Workshop 2023

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Image sensors for optical metrology in semiconductor device manufacturing

Arie den Boef

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Delft University of Technology

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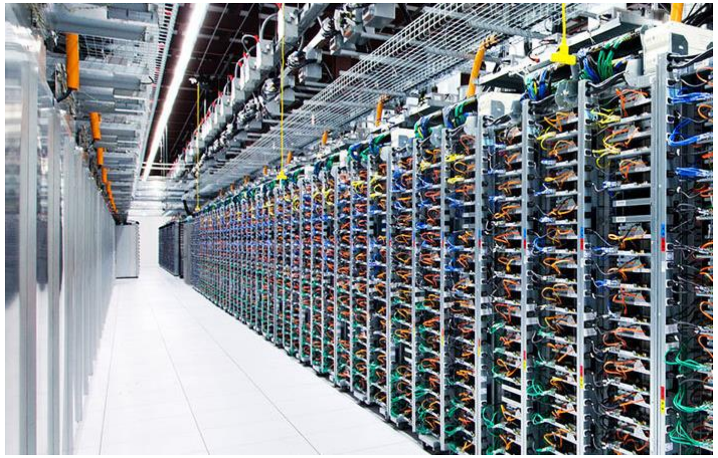
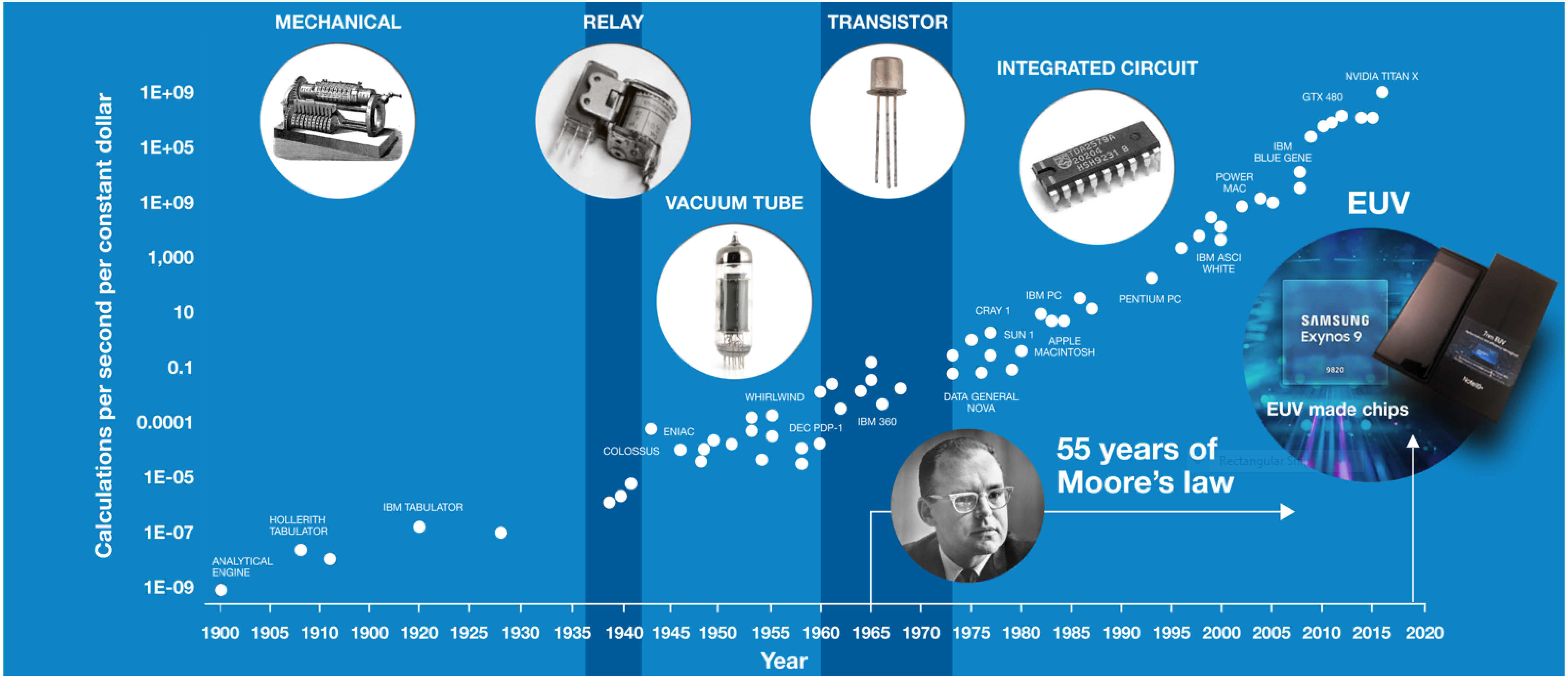
    - the revolution of computing power and chips
    - the role of lithography in semiconductor device manufacturing
    - the importance of metrology in lithograpy (patterning)
- Overlay metrology
    - concept
    - challenges and solutions enabled by image sensor innovations
- Critical Dimension (CD) metrology
    - concept
    - challenges and solutions enabled by image sensor innovations
- Summary

In our world today, chips are everywhere



The world has been improving computer power for 120 years

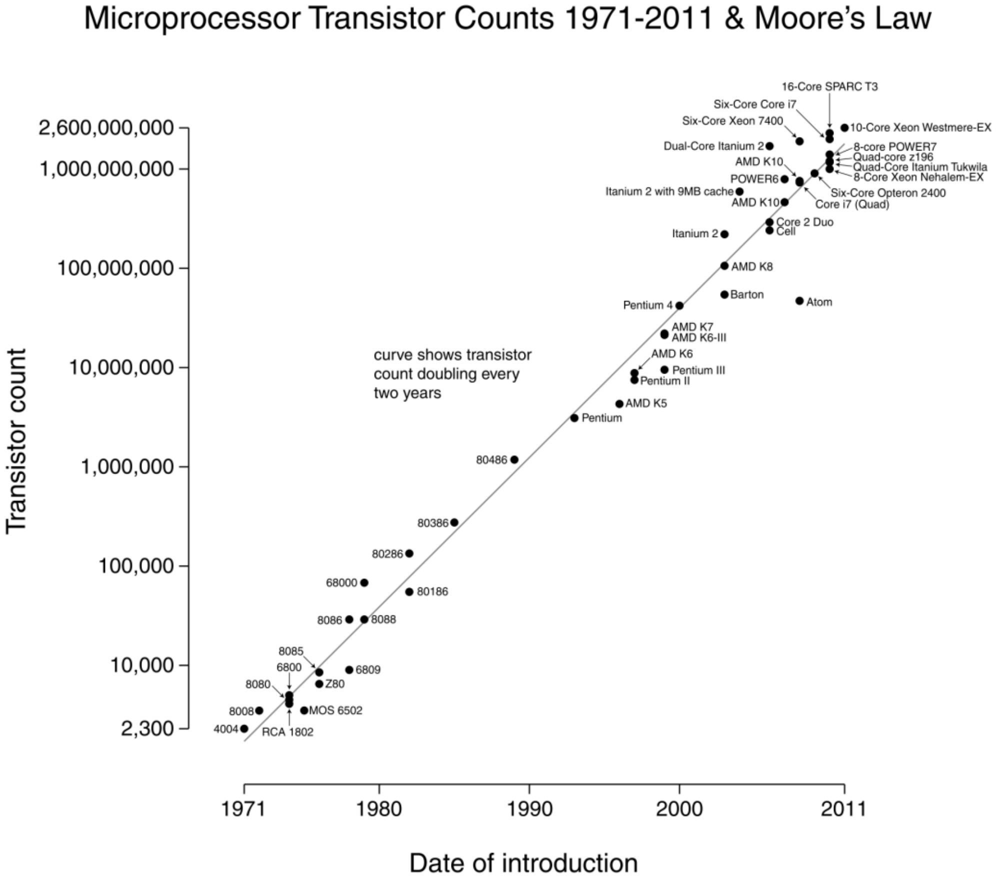
18 orders of magnitude increase of calculation speed per dollar, and continuing



