Overview of Lithography: Challenges and Metrologies

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Progress in Lithography

- Progress in lithography has been the result of many advances.
  - Better lenses, resists, chemical-mechanical polishing (CMP), etc.
- The largest impacts have been made by changes in wavelength.

g-line $\rightarrow$ i-line $\rightarrow$ KrF $\rightarrow$ ArF $\rightarrow$ F_2

436 nm $\rightarrow$ 365 nm $\rightarrow$ 248 nm $\rightarrow$ 193 nm $\rightarrow$ 157 nm

1 μm $\longrightarrow$ 360 nm

Shorter wavelengths

- Shorter wavelengths make a number of problems easier.
  - Improved depth-of-focus.
  - Smaller mask error factor.
  - Larger image log-slope.
    - Improves exposure latitude, sensitivity to resist thickness, and increases resist side-wall slope.

- **We are running out of wavelengths.**

Why are we running out of wavelengths?

- Optical lithography is defined as a lithographic technology that:
  - Uses photons to induce chemical reactions in a photoresist.
  - Has the potential for image reduction using projection optics.
  - Involves a transmission photomask.

Why are we running out of wavelengths?

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No solution is apparent for wavelengths < 157 nm.

What goes wrong at λ < 157 nm?

- Photomasks today are made from fused silica.
- Fused silica has a number of advantageous properties.
  - Chemical stability.
  - Transparency for ultraviolet light.
  - No intrinsic birefringence.
  - A low coefficient of thermal expansion.

What goes wrong at $\lambda < 157$ nm?

- A low coefficient of thermal expansion.
  - 0.5 ppm/^{o}C.
    - If a mask changes temperature by 0.1^{o}C, then the distance between two features separated by 50 mm will change by 2.5 nm.
    - This change in registration can be absorbed into overlay budgets.
      - After reduction by 4×.

Year of Production	*2010*	*2013*	*2016*
DRAM ½ Pitch (nm) = node	45	32	22
Overlay	18	13	9

What goes wrong at $\lambda < 157$ nm?

- The transparency of fused silica must be modified by fluorine doping to have adequate transparency for use as substrates for photomasks at 157 nm.
  - The transmission falls off sharply for smaller wavelengths.
- An alternative material must be used.
  - CaF_2.
- The coefficient of thermal expansion of CaF_2 is 19 ppm/^{o}C.
  - Versus 0.5 ppm/^{o}C for fused silica.
- The 2.5 nm of mask registration error becomes nearly 50 nm.

What goes wrong at $\lambda < 157$ nm?

There will be no optical lithography for wavelengths < 157 nm.

(Maybe. More later.)

What are our choices?

- We will need to operate very close to the resolution limit of the optics.

or

- We need to adopt a radically new approach to lithography.

- Either of these will be hard to do.

International Technology Roadmap for Semiconductors (ITRS)

I will talk about three of the most difficult challenges going forward in lithography:

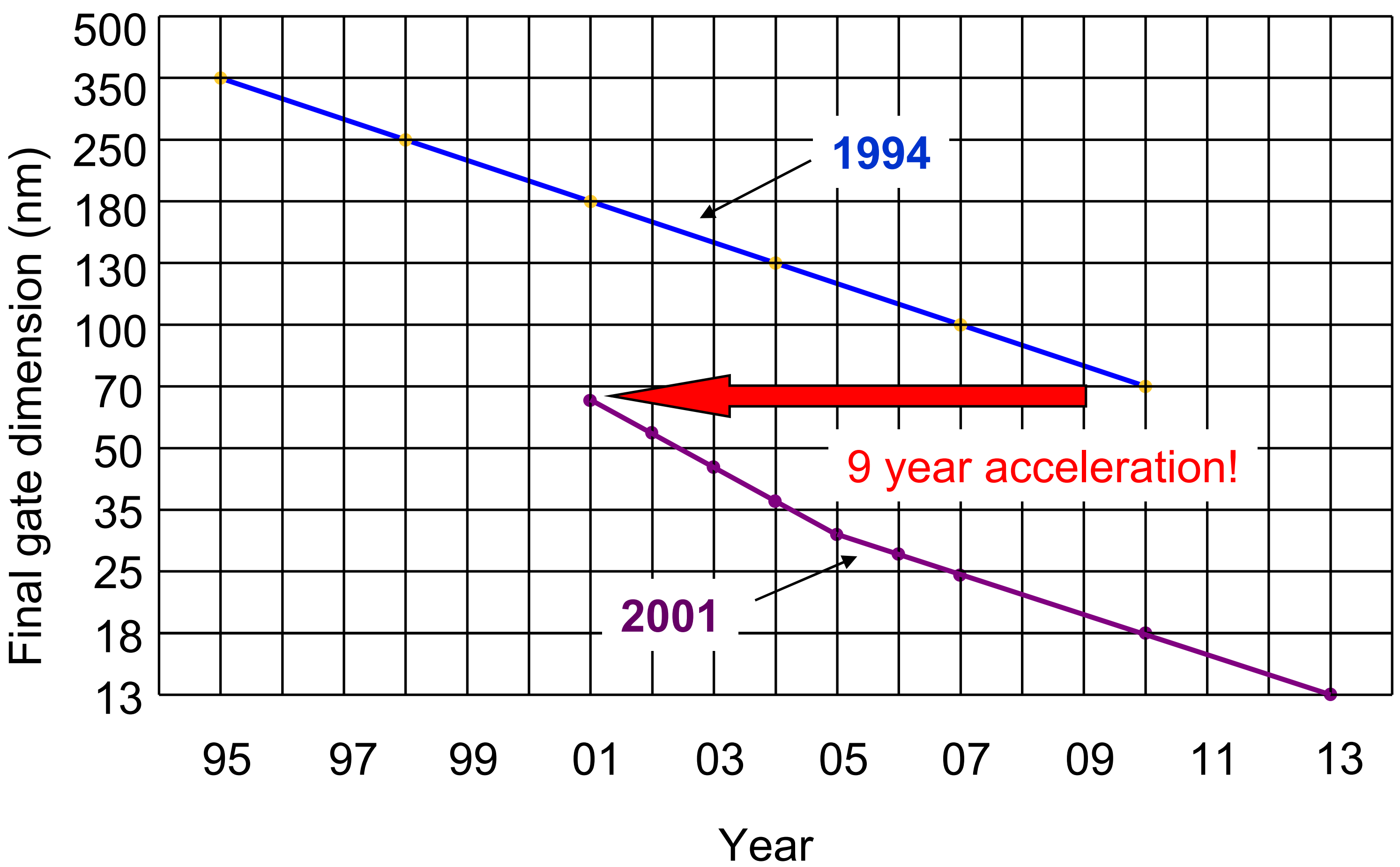
- Gate CD control.
- The introduction of completely new lithographic technologies.
  - Extreme Ultraviolet (EUV) lithography, for example.
- The escalating costs of lithography.

