Addressing Metrology Challenges in D2W Bonding: An Overview of Tokyo Electron's X-ray Imaging Program Focused on Overlay

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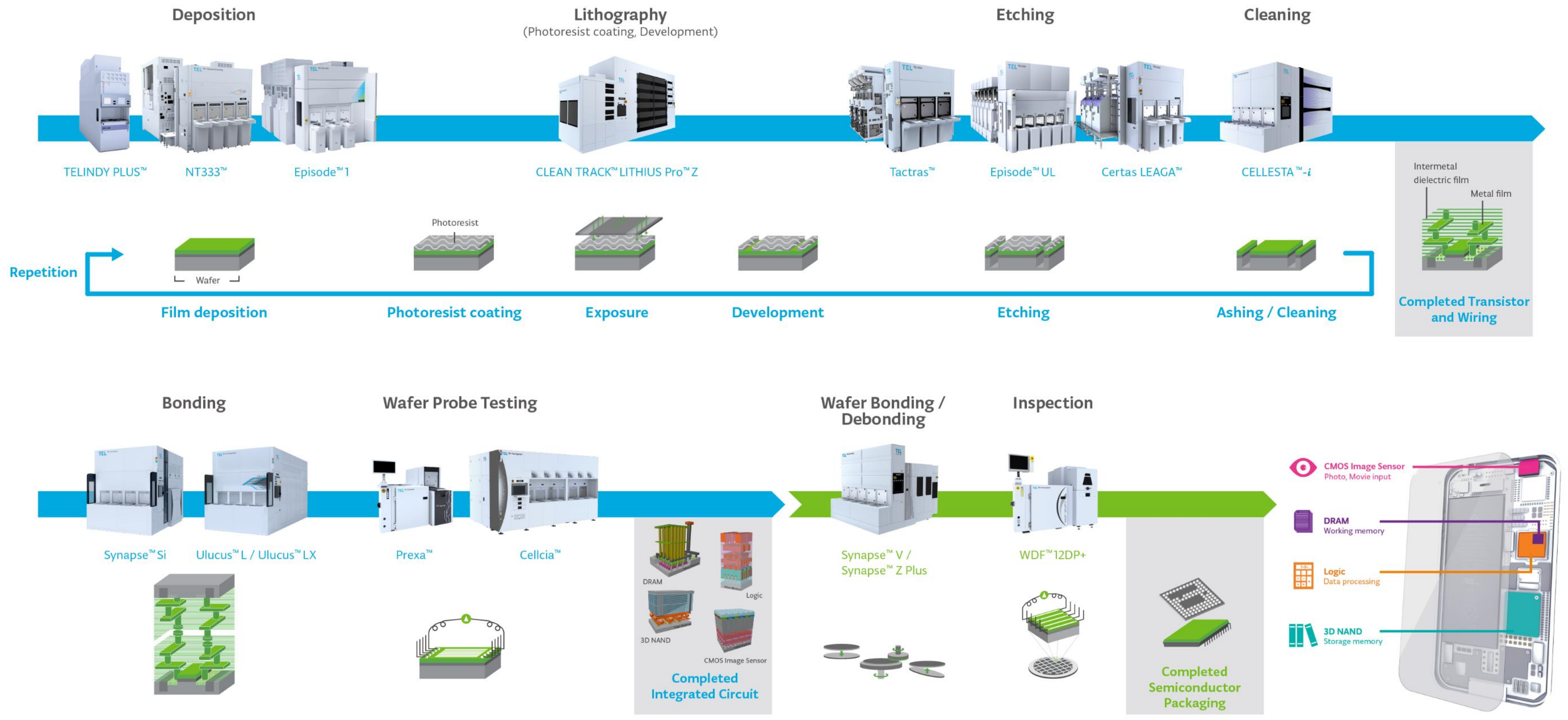
TELCC-SMP-004

Semiconductor Manufacturing Process

Wafer Process (Front-end)

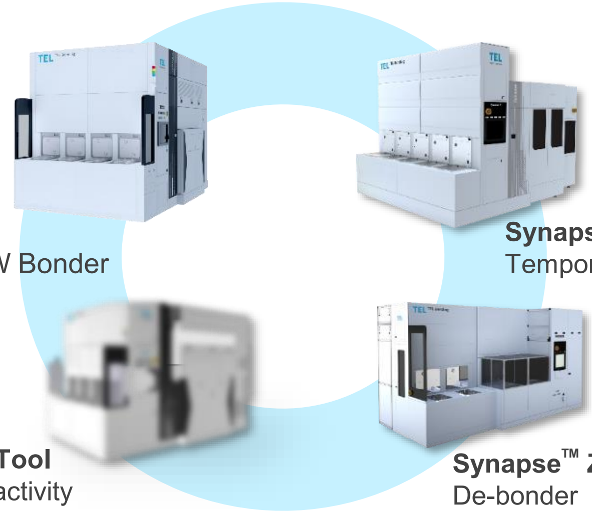
Assembly and Test Process (Back-end)



TEL 3D Integration (3DI) Product Line-Up

Bonding

(Wafer level / Die level)



Synapse™ Si
Fusion/HB W2W Bonder

Synapse™ V
Temporary bonder

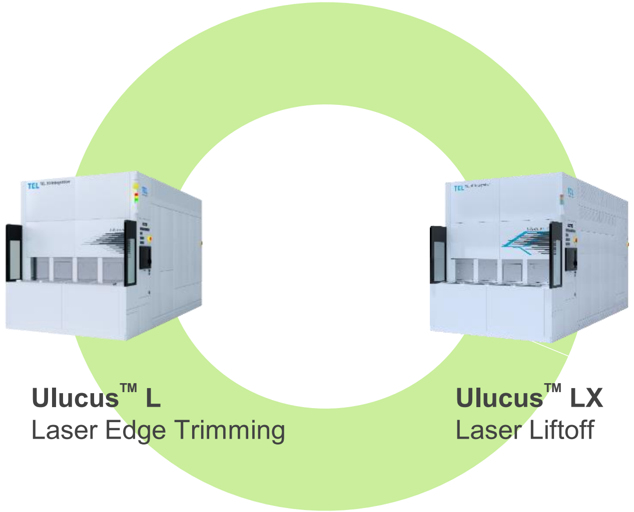
D2W Cluster Tool
Development activity

Synapse™ Z Plus
De-bonder

- **W2W Permanent Bonder**
- **Temporary Bonder**
- **De-bonders**
- **D2W Fusion /Cu Hybrid Bonder**

Laser Processing

(Removal Solutions)

