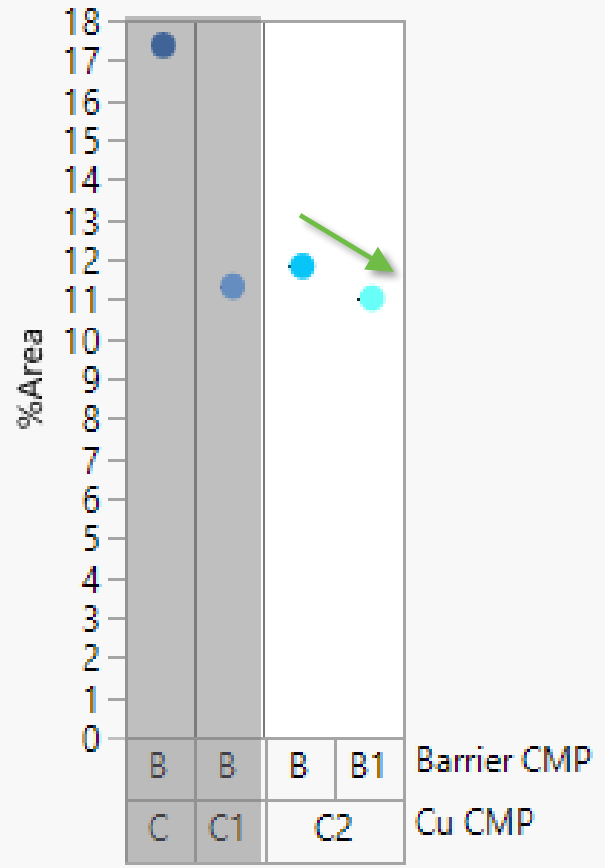
Cu C1+ Barrier B

Cu C2 + Barrier B

Cu C2 + Barrier B1



Band Unbonded %Area



- Changing the Barrier CMP Process, from B to B1, helps to reduce Unbonded %Area

→ **HR-SAM Image Analysis → Detect CMP process performance → Choose best process for bonding**

