USE OF SYNCHROTRONS IN SEMICONDUCTOR R&D

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SEMICONDUCTORS ⇨ INTEGRATED CIRCUITS (IC)

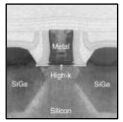
HVM

Min. feature size: 1.5 μm

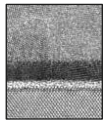
Min. feature size: 0.8 μm

Dennard scaling

90 nm: SiGe

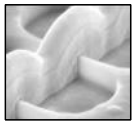


45 nm HKMG



2D→3D

22 nm: Fin-FET



Fin-FET→GAA

2 nm: GAA-FET 2025

Images from: List of Intel processors - Wikipedia

1980s | 1990s | 2000s | 2010s | 2020s

Image from: ENIAC - Wikipedia

Computer in 1946

- 18000 vacuum tubes
- Weighed more than 25 tons
- 5000 operations per second
- Cost $ 500,000 (~$7 million today)

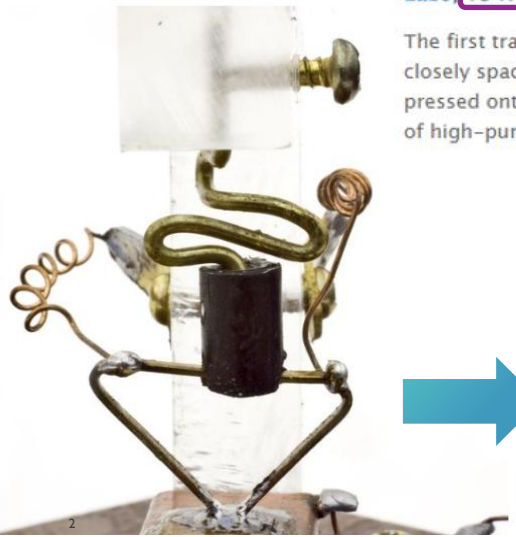


Image from: Inventing the Transistor - CHM Revolution (computerhistory.org)

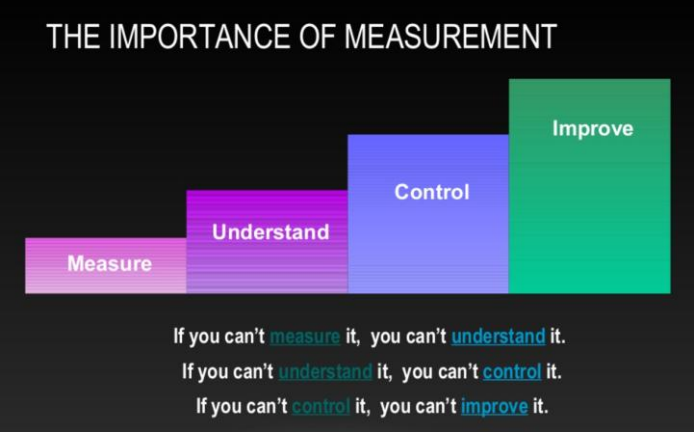
First transistor (replica), Bell Labs, 1947

The first transistor used two closely spaced gold contacts pressed onto the surface of a slab of high-purity germanium.