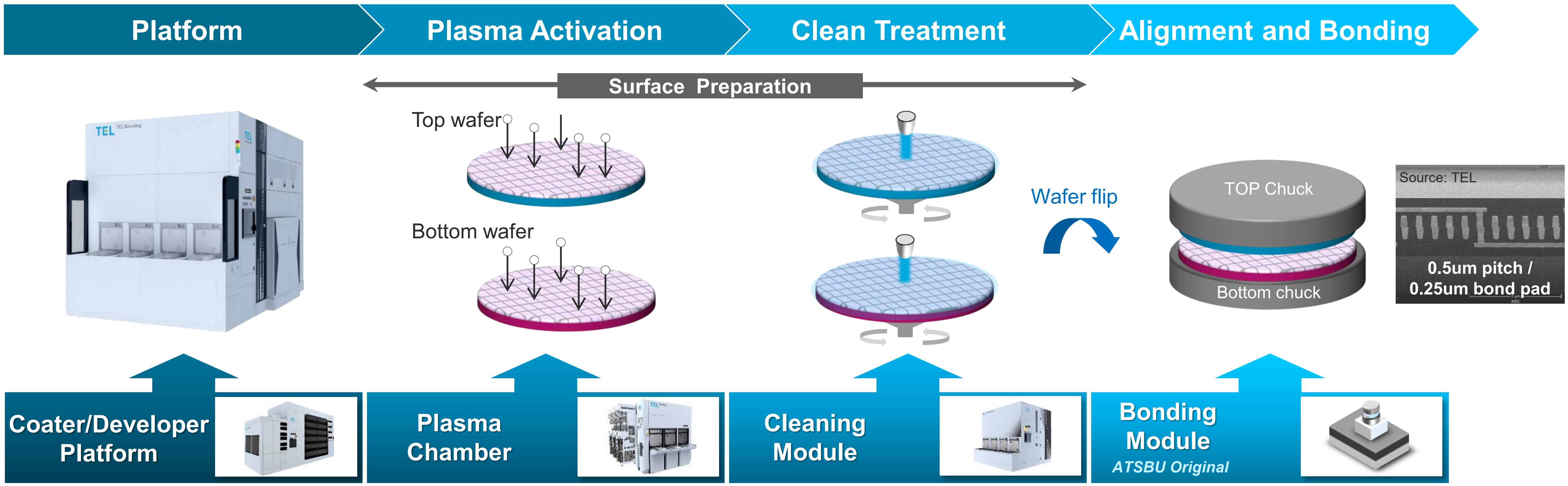


Ulucus™ L
Laser Edge Trimming

Ulucus™ LX
Laser Liftoff

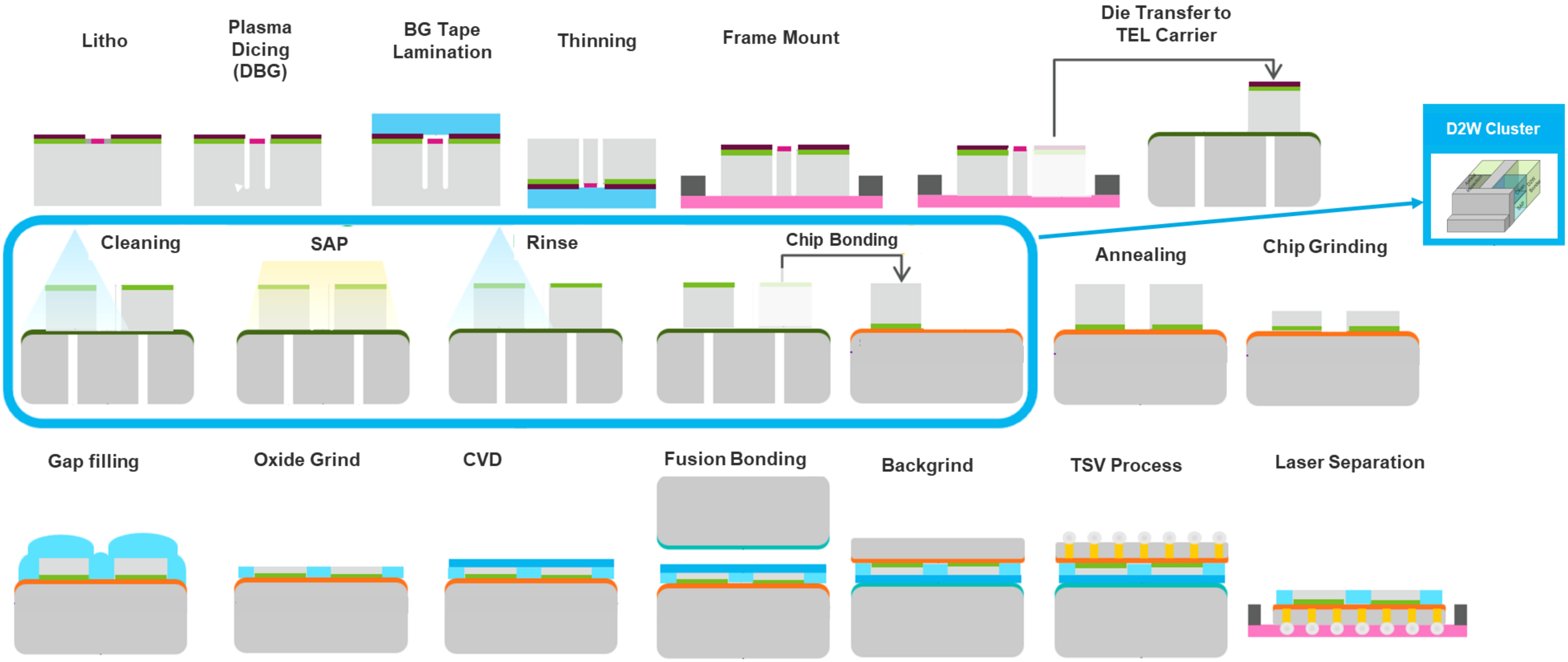
- **Laser Edge Trimming**
- **Laser Lift Off**

W2W Permanent Bonder Synapse™ Si



- Fusion and Cu hybrid bonding technology
- Moving toward High-Volume Manufacturing with major memory and logic customers

D2W Process Flow



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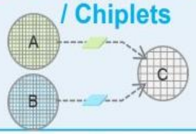
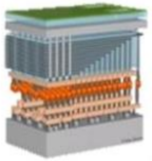
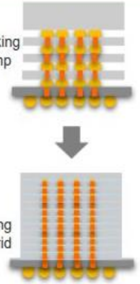
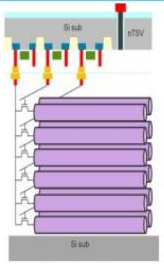
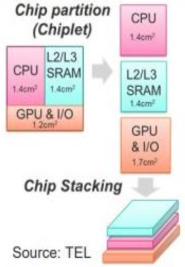
Metrology Challenges for D2W Hybrid Bonding

Device	CIS	NAND	DRAM		Logic		
	BSI	3D NAND	HBM	3D DRAM	Backside PDN	Sequential CFET	Disaggregation / Chiplets
Stacking Device	Sensor + (Memory) + Logic	Cell + Peripheral	DRAM : DRAM + Logic	Cell + Peripheral	Logic + Bare Si	Logic + Logic	
Bonding	W-W Cu Hybrid	W-W Cu Hybrid	D-W Cu Hybrid	W-W Cu Hybrid	W-W Ox Fusion	W-W Ox Fusion	D-W / D-D Cu Hybrid
3D I/O Pitch	3 μm →1 μm	1 μm →0.5 μm	40 μm →25 μm	1 μm →0.5 μm	Sub μm (nTSV)	Sub μm (nTSV)	10 μm →1 μm
Structure				 Source: TEL 3D DRAM structure			 Source: TEL
Status	HVM	R&D~HVM	R&D	R&D	R&D	R&D	R&D

No scribe line for overlay checking!
Fiducial size needs to be smaller!