Die Scale Quantification of Bonding Quality

Cu CMP

Center Die

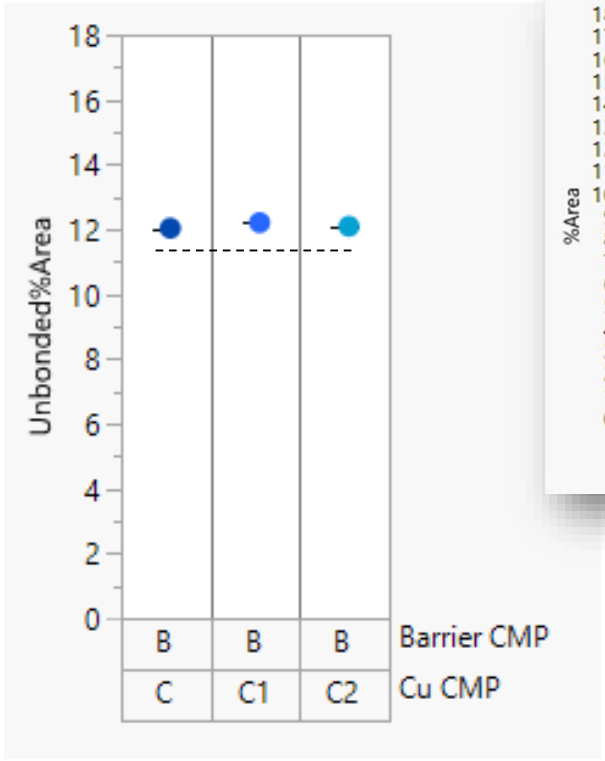
Cu A + Barrier B

POR

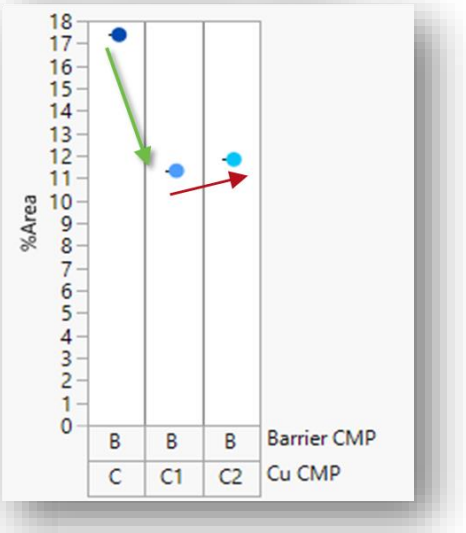
Cu C1+ Barrier B

Cu C2 + Barrier B

Die Unbonded %Area



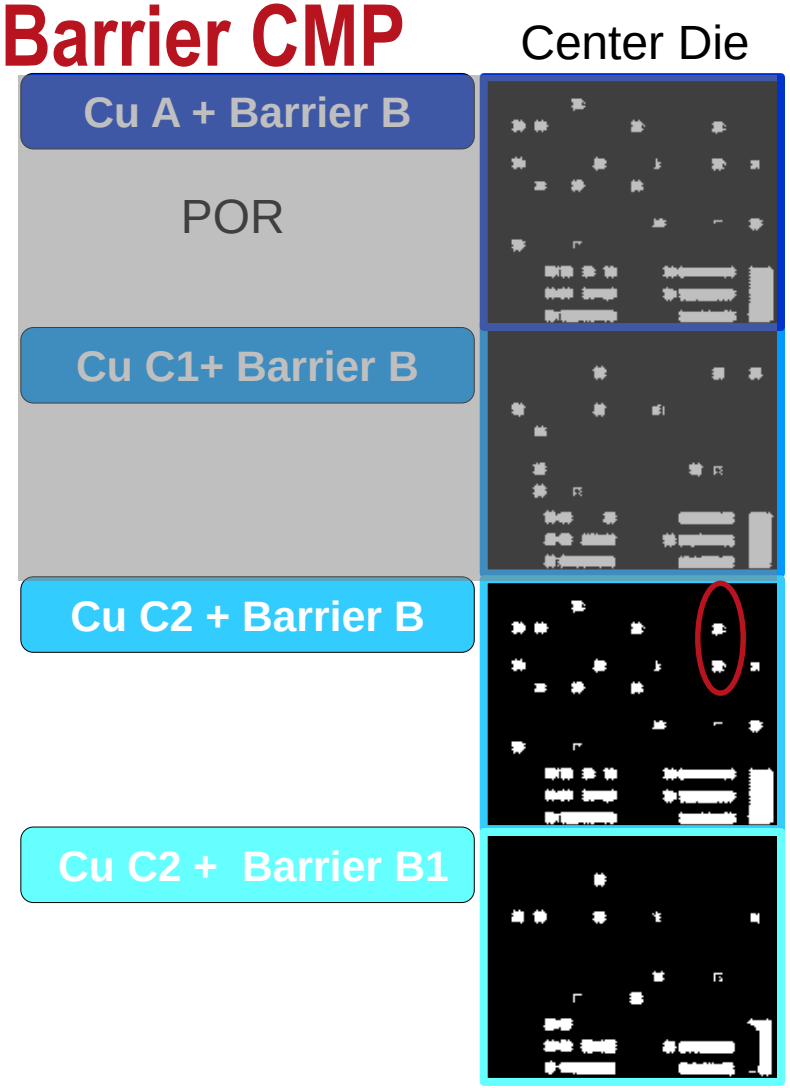
Band Unbonded %Area