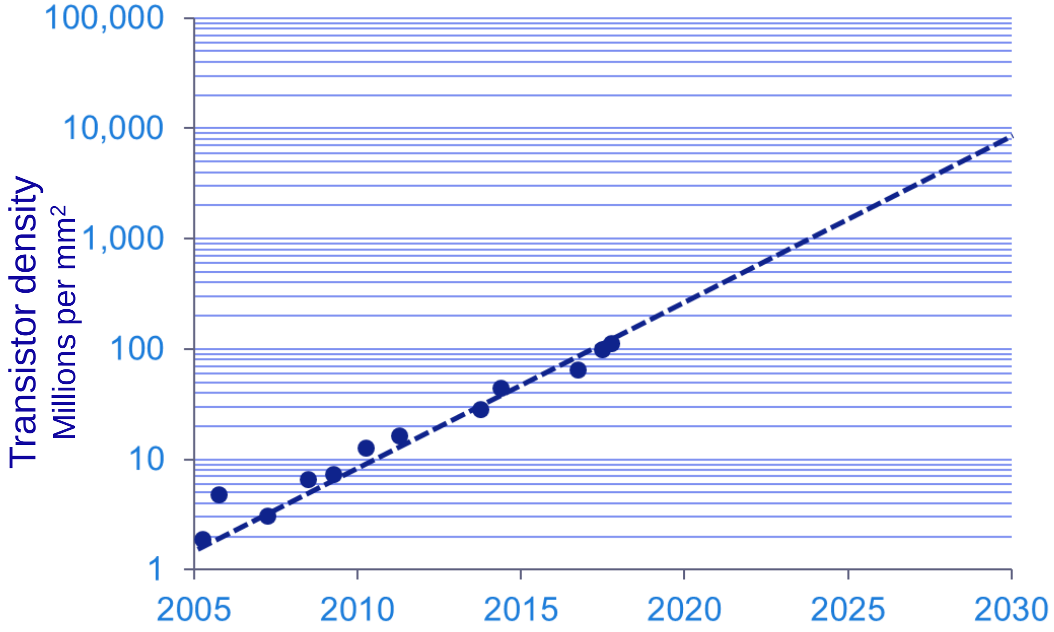
Source: Ray Kurzweil, Steve Jurvetson

Driving the semiconductor industry: Moore’s Law

Gordon Moore (1965): Number of transistors per chip doubles every year.



We see this trend continuing beyond the next decade



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The impact of Moore's law is visible in the world around us

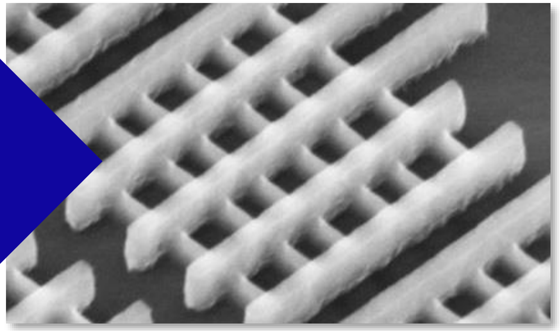
IBM 5150

Apple iPhone 13 Pro

IBM 5150		Apple iPhone 13 Pro
1984	year manufactured	2021
$1500-$3000 $3500-$7000 today	price	$999-$1299
16-bit Intel 8088 4.77 MHz	processor	Apple A15 bionic chip (5 nm EUV)
16-265 kB	working memory	6 GB
5" floppy disk 160 kB	internal storage	up to 1 TB
640x200 pixels	monitor	2532 x 1170 pixels
0.33-0.75 million	instructions per sec	16 trillion
12.7 kilogram	weight	203 grams