Process Control Challenges:

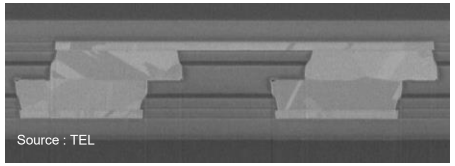
Overlay alignment

Defectivity (e.g. voiding)

Film thickness and uniformity

Surface profile and roughness

Shape and bow



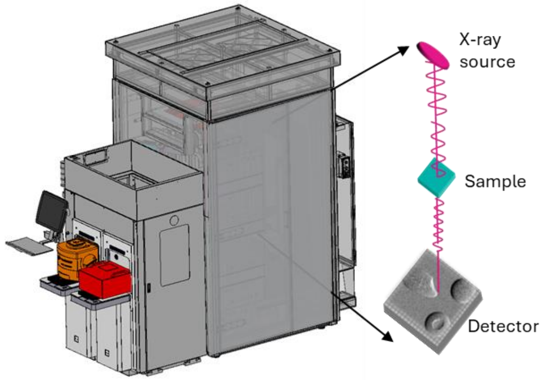
Source : TEL

Source : TEL

Imaging Solutions for Overlay

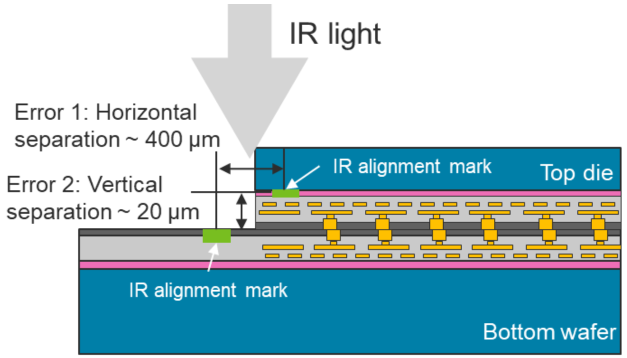
Parameter	IR	Std X-ray	New X-ray
Penetrate metal and highly doped Si	No	Yes	Yes
Depth of focus (DOF)	Very limited	Unlimited	Unlimited
Field of view (FOV)	Small	Large	Large
Overlay accuracy	< 50 nm	> 1µm → Advanced Moiré fiducials	< 50 nm
Device Damage	No	Yes → Multi-modal imaging	No/low risk

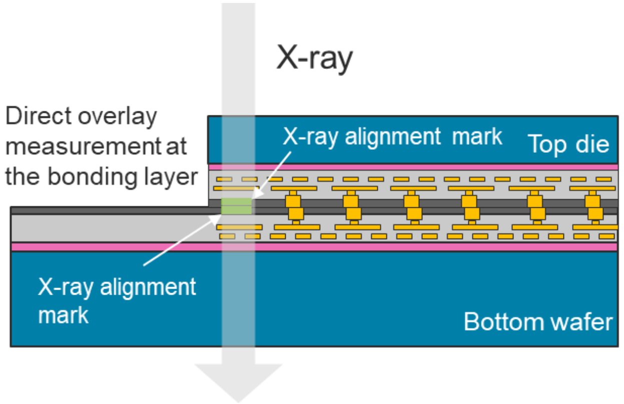
New X-ray imaging program for TEL's integrated metrology



Source : TEL

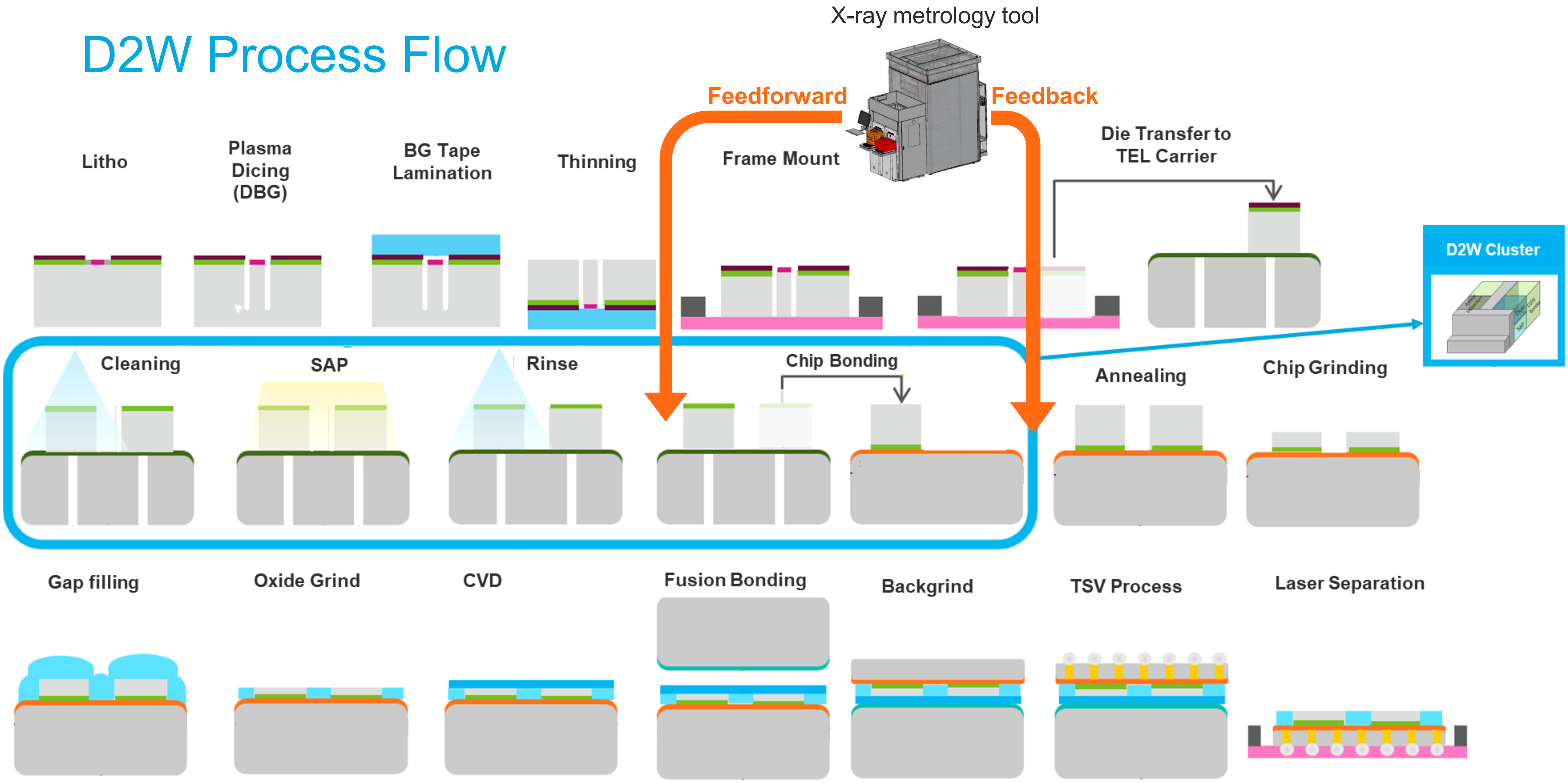
(EPTC 2024, SPIE 2025, SEMICON SEA 2025)





