# Wafer Cleanliness: Challenges from an Increasingly-Complex Fab Process

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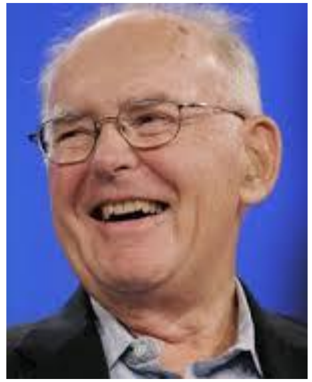
# Tech Leadership = Following 'Moore's Law'

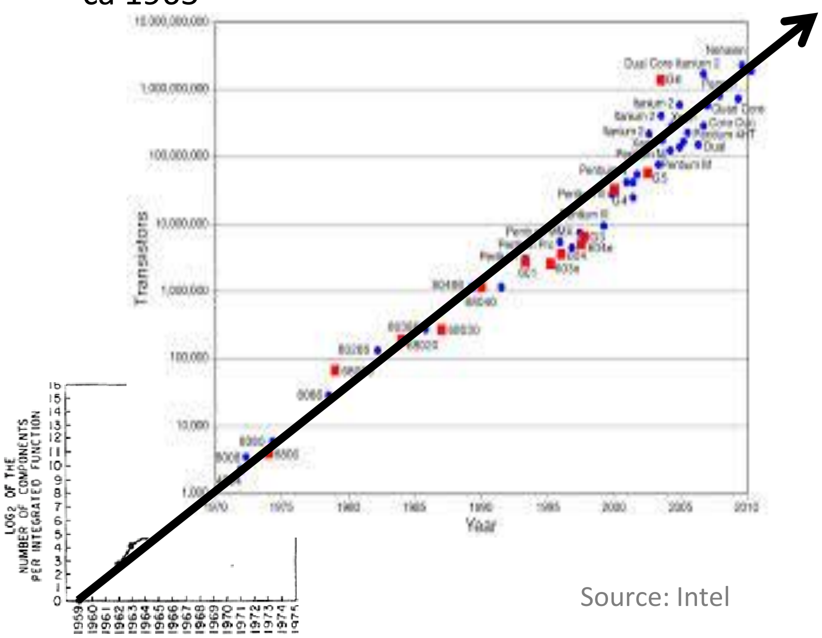
**Gordon Moore**
ca 1965



ca 2010

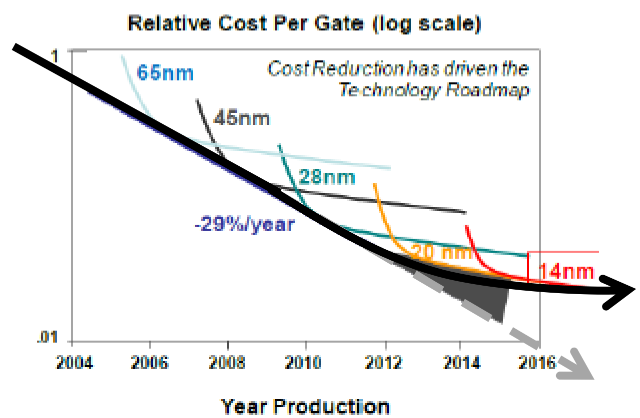
**Moore's famous prediction:**

"The number of transistors on an integrated circuit will double every ~18 months."



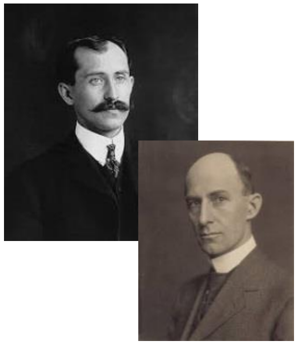

Source: Intel

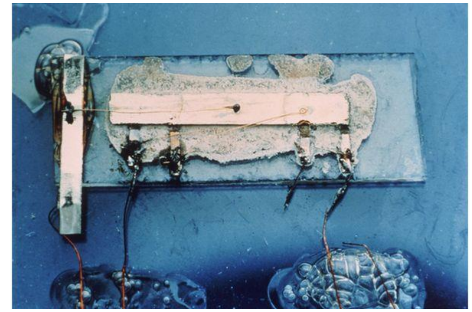
Cost may end Moore's Law before physics will:

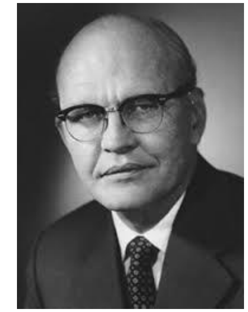



Source: Qualcom

# Moore’s Law in Perspective







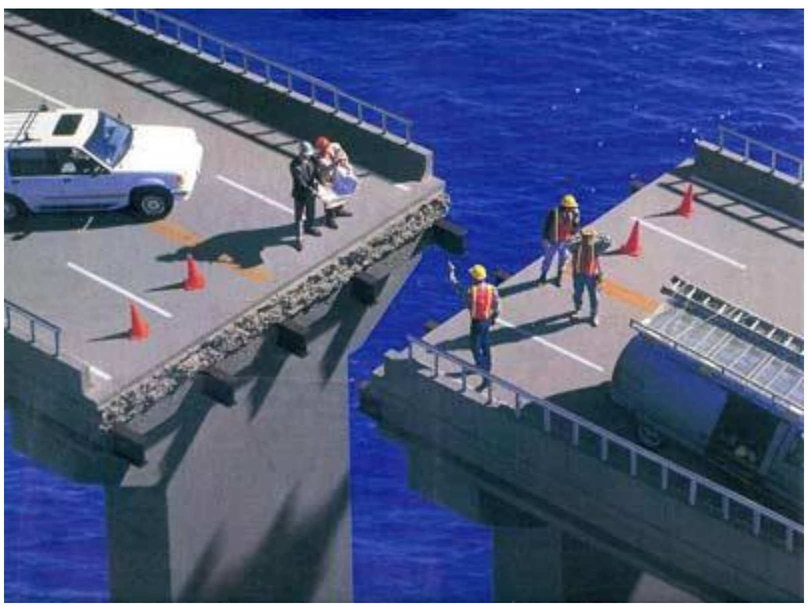
- Airplane
  - 1903: Wright Bro’s of NC
  - 7mph @ 0.7mpg
  - After 56 years (1959)
  - 224 billion mph

- Integrated Circuit
  - 1959: Jack Kilby of TI
  - 1 transistor
  - After 56 years (2015)
  - 32 billion transistors

***Jack*** would now be able to travel from ***Dallas, TX to NYC*** in ***6.9 nanoseconds*** on ***just the fumes*** from ***a drop of gas!***

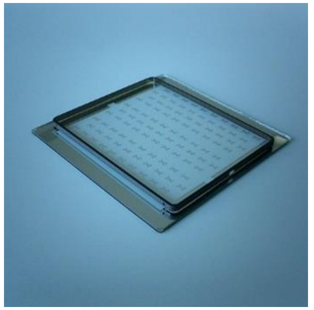
# Challenges in IC fabrication

- Photomask and Wafer Defects
- Integration Complexity
- Data Comprehension
- Process Limitations



So many things can go wrong!

