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EECS251B : Advanced Digital Circuits and Systems

Lecture 9 – Modern Technologies

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2022 ISSCC: Feb. 19-26

(virtual)

Main program, forums, tutorials, events

Recap

- Technology affects circuit design
  - Optimized for standard cell, SRAM density
  - Recent scaling not uniform per layer
- Lithography restricts layer orientation, length quantization
  - Favors layout regularity
  - Has implications on variability
- FinFETs add more restrictions (width quantization)

Lithography Implications

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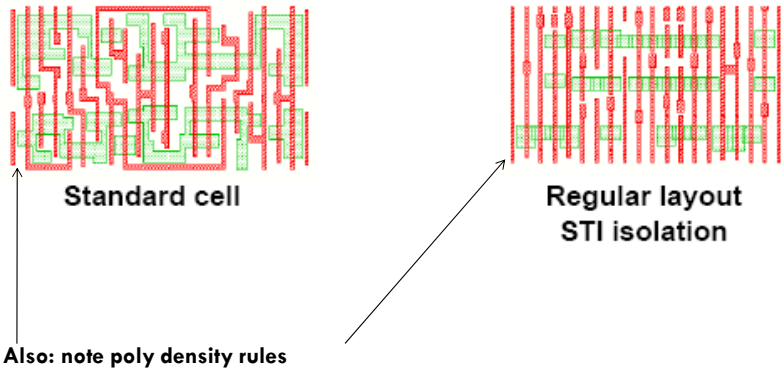
Litho (4): Restricted Design Rules (~45nm Node)



J.Hartmann, ISSCC'07

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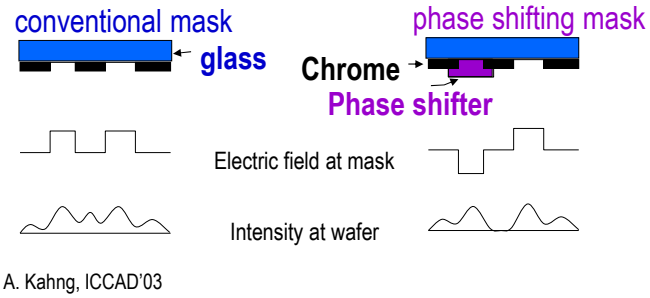
Litho (5): Phase-Shift Masks

- Phase Shifting Masks (PSM)
  - Creates interference fringes on the wafer →Interference effects boost contrast →Phase Masks can make extremely small lines



A. Kahng, ICCAD'03

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Litho (6): Double Patterning

- Double exposure double etch
  - Double exposure double etch
  - Pitch split, litho-etch-litho-etch (LELE)
- Self-aligned methods
  - Self-aligned double patterning
  - Self-aligned quadruple patterning

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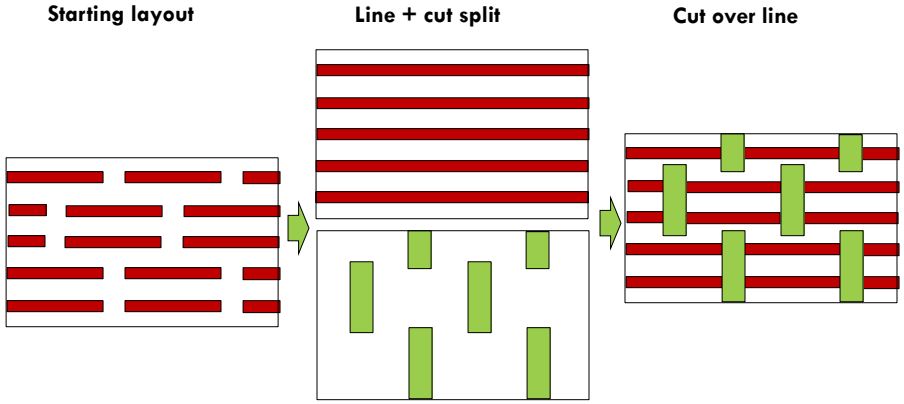
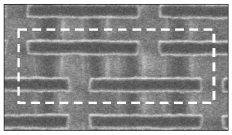
Double-Exposure Double-Etch