1970s

1971: Intel 4004

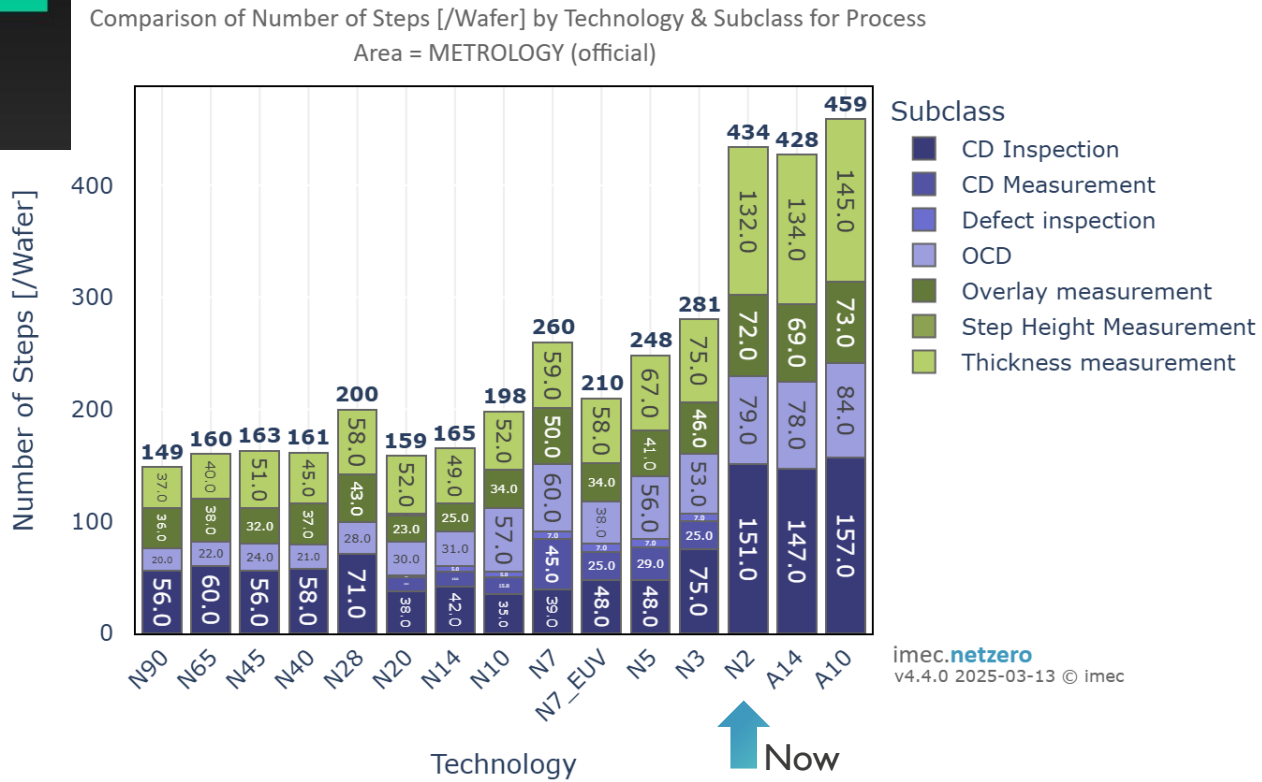
Image from: Intel 4004 - Wikipedia



THE NEED FOR MEASUREMENT

Metrology need

- HVM: Process control →
  - Enabling ROI
- R&D: Understanding
  - Enabling next-gen ICs to remain competitive



IMEC FORECASTS

- CMOS scaling for memory, logic & interconnect
  - New architectures, 3D, D2W, …
  - New materials, HZO, IGZO, …

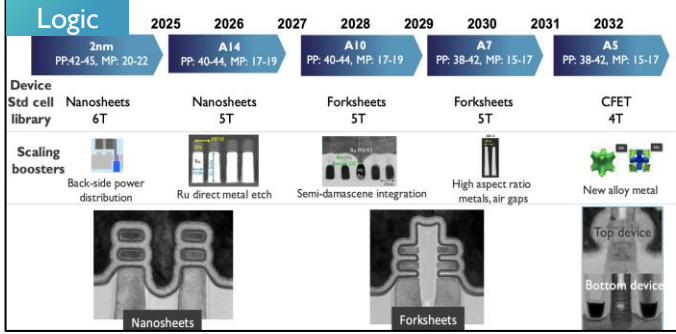
  More complex analysis needed faster

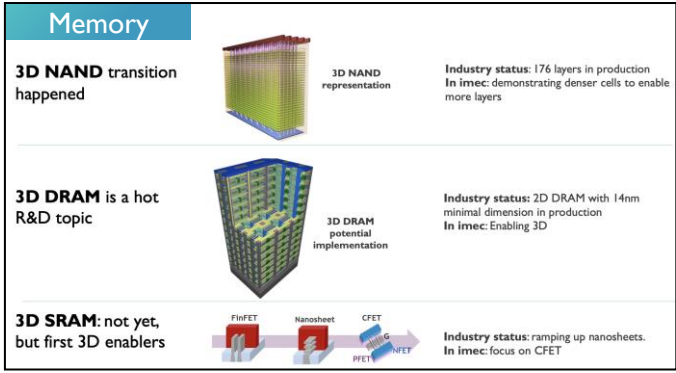
- Beyond CMOS for memory, logic & interconnect
  - 2D materials
    - Graphene
    - TMDs
    - CNTs