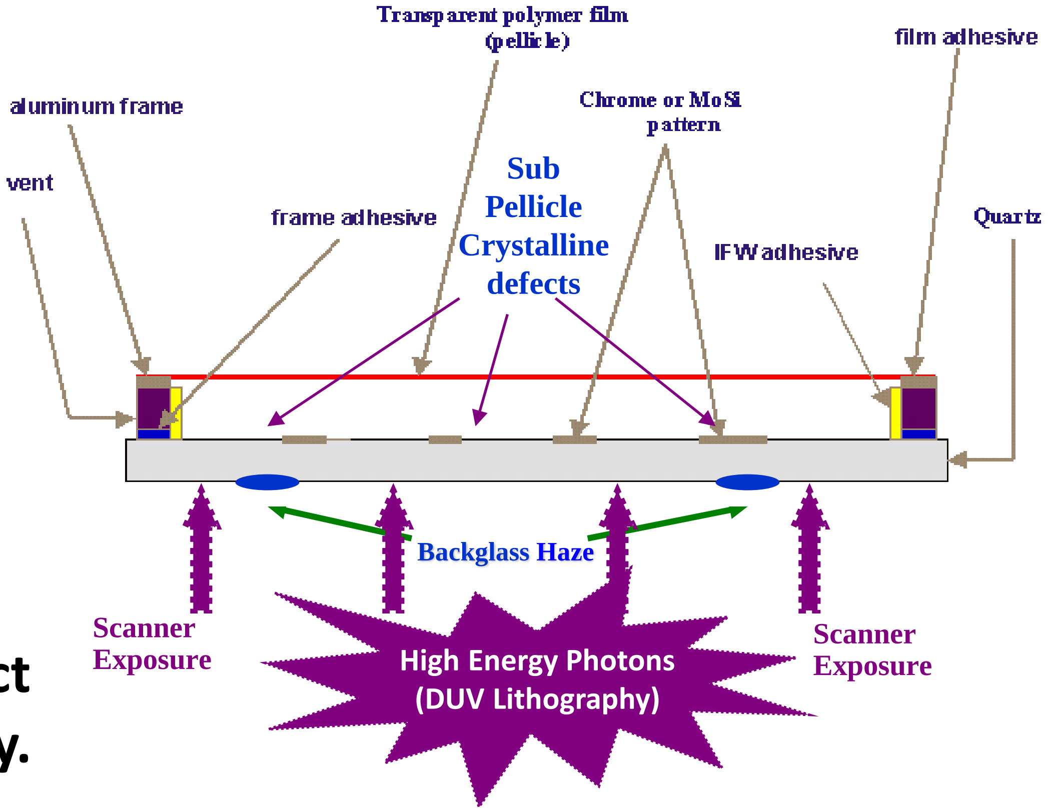
# Fab Defects on Photomasks



The **materials** and **ambient** trapped between the pellicle film and the mask surface create a reactant-rich atmosphere.

This "reaction chamber" produces organic and inorganic precipitates by photochemical means and called **progressive defects**.

A similar mechanism can trigger backside glass progressive defect formation **(haze)** simultaneously.



# Photomask Defect Composition Analysis

**Most common haze crystals are made of:**

**ammonium sulfate** $[(NH_4)_2SO_4]$

**ammonium oxalate** $[(NH_4)_2C_2O_4.H_2O^+]$

Cleaning / Environment

**Many other compounds were also identified on photomask surfaces:**

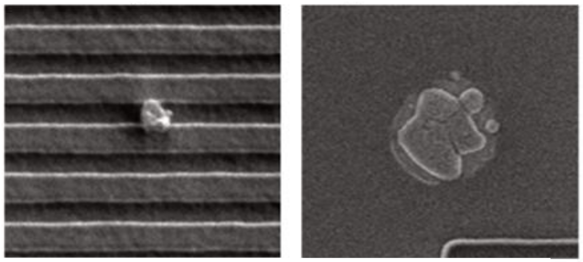
• ammonium carbonate • ammonium carbamate • acrylonitrile butadiene styrene co-polymer • dimethyl phthalate • diethyl phthalate • dibutyl phthalate • dioctyl phthalate • palmitic acid • 2,4-di-t-butyl phenyl phosphite • 2,6-di-t-butyl phenyl phosphite • cellulose nitrate • methyl palmitate • potassium phosphate • cyanuric acid • stearic acid • t-butyl benzene • Tinuvin® • oleic acid amide • brassidic acid amide • cyanoacrylate adhesive • poly(dimethyl siloxane) • silicic acid • ammonium silicate • poly(methyl methacrylate) • poly(butyl methacrylate) • poly(methacrylic acid) • poly(vinyl chloride) • poly(vinylidene chloride) • poly(tetrafluoroethylene) • sodium ions • potassium ions • calcium ions • ceric ammonium salts • organosilanes • organosiloxanes • alkyl fluorosulfonic acids • aryl fluorosulfonic acids • langmuir-blodgett films of long chain polar aliphatic compounds • sodium chloride • potassium chloride • glycine • protein residues • santovar® • nickel acetate • nickel sulfate • chromium sulfate • nylon • organoamines • nitrile compounds

Source: Grenon Consulting, Inc.