Overlay checking in metal-dense environment

D2W Process Flow



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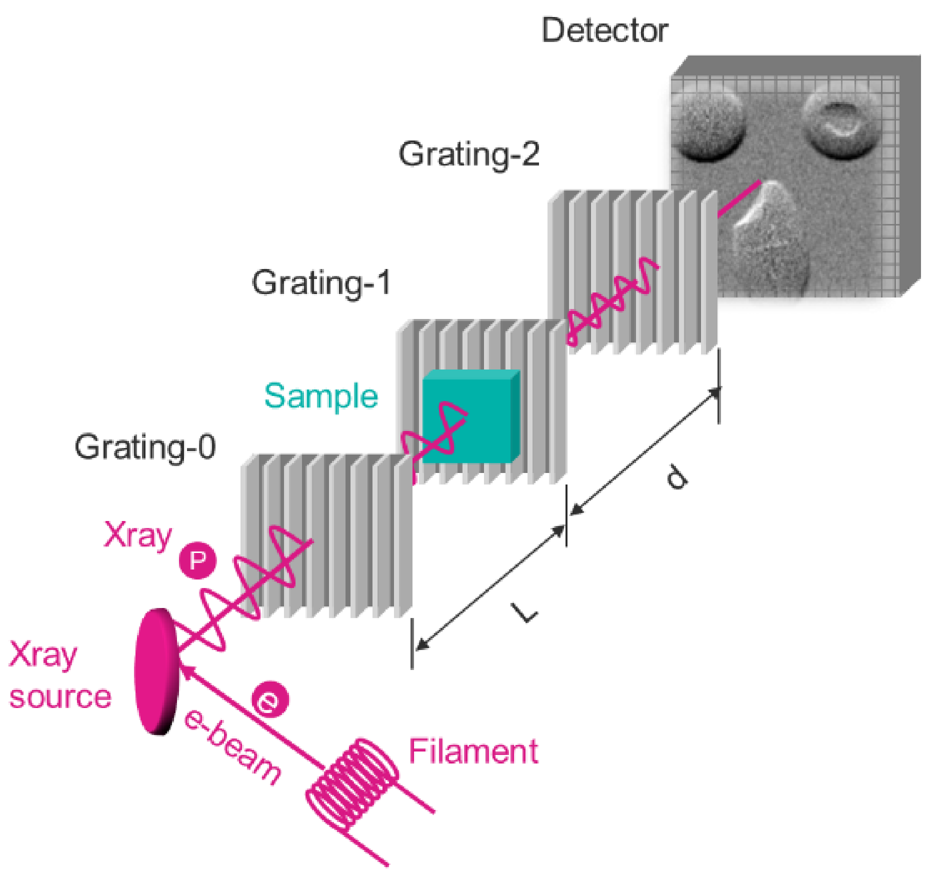
Multi-Modality X-ray Imaging System

X-ray grating interferometry



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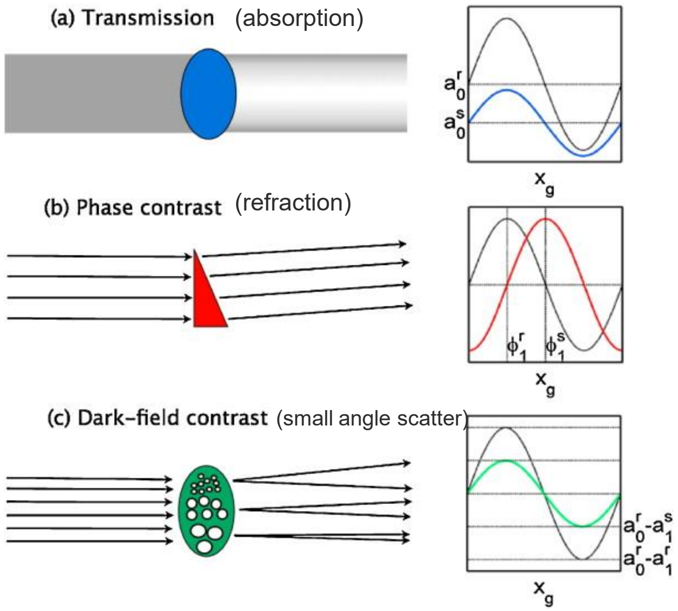

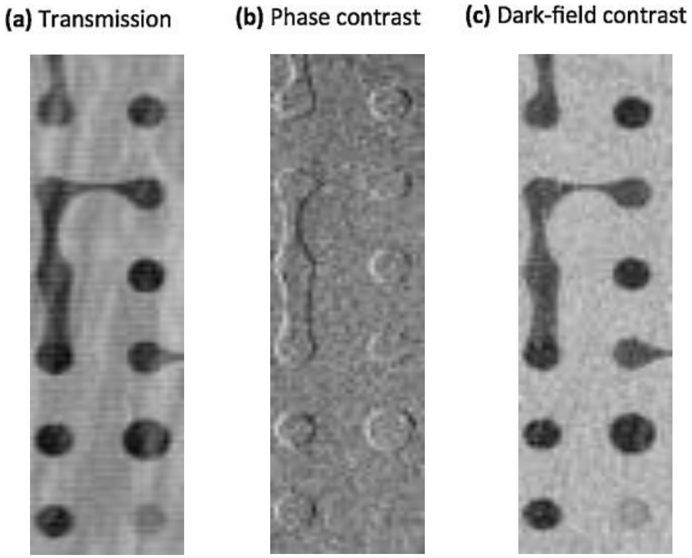

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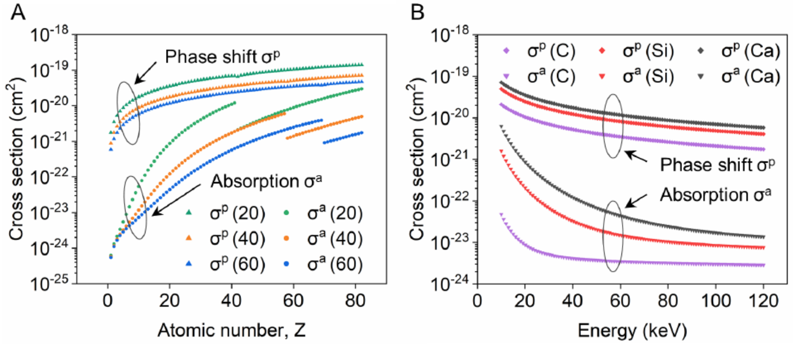


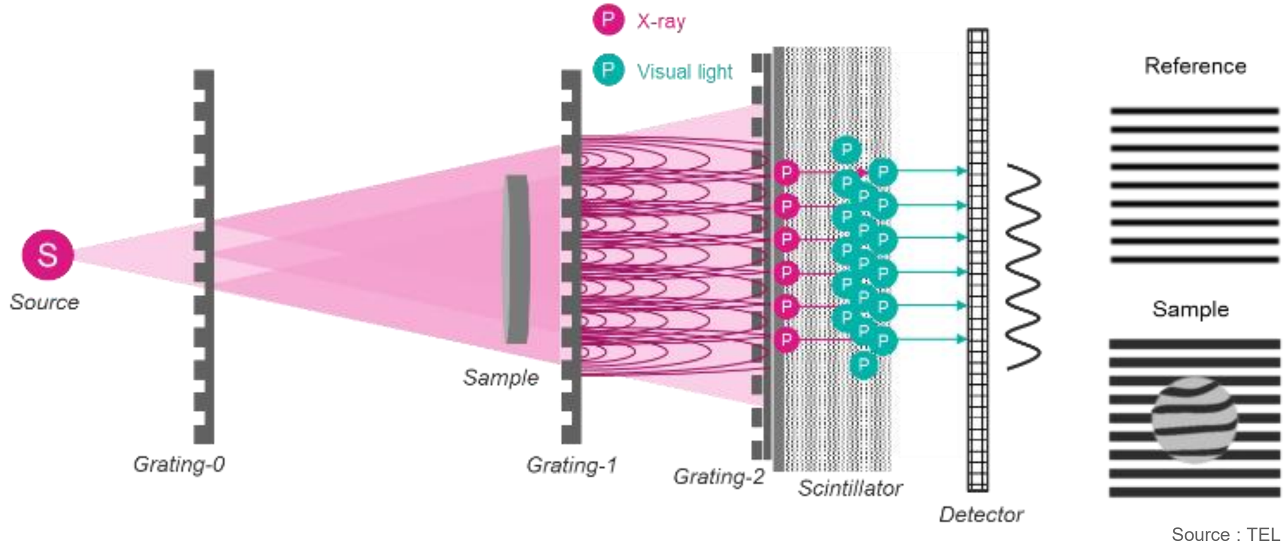
Fig. S1. Interaction cross sections of the phase shift (σᵖ) and absorption (σᵃ) per atom. (*A*) Phase shift and absorption cross sections as a function of atomic number Z for 20 keV, 40 keV, and 60 keV X-rays (7). (*B*) Phase shift and absorption cross sections for three low-Z materials: C, Si and Ca calculated in the energy range 10-120 keV.

