Nanofabrication

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Outline

- **Top-Down Approaches**

  -- Conventional lithography (radiation-based)

  -- Nanoimprint and nanoprint (non-radiation-based)

  -- Etching
- **Bottom-Up Approaches**

  -- Self assembly

  -- Guided self-assembly

  -- Molecular epitaxy
- **Commercial Nanoimprint tools and solutions**

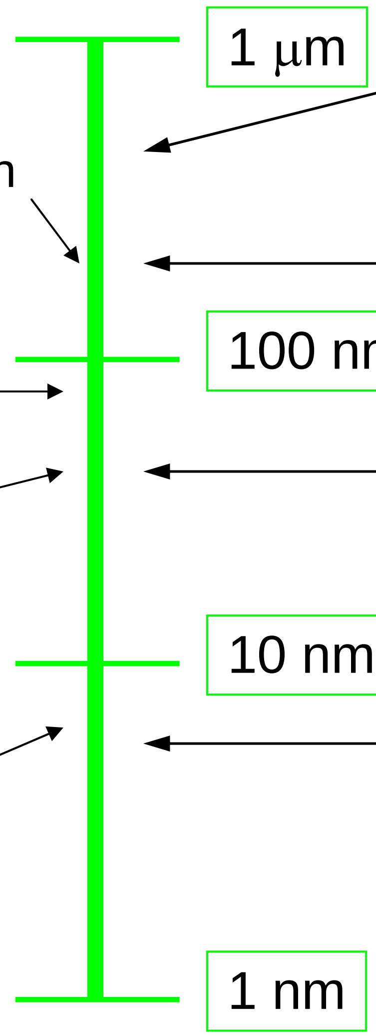
Nanotechnology Leads to Discovery and Innovation

Because …..

As a device size becomes less than a fundamental physical length scale, conventional theory may no longer apply.

-- S.Y. Chou (Nanotech Report 1998)

Examples of Fundamental Length Scales and Impaccts



Visible light wavelength
->Subwavelength optics
Optical ICs

Optical Phonon Scattering Length
->Velocity overshoot and
Fast transistors

Magnetic domain wall size
->New fast magnetic devices
Ultra-high density memories