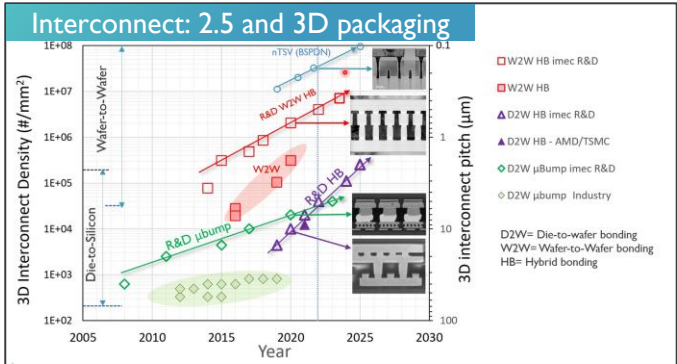
  New measurement requirements (mobility, spin, spin dynamics, …)

- Beyond von Neuman (quantum compute)
  - Josephson junction?
  - Si spin qubit, … ?

  Required metrologies to be defined







PHOTOELECTRON EMISSION TECHNIQUES (XPS, PES, …)

IN SYNCHROTRON, LAB & FAB ENVIRONMENTS

Synchrotron / Lab (offline)

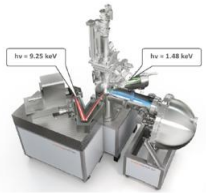
- Fundamental understanding
- Path finding (exploration)
- Implementation (testing)

Primarily supports R&D

Lab (offline) / Fab (inline)

- Process development
- Process refinement
- Quality control

Primarily supports production



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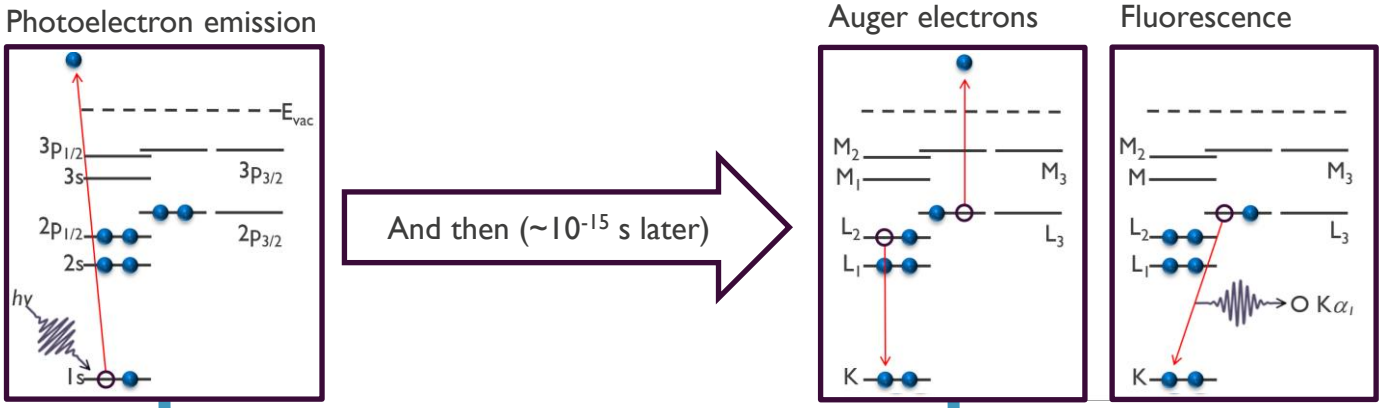
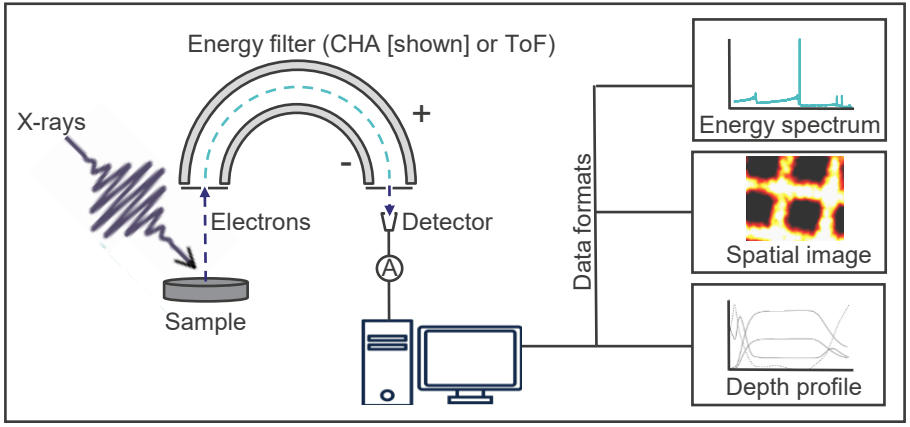
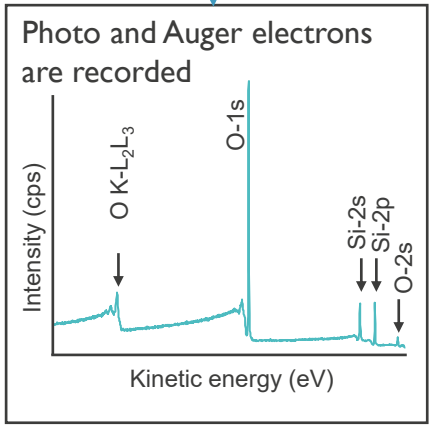
PHOTOELECTRON EMISSION (BASES OF XPS, PES, …)