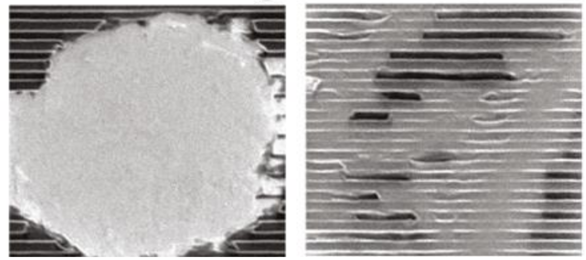
# Fab Defects on Wafers

**Near-perfect tool maintenance and wafer cleaning capabilities required !**

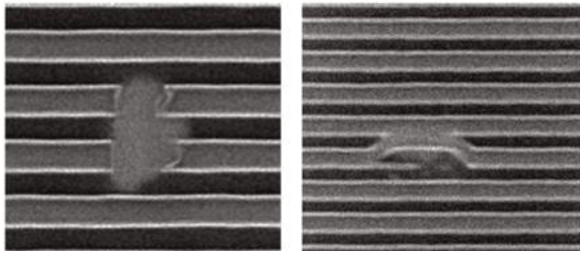
**Bacteria/Stains**



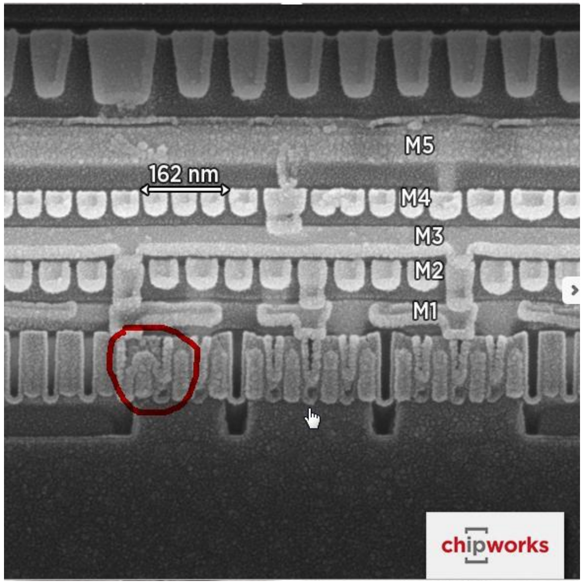
**Large Area**



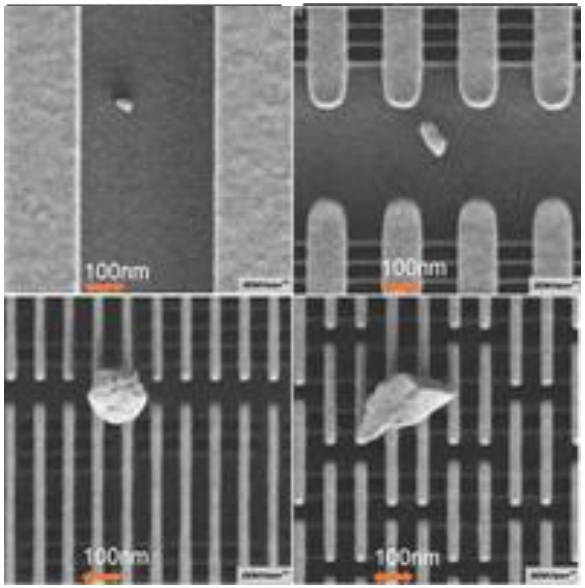
**Line Breaks**



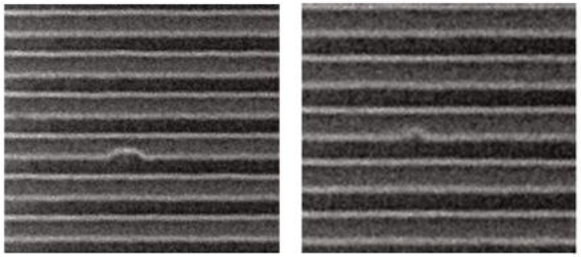
**Malformed Gate**



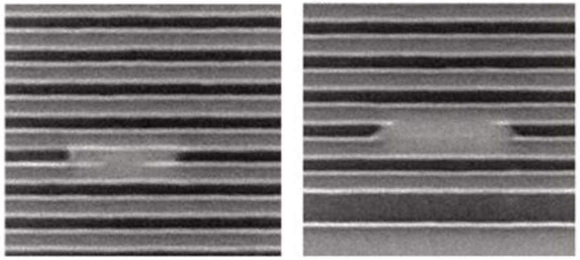

**Fall-On Particles**




**Mouse Bites**

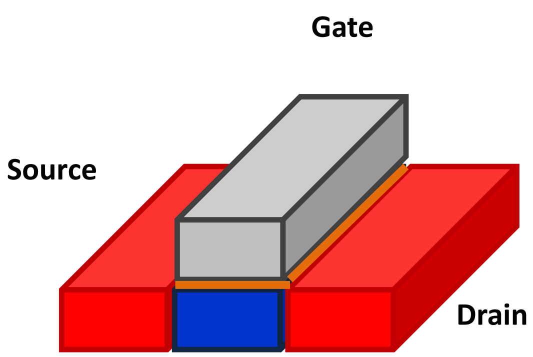


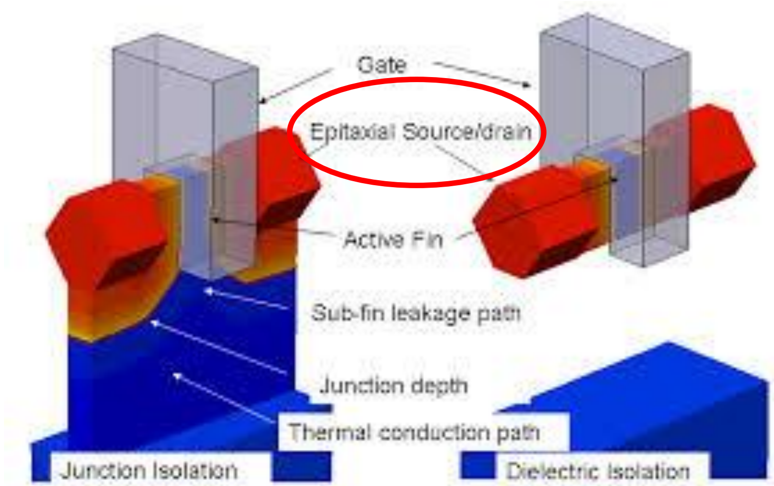
**Bridges**



# Integration Complexity - Structure

- Planar to Vertical Transistor Architecture




Planar MOSFET

Vertical FinFET

# Integration Complexity – IC Periodic Table

(after John Robertson, CUED)

| 1A | 2A | 3B | 4B | 5B | 6B | 7B | 8B | | | 1B | 2B | 3A | 4A | 5A | 6A | 7A | 8A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| Rb | Sr | Y | Zr | Nb | Mo | | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| Cs | Ba | La* | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | | | |

| * | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ce | Pr | Nd | | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |


(after John Robertson, CUED)

| 1A | 2A | 3B | 4B | 5B | 6B | 7B | 8B | | | 1B | 2B | 3A | 4A | 5A | 6A | 7A | 8A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| Rb | Sr | Y | Zr | Nb | Mo | | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| Cs | Ba | La* | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | | | |

| * | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ce | Pr | Nd | | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |


**Today, nearly <u>two thirds</u> of the non-radioactive elements are used in every chip!**

(after John Robertson, CUED)

| 1A | 2A | 3B | 4B | 5B | 6B | 7B | 8B | | | 1B | 2B | 3A | 4A | 5A | 6A | 7A | 8A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| Rb | Sr | Y | Zr | Nb | Mo | | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| Cs | Ba | La* | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | | | |

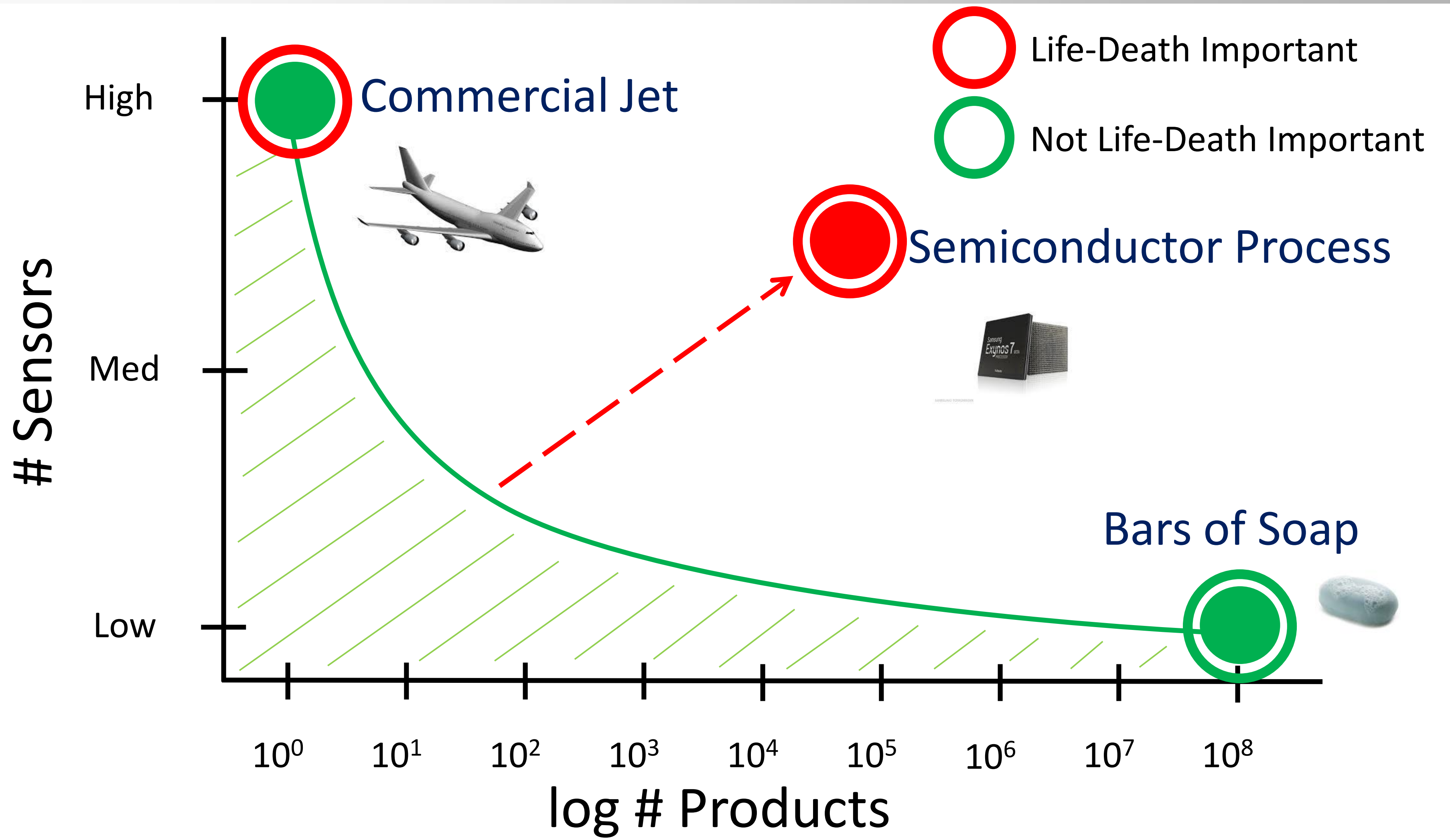
| * | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ce | Pr | Nd | | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |

# Data Comprehension: Sensory Overload!


**>100,000 sensors**

More information is ignored than is used!