Key to Moore's Law: Making smaller transistors

Transistor length keeps shrinking

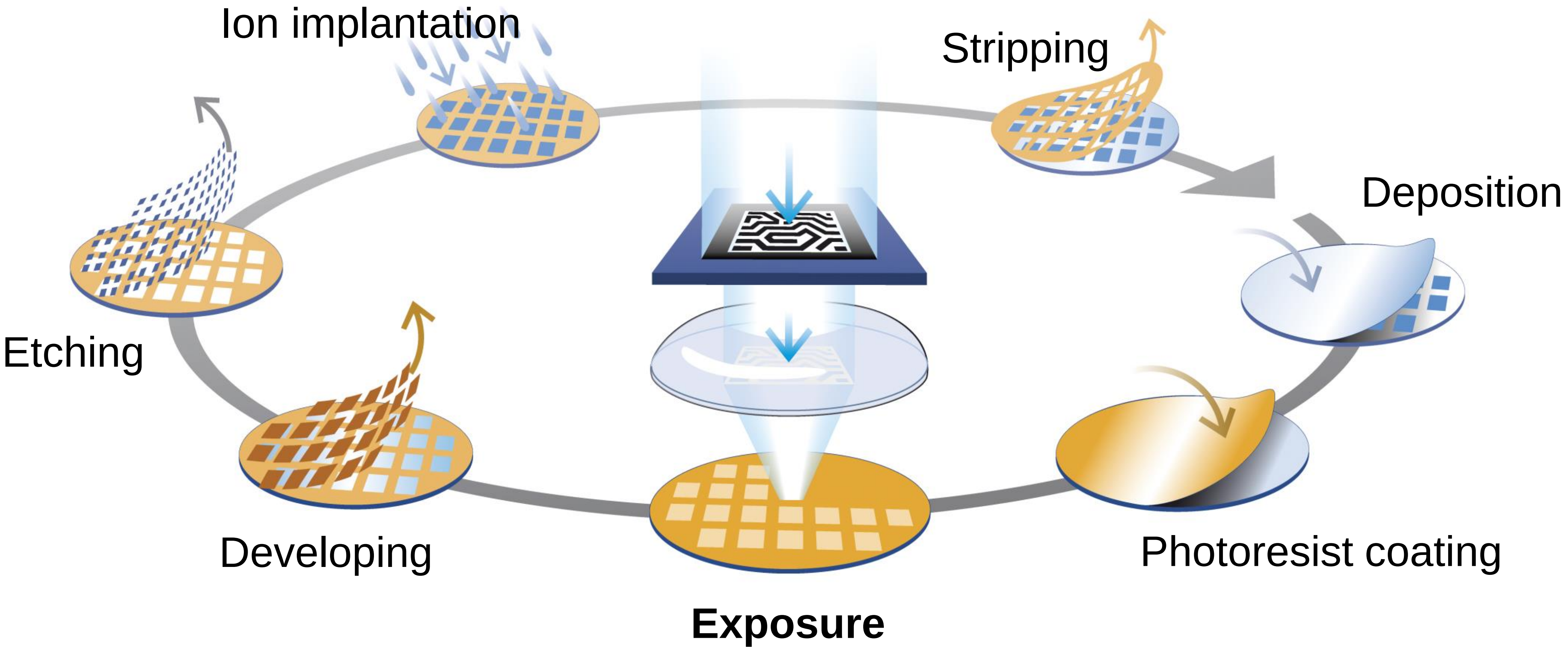


The first integrated circuit on silicon, on a wafer the size of a fingernail

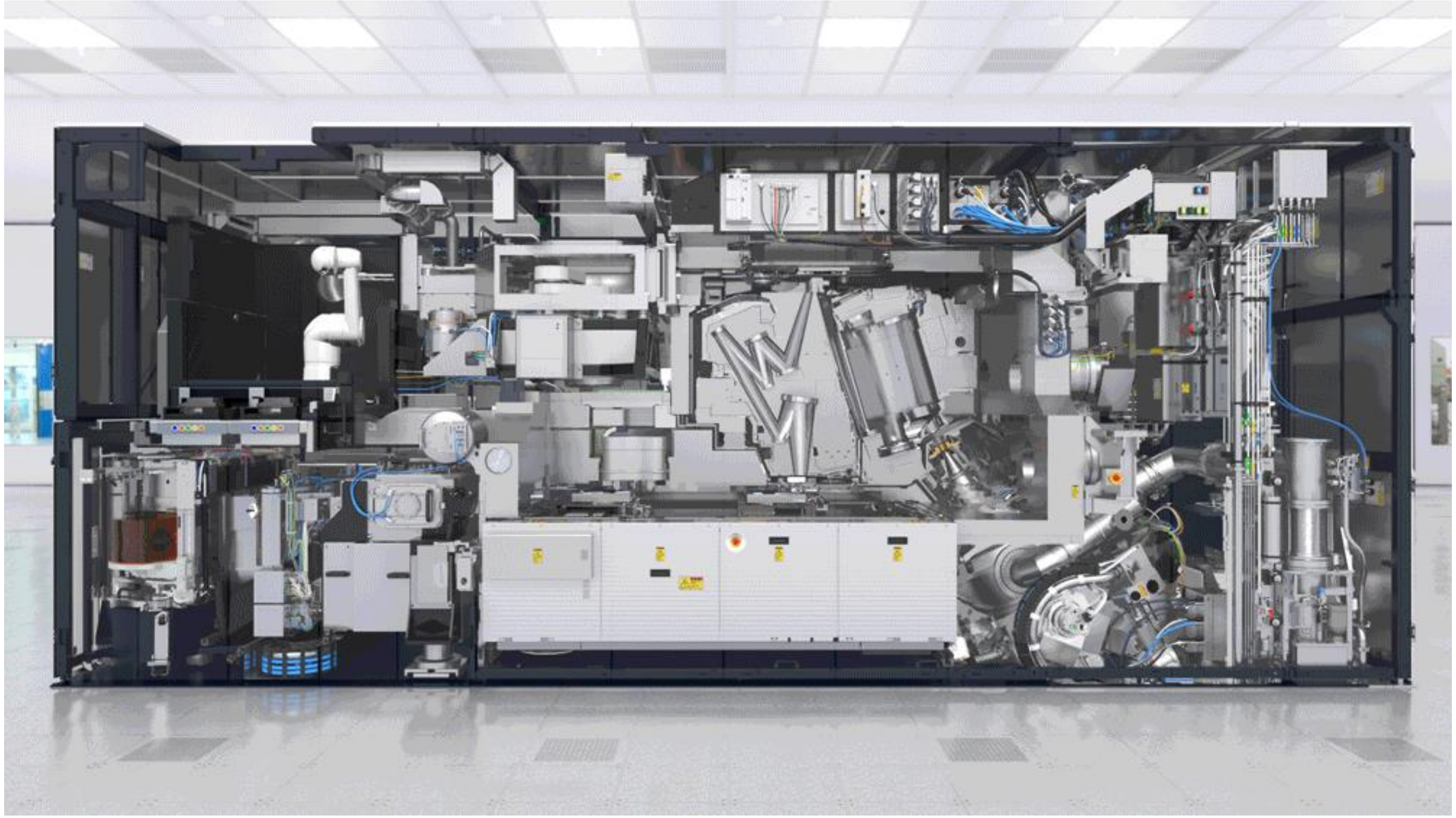
(Fairchild Semiconductor, 1959)

Today: Billions of transistors on the same area

The semiconductor chip manufacturing loop

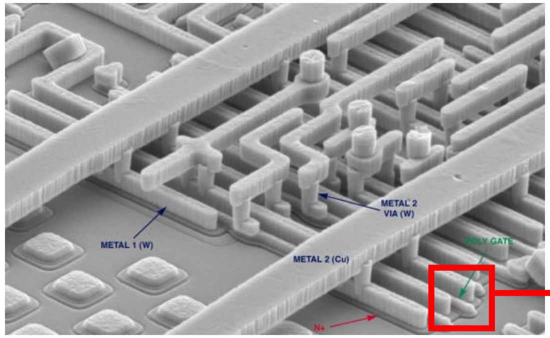


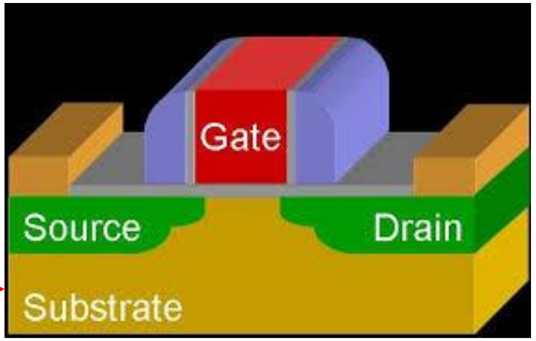
How a lithography system works



A chip is made of dozens of layers

Overlay (OV) and CD-Uniformity (CDU) are critical for device performance

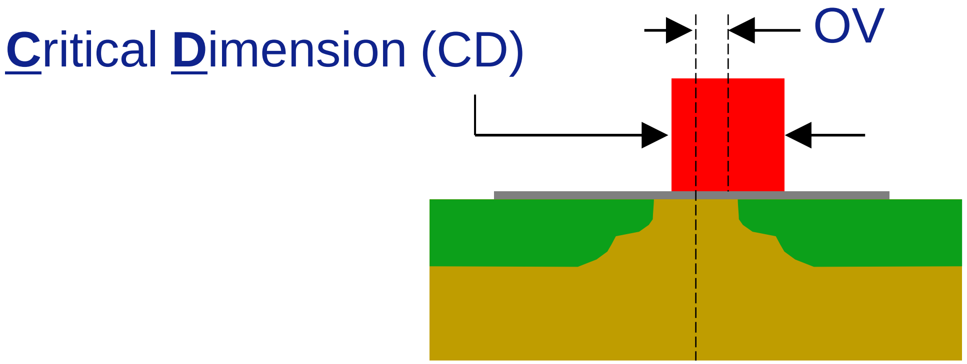




Rule-of-thumb:

OV ≈ 30 % of CD

CDU ≈10 % of CD



Today's devices: CD ≈ 7 nm

OV < 2.5 nm

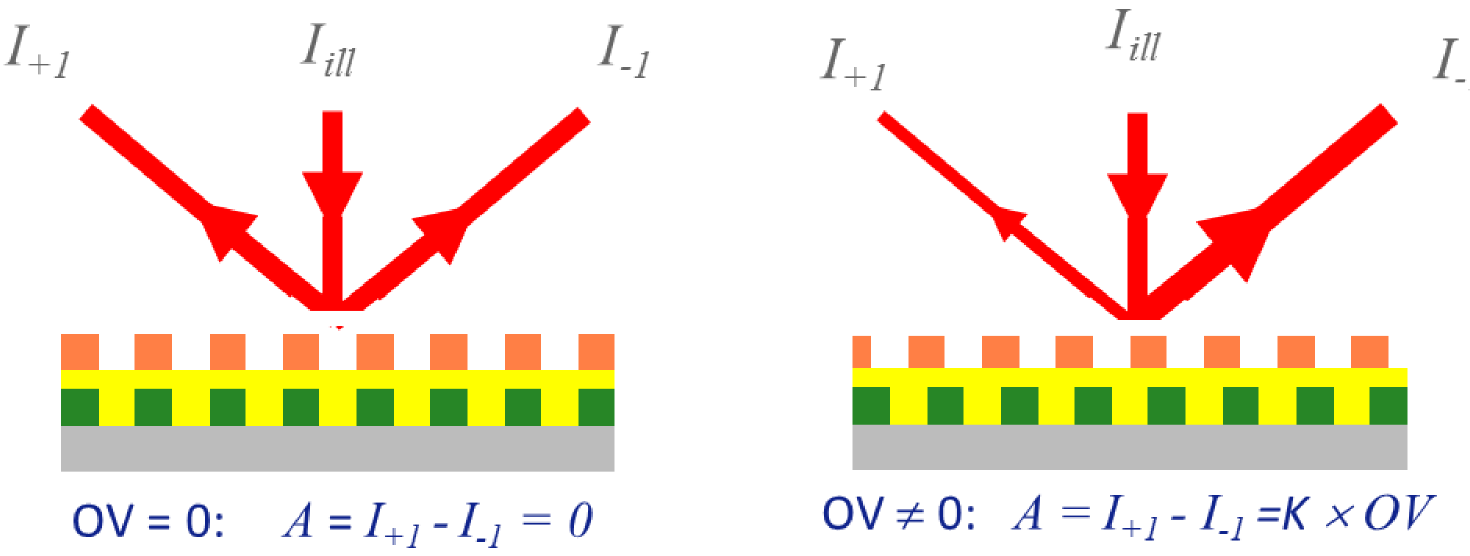
CDU < 0.8 nm

- this drives the need to control OV and CD during the patterning process
- in order to control OV and CD we must be able to measure overlay and CD
- optical metrology techniques that rely on image sensor technology are often used for this purpose