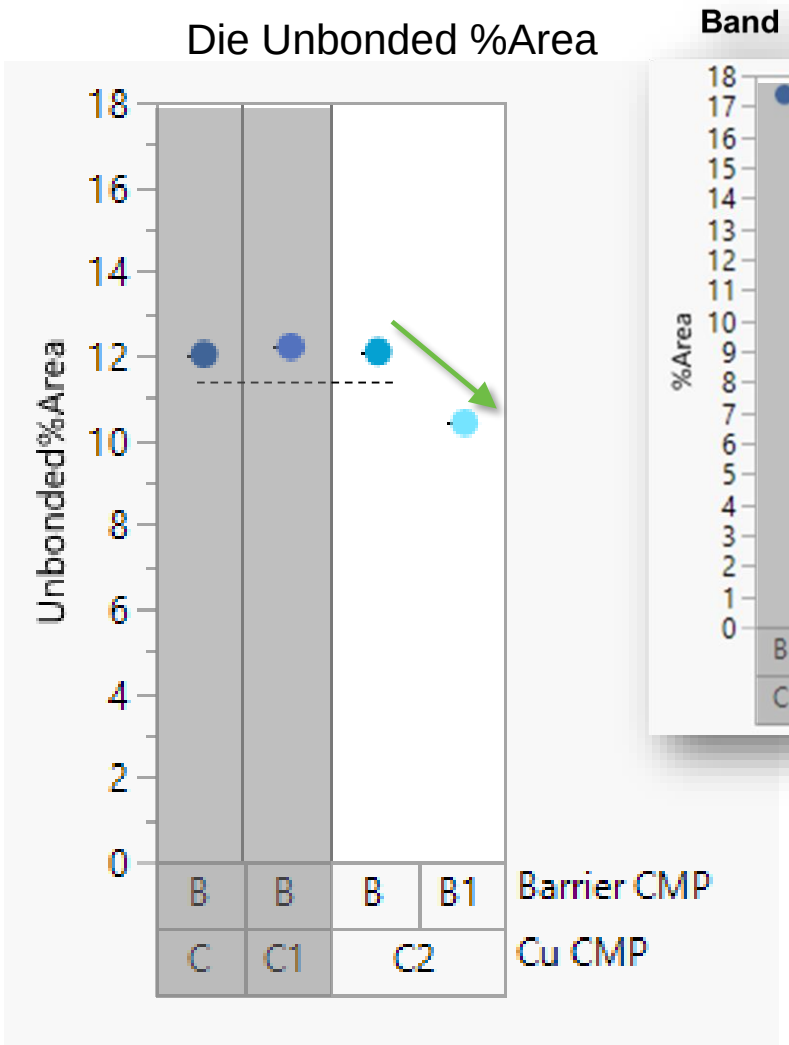


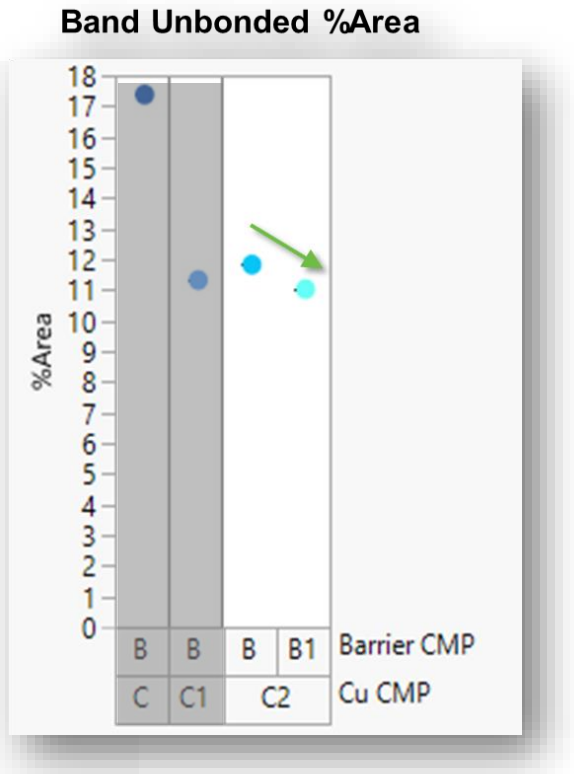
- Similar Unbonded %Area at die scale for the 3 Cu CMP processes
- White pixel distribution highlight repetitive unbonded Cu arrays → **Mask design importance** in terms of pitch & density