What will be the hardest problems?

- As one looks at the ITRS today, the biggest lithography challenges involve critical dimension (CD) control.
  - Particularly for microprocessors.

Year of Production	*2002* *115 nm*	*2003* *100 nm*	*2004* *90 nm*	*2005* *80 nm*	*2006* *70 nm*	*2007* *65 nm*
MPU/ASIC						
Gate length (nm, in resist)	**75**	**65**	**53**	**45**	**40**	**35**
Gate length (nm, post-etch) (physical length)	**53**	**45**	**37**	**32**	**28**	**25**
Gate CD control (nm, 3 sigma, post-etch, 10% of CD, litho only)	**4.3**	**3.7**	**3.0**	**2.6**	**2.3**	**2.0**

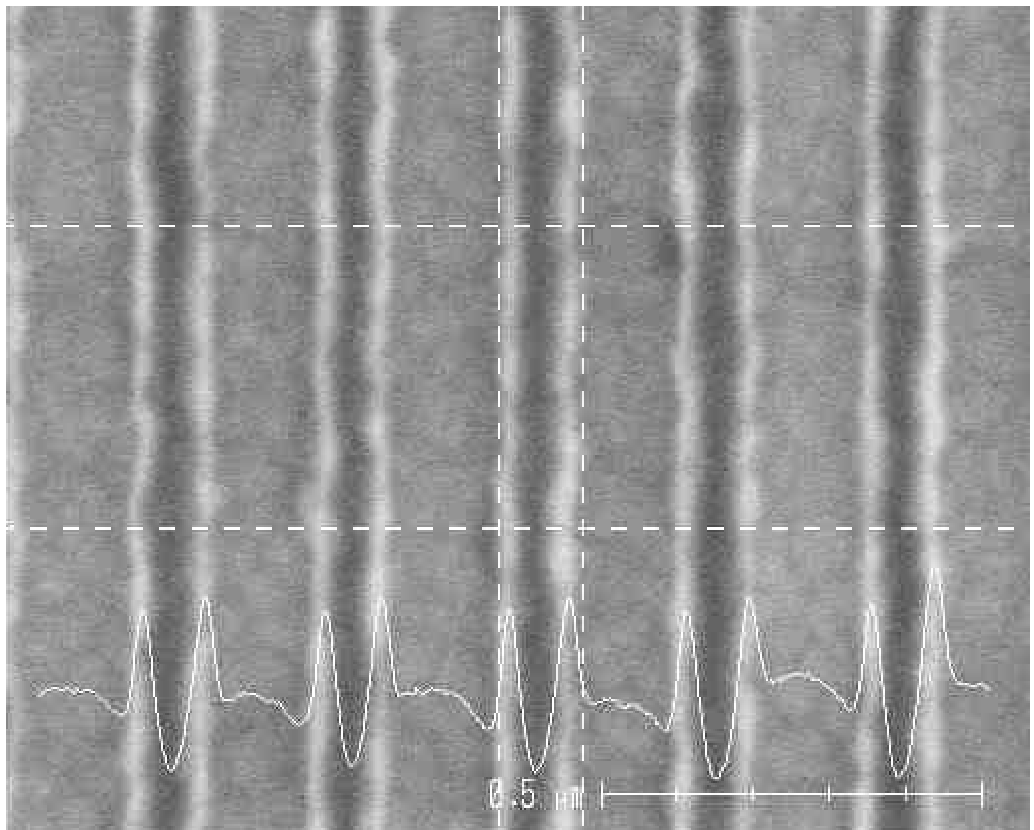
What will be the hardest problems?



What will be the hardest problems?

- CD variation results from a number of factors.
  - Reticles.
  - Exposure tools.
    - Stepper lenses.
    - Focus variation.
    - Dose control.
  - Resist processing.
    - Bakes, for example.
  - Line-edge roughness (LER).
  - Metrology.

What will be the hardest problems?



What will be the hardest problems?

AMD

- Suppose metrology accuracy needs to be 10% of requirements.

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Metrology accuracy (nm, 3 sigma)	**0.43**	**0.37**	**0.30**	**0.26**	**0.23**	**0.20**

- Improvement will require attention to contributions that are a fraction of the total requirement.
  - Metrology will need to be capable of dealing with individual contributions.

What will be the hardest problems?

- Fortunately, we do not always need to measure resist features or CDs directly on the wafer to prove to ourselves that things have been improved.
  - Reticles can be measured at 4×.
  - Hotplates temperatures can be measured.
  - Lens aberrations can be measured by interferometry.

- It will still be hard!

Resolution

$$\text{resolution} = k_1 \frac{\lambda}{NA}$$

Lord Rayleigh
(John Strutt)

Ernst Abbe

What will be the hardest problems?

- As we make features smaller, everything must be controlled better.
  - This becomes increasingly difficult the smaller k_1 becomes.
- We are reaching practical limits.
- We are also reaching physical limits.