Overlay metrology

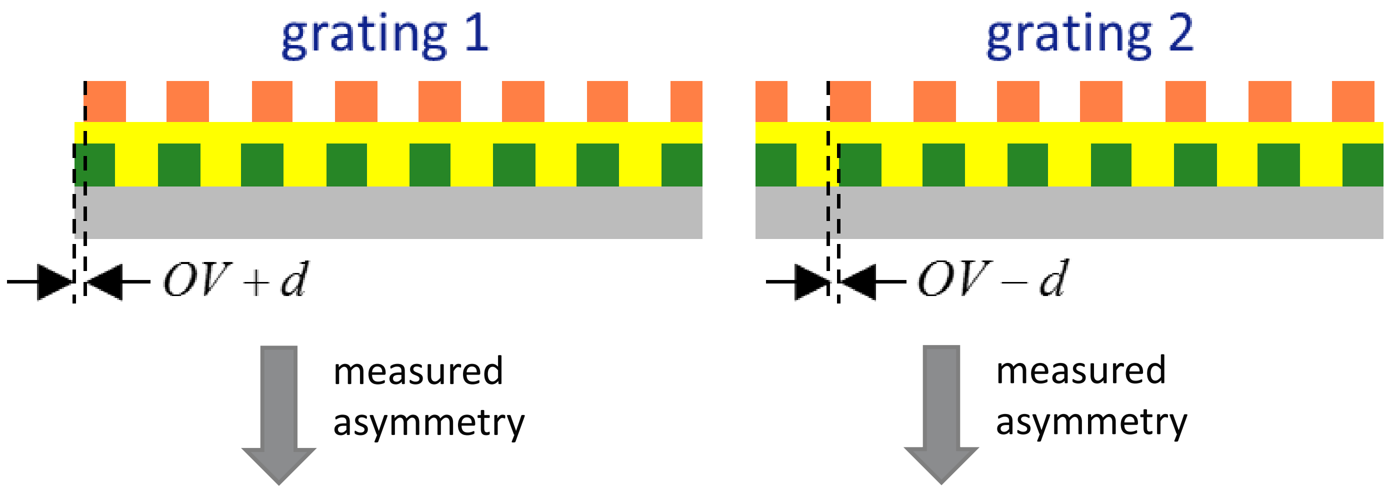
Diffraction-Based Overlay metrology (DBO) measures overlay with sub-nm precision

DBO measures an intensity unbalance between diffraction orders:



- overlapping gratings are used as a dedicated overlay metrology target
- typical grating size is ≈ 8×8 μm^2

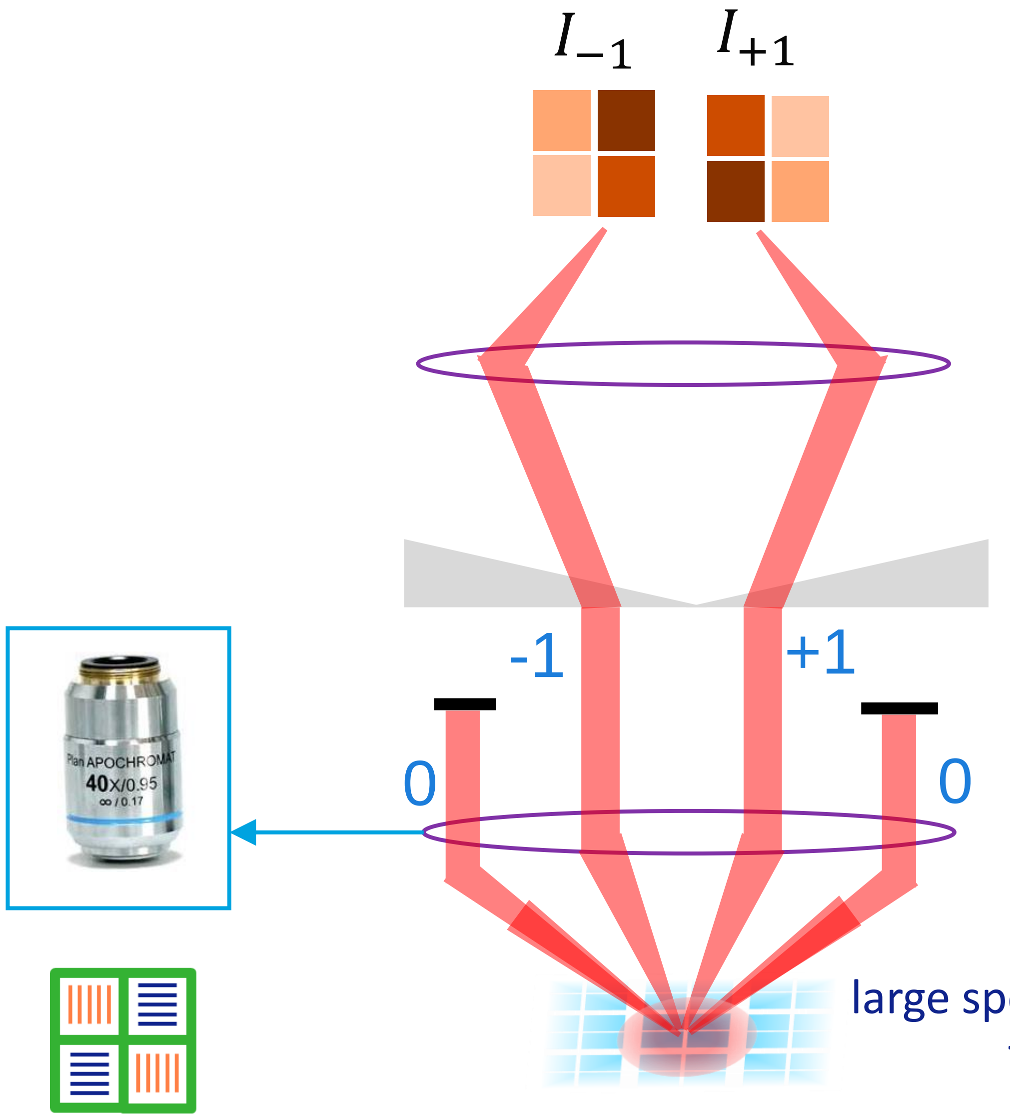
Overlay sensitivity *K* is stack-dependent and is eliminated with 2 "biased" gratings:



$$A_{+} = K(OV + d) \qquad A_{-} = K(OV - d)$$

$$OV = d\left(\frac{A_{+} + A_{-}}{A_{+} - A_{-}}\right)$$

Darkfield microscopy is used for diffraction-based overlay metrology



large spot illuminates the full target

ASML's YieldStar metrology tool

ASML

Good overlay is realized using optical overlay metrology in a control loop

Challenge: wafer deformation drives the need for dense overlay sampling

many small overlay targets must be measured per wafer lot for robust overlay control

film deposition on a wafer leads to in-plane wafer deformation

example:

3D-memory
> 100 layers

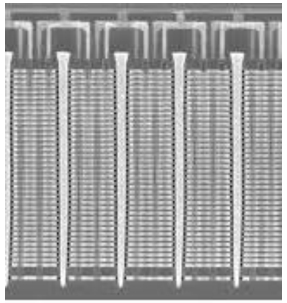
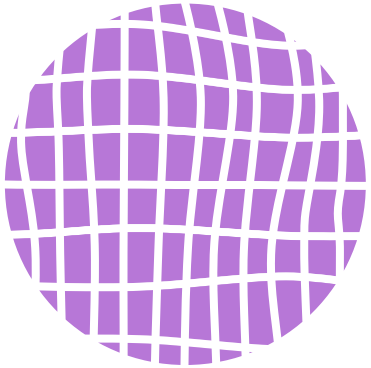
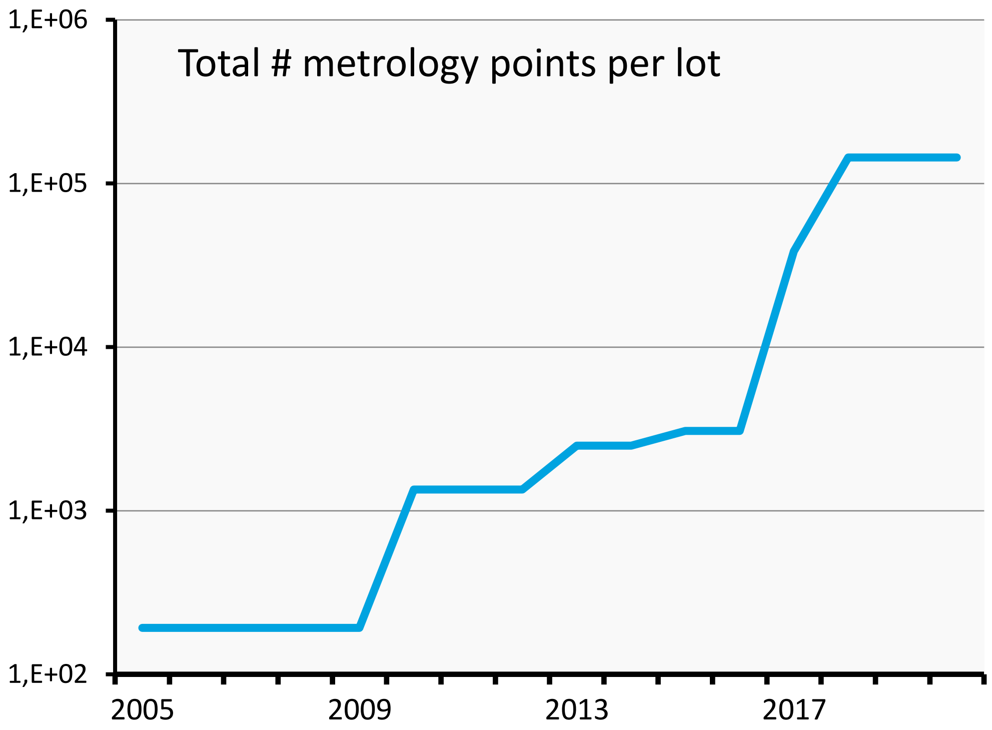