Result:



SRAM image from K. Mistry, IEDM'07

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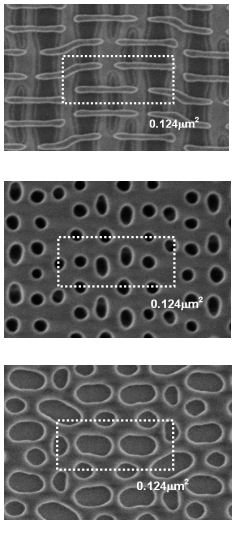
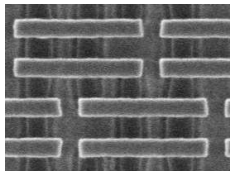
32nm Examples

Single exposure



Double exposure



IEDM'08

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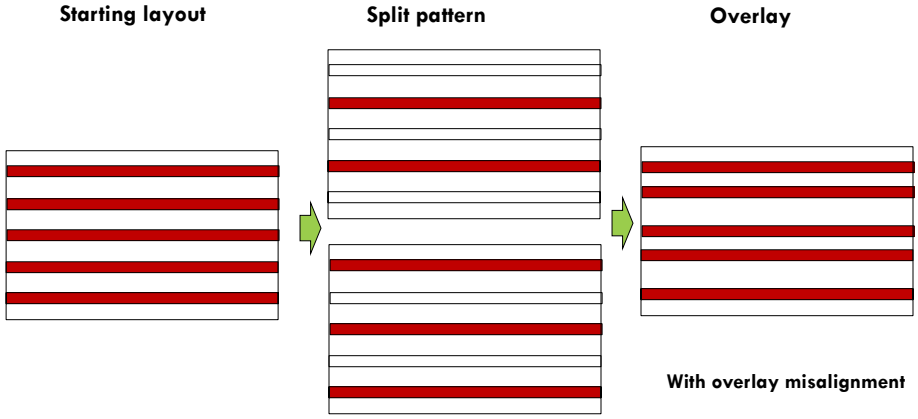
Pitch-Split Double Exposure



Also called litho-etch-litho-etch (LELE)

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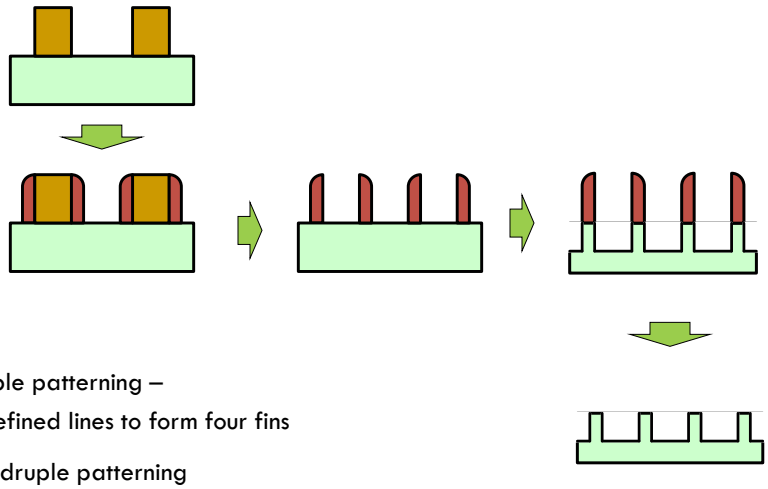
Self-Aligned Double Patterning (SADP)



- SADP: Double patterning –
  Two litho-defined lines to form four fins
- SAQP: Quadruple patterning

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Litho: Design Implications

- Forbidden directions
  - Depends on illumination type
  - Poly lines in other directions can exist but need to be thicker
- Forbidden pitches
  - Nulls in the interference pattern
  - Multiple patterning
- Forbidden shapes in PSM, multiple-patterning
- Assist features
  - If a transistor doesn't have a neighbor, let's add a dummy

Litho: Current Options (Beyond 10nm)

- Multiple patterning
  - NA ~ 1.2-1.35
- EUV lithography
  - λ = 13.5nm

Normalized wafer cost adder*	
SE	1
LELE	2.5
LELELE	3.5
SADP	2
SAQP	3
EUV SE	4
EUV SADP	6