Die Scale Quantification of Bonding Quality

Barrier CMP

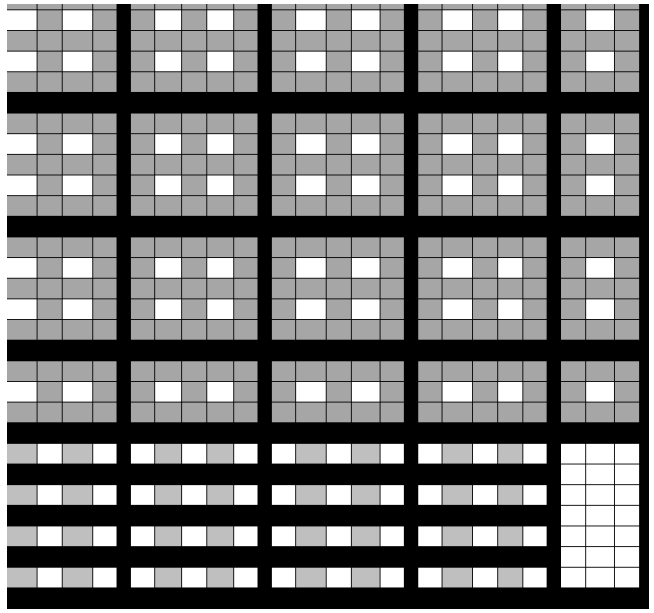




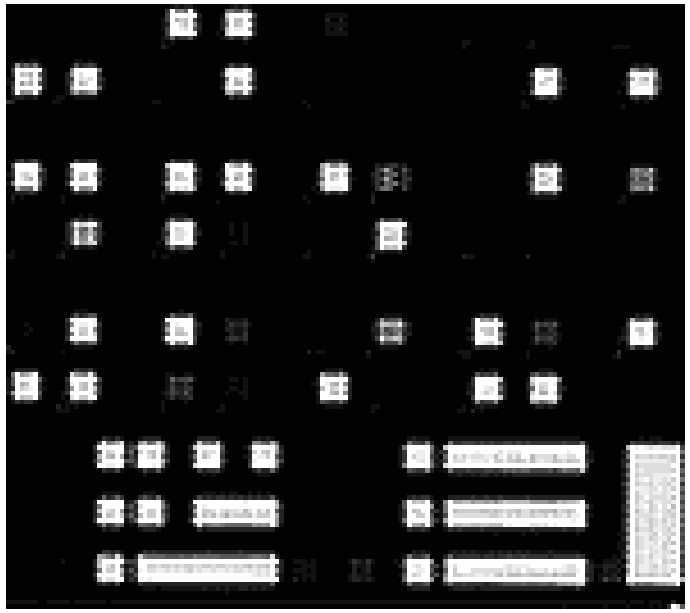


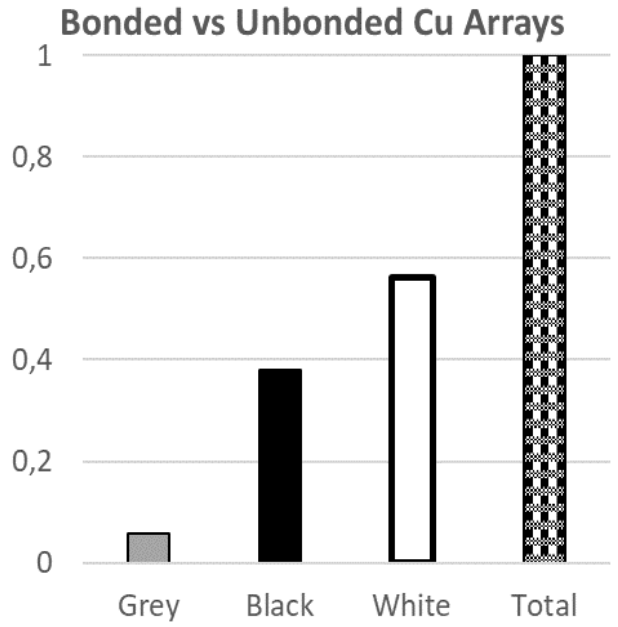
- Changing Barrier CMP process from B to B1 show significant white pixels reduction
  →**Barrier CMP have local impact, at Die scale**, allowing to increase bonding process window in terms of density and pitch