Best configuration to:

- **Minimize** transmission image sensitivity to reduce device damage
- **Maximize** phase contrast and dark-field modality images sensitivity

Reference: 10.1073/pnas.2103126118

Simulation Capability for X-ray Grating Interferometry



Source : TEL

Fourier transform

Complex values, $\tilde{I}_{ref}$ and $\tilde{I}_{sample}$
- Phase (Φ)
- Amplitude (a_1)
- DC (a_0)

→

Transmission image

Phase contrast image

Dark-field image

Source : TEL

Goals

- Simulate experimental outcome
- Design test vehicles/ fiducials

Design Advantages

- Uses Fourier optics concept to model grating interferometry → generate multi-modal images quickly with good accuracy

Competitive Edge

- New algorithm development for fiducial placement in a metal-dense zone
- New fiducial designs for multi-die high bandwidth memory (HBM) overlay

Contents

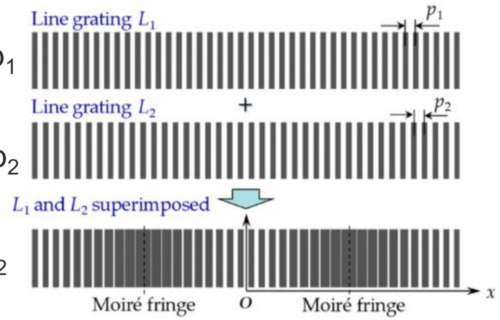
Moiré Fiducials for Overlay

- Moiré-type alignment marks provide magnification and improve sensitivity

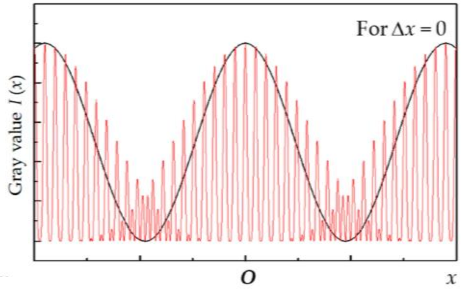
Top layer Moire grating, p_1

Bottom layer Moire grating, p_2

Overlayed patterns, p_M: $p_M >> p_1$ or p_2

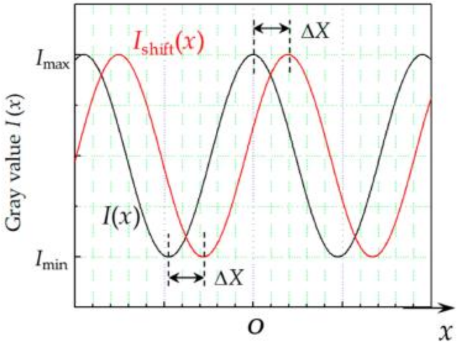


Moiré fringe shift ΔX



$\Delta x \neq 0$

Misalignment between p_1 and p_2

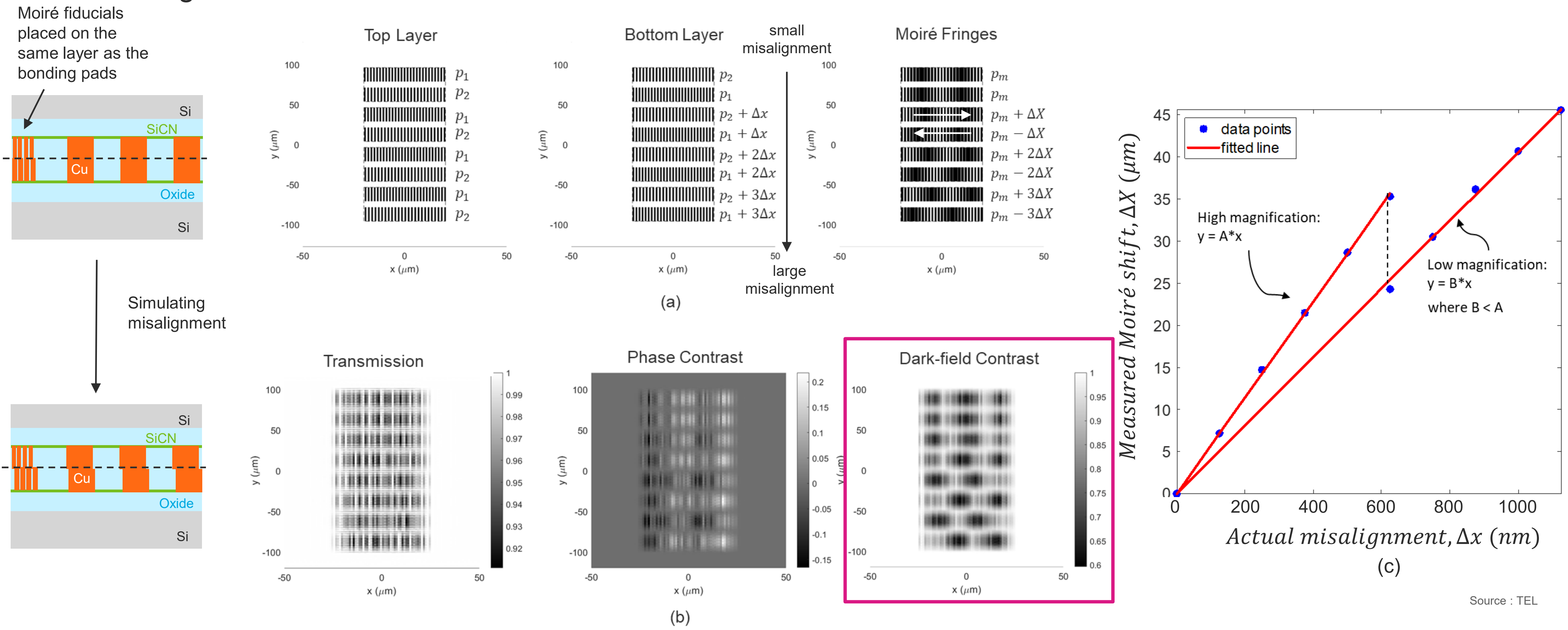


Moiré magnification factor: $$M = \frac{\Delta X}{\Delta x} = \frac{p_1 + p_2}{2(p_2 - p_1)} = \frac{p_1 + p_2}{2\Delta p}$$