Phase Coherent Length
->Quantum effects

DNA Persistent Length
->DNA sorter

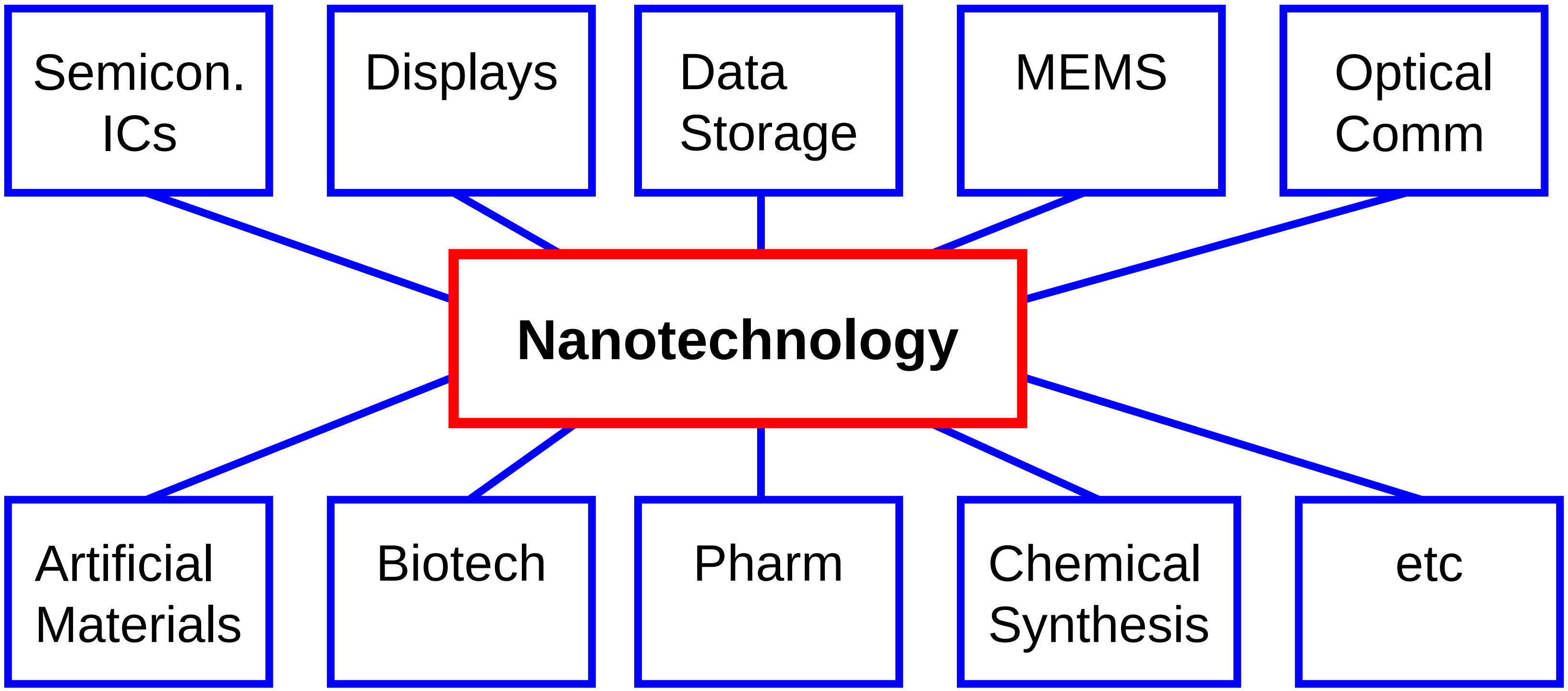
Nanocrystal size
->single crystal on α-substrate
New way to build transistors

Molecule size
->Molecular electronics

Quantum energy > RT energy
->Room Temp Single Electron Devices

Nanotechnology Impacts Multi-Disciplines

Nanotechnology makes "old products" new ways and "new" products that can't be made before. It will grow *exponentially* to **multi-dimensional, multi-billion dollar** market in a few years.



Nanofabrication

- Nanofabrication is the vehicle to bring us to the nanotechnology dreamland of multi-dimensional and multi-trillion-dollars markets.
- Today, we do not yet have a commercial general-purpose nano-manufacturing tool.
- Without nanofabrication, nanotechnology will be a pie in the sky.

(--S.Y. Chou)

Nanofabrications

- **Top-Down Approaches**
  - -- Conventional lithography (radiation-based)
  - -- Nanoimprint and nanoprint (non-radiation-based)
  - -- Etching
- **Bottom-Up Approaches**
  - -- Self assembly
  - -- Guided self-assembly
  - -- Molecular epitaxy