# Too Much For Humans To Digest!



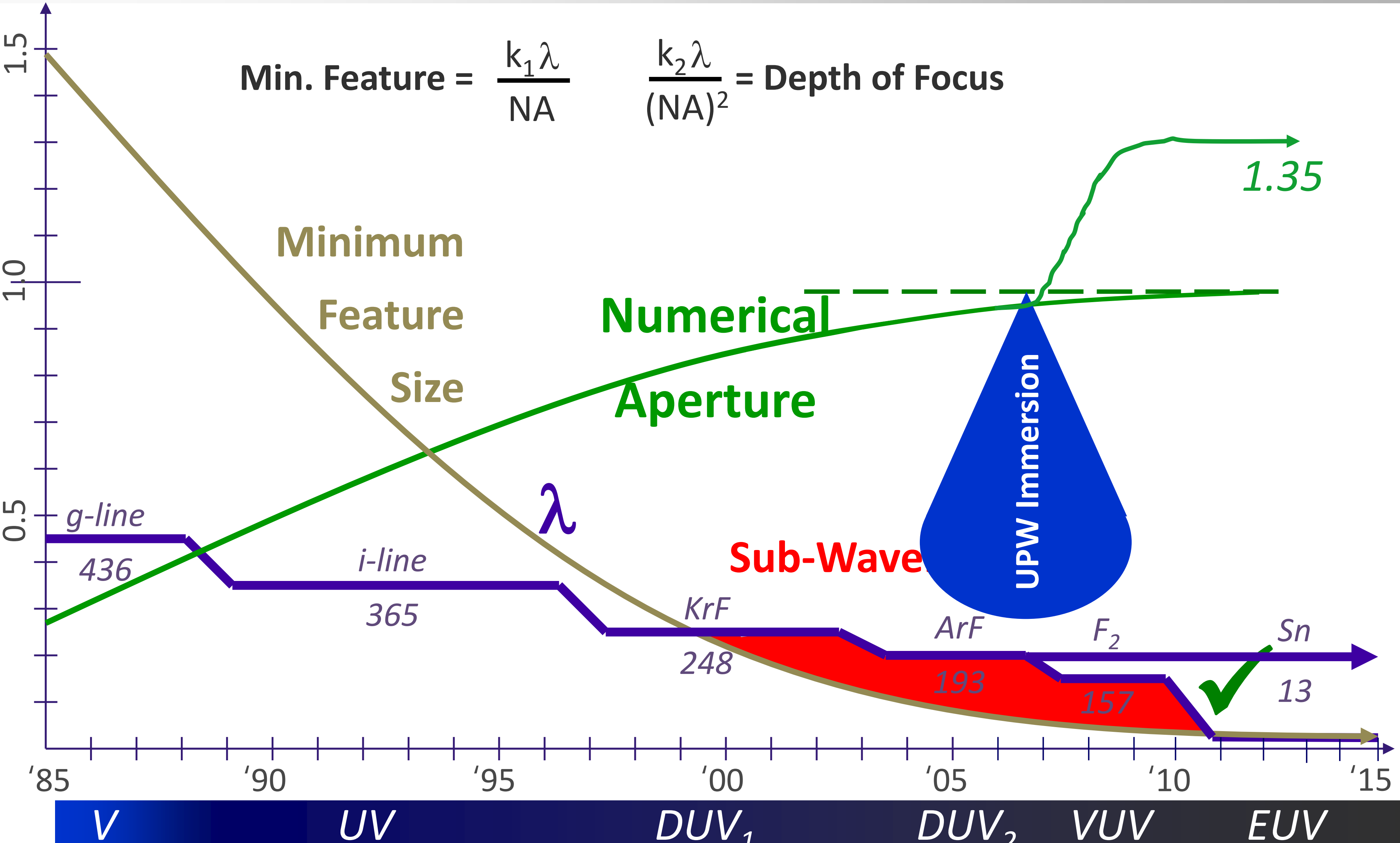

- Toward high end of Sensors AND Products!

# Process Limitations: The Lithographer's Paradox

Lord Rayleigh

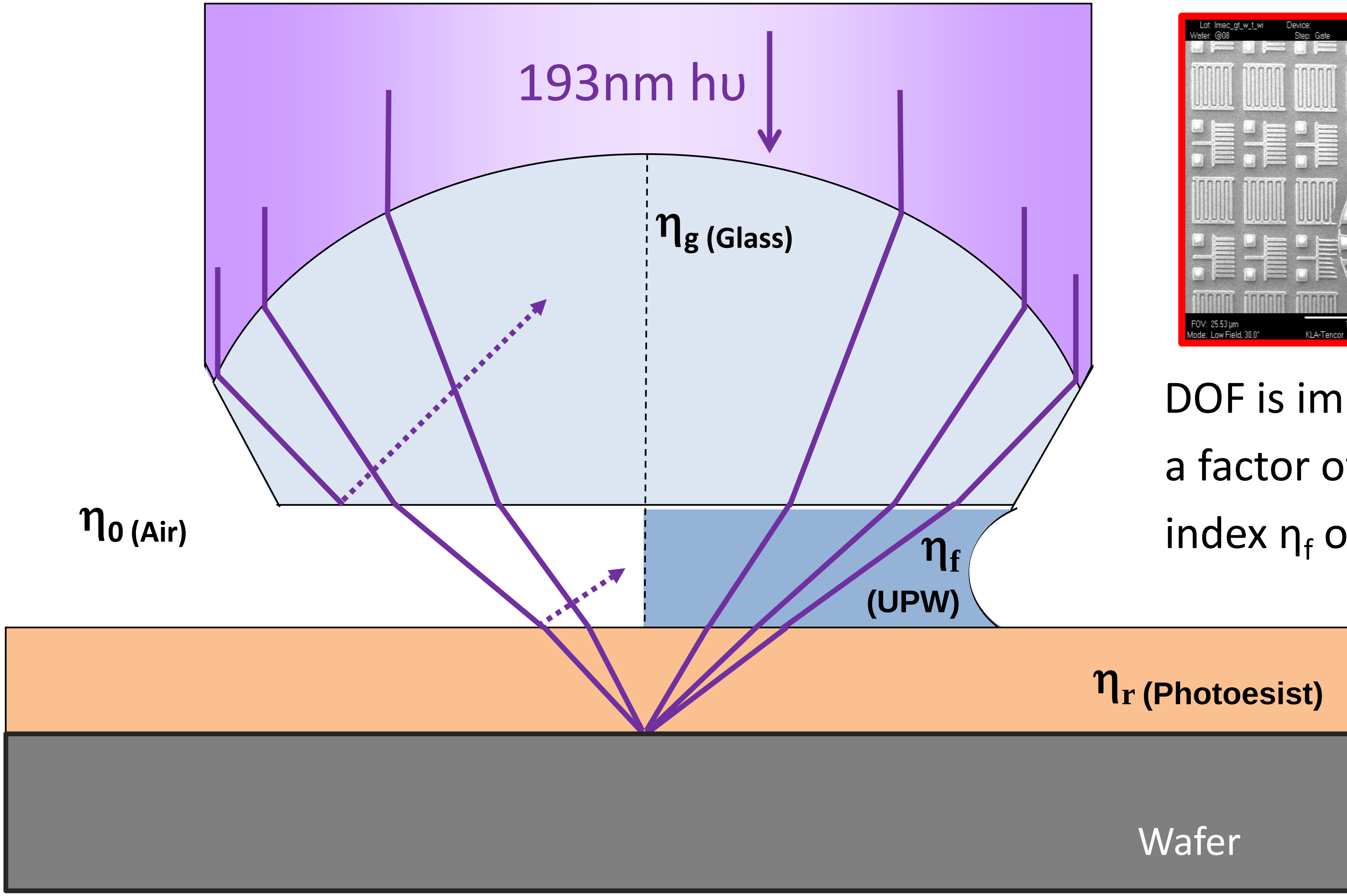
$$\text{Min. Feature} = \frac{k_1\lambda\downarrow}{NA\uparrow} \times \frac{\uparrow k_2\lambda}{\downarrow(NA)^2} = \text{Depth of Focus}$$