Reference: 10.3390/mi10050339

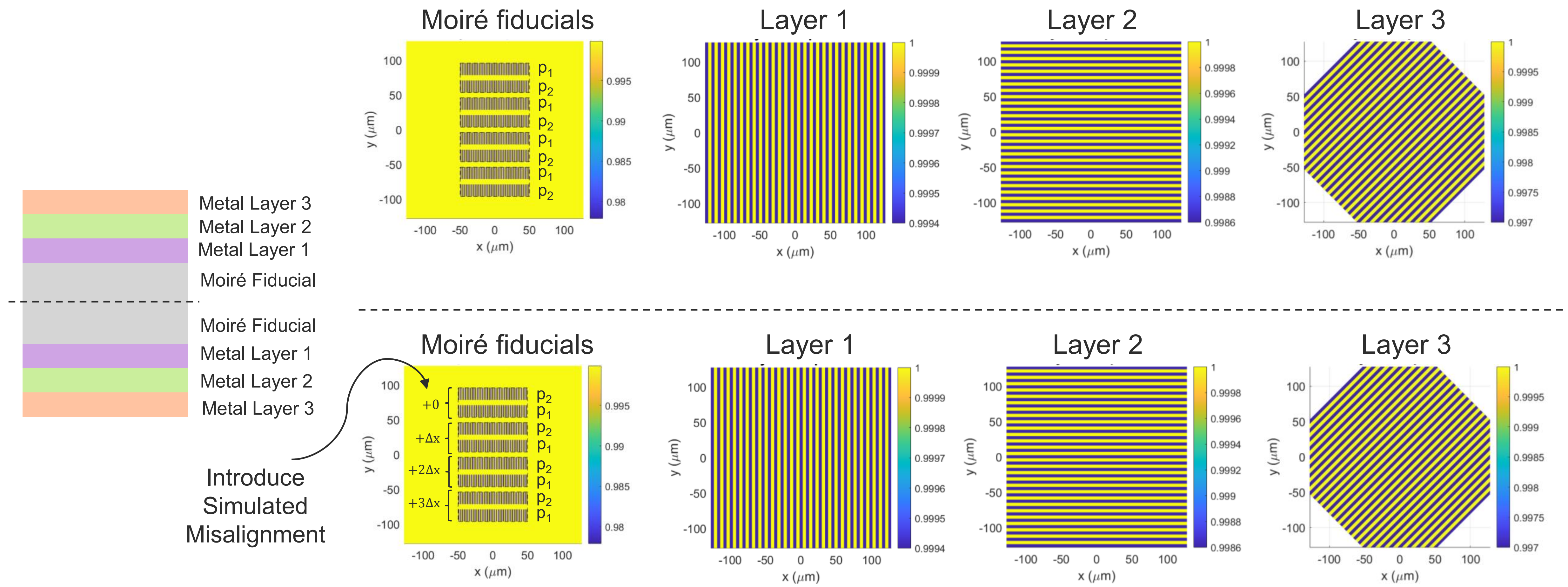
Dual-Row Moiré Fiducials

- Upper row and bottom row Moiré fringe moves in the opposite direction: relative shift becomes 2x Moiré magnification



Source : TEL

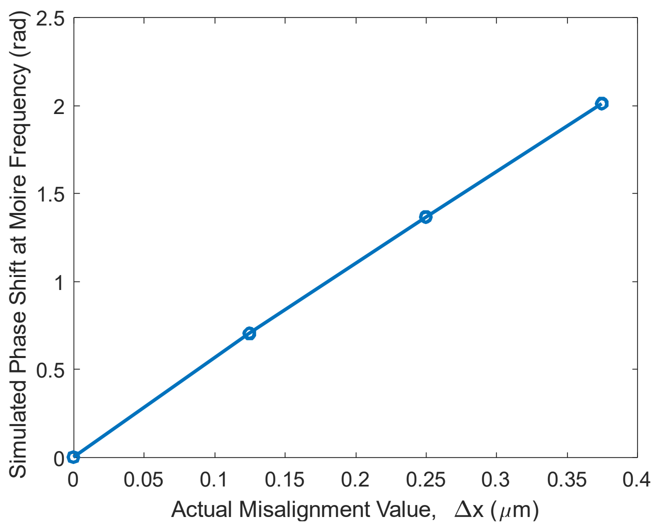
Embedded Moiré Fiducials in a Metal-Dense Zone



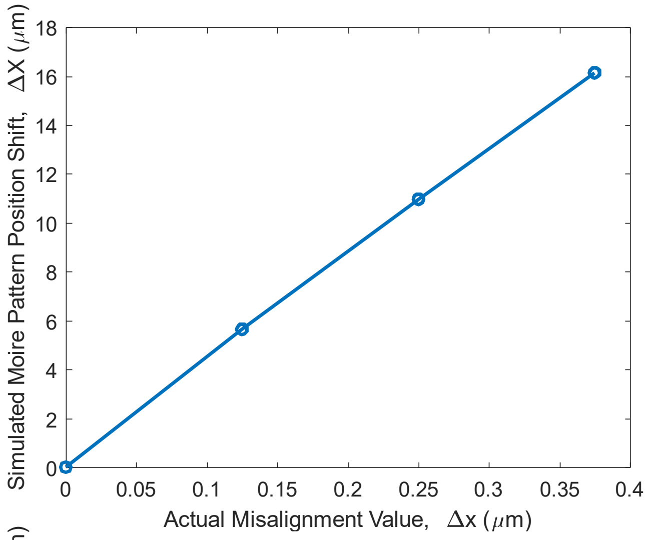
Source : TEL

Moiré Fiducials Not Affected by Additional Metal Layers

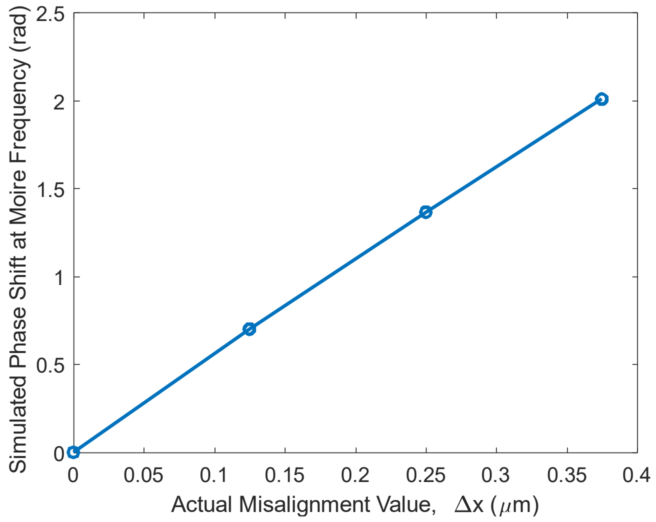
Moiré fiducials in a metal-free zone



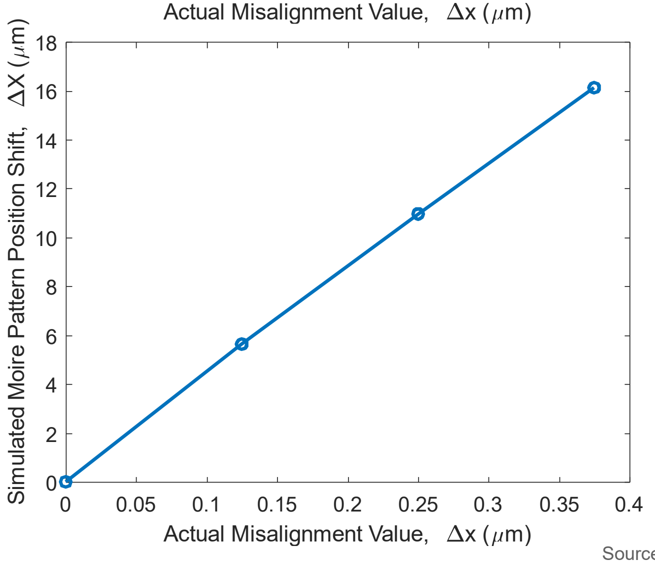
Converting phase difference to overlay errors