Different Lithographies

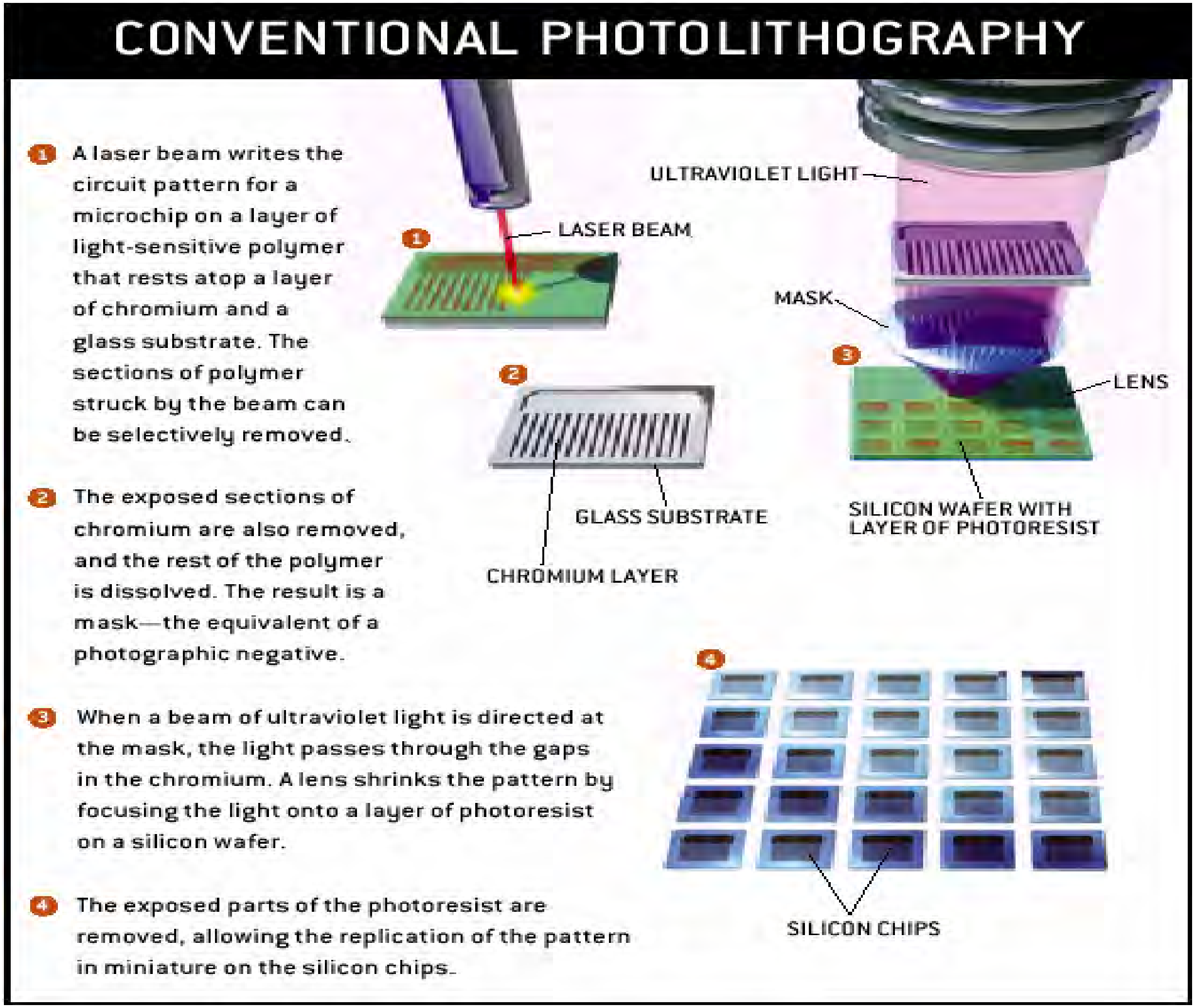
- **Radiation-based lithography**
  - Photolithography (deep ultraviolet, x-ray, extreme ultraviolet)
  - Electron beam lithography (scanning, projection)
  - Ion beam lithography (scanning, projection)
  - Maskless lithographies

- **Non-radiation-based lithography**
  - Nanonimprint
  - Nanoprinting (ink stamping, ink jet, dip-pen lithography)