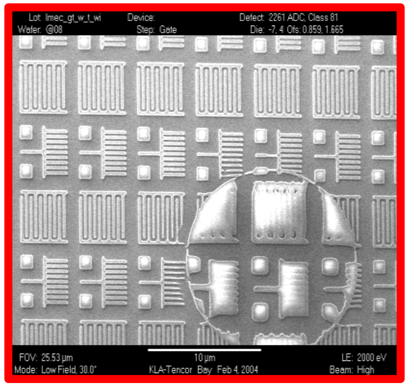
# Wavelength and NA Evolution



# NA Game Changer: Immersion Lithography (UPW)

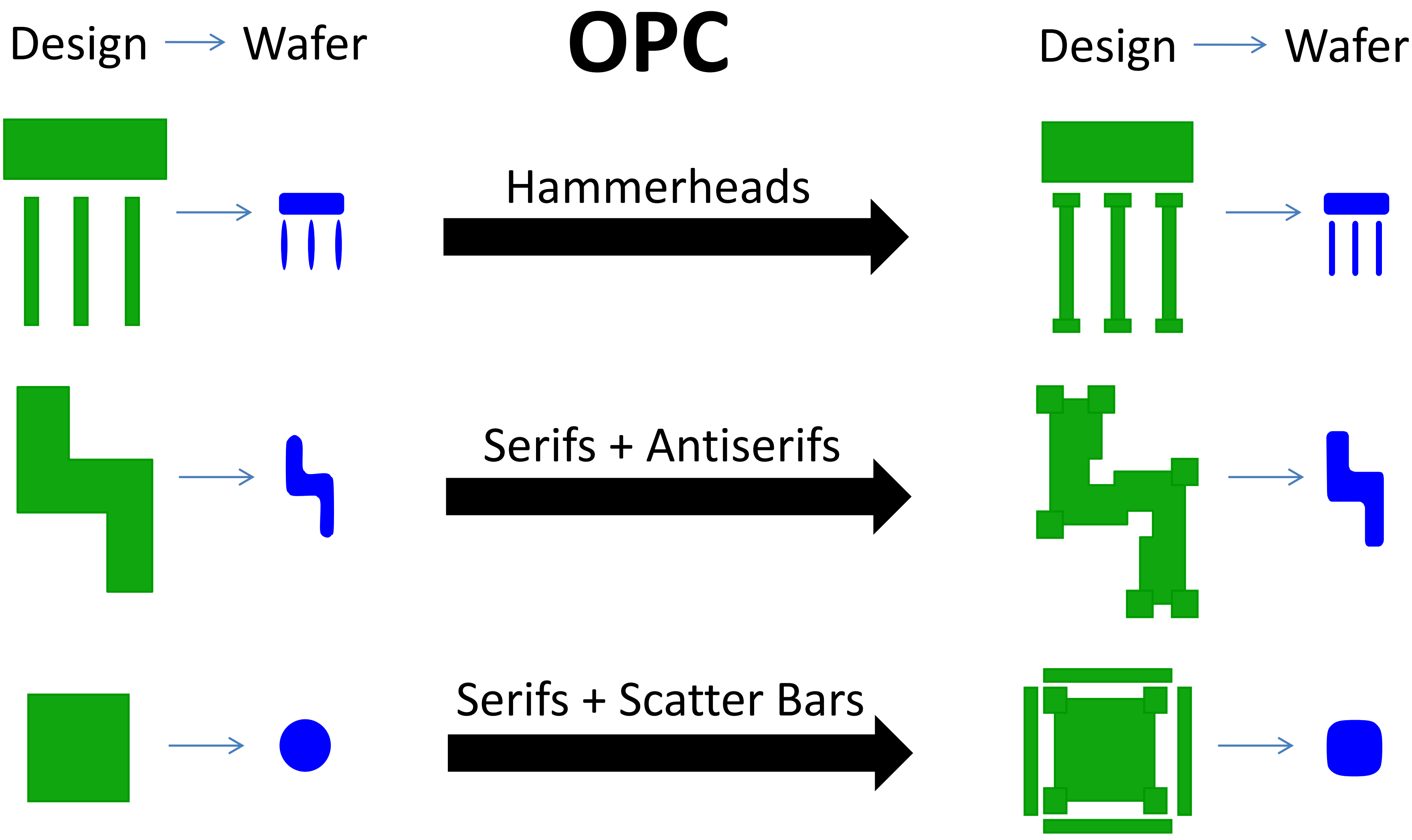
Snell's law: $NA = \eta_0 \sin\theta_0 = \eta_f \sin\theta_f = \eta_r \sin\theta_r$



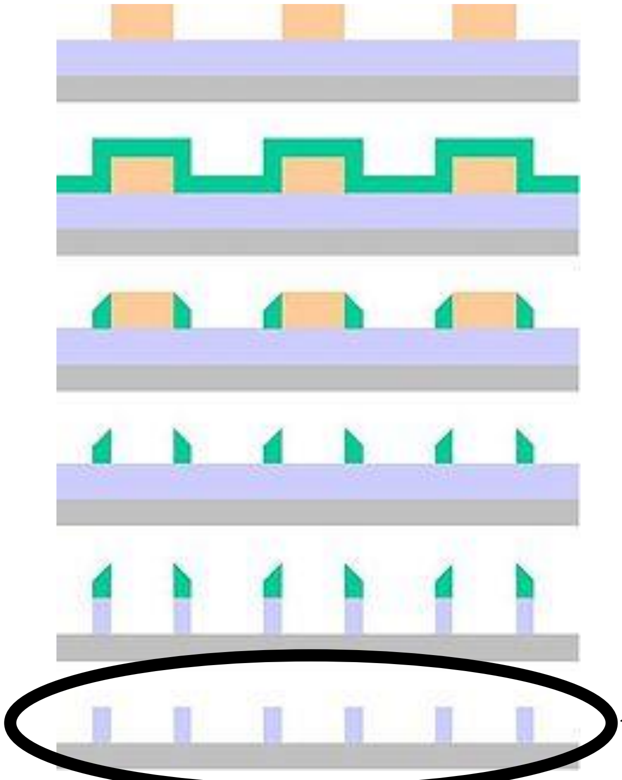
DOF is improved by a factor of the UPW index $\eta_f$ or more.