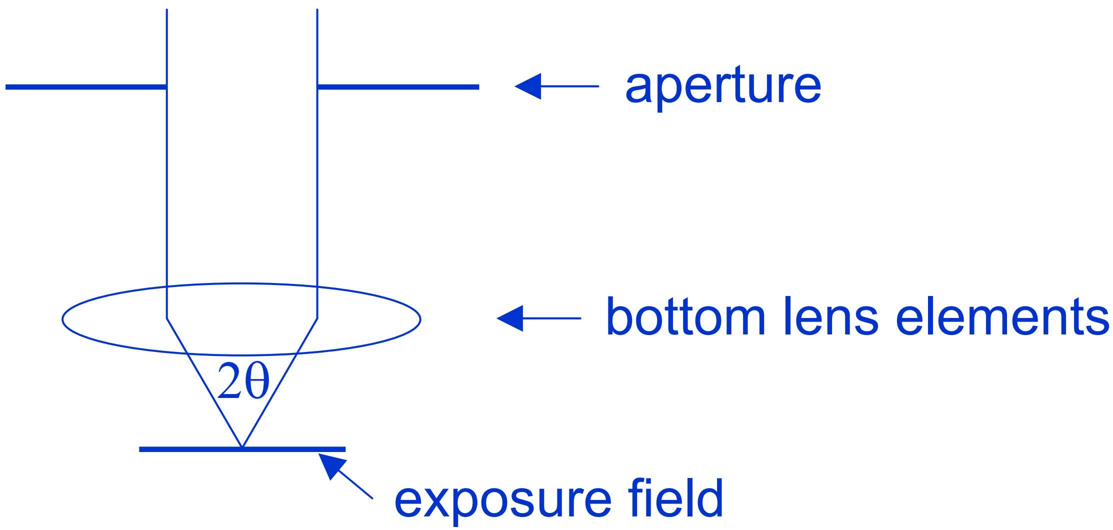
How far can optical lithography go?

$$\text{resolution} = k_1 \frac{\lambda}{NA}$$

- λ: $\geq$ 157 nm
- k_1: $\geq$ 0.25
- NA: ?

Resolution

$$\text{resolution} = k_1 \frac{\lambda}{NA}$$



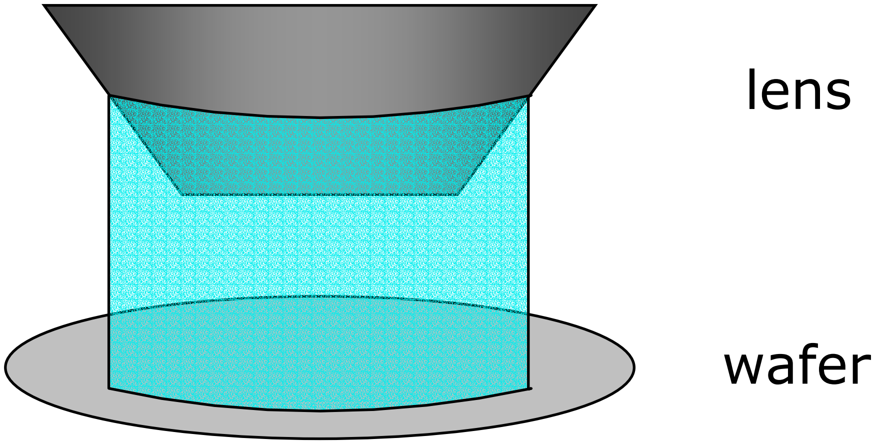
$$NA = n \sin\theta$$

Lord Rayleigh
(John Strutt)

Ernst Abbe

Immersion lithography

- One way to increase the numerical aperture is to employ immersion imaging.



- Immersion can potentially enable NA > 1.
  - This technology will have its own challenges.

Immersion lithography

- Immersion lithography challenges:
  - Moving wafers in and out of the fluid.
  - Scanning.
  - Bubbles.
  - Immersion fluid transparency at 157 nm.
- Work on this has begun only recently.
  - Time and money are needed for proof-of-principle and development.

What is the resolution limit of immersion lithography?

$$\text{resolution} = k_1 \frac{\lambda}{NA}$$

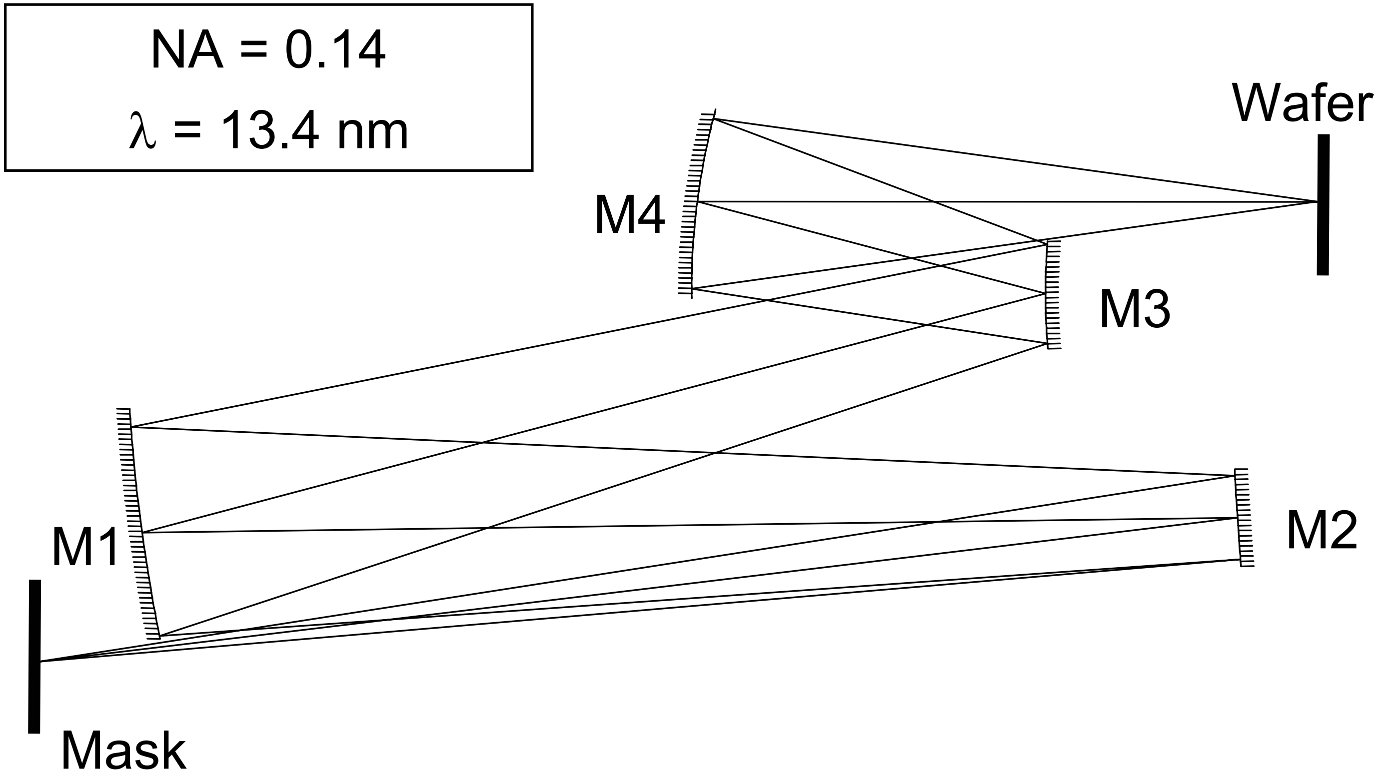
- Assume
  - $k_1 > 0.25$ theoretically, but $k_1 \geq 0.3$ is more realistic.
  - $\lambda = 157$ nm
  - $NA = 1.3$
- Resolution of optical immersion lithography > 36 nm.