*TEL™ Internal calculation

Cost adder reduced with increased power/throughput of EUV

A. Raley, SPIE'16

Modern Bulk/finFET/FDSOI processes

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Some of the Process Features (Designer's Perspective)

1. Shallow-trench isolation
2. High-k/Metal-gate technology
3. Strained silicon
4. Thin-body devices (28nm, and beyond)
5. Copper interconnects with low-k dielectrics

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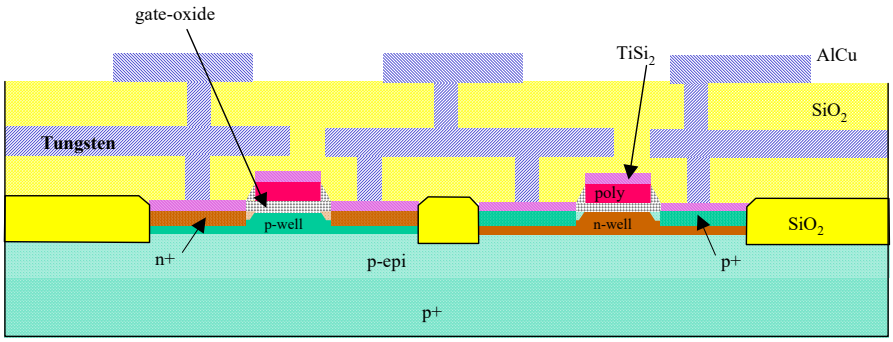
1. Shallow Trench Isolation

- Less space needed for isolation
- Some impact on stress



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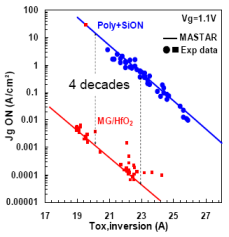
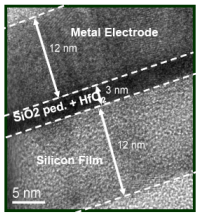
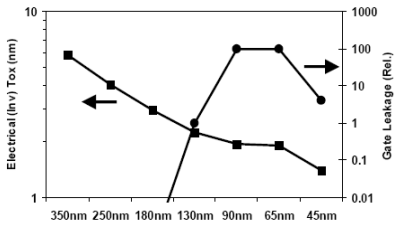
2. Hi-k/Metal gate



Gate leakage can be improved by 4 decades by using High-K/Metal Gate Stack

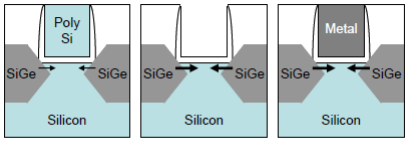


TEM X-section of HighK /Metal Gate Stack on FDSOI



K. Mistry, IEDM'07

Replacement gate technology (Intel)



Form Transistors | Remove Poly Si | Deposit Metal Gate

S. Natarajan, IEDM'08

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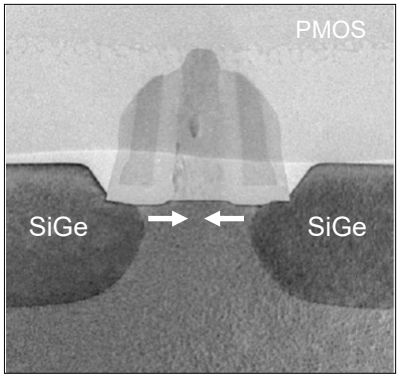
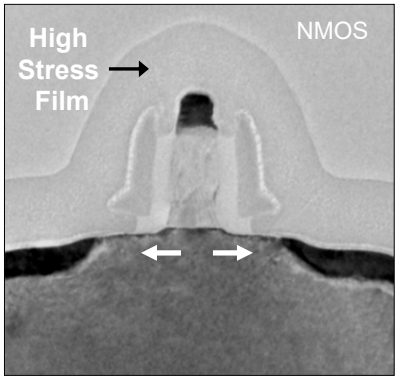
3. Strained Silicon