EDX
XRF
XES
etc.





PES inclusive of XAFS and ARPES, are also photoelectron techniques.

These are primarily carried out at synchrotrons.

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XPS VERSUS PES…

BOTH STEM FROM THE SAME PHYSICAL PROCESS (PHOTOELECTRON EMISSION)

XPS (including HAXPES)

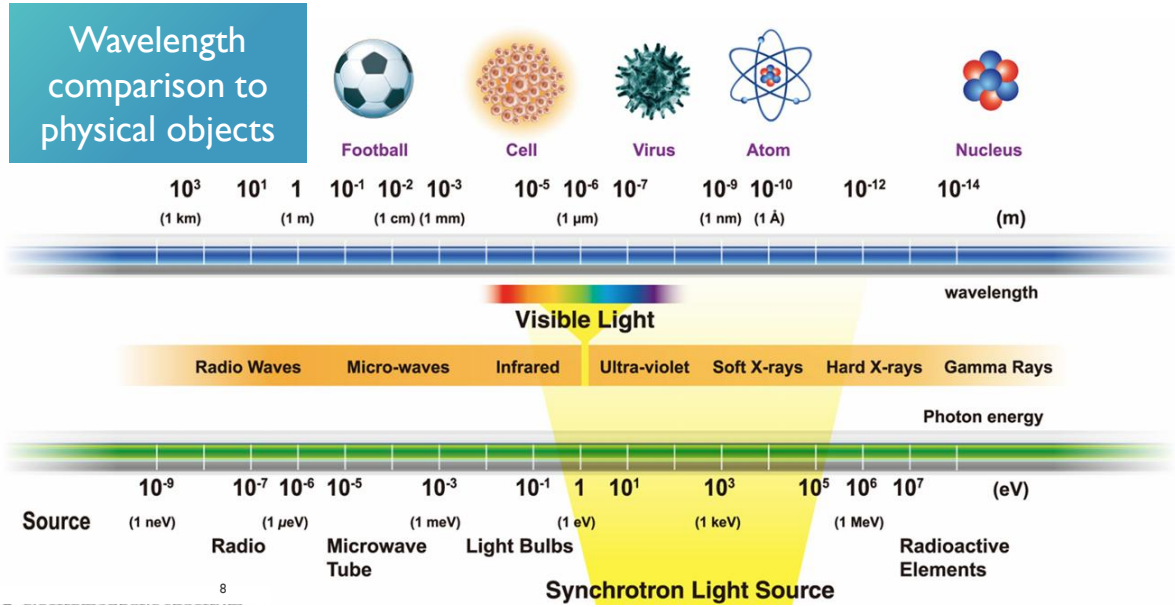
- Developed for carrying out quantitative surface analysis inclusive of speciation analysis
- A photon beam that is of fixed energy and that is unpolarized is optimal
- Anode sources are best as these are cheap and compact