Next Generation Lithography

- To overcome the limits of optical lithography, a different approach to lithography will be required.
  - EUV lithography.
  - Electron projection lithography (EPL).
  - Maskless lithography
- Any one of these will require significant advances in exposure tools, resists, masks (except maskless) and metrology.
- We have invested 25 years in learning about projection optics, optical resists, and optical masks.
- With a change in technology type, we need to start over.

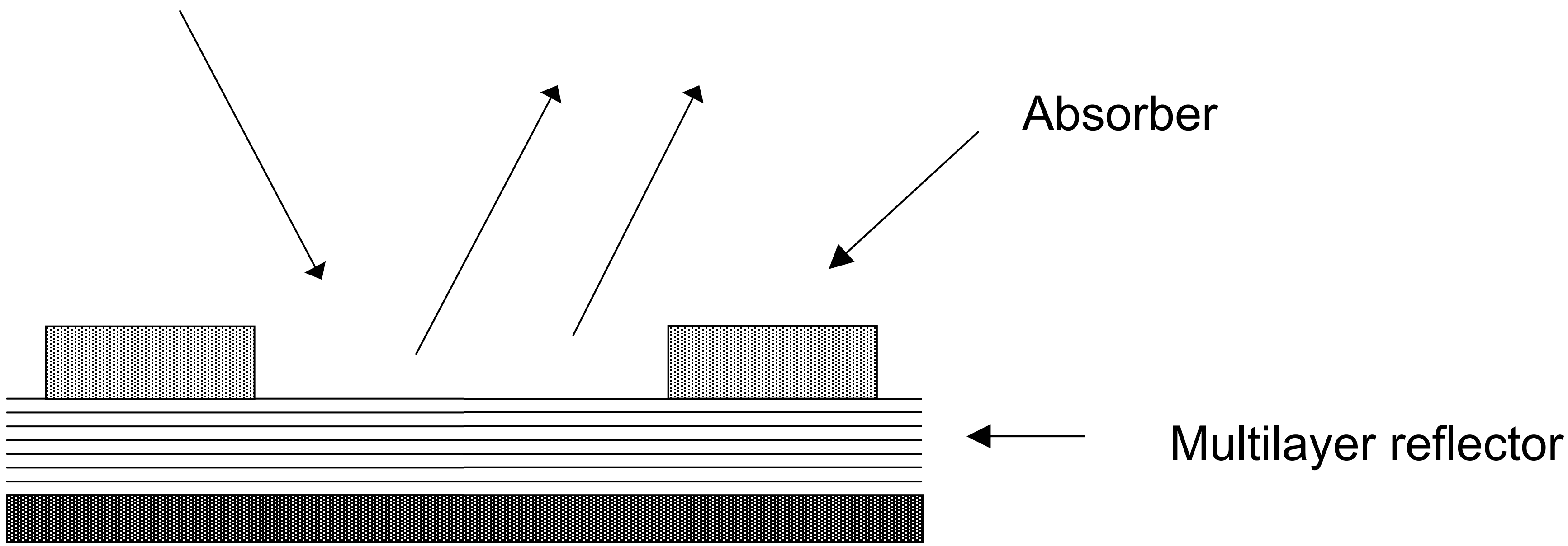
EUV Lithography

- EUV lithography involves reflection optics and masks.