Compressive channel strain
30% drive current increase
in 90nm CMOS

Tensile channel strain
10% drive current increase
in 90nm CMOS

Intel

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Intel's Strained Si Numbers

Performance gains:

	90 nm		65 nm	
	NMOS	PMOS	NMOS	PMOS
μ	20%	55%	35%	90%
IDSAT	10%	30%	18%	50%
IDLIN	10%	55%	18%	80%

S. Thompson, VLSI'06 Tutorial

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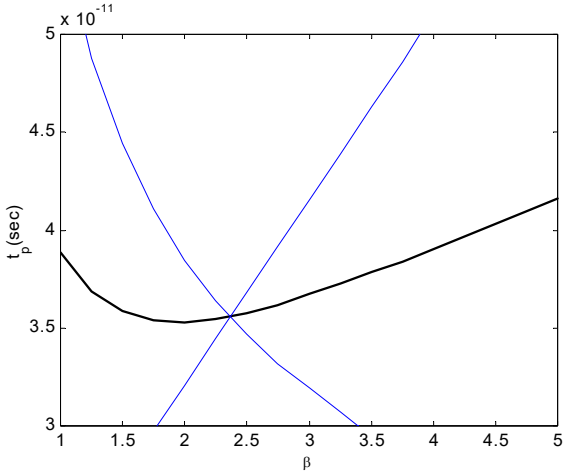
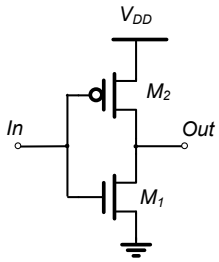
β-Ratio

- β=Wp/Wn



From Rabaey et al, DIC, 2nd ed, for 250nm CMOS



$W_2 \sim 2$

$W_1 = 1$

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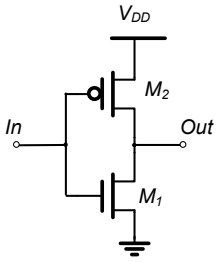
Strained Silicon: Implications on Sizing

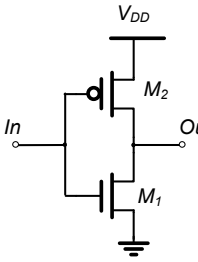
- No strain



$W_2 \sim 2$

$W_1 = 1$

- Strained Si



$W_2 = 1.6$

$W_1 = 1$

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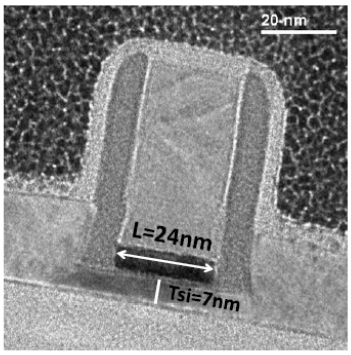
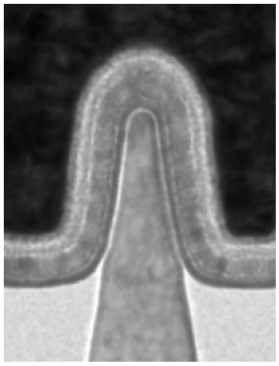
5. Thin-Body Devices

- 28nm FDSOI



N. Planes, VLSI'2012

- 22/14nm finFET

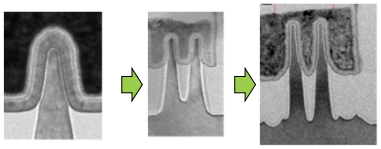


C. Auth, VLSI'2012

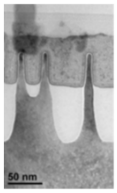
5. FinFETs

- FinFET scaling

22/20nm **16/14nm** **10nm**

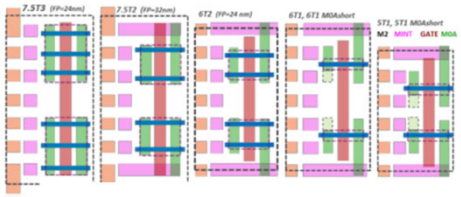


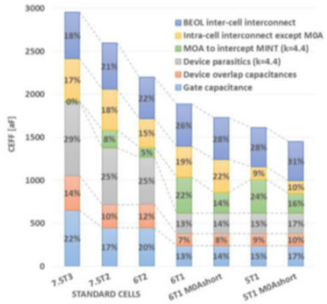
Intel, IEDM'12 **Intel, VLSI'14** **Intel, IEDM'17**