Photolithography

A. Mask Making

B. Exposures



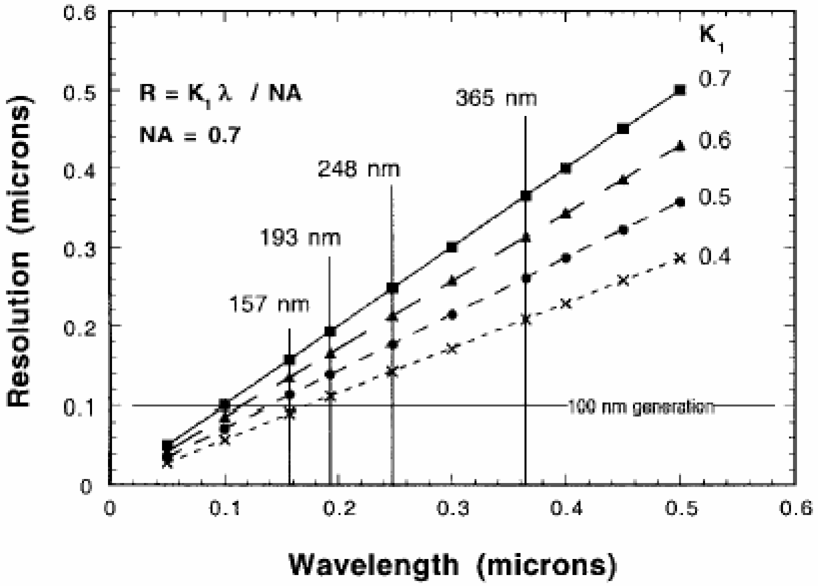
Whitesides, Sci. American, 2001

Physics of Radiation Based Lithography

- Theoretical resolution = $(K_1 \lambda) / (NA)$
- Theoretical Depth of Focus = $(K_2 \lambda) / (NA)^2$

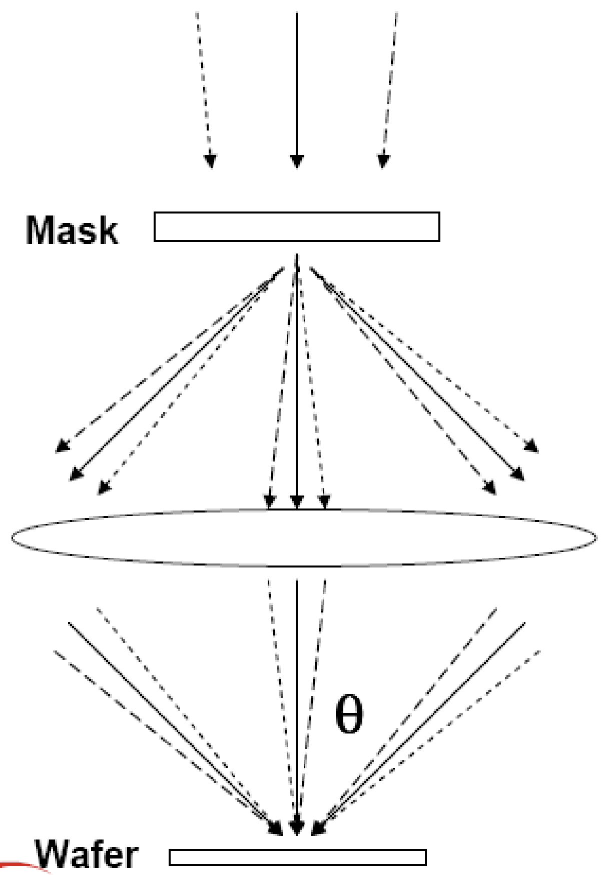
(λ: wavelength, NA: numerical aperture, K_1 and K_2 are constants)

- Real resolution also depends on resist properties, mask resolution enhancement technologies, etch process



Stulen, at al., IEEE J. of Quan, Elec., 1999

Resolution of Optical Lithography



- **Optical projection imaging has been the preferred means of patterning semiconductor chips over the past 20 years**