# Optical Proximity Correction - $k_1$



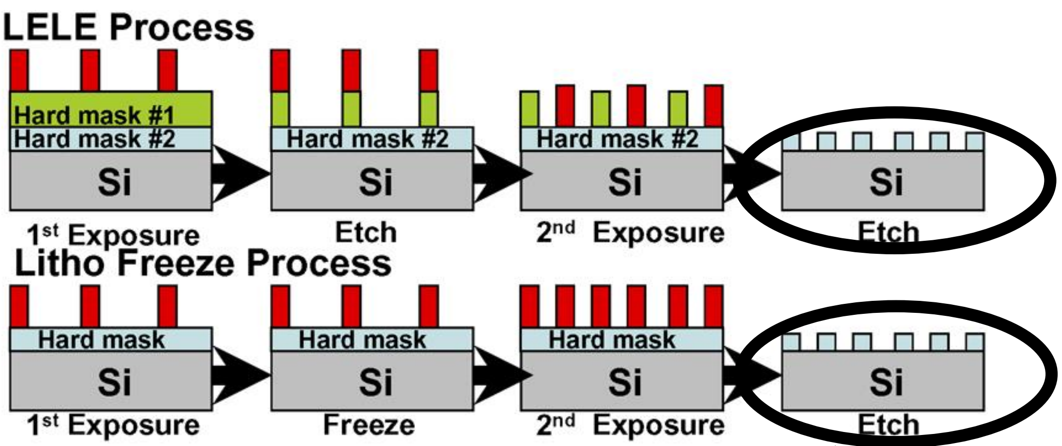
# Another $k_1$ Innovation: Double Patterning

## Spacer Type:



Ref: Paul Zimmerman

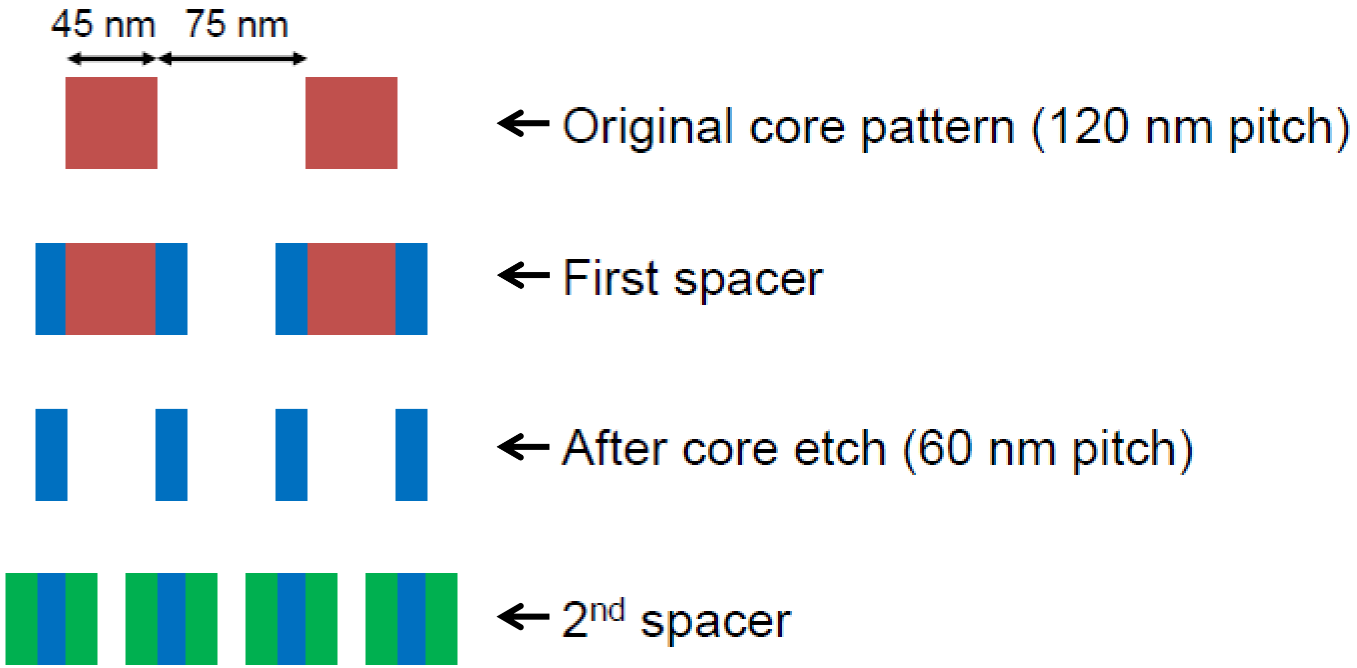
## Litho-Etch-Litho-Etch:

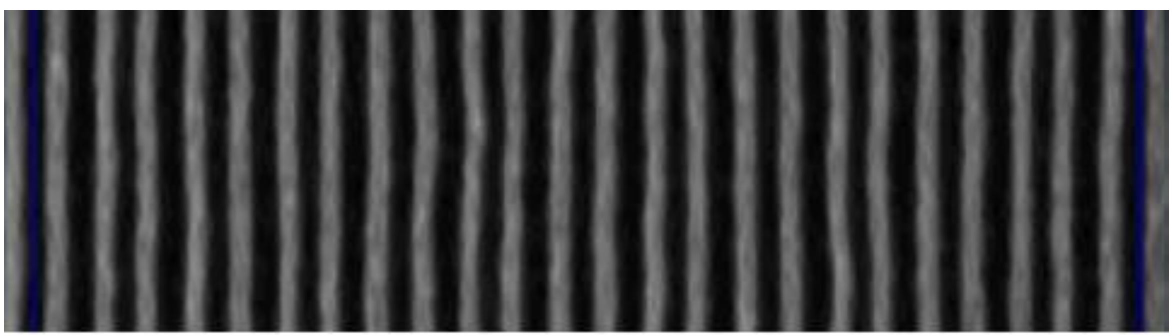



Ref: Brian Wang

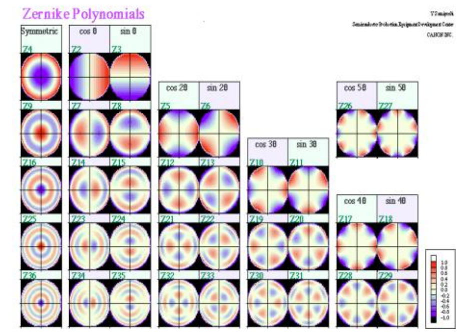
Previously took only one lithography step

# Too Much Innovation? Quadruple Patterning



Source: Nikon LithoVision 2015



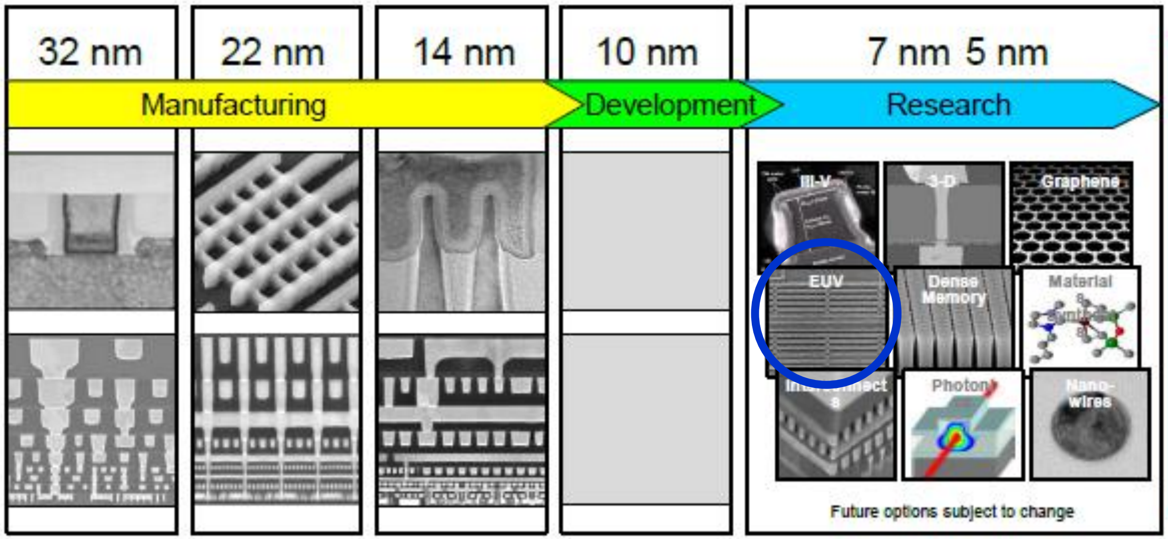

**Future Options**

- Octuple
- LELELE
- LELELELE
- …
- EUV (Single)?