image of V-NAND flash array

wafermap with distorted wafer grid



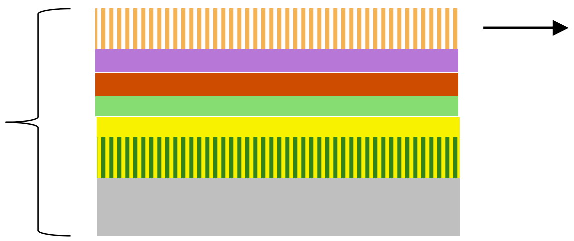


Another challenge: We need a large wavelength range and deal with low signals

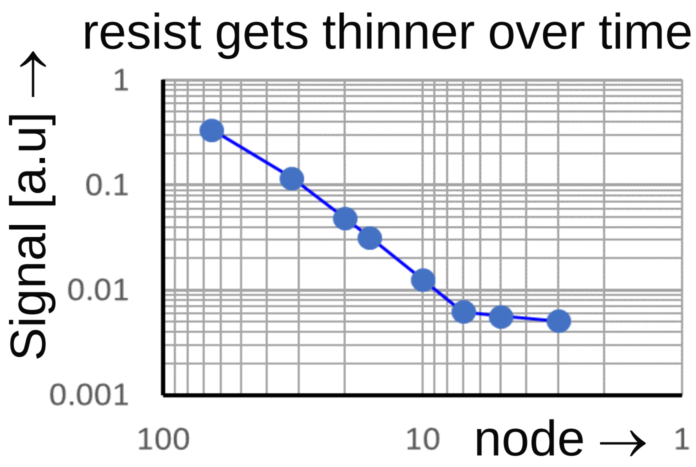
Large wavelength range

Novel materials with large variety in optical properties. This is driven by:

1. Novel device types
2. Trend towards 3D-integration



low signal



To summarize: significant challenges exist for future overlay metrology tools

1. Small acquisition time to allow dense sampling even in case of low signal levels
2. Capability to acquire high-resolution images at multiple wavelengths for process robustness
3. Large wavelength range to cover large application space and materials

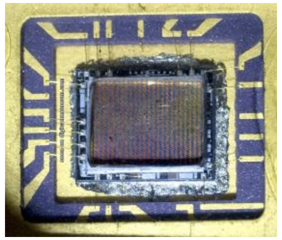
Progress in image sensor technology enables cost-effective solutions to these challenges

Impressive progress progress is being made in image sensor performance

pixel rate doubles ≈ every 3 year while improving performance as well

1975

Fairchild CCD

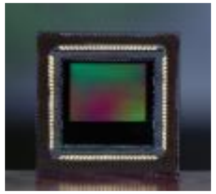


Kodak portable camera
100 × 100 pixels
10 frames / second

10^4 higher pixel rate

2015

Luxima cMOS

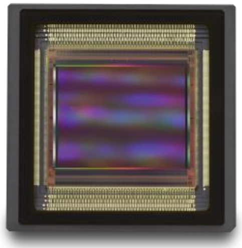


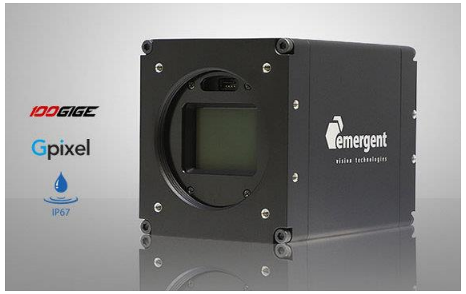
Optronis camera:
1300 × 1000 pixels
1050 frames / second

6× pixel rate

Q1-2021

gPixel cMOS





Emergent Vision Technologies:
5120 × 4096 pixels
400 frames / second

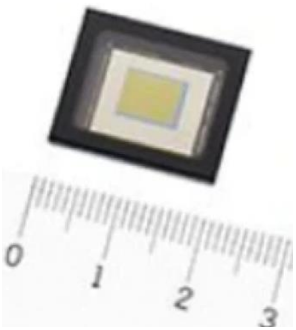
This progress in frame rate is beneficial for metrology that is driven by "speed-at-highest-performance"

Sony's SenSWIR™ technology significantly extends the wavelength range

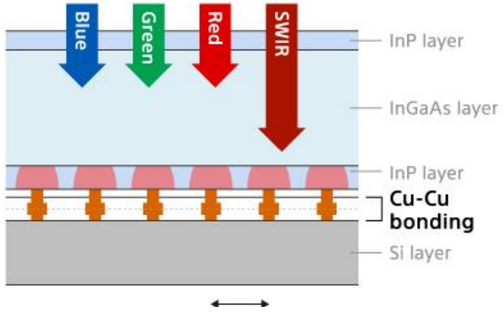
Cu-Cu bonding of InGaAs on Si offers small pixels with high quantum efficiency over larger wavelength range

Sony IMX990 CMOS image sensor can be a big step forward in metrology

small size

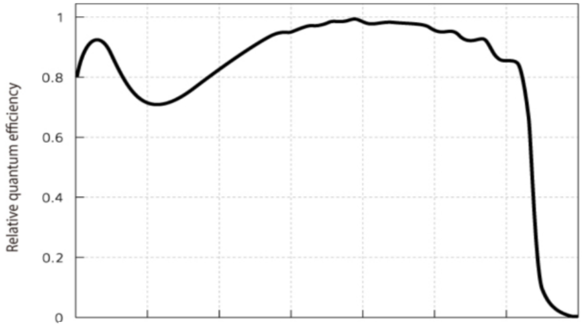


small pixels (Cu-Cu bonding)



5×5 μm² pixels

good QE from 400 – 1600 nm



400 λ→ [nm] 1800

High-definition Visible-SWIR InGaAs Image Sensor using Cu-Cu Bonding of III-V to Silicon Wafer.

S. Manda, R. Matsumoto, S. Saito, S. Maruyama, H. Minari, T. Hirano, T. Takachi, N. Fujii, Y. Yamamoto, Y. Zaizen, T. Hirano, and H. Iwamoto
Sony Semiconductor Solutions Corporation
email: Shuji.Manda@jp.sony.com

Published in: 2019 IEEE International Electron Devices Meeting (IEDM)

DOI: 10.1109/IEDM19573.2019.8993432

Graphene-CMOS integration combined with Quantum dots offers an alternative way to extend the wavelength range

See for example *Nature Photonics* **volume 11**, pages 366–371 (2017); https://doi.org/10.1038/nphoton.2017.75

ARTICLES
PUBLISHED ONLINE: 29 MAY 2017 | DOI: 10.1038/NPHOTON.2017.75
nature photonics

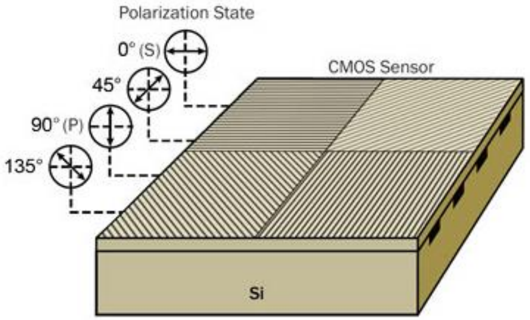
Broadband image sensor array based on graphene–CMOS integration