Die Scale Quantification of Bonding Quality
Unbonded Cu Arrays Identification



Center Die

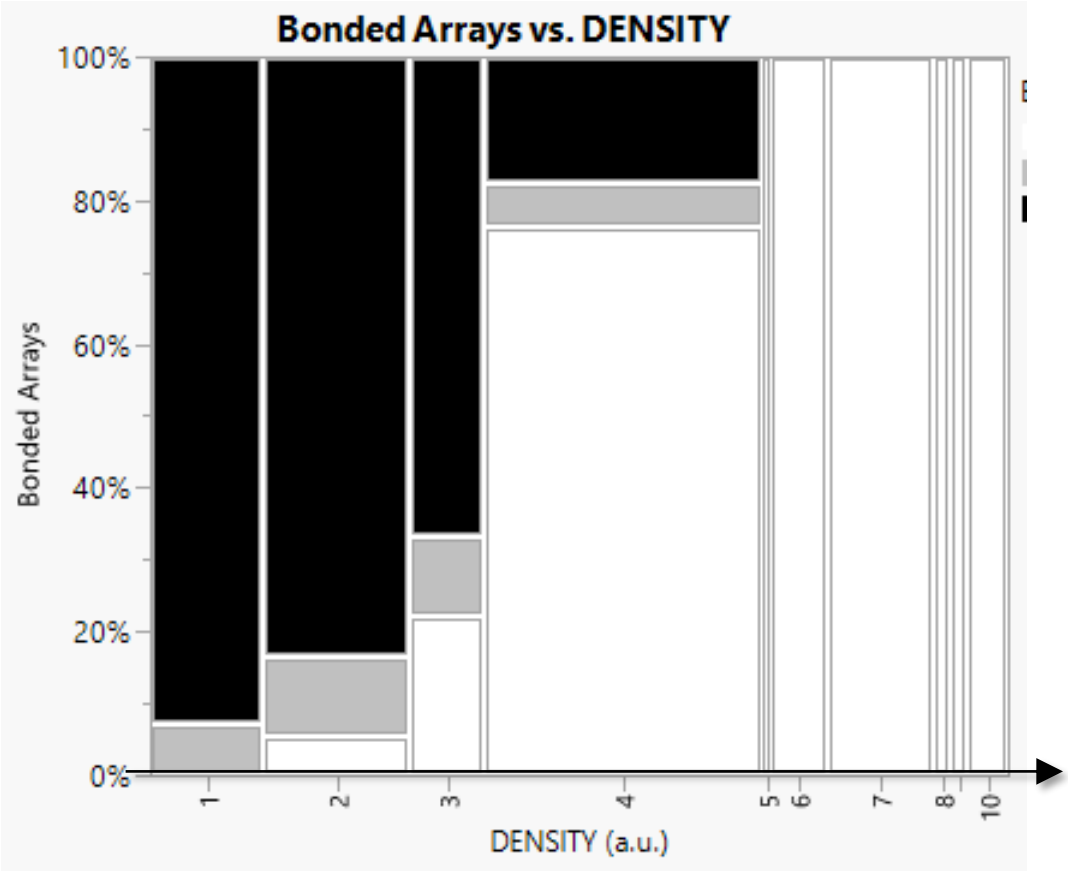




- Based on mask design file (left-side), unbonded Cu arrays were identified and counted on HR-SAM Image (middle)
- Graph on right-side shows that, for these specific conditions, a large number of Cu-arrays (white bar on graph) were not bonded:
  - ~ 56% unbonded arrays (white bar)
  - ~38 bonded arrays (black bar)
  - ~6% mixed (grey bar) : these arrays, on limit between bonded/unbonded are important to focus on for CMP process optimization

Die Scale Quantification of Bonding Quality

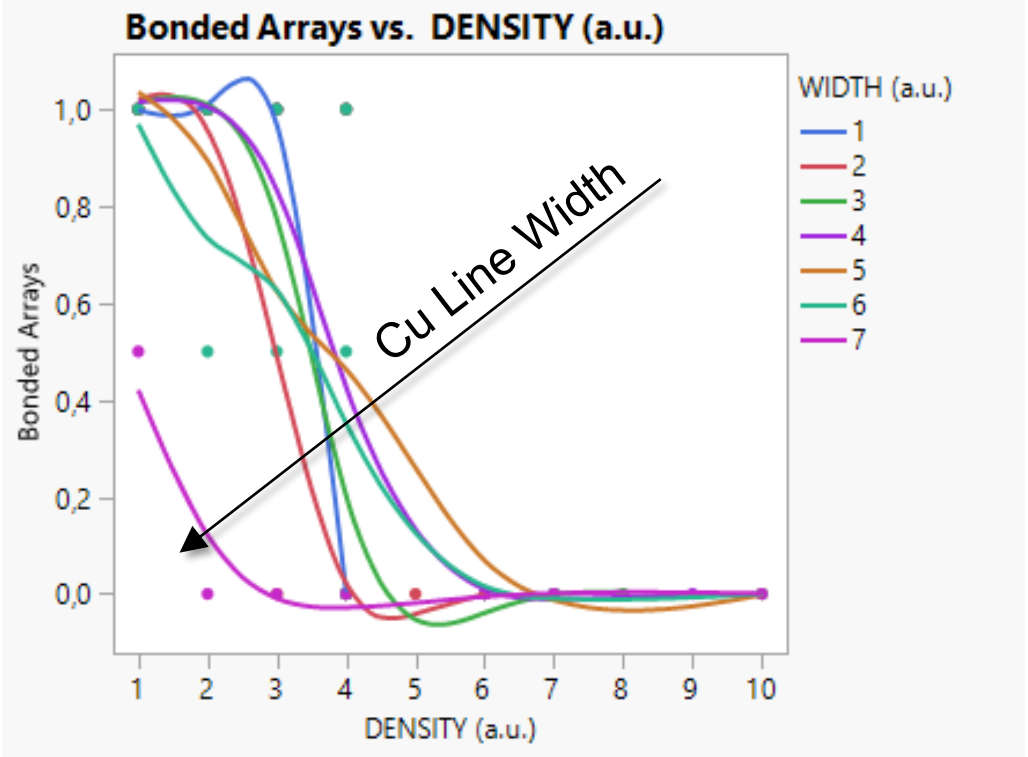
Density Influence



- Low Cu density patterns allow high bonding yield
- Increasing Cu density decrease bonding yield
- There is a Cu density threshold, above which spontaneous hybrid bonding do not occur