Moiré fiducials in a metal-dense zone



Converting phase difference to overlay errors

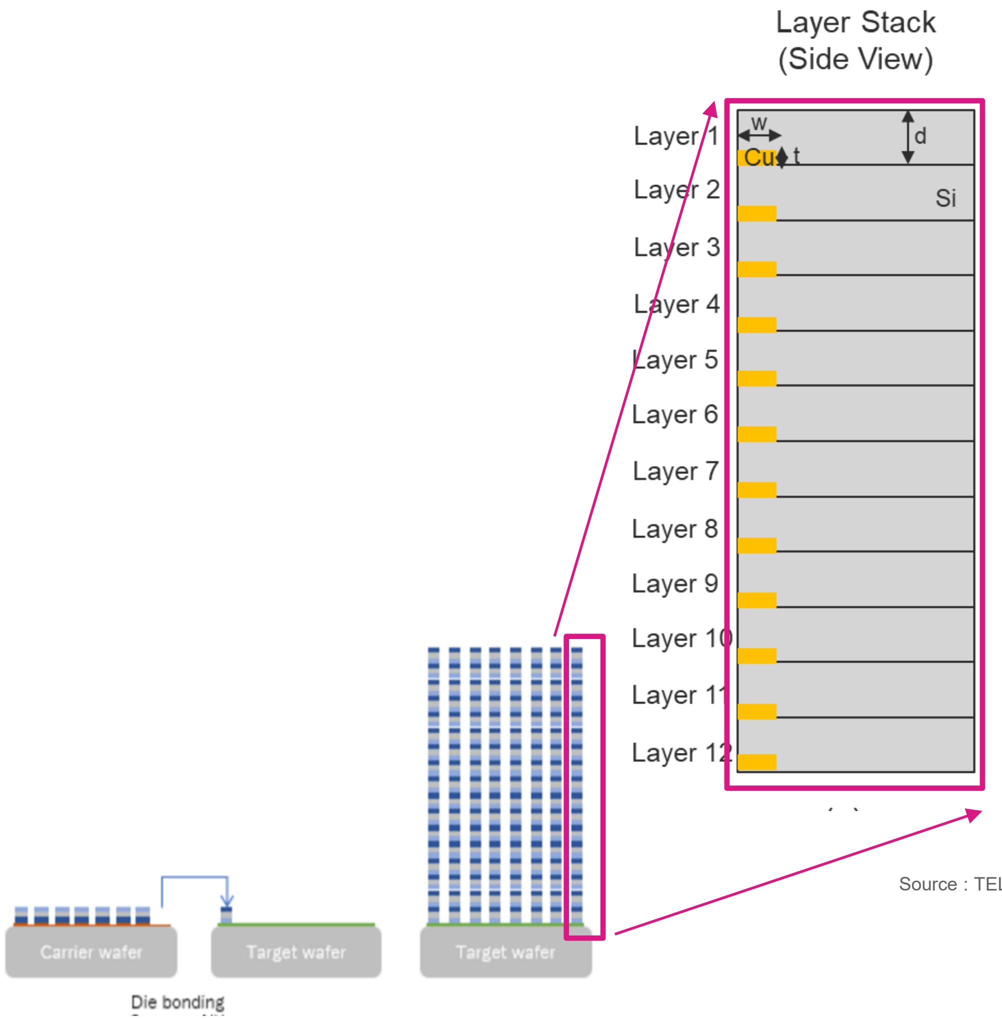


Source : TEL

No need metal clear-out zone

Multi Layer Overlay for High Bandwidth Memory

- Problem statement:
  - How to detect misalignment between any 2 layers in a multi-layer stack non-destructively?
- TEL's solution:
  - Special Moiré fiducials
  - Multi-modality X-ray imaging



Source : TEL

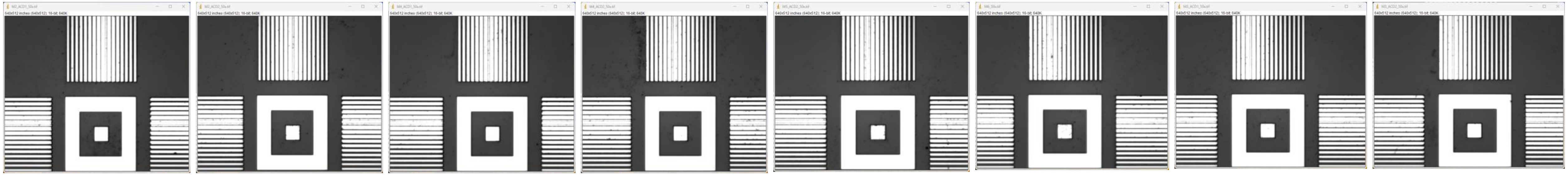
Keep the same fiducial design on all layers

Moiré Fiducials Overlay Compatible with IR and X-ray

Mask designed shift
Measurement

IR reflection (50x)

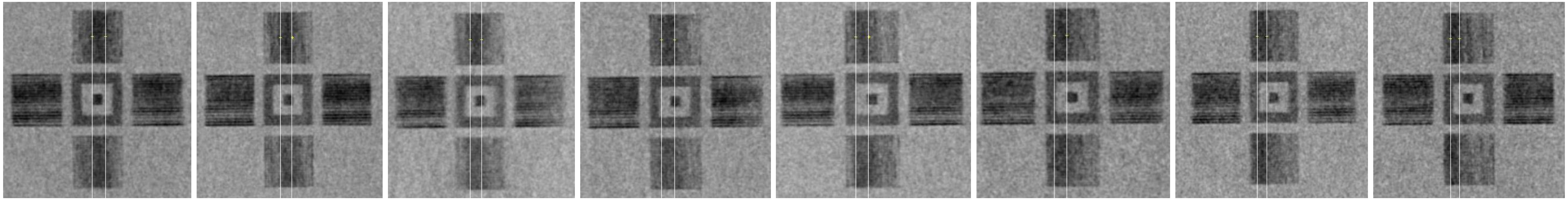
-0.25 µm | 0 µm | 0.25 µm | 0.5 µm | 0.75 µm | 1 µm | 1.25 µm | 1.5 µm