EUV Lithography

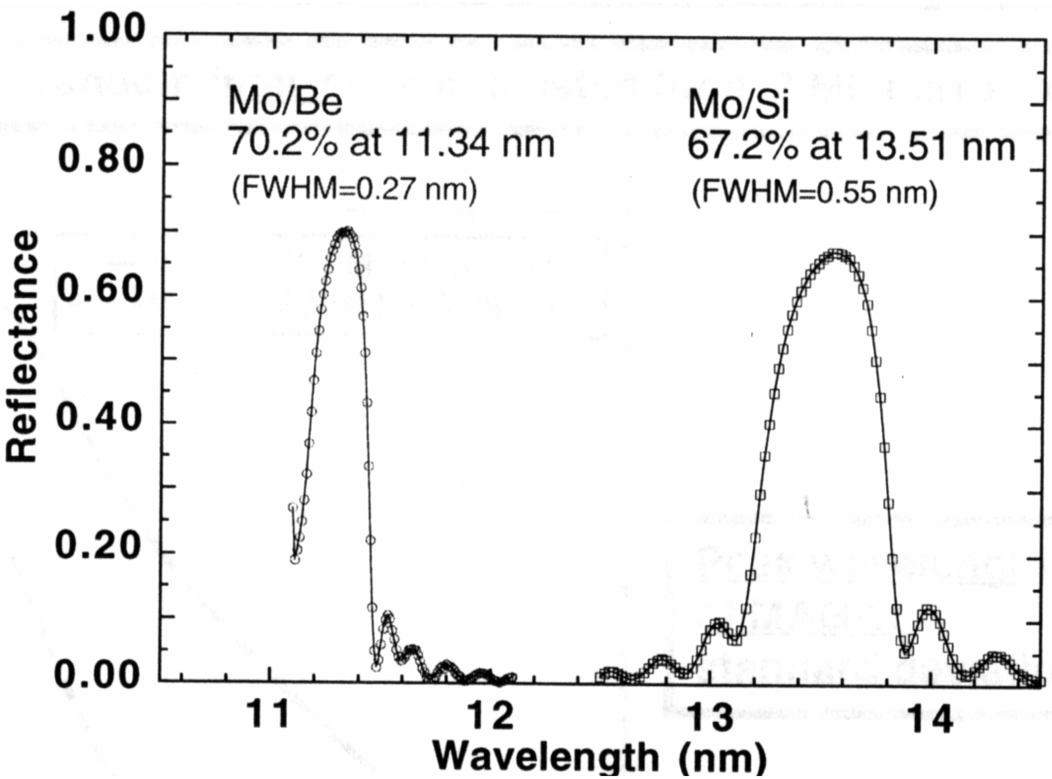
- High reflectivity is achieved through the use of multi-layer Bragg reflectors.



EUV Lithography

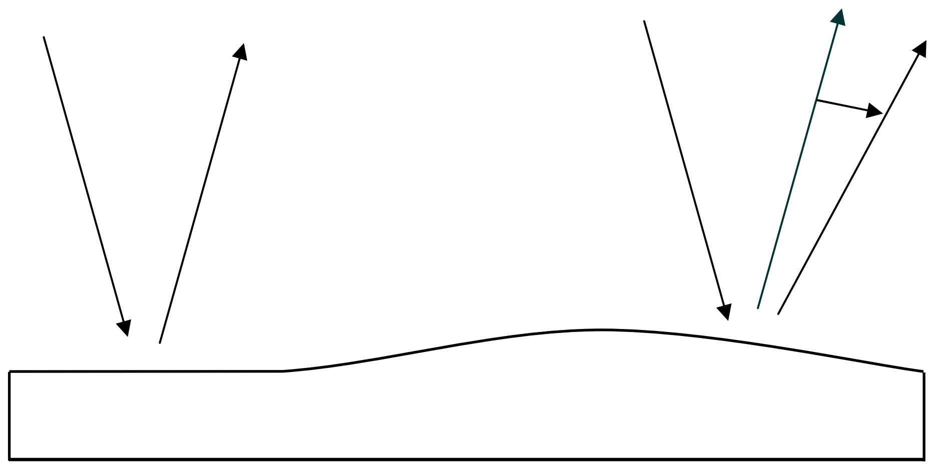
- Multilayers will need to have well controlled peak wavelengths.

New metrology capabilities will be required.