Die Scale Quantification of Bonding Quality

Line Width Influence



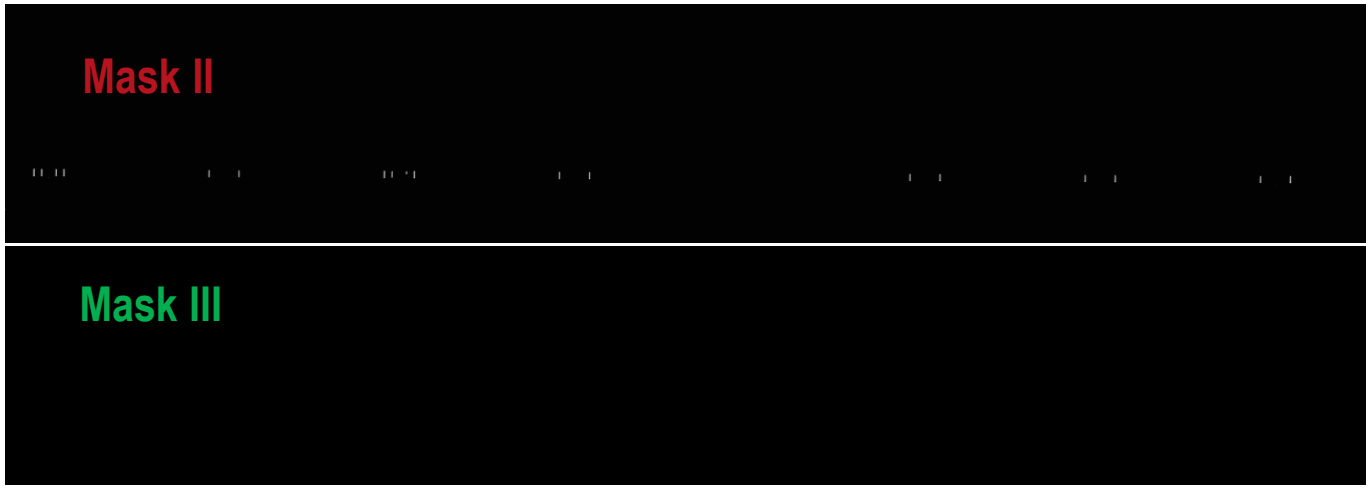
- Thinner Cu lines show better bonding yield across the different Cu arrays densities
- **In design terms, for Cu density & pitch, Smaller is Better for bonding performance**