**Limiting Factors**

1. Overlay
2. Yield
3. Cost

# What IC Challenges Lie Ahead?



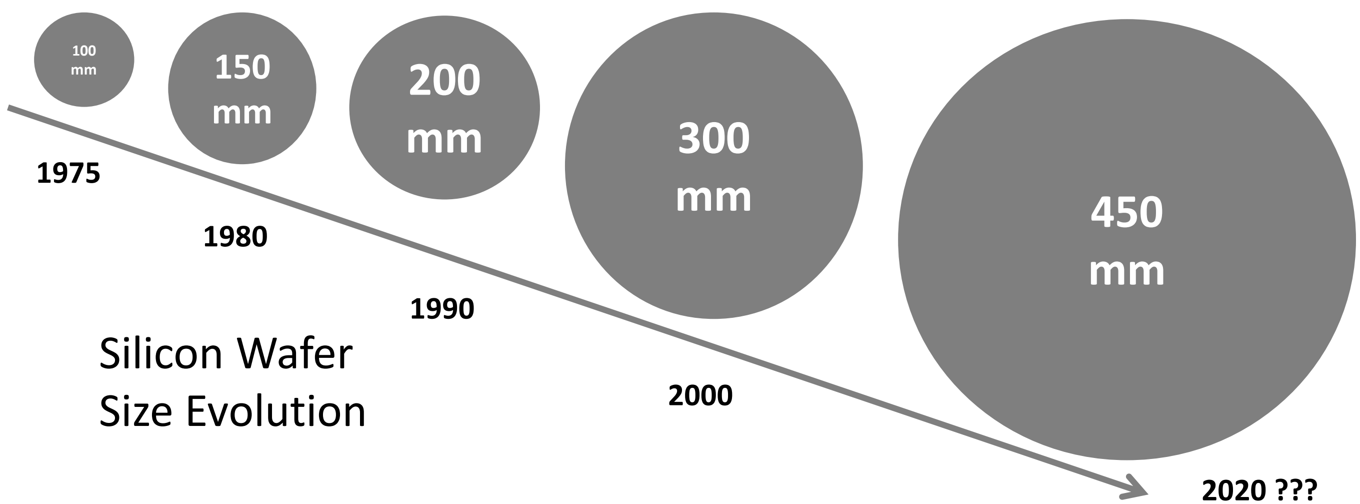

**The Future...**

New Equipment & Materials

Higher Density & Integration

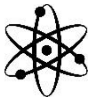
Lower Cost Per Transistor

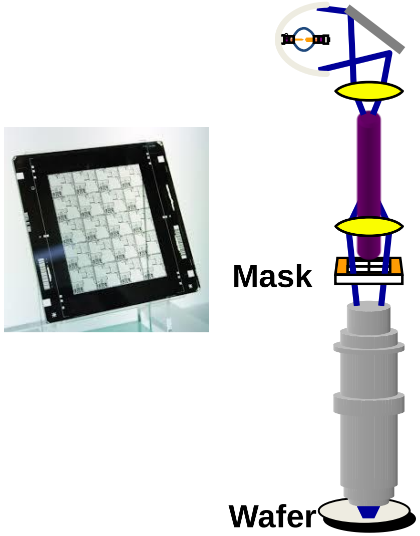
Source: LithoVision 2015

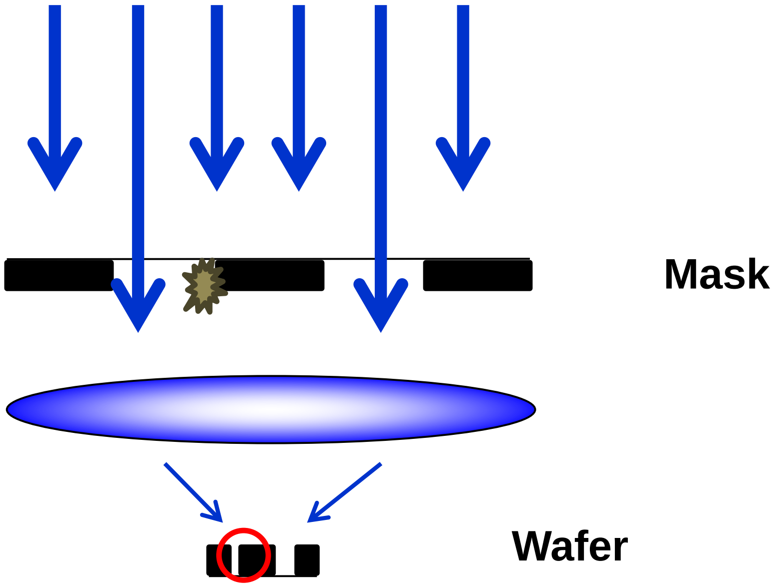



Silicon Wafer
Size Evolution

# Moore's Law and Contaminant Size

- Particulates Example
  - UPW spec <200pcs/liter @ >**50nm**
  - Max defect size on mask 7-10% of wafer CD (~1-2 nm)
  - Size spec needs to track with node shrinks
  - 14nm: **1.0nm** → 10nm: **0.7nm(7Å)** → ... 

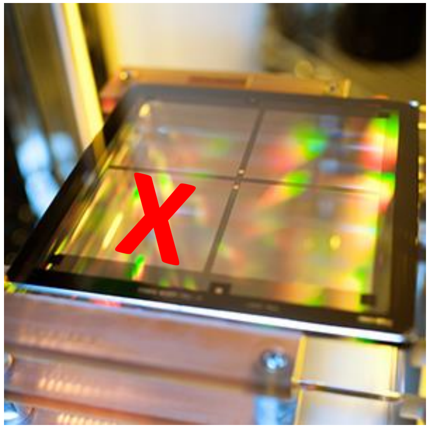


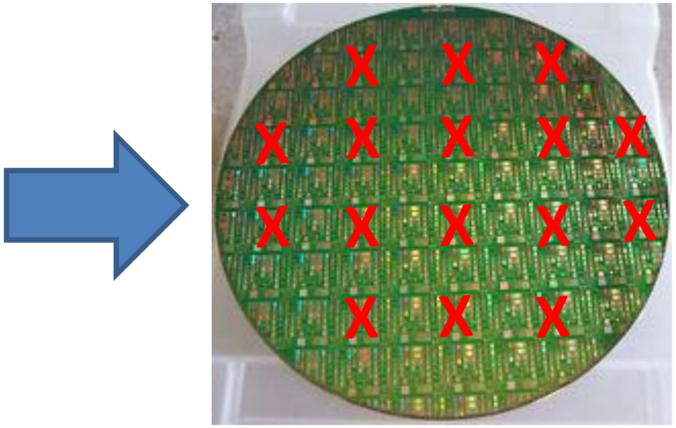



# Contaminants Can Destroy Wafer Yield

- Bacteria Colony-Forming Units (CFUs)

  - Typical size is 1-8µm in length
  - One CFU/liter could easily destroy dozens of logic die
    - UPW is used dozens of times in Cleans, CMP, & Photo steps





  - If it kills one die on a photomask, then all wafers shot with that mask will suffer yield loss for that die