PES (including XAFS & ARPES)

- Developed for carrying out experiments in condensed matter physics
- A photon beam that can be scanned in energy and/or polarized is optimal
- Synchrotron sources deemed best (highest flux and flexibility)

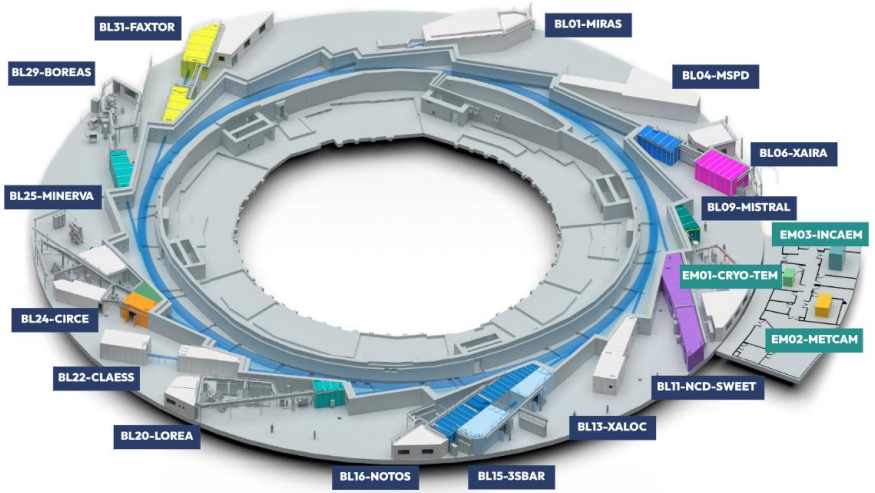
WHAT ARE SYNCHROTRONS

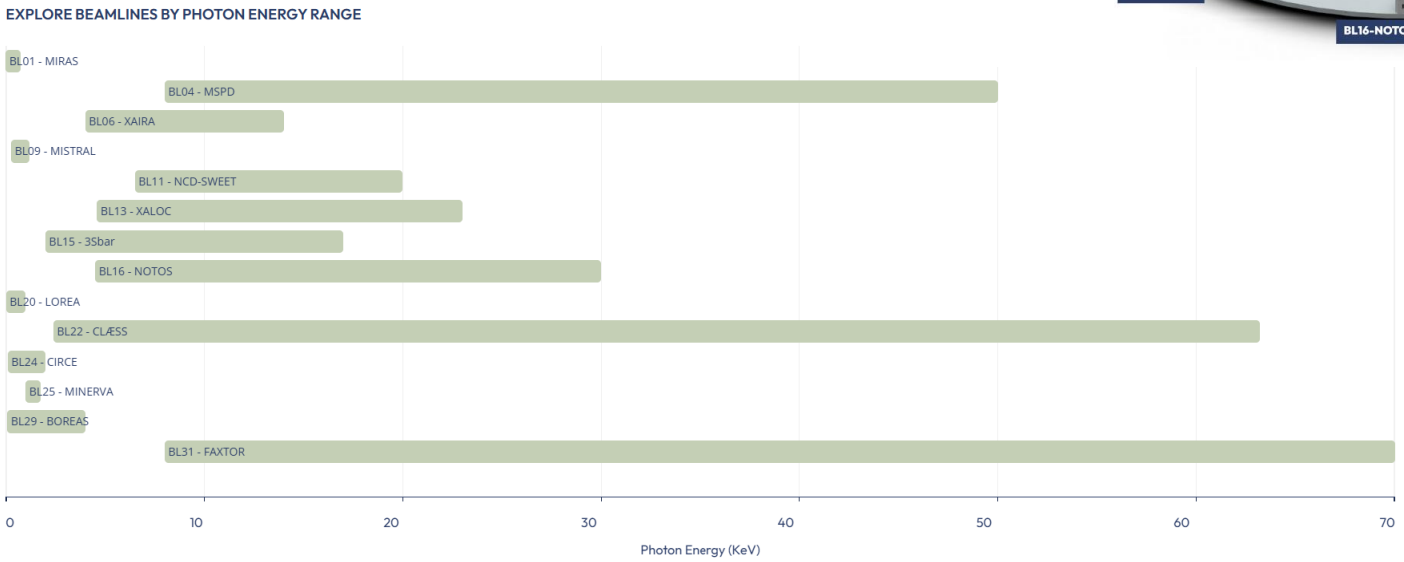
- These are among the brightest man-made light sources that extends into the X-ray regime
- These enable for the most sensitive metrologies
  - Orders of magnitude more sensitive than lab/fab-based metrology platforms
- But these are large facilities
  - Orders of magnitude larger than lab/fab-based platforms