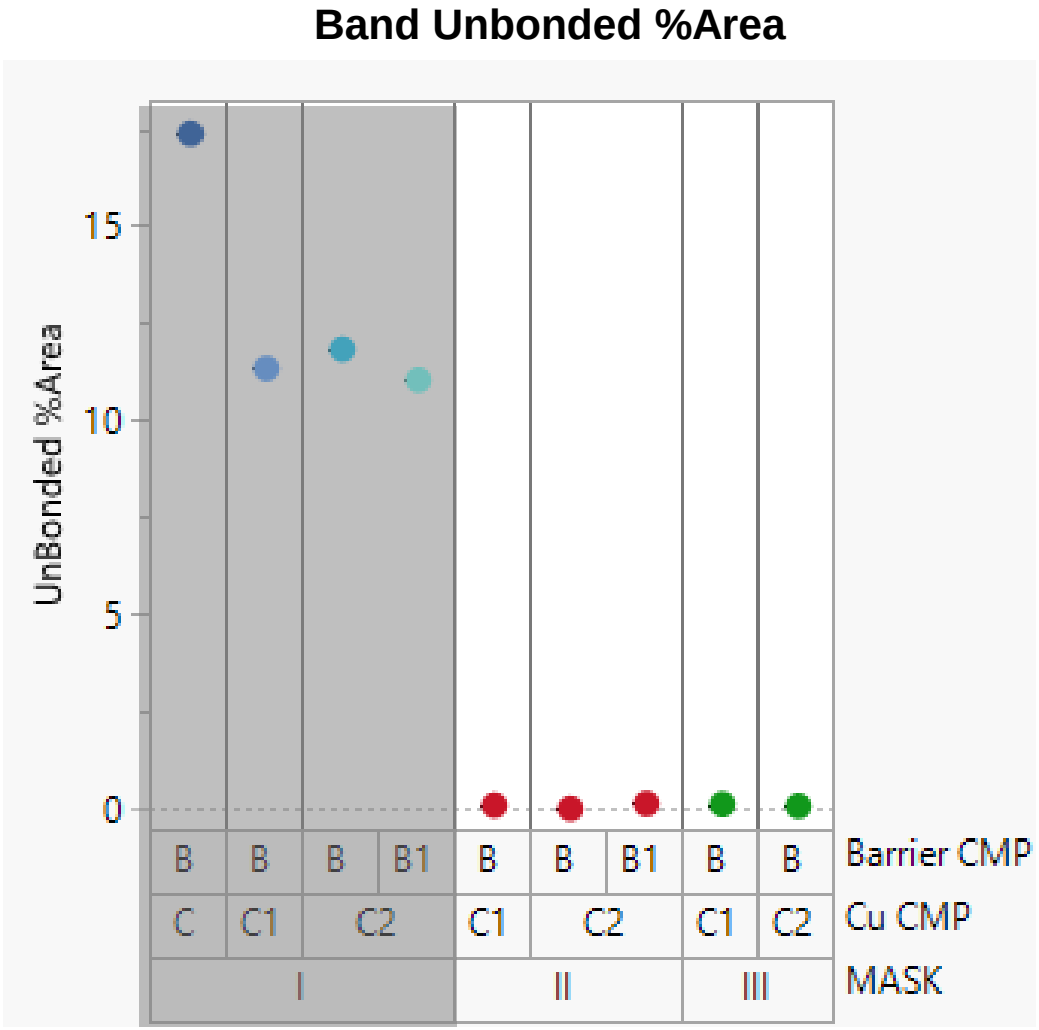
Validation of the Quantification Protocol

Wafer Scale Quantification of Bonding Quality

CMP Process Impact

- HR-SAM Image analysis was validated on different masks (II & III)