- N-P spacing

- Track scaling

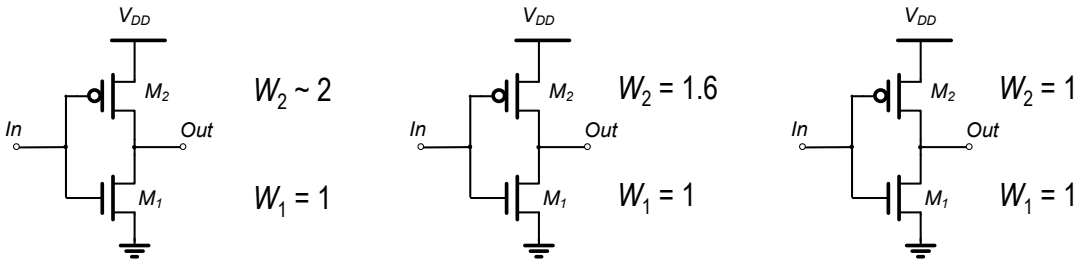




Garcia Bardon, IEDM'16

FinFETs and gate P/N sizing

- The use of strain closes the gap between N and P on currents to ~1:1
- No strain
- Strained planar Si
- FinFET



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5. FDSOI

2012 2013 2014 2015 2016 2017

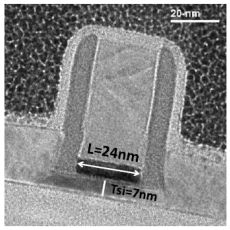
28FDSOI (STMicroelectronics)

28FD-SOI (Samsung)

22FDX (GLOBALFOUNDRIES)

12FDX (GLOBALFOUNDRIES)

18FDS (Samsung)



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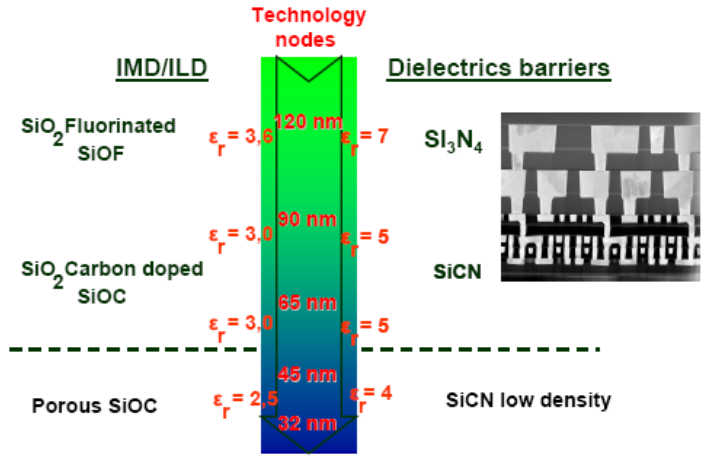
5. Interconnect



J. Hartmann, ISSCC'07

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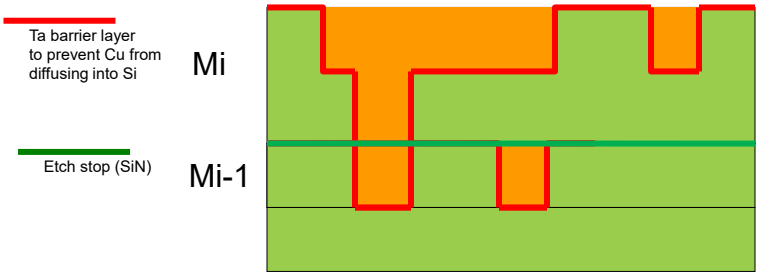
Interconnect: CMP