Stijn Goossens[1†], Gabriele Navickaite[1†], Carles Monasterio[1†], Shuchi Gupta[1†], Juan José Piqueras[1], Raúl Pérez[1], Gregory Burwell[1], Ivan Nikitskiy[1], Tania Lasanta[1], Teresa Galán[1], Eric Puma[1], Alba Centeno[2], Amaia Pesquera[2], Amaia Zurutuza[2], Gerasimos Konstantatos[1,3*] and Frank Koppens[1,3*]

Cameras using this technology are already available:

Polarization-sensitive image sensors are also of interest for metrology applications
robustness and precision of overlay metrology can be very polarization dependent

Sony PolarSens IMX253MZR enables parallel imaging of multiple polarization states



Each pixel has its own wiregrid polarizer

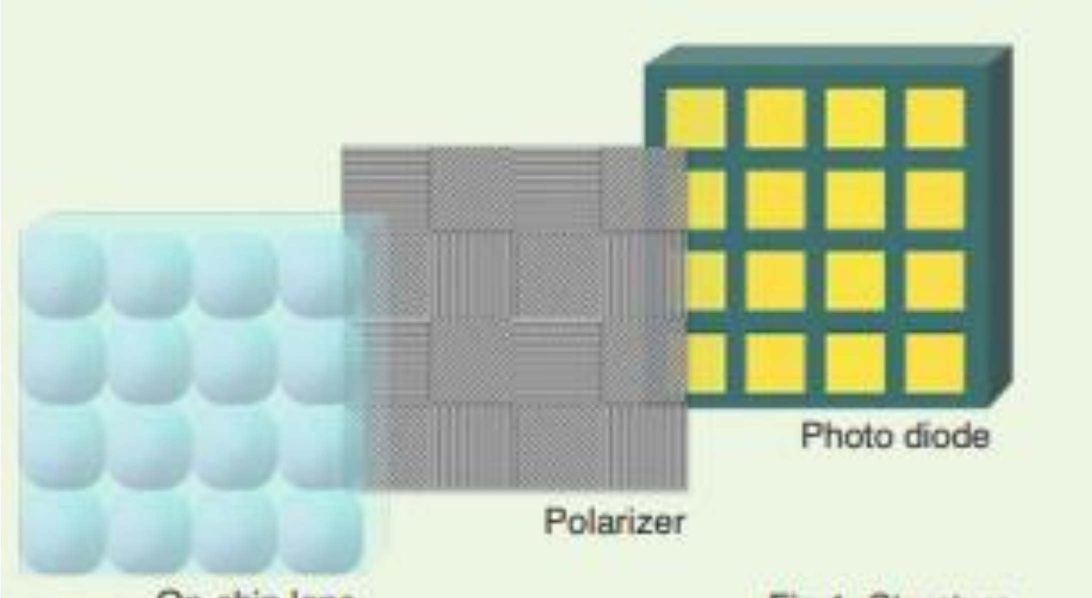


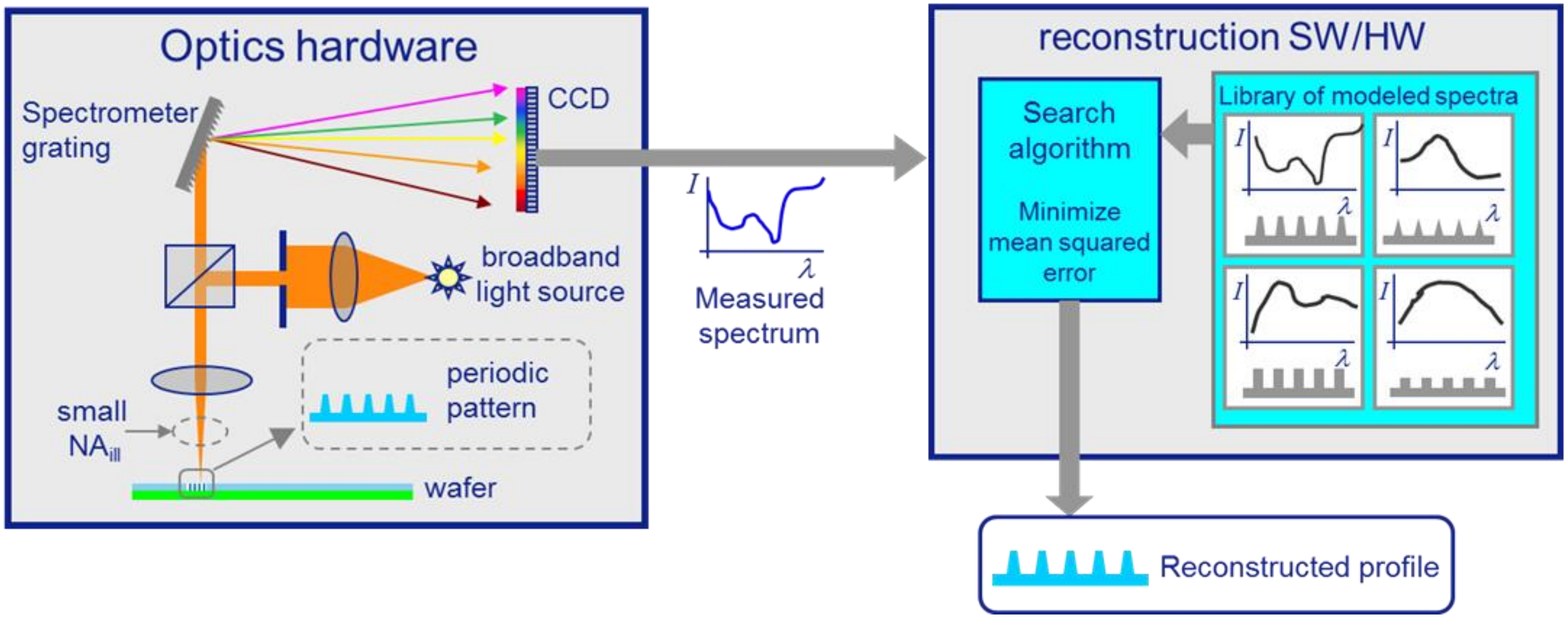
Fig.1. Structure

IMX250_264_253MZR_MYR_Flyer_en.pdf (sony-semicon.com)

CD metrology

CD metrology can be done with spectroscopic scatterometry

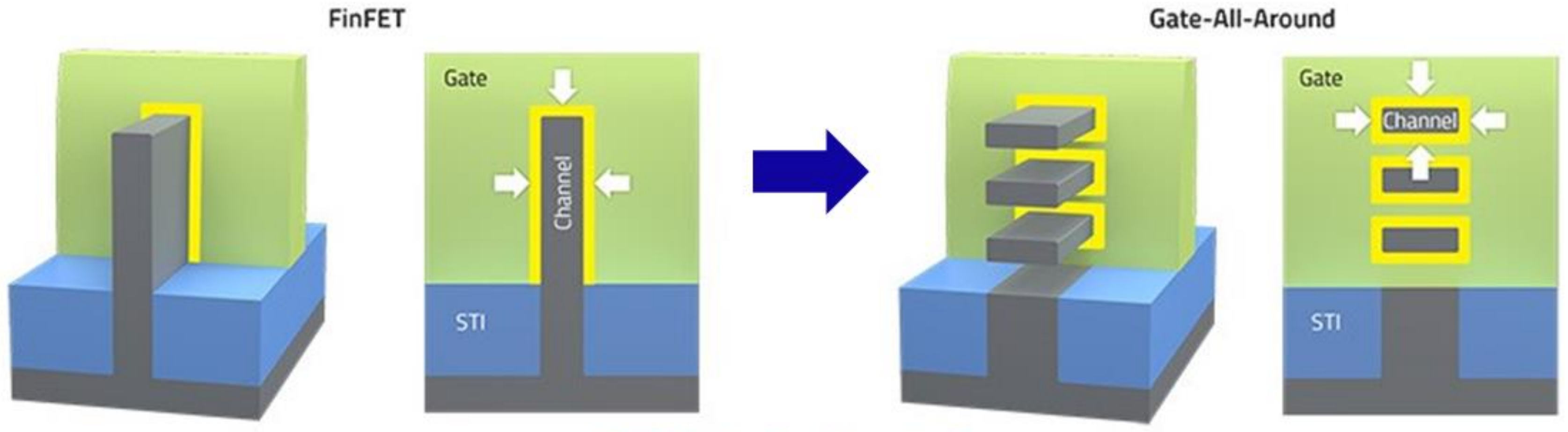
also called: Optical-CD (OCD)