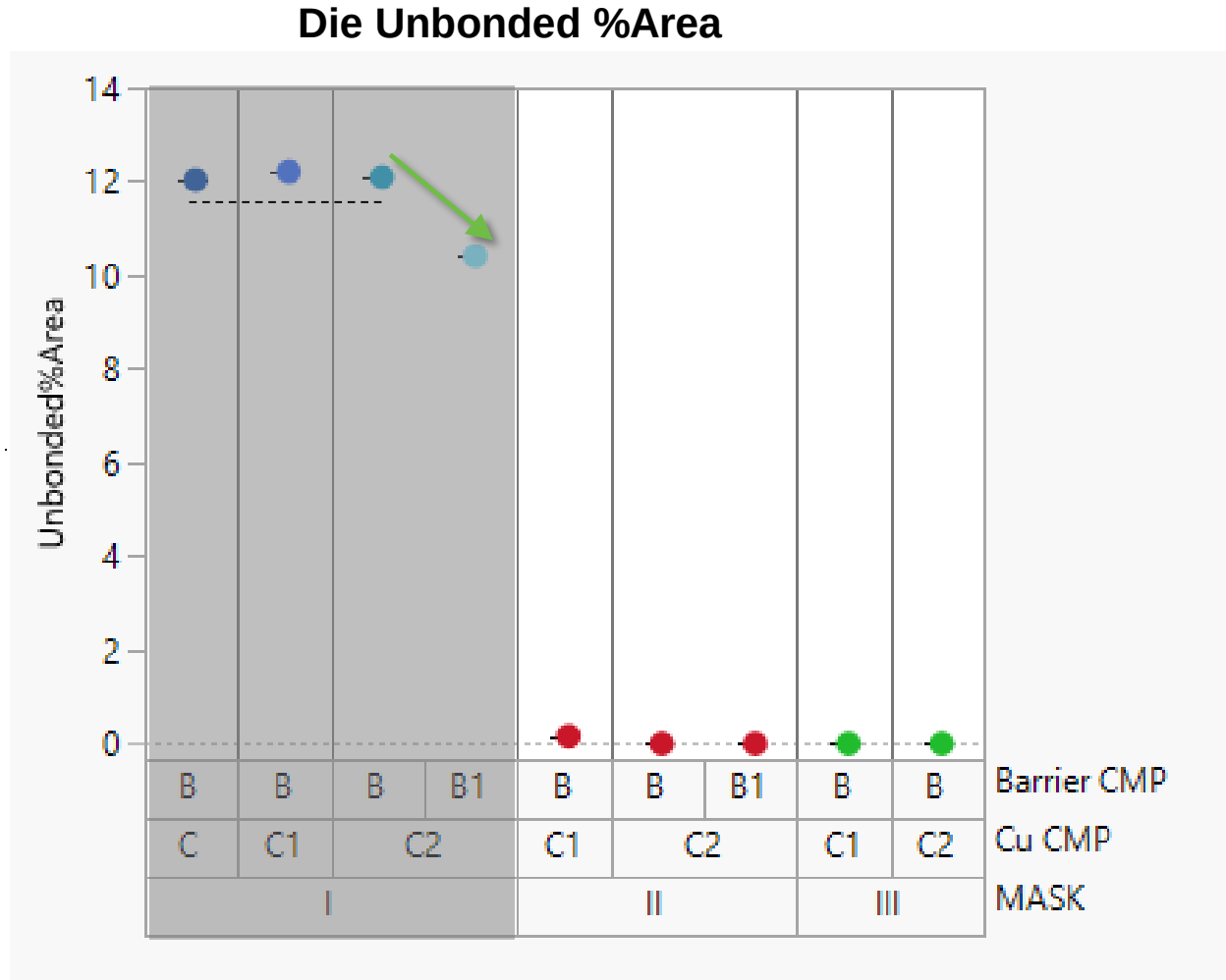


- While for heterogeneous **Mask I**, CMP Process Conditions Impacted Unbonded %Area, for **Mask II** (pitch variation) and **Mask III** (density variation) changing CMP process conditions doesn't seem to have significant impact, as wafers are completely bonded
- **More homogenous designs as masks Mask II and Mask III are very robust against CMP process conditions**

Die Scale Quantification of Bonding Quality

Design Impact

- For all masks, bonding yield performance is independent of Cu CMP Process performance (for investigated conditions…)
- **Mask I**, bonding performance at Die Scale is impacted by Barrier CMP Process
- **Mask II**, with **pitch variation** show excellent bonding quality for B & B1 barrier CMP processes
- **Mask III**, with **density variation,** show **best bonding yield,** with no unbonded/white pixel, independently of investigated Cu or Barrier CMP process



Summary

- Alternative metrology, based on HR-SAM image analysis, was used in order to quantify bonding quality.
- Method including image thresholding, white/black pixel ratio extraction with automated FIJI scripts was used
- Hybrid bonding quality was quantified : different CMP processes and design masks
  - Wafer scale → CMP process signature,
  - Die scale → impact of pattern design
- Heterogeneous **Mask I** (density & pitch) → Impact of Cu CMP process: changing Cu CMP Process from POR C to new processes C1 & C2 show significant improvement
- Homogenous **Mask II** (pitch variation) and **Mask III** (density variation) : much more robust in terms or Cu CMP process window
- For the Barrier CMP, bonding yield is sensitive at die scale → the pattern design is very important, homogenous masks II & III showing very low or even no unbonded area.
- **Smaller is better for both pitch and density in terms of bonding performance**
- **Proper CMP process tuning is important and has to be developed/optimized for different masks layouts**
- *Image Analysis through Machine Learning available directly on Scanning Acoustic Microscopes would help to improve hybrid bonding process development*

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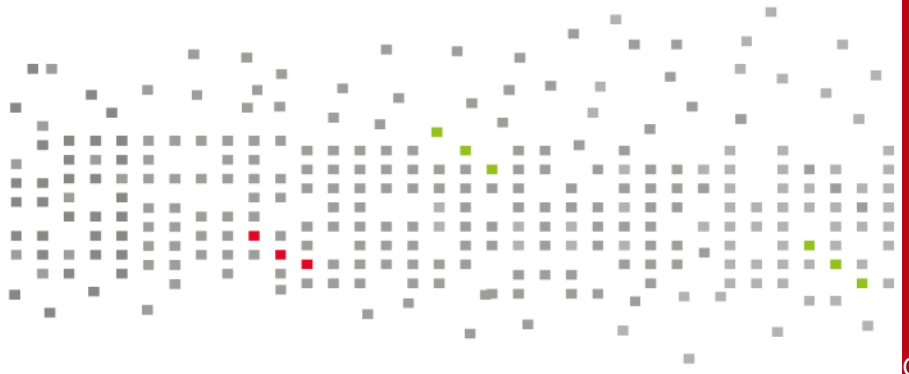

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