Cu interconnect: Dual damascene process



- Metal density rules (20%-80%)
- Slotting rules
- Also: Antenna rules

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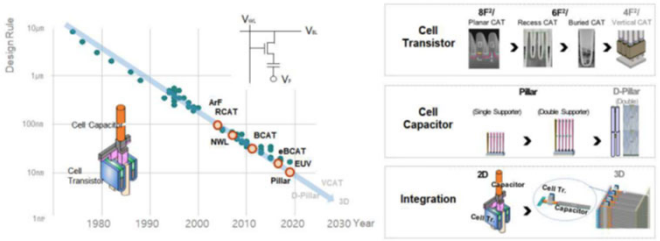
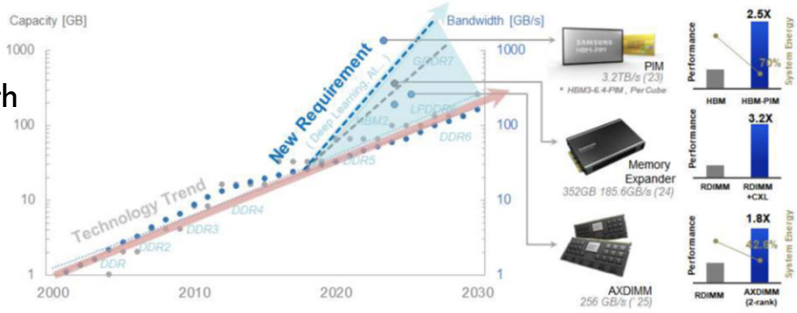
DRAM Scaling