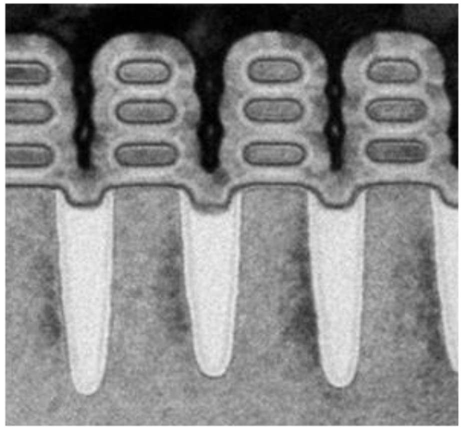
- ➢ OCD is often used in combination with e-beam metrology (“CD-SEM”)
- ➢ Today’s OCD tools are challenged by smaller and more complex device patterns

Gate all around (GAA), “nanosheet” transistors

new 3D devices pose significant metrology challenges



FinFETs Give Way to Gate-All-Around | Lam Research

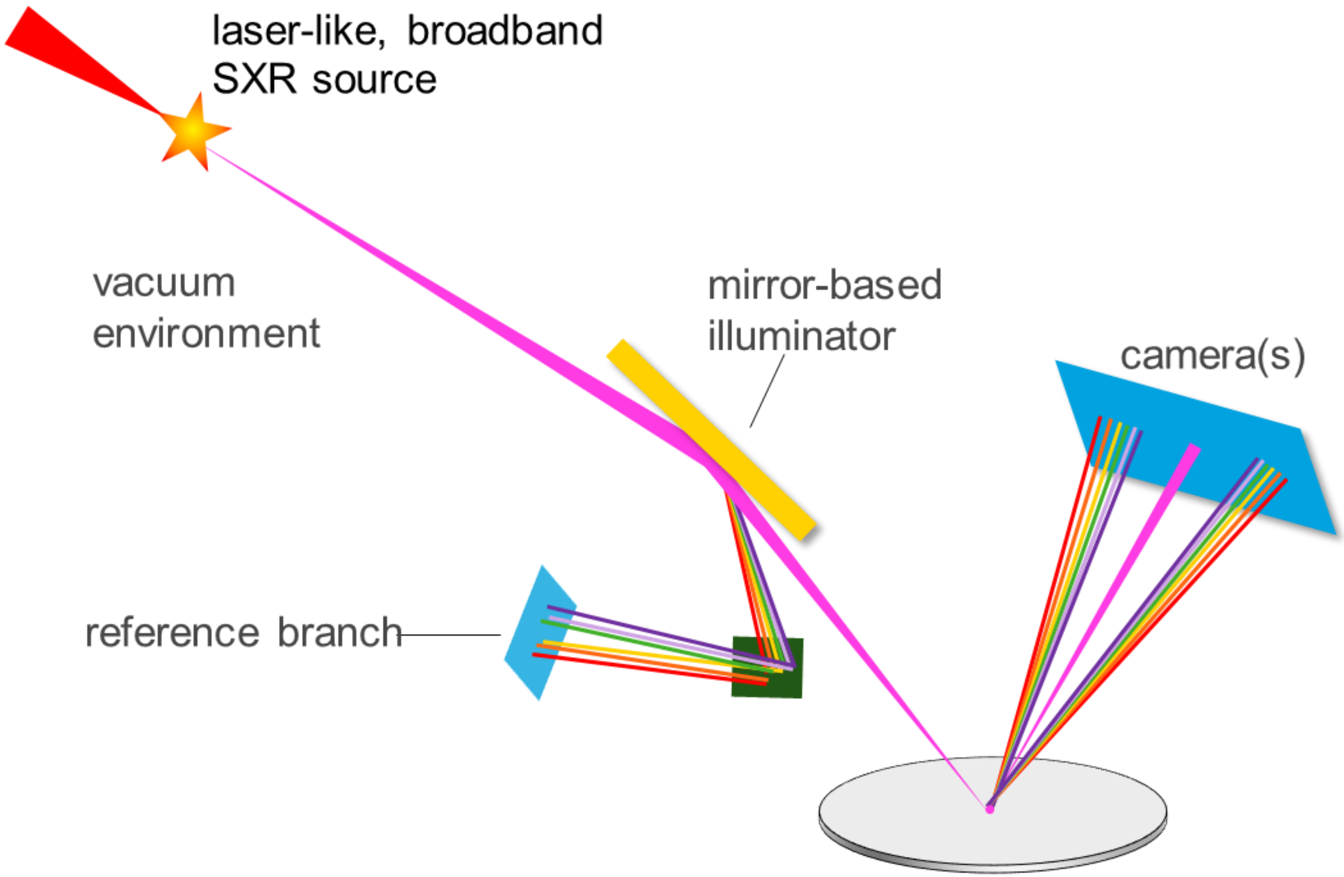


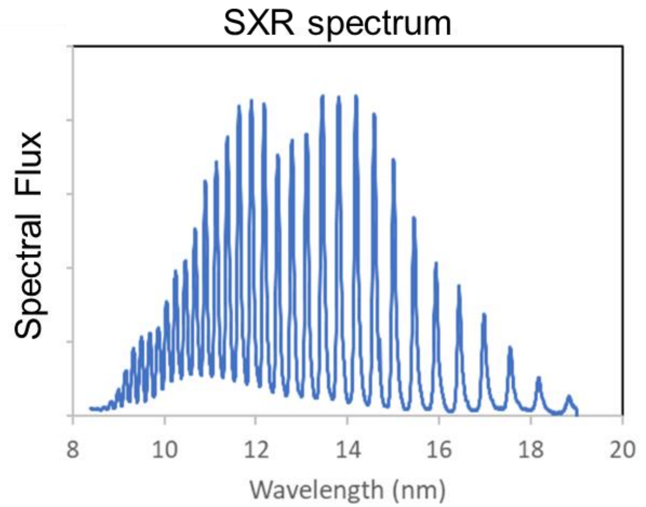
The Nanosheet Transistor Is the Next (and Maybe Last) Step in Moore's Law - IEEE Spectrum

- Metrology solutions are needed to enable monitoring/control of **individual** nanosheets.
- Most traditional techniques only give **average** properties.

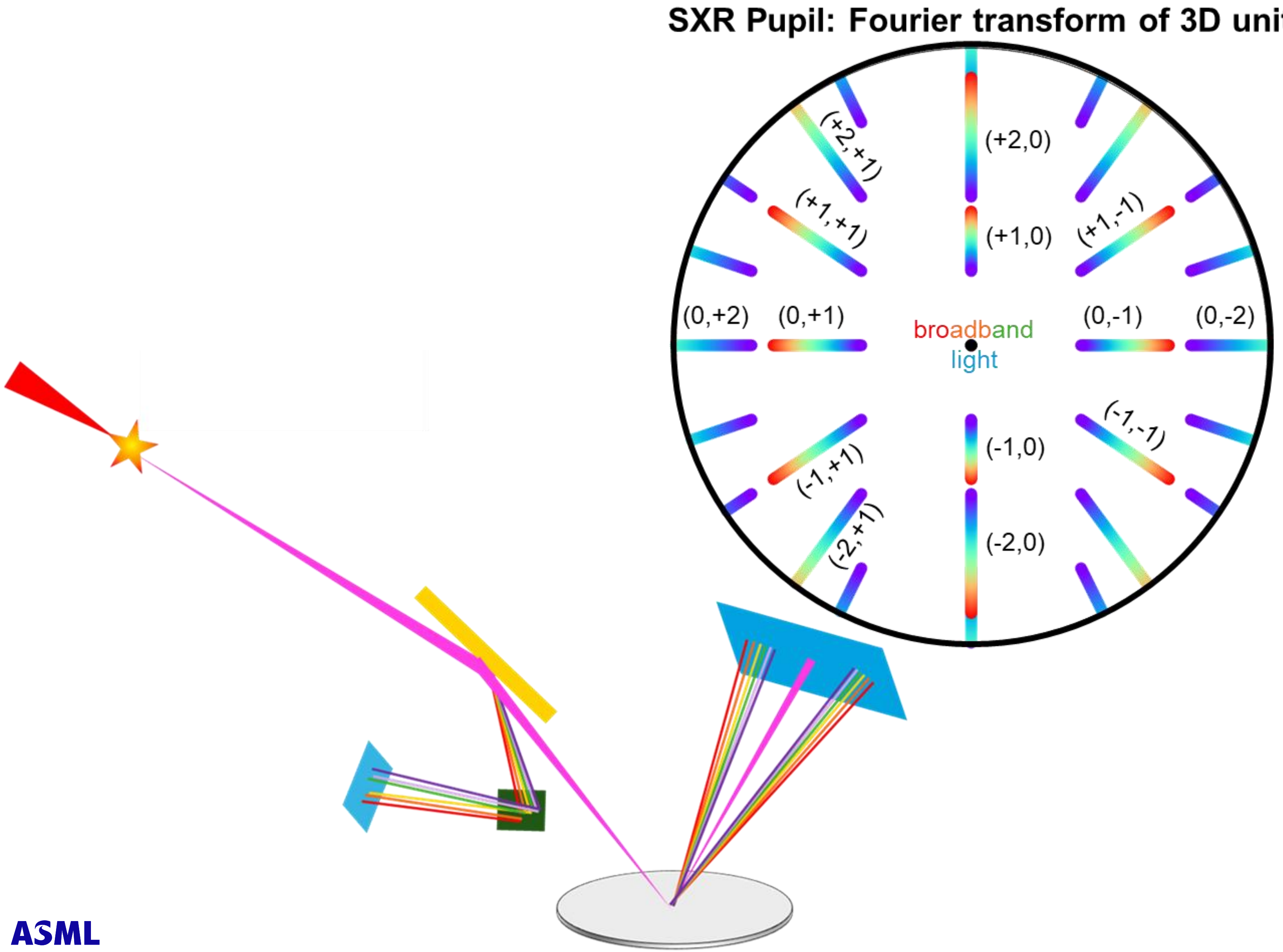
Soft X-Ray (SXR) scatterometry Concept

Broadband, high-brightness, short-wavelength scatterometry.

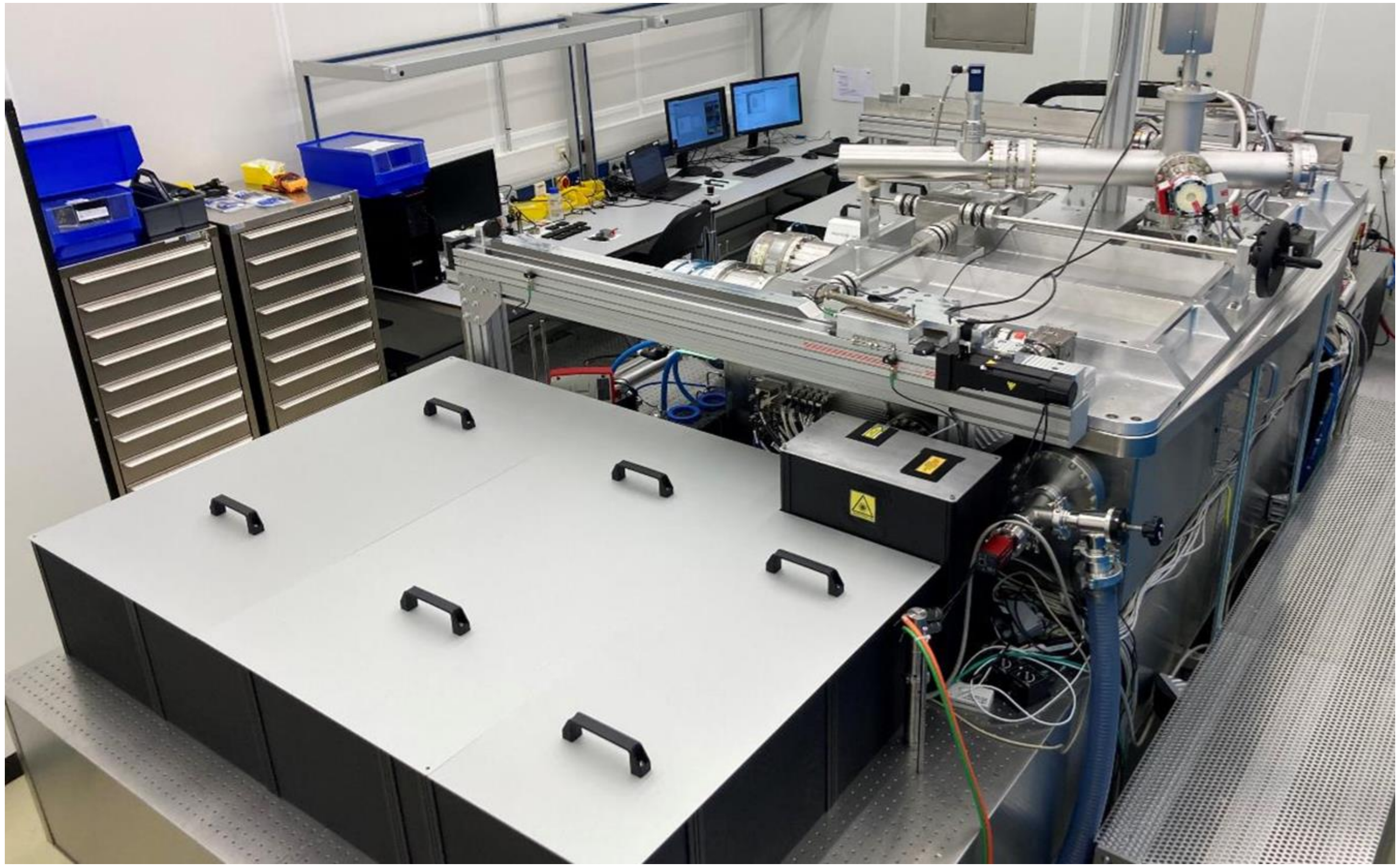




SXR Signal Formation: propagating diffraction orders carry rich information



Proof-of-concept of SXR-scatterometry at ASML



spectrum on array of GAA devices

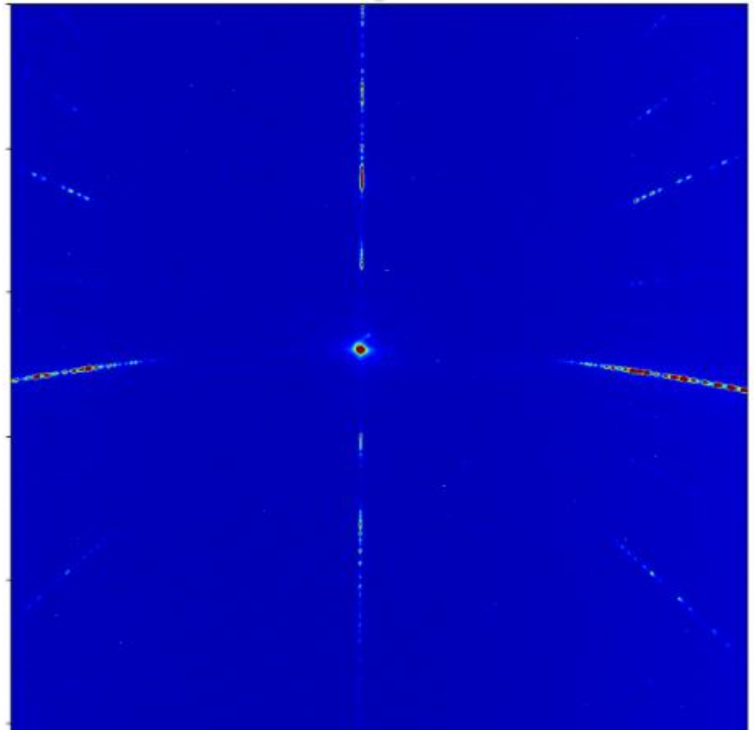


Image sensor challenges:

- only few pixels receive light
- read out time
- full-well capacity

Summary

- The aggressive reduction in device dimensions has resulted in significant challenges in measuring and controlling CD and overlay
- Image sensor innovations have enabled solutions that help addressing these challenges
- However, Moore's law will result in smaller and more complex device pattern resulting in the need for even more advances in image sensor technology

Thank You