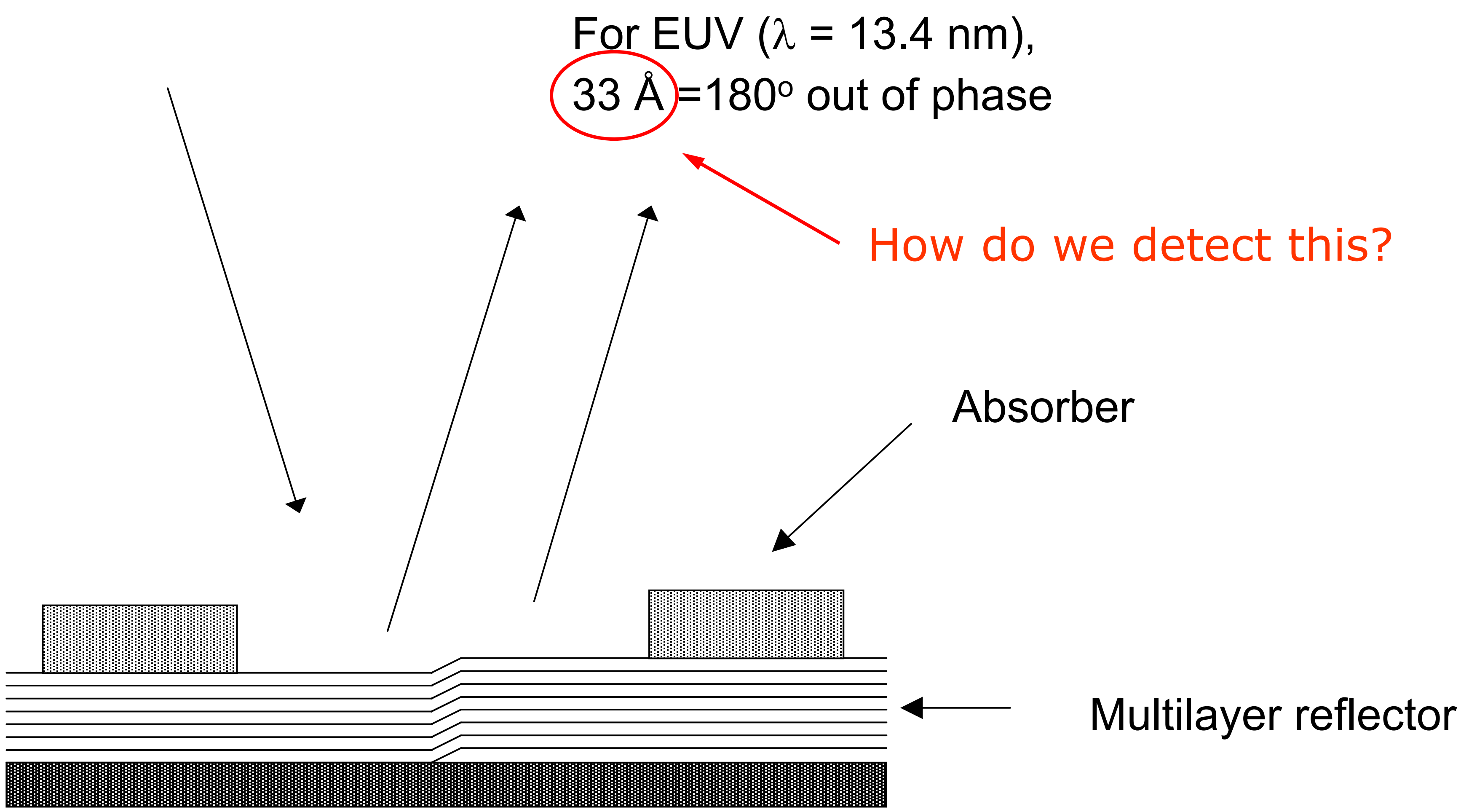
EUV Lithography

- Mask flatness is required well beyond anything required currently.



Spec for flatness = 45 nm P-V at the 32 nm node.

EUV Lithography



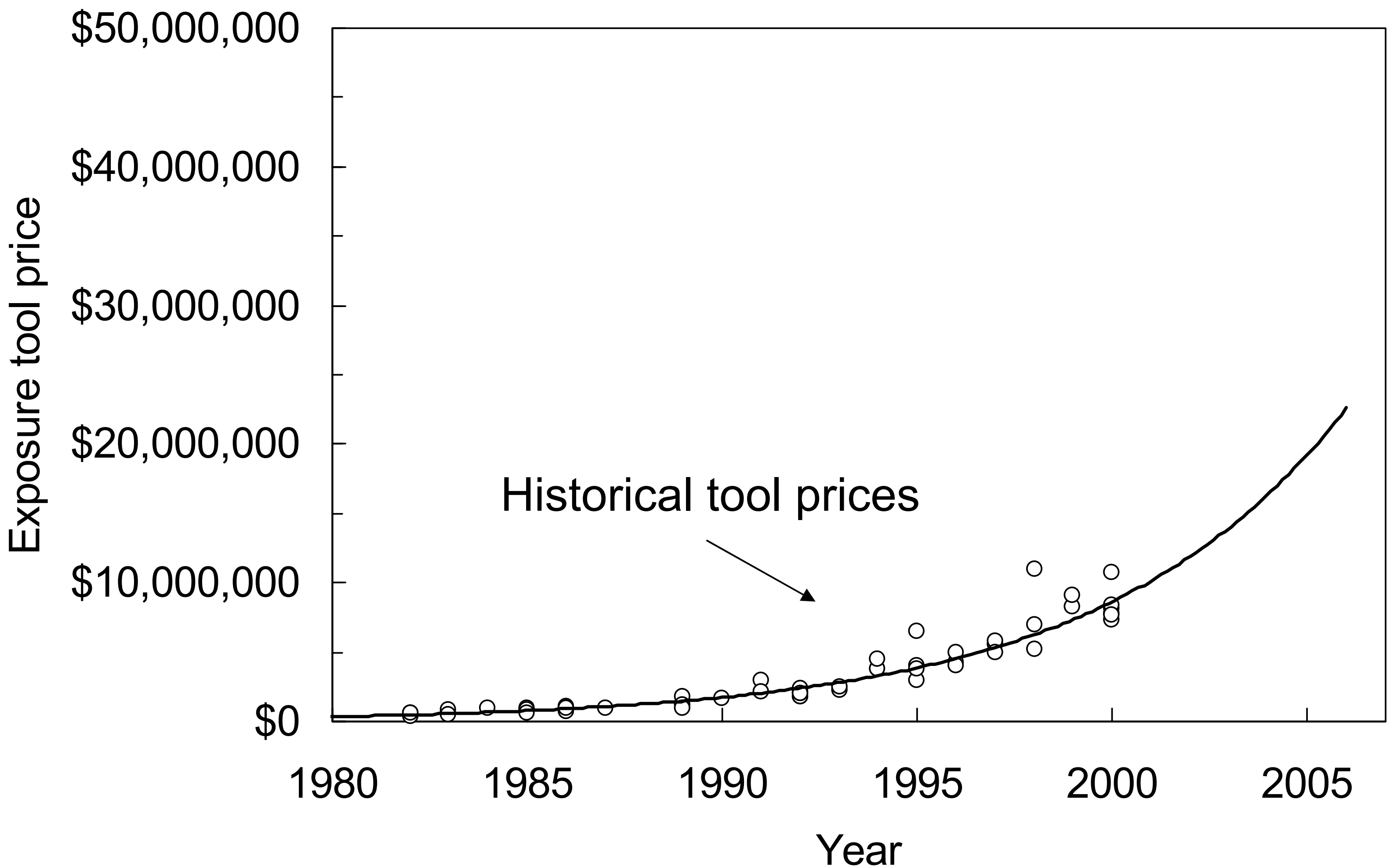
EUV Lithography

- Examples of new metrology capabilities required for EUV lithography.
  - Flatness measurements for masks.
    - 10's of nanometers of accuracy.
  - Reflectance at EUV wavelengths.
  - Mask defect detection.
    - < 50 nm in width and only a few nm high.
  - Surface roughness < 1 nm (rms).