Source : TEL

X-ray multi-modal

-0.25 µm | 0 µm | 0.25 µm | 0.5 µm | 0.75 µm | 1 µm | 1.25 µm | 1.5 µm

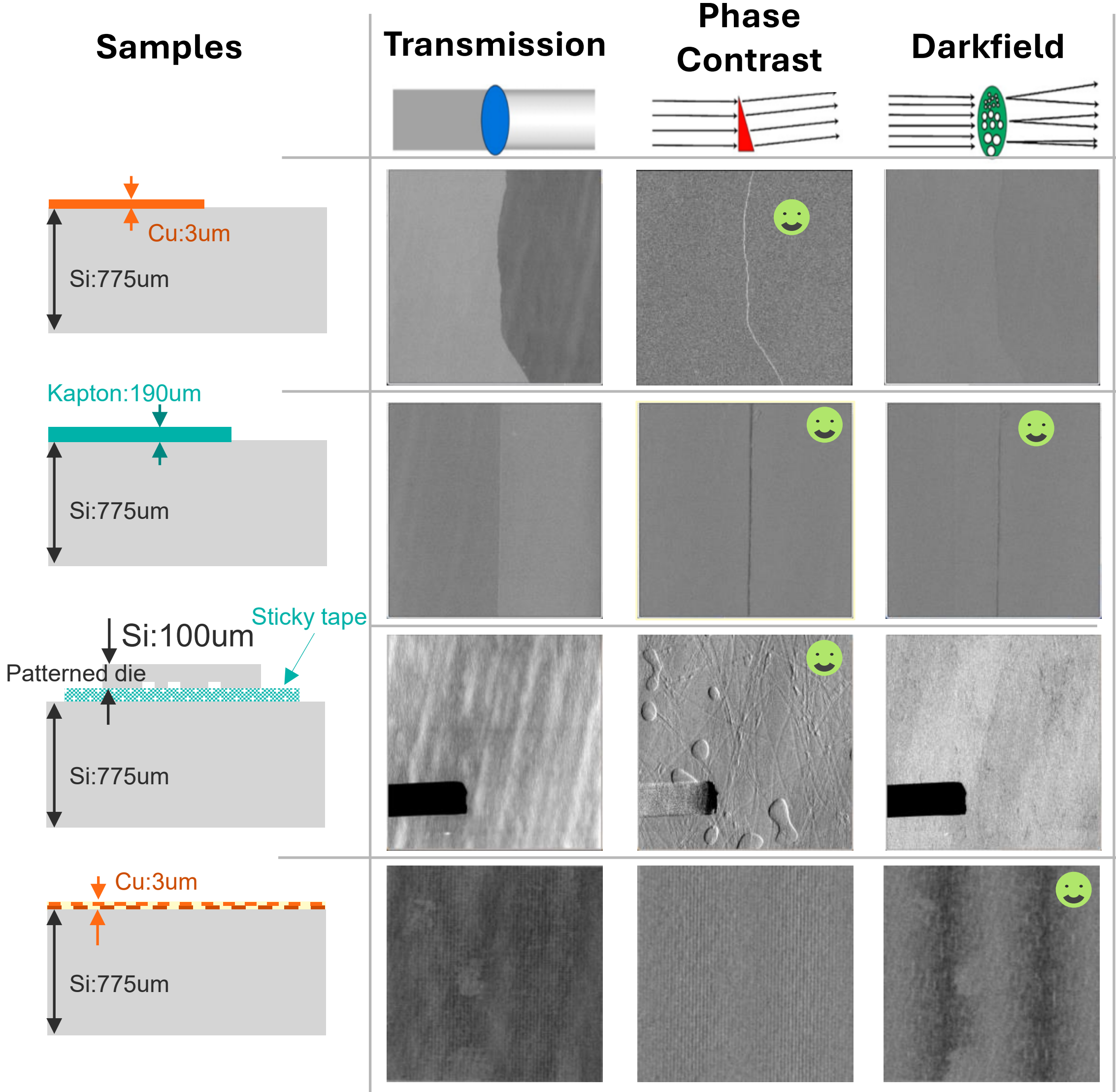


-0.16 µm | 0.18 µm | 0.33 µm | 0.67 µm | 0.92 µm | 1.05 µm | 1.27 µm | 1.34 µm

Source : TEL

Discrepancy includes fabrication errors.

Examples of Multi-Modal Images



Characterization

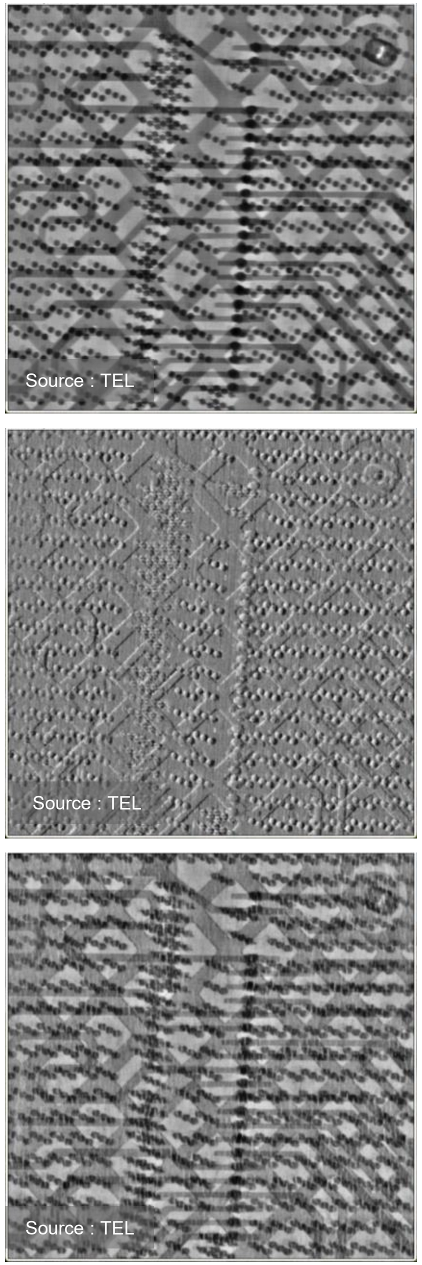
Strong phase coherence for edge of metal

Strong phase coherence and small angle scatter for edge of dielectric

Strong phase image shows high CNR for low-z material

Darkfield image shows strong Moiré fringe intensity for different pitch patterns

Source : TEL



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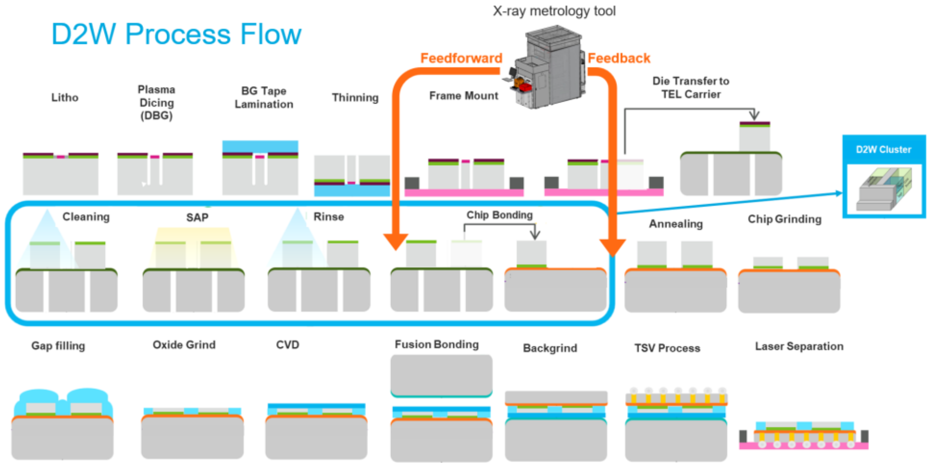
Summary

- TEL’s 3DI product portfolio incudes temporary, fusion and hybrid bonding (W2W and D2W) and laser processing (edge trim and wafer separation/debonding)
- D2W bonding is in development for chiplet and HBM die-stacking applications.16 hi stacking for blanket dielectric was demonstrated
- Multi-modal X-ray imaging for feedforward and feedback
  - Transmission, phase, dark-field images
  - Minimized damage and maximized sensitivity
  - High resolution maintained for a large field of view with short exposure time
  - Demo-ready in Q2 2026
- Overlay
  - Metal-dense environment
  - Moiré fiducials for multi-die HBM overlay
  - Co-exist with IR with additional advantages



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  - Hardware development: Holger Tuitje, Shad Pierson, Zheng Yan, Yaowu Ma, Pham Chien
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  - Data analysis & AI algorithm: Andrew Reid
  - Test vehicle: Hirokazu Aizawa, Angelique Raley, Ilseok Son

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