- DRAM density scaling:
  - Transistor
  - Cap
  - Integration

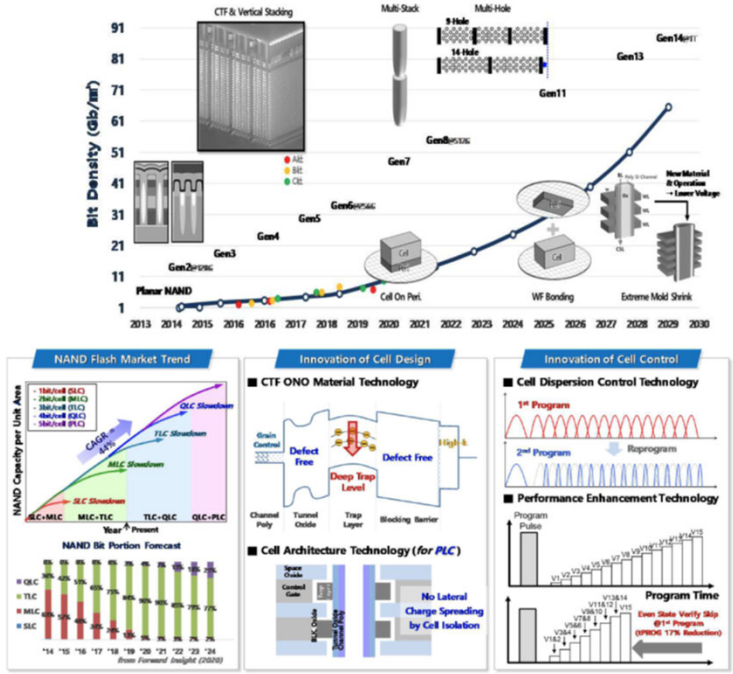
- DRAM capacity/bandwidth



K.Kim, IEDM,'21

Flash Scaling

- Density and architecture scaling

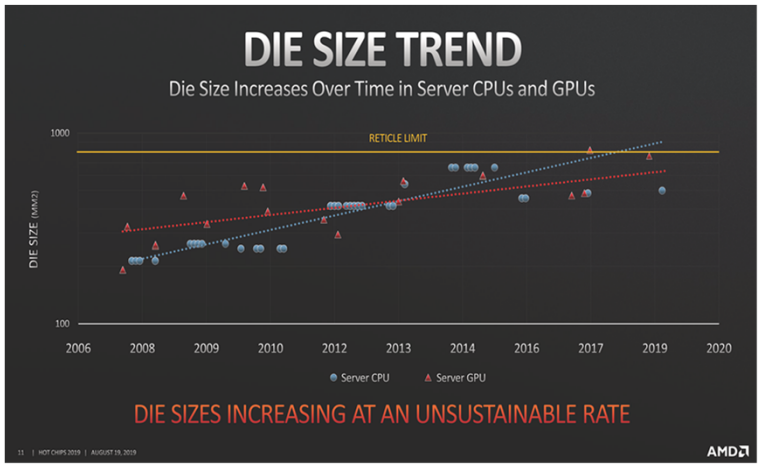


K.Kim, IEDM,'21

Chiplets

Die Size Trend

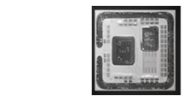
- To increase functionality and performance, die sizes have been increasing
  - Yield, cost tradeoffs

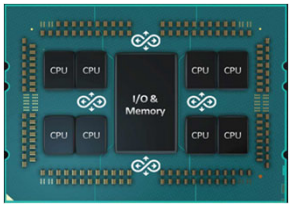


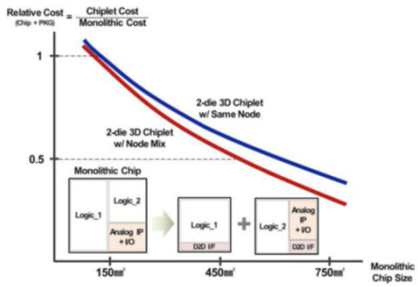
L. Su, HotChips'19 Keynote

Migration to Chiplets

- Split the product into multiple dies
  - Same or mixed technologies
- Increase functionality, performance @ lower cost
- Mix technologies



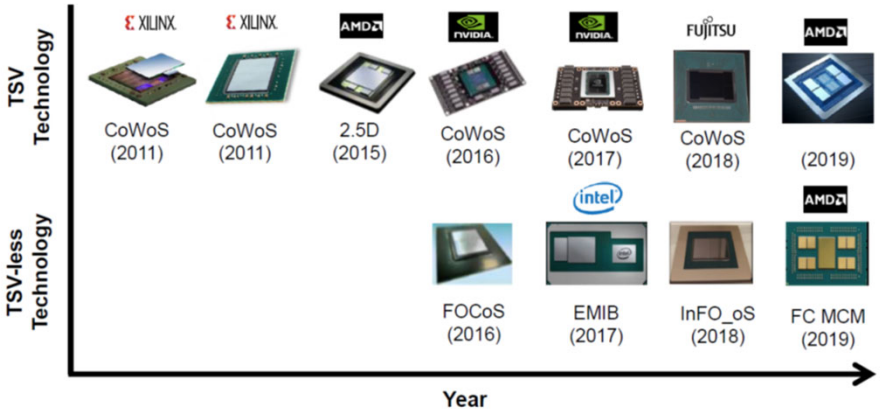




Plot from K.Kim, IEDM'21

2.D Chiplet Interfaces

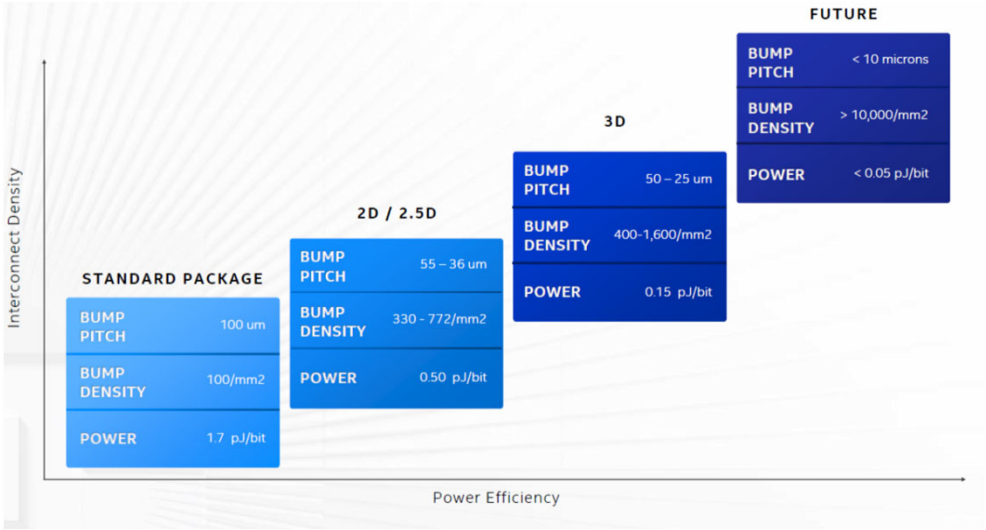
- High-denisity interfaces have been evolving over the past decade