# A Mathematical Perspective

>5 billion *non-redundant* transistors in a logic chip

x >600 chips per wafer

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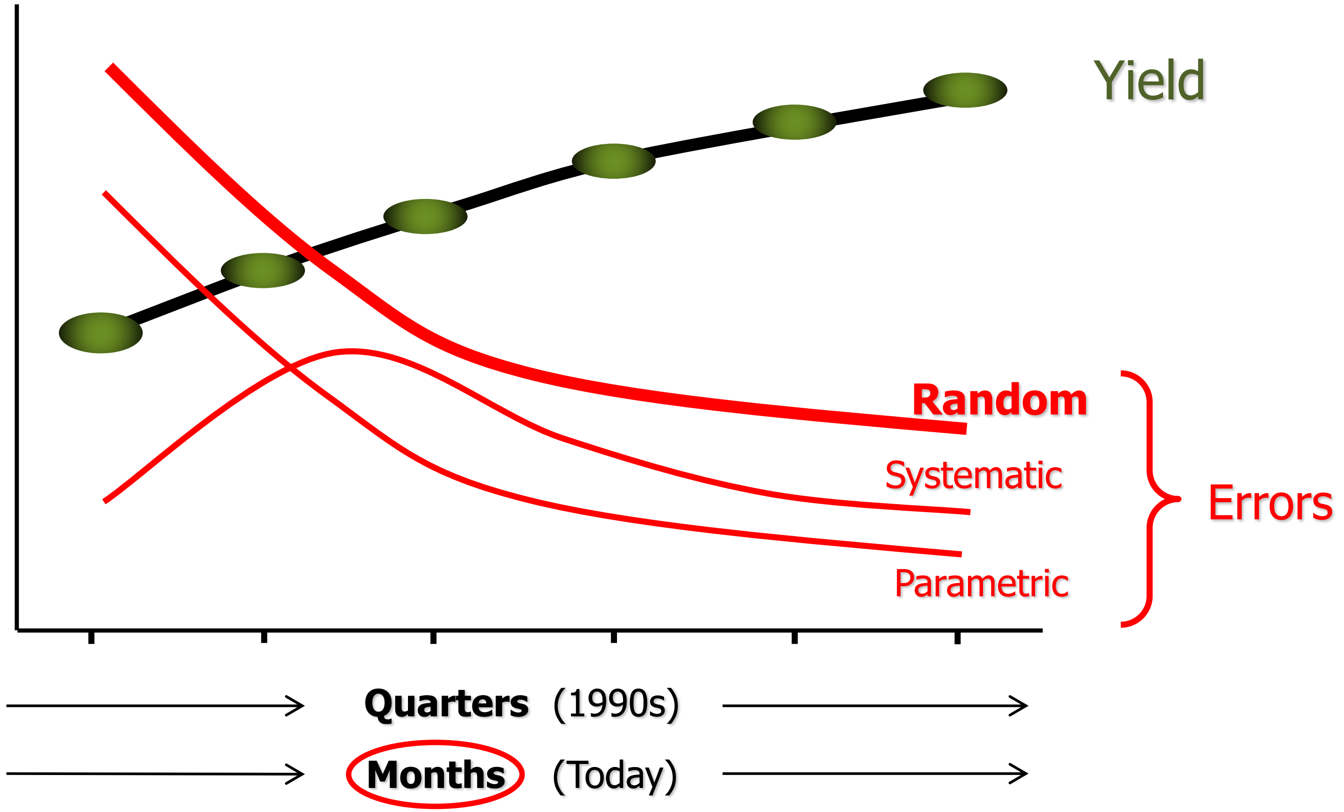
>**3 trillion** sites on every wafer needing to be perfect!

There are also ~$\mathbf{3.35x10^{25}}$ molecules/liter in UPW

| Today's UPW impurity specs: | | "Allowed Bad" |
|---|---|---|
| **ppt** for metals, ions, boron | → | **33.5 trillion** |
| **ppb** for TOC, DO, Total $SiO_2$, $H_2O_2$ | → | **33,500 trillion** |
| **pcs/liter** for particles and bacteria | → | **Dozens** |

# Yield-Up Speed is Critical

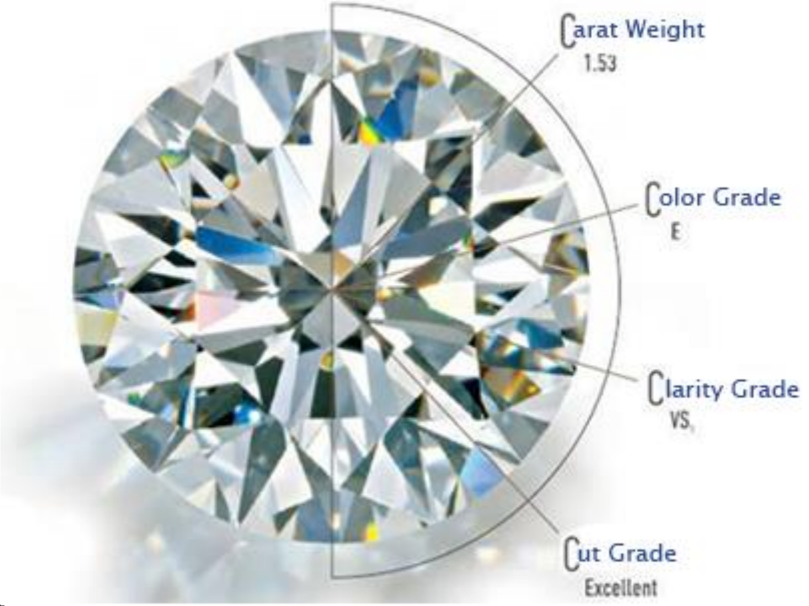
- Typical Yield Improvement Dynamics




Now vulnerable to <u>picoscale</u> differences and perturbations!

# What Do Fabs Need of Suppliers?

- Excel in the Four C's
  - Capability
  - Collaboration
  - Consistency
  - Communication



# Capability – Key to *getting* yield

- Anticipate & explore new formulations and methods of synthesis
- Utilize most advanced metrology & inspection
- Innovate better particulate and ionic contamination elimination solutions
- Outgoing quality testing sampling to guarantee 100% of shipment

# Collaboration – Key to *improving* yield

- Share roadmaps and needs from the current node down to n+2
- Share metrology, inspection, & analytical tool lists and cross-verify with fab

- Share and test ideas with fab and fab tool suppliers (e.g. layer-specific formulations)
- Share in enabling green-ness (packaging, recycling, etc.)

# Consistency – Key to *stable* yield

- Structured risk elimination
  - Assume all changes matter
- Sub-supplier management by fab QA personnel

- Batch-to-batch uniformity beyond the CofA
- Reduce variability post manufacture through installation and use
  - Shipment and storage conditions
  - Filter prep time

# Communication – Key to *not 'tanking'* yield

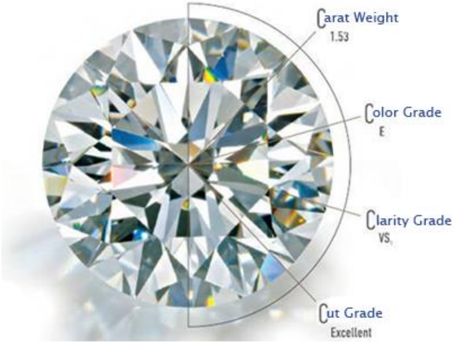
- Advise fab on filtration and blending strategies
- Report manufacture, delivery, and storage conditions

- Proactively report or recall excursions of any kind once discovered
- Be open to fab feedback (Avoid "I told you so" moments.)

# Summary

- **Making Advanced Semiconductors is HARD!**
  - Defectivity
  - Integration complexity
  - Data/Sensor comprehension
  - Process limitations

- **Four C’s to Success in this Business**
  - Capability is key to getting yield.
  - Collaboration is key to improving yield.
  - Consistency is key to stable yield.
  - Communication is key to not “tanking” yield.




## Thank you, any questions?