- **Resolution of an optical projection system is usually expressed as**

$$HP_{MIN} = k_1 \lambda / \sin\theta$$

- **Min. Half Pitch (HP) must be greater than**

$$0.25\, \lambda / \sin\theta$$

- **Sinθ is the Numerical Aperture (NA) of the projection lens**

Progress in Optical Lithography

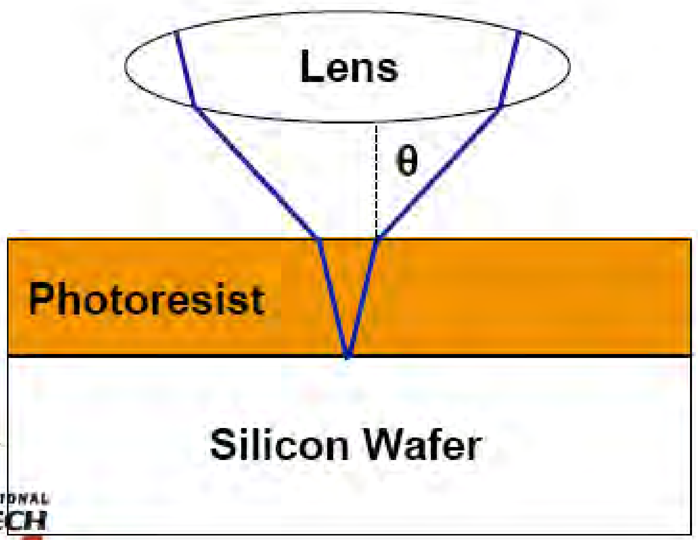
$$HP_{MIN} = k_1 \frac{\lambda}{NA}$$

Finer resolution can be achieved by

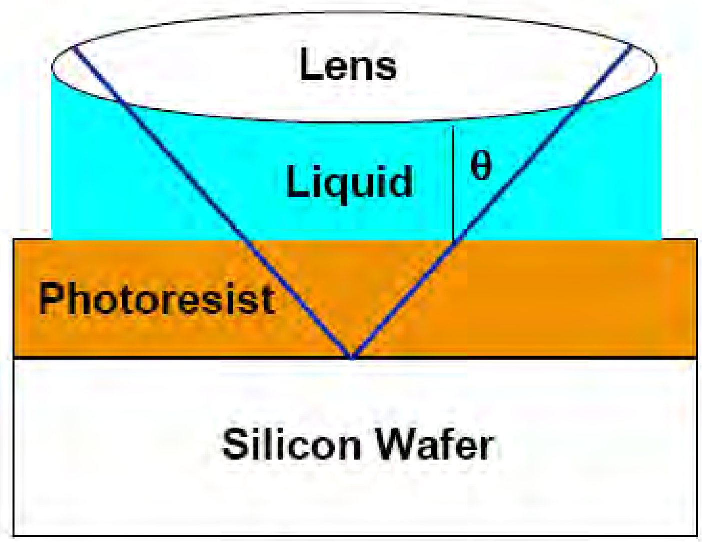
- Increase of NA (0.8 @ 248 nm, 0.85 to appear @ 193 nm & 157 nm)
- Reduction of wavelength (436, 365, 248, 193, 157 nm)
- Reduction of k_1
  - Progress in mask making
  - Progress in lens making (precision optics)
  - Better photoresists
  - Better process control
  - Resolution Enhancement Techniques (RET)