K.C.Yee, D.Yu, IEDM'20 Short Course

Interconnect Density Scaling

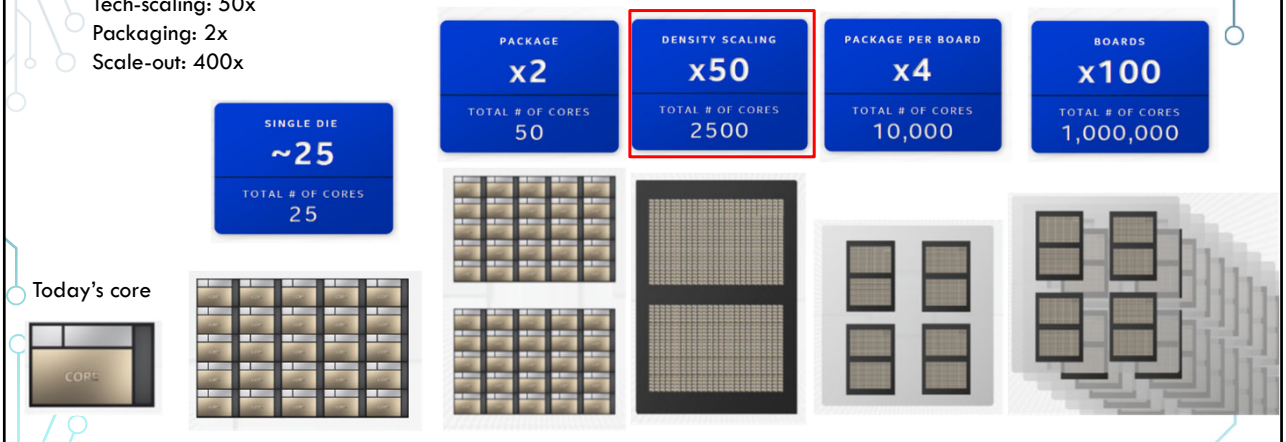
- Bump density and BW/edge or BW/area



Adapted from R. Koduri keynote, Hot Chips 2020

Scaling is scale-out … Getting to 1M cores/system

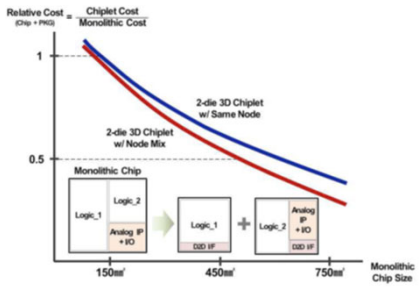
On-chip integration: 25x
Tech-scaling: 50x
Packaging: 2x
Scale-out: 400x



Adapted from R. Koduri keynote, Hot Chips 2020

Some Open Issues

- High-value (e.g. hyperscale) products are driving the chiplet technology
  - What about sub-150mm2 dies?



Cost of disintegration:
- AIB 1.0: 12mm² in 16nm @ $0.1/mm² = $1.2 on each side (50k mm² on a $5k 12-in wafer;
  5nm wafers are $15k – chiplet interface is 2 x $4)
- Substrate cost: >$10 (could be >$100)
- Test escape losses

Sum: $25+ (but can be >$100)

Chiplets are not for free

Can they offset the NRI costs?
Make medium volume ASICs affordable?

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Summary

- FinFET and FDSOI processes deployed now
  - Expected to be replaced by nanosheets
- Lithography and manufacturing restrict design rules
  - Need to be aware of implications on design
  - EuV entering production
- More changes coming: forksheets, buried power rails, chiplets – 2.5D and 3D
  - Plurality of interconnect standards

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Next Lecture

- Transistor models, gate sizing