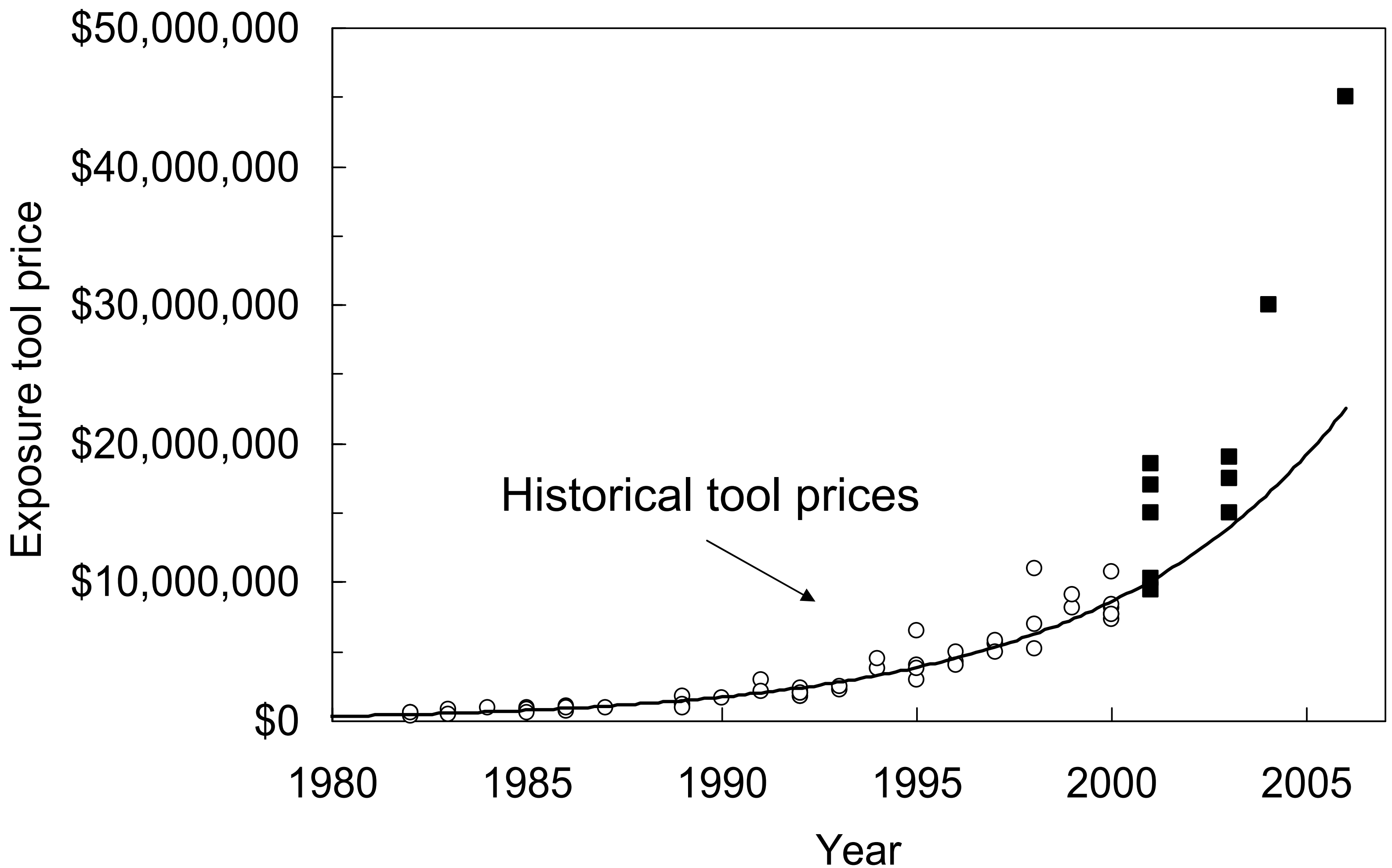
The next big step lithography

- There are a number of options for the next step in lithographic technology.
  - EUV Lithography.
  - Electron Projection Lithography.
  - Maskless lithography.
- All of these require major advances in technology.
  - Tools.
    - Light sources.
  - Resists.
  - Masks.
  - Process control.
- Major advances are hard to do.