Resolution Improvement by Immersion – Principle

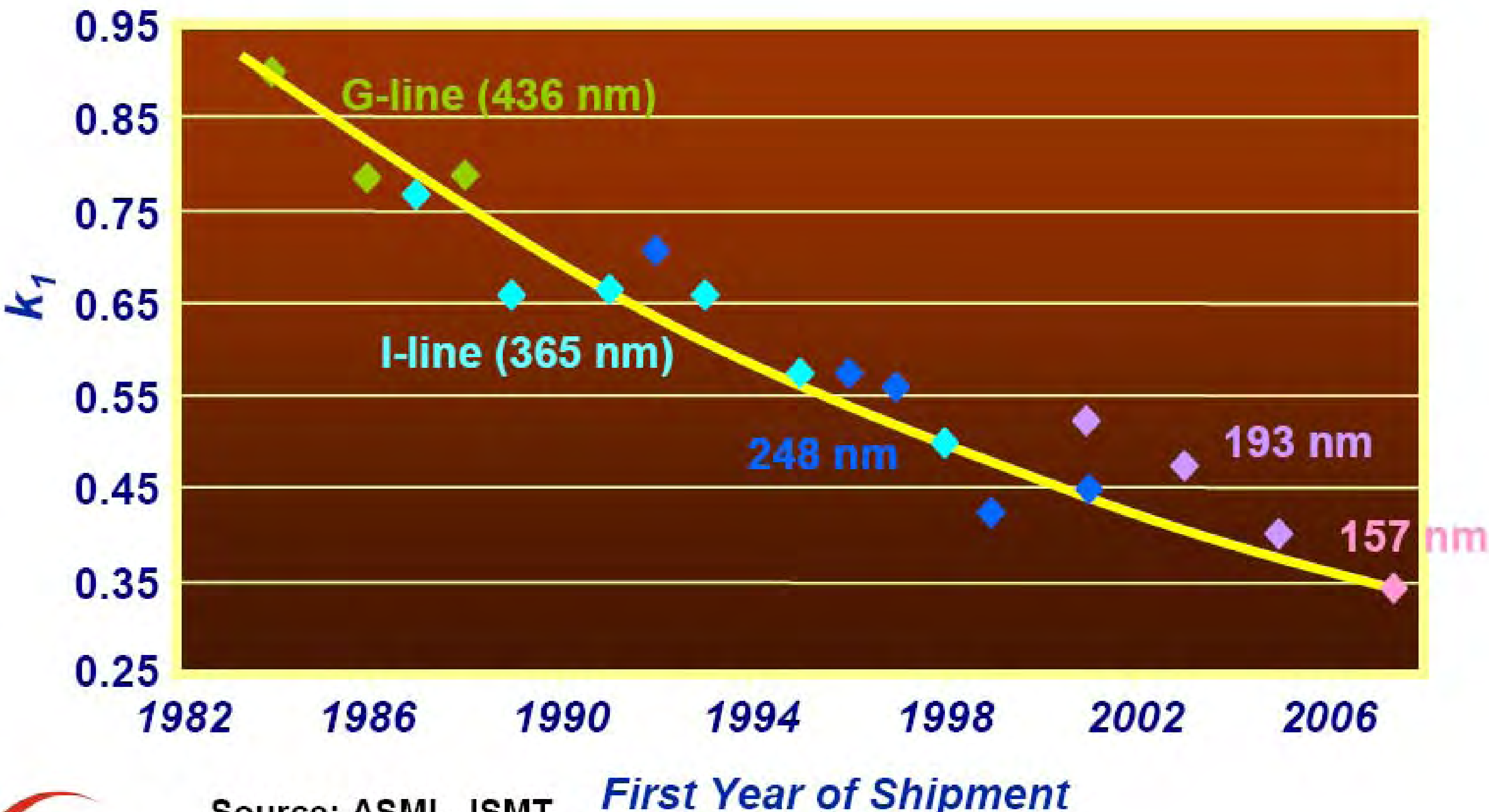
$$HP_{MIN,DRY} = \frac{1}{4}\frac{\lambda_{RESIST}}{\sin\alpha_{RESIST}} = \frac{1}{4}\frac{\lambda_{AIR}/n_{RESIST}}{\sin\theta/n_{RESIST}} = \frac{1}{4}\frac{\lambda_{AIR}}{\sin\theta}$$



$$HP_{MIN,WET} = \frac{1}{4}\frac{\lambda_{RESIST}}{\sin\beta_{RESIST}} = \frac{1}{4}\frac{\lambda_{AIR}/n_{RESIST}}{n_{LIQUID}\sin\theta/n_{RESIST}} = \frac{1}{4}\frac{\lambda_{AIR}}{\sin\theta}\Big/ n_{LIQUID}$$