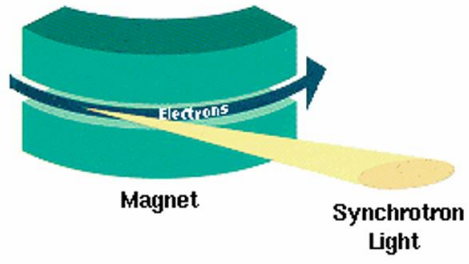


THE ALBA SYNCHROTRON

- Photons are produced as electrons traveling at near relativistic speeds are forced to follow near circular paths

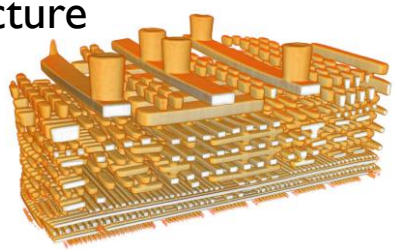




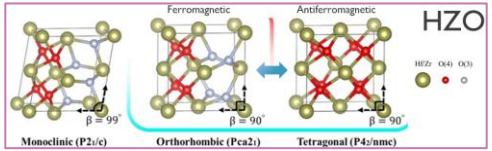


EXPERIMENTAL POSSIBILITIES

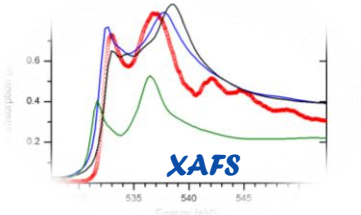
- Imaging of physical structure
  - XCT to ptychography