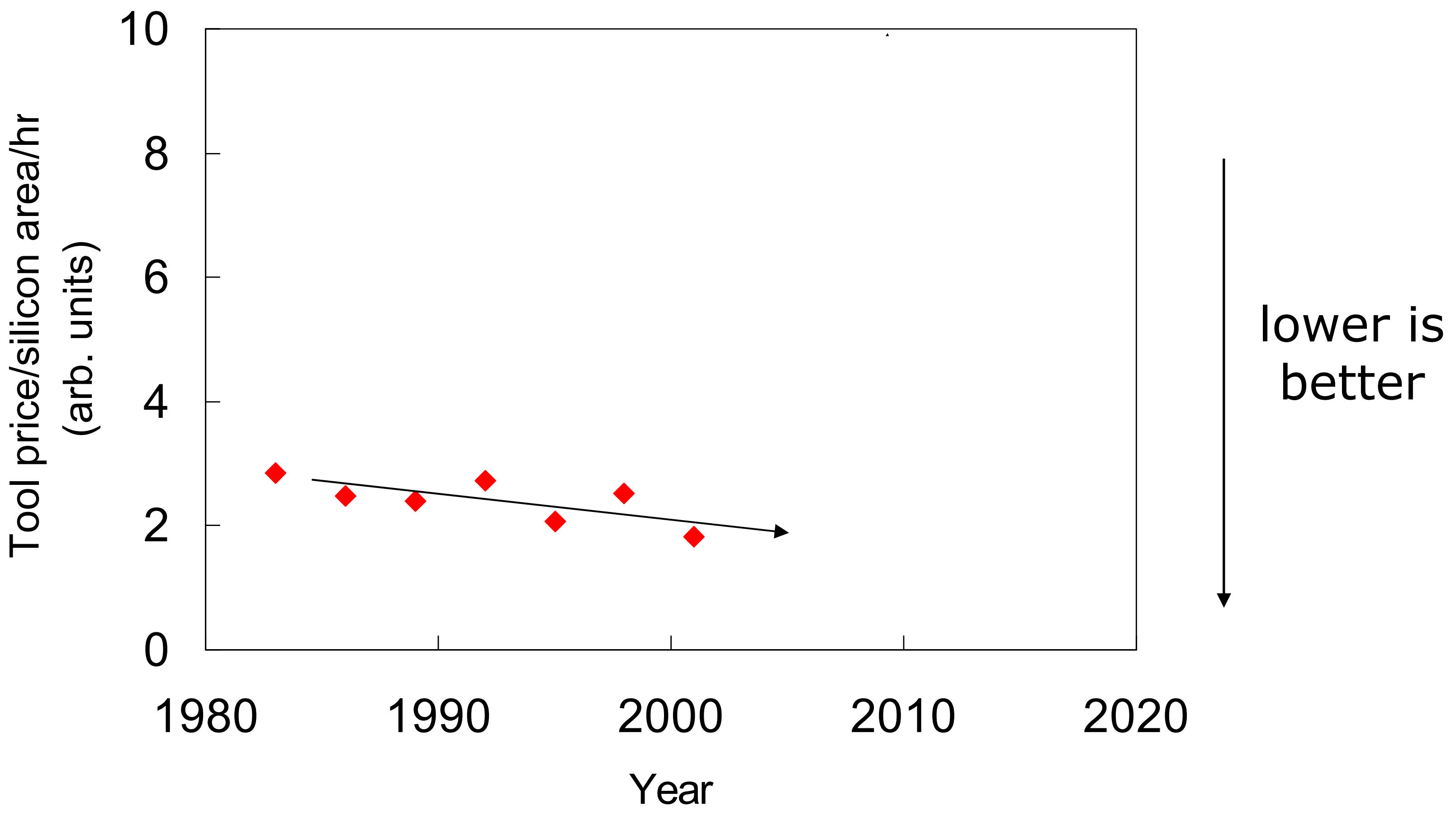
Lithography costs



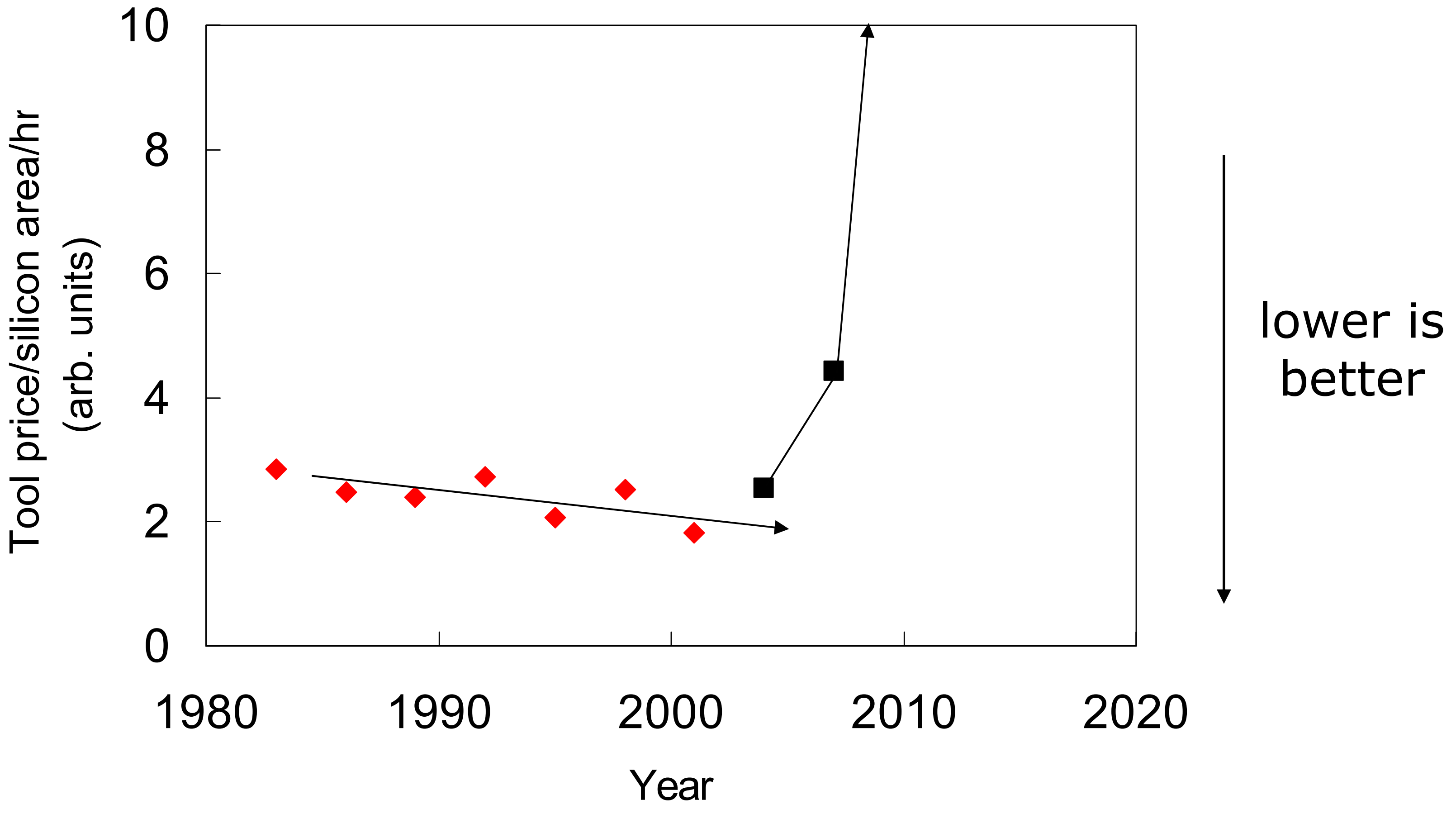
Lithography costs



Lithography costs



Lithography costs



Lithography costs

- The problem may not be just which lithographic technology is cheaper.
- The problem may turn out to be:

What lithographic technology will enable the semiconductor industry to continue to produce higher performance PCs for less than $1000?

How do we pay for the R&D?

- The semiconductor industry made money when there were three years between nodes.
- I have seen no economic analysis that says two years per node maximizes profits for our industry.
  - The worst downturn in the history of our industry has occured with a two year/mode pace.
  - I do not think that one year per node is the answer.
- Innovation is needed.
  - Slow down and think!

Summary

- The end of optical lithography is finally approaching.
  - But not immediately!
- Introducing new lithographic technologies will be hard and expensive.
- The speed at which the semiconductor industry travels over the roadmap will slow down.

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