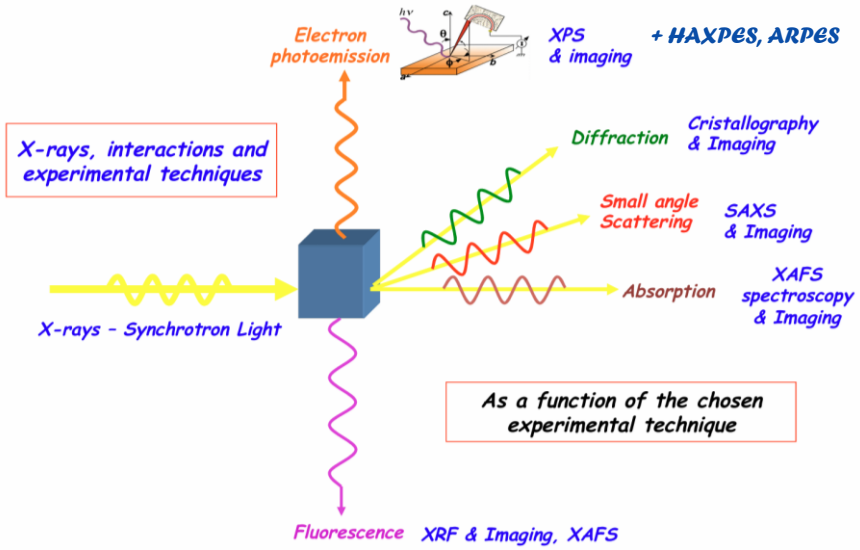


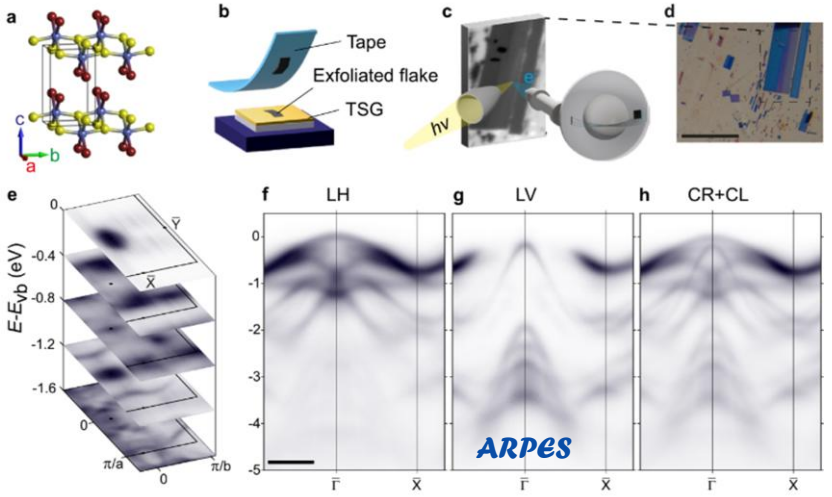
- Lattice structure (crystalline)
  - Diffraction to photoelectron holography



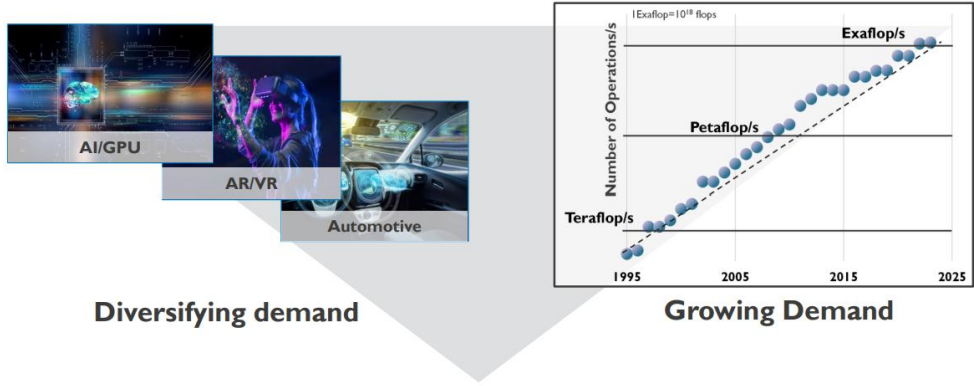
- Chemistry (speciation, electronic structure)
  - XAFS to ARPES, …



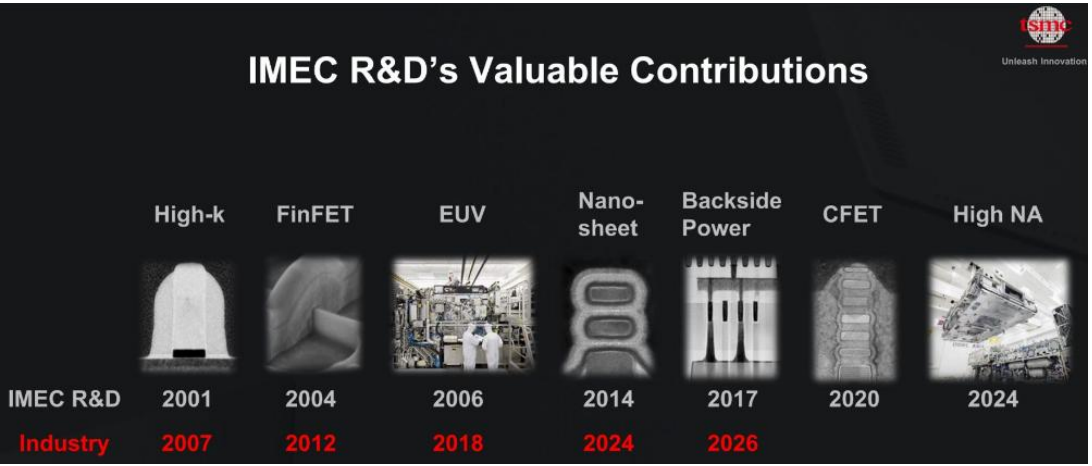




FUTURE



- More demand (AI driven)
- More diversity (TMDs, CNTs, …)
- Imec R&D starts ~10 years earlier
  - Builds on academic R&D which starts even earlier



Longer term

- Spintronics in logic and memory
  - Note: Spintronics is already used in Magneto-resistive RAM (MRAM)
- Move from ferromagnetic to antiferromagnetic memory? (is altermagnetism the next frontier?)

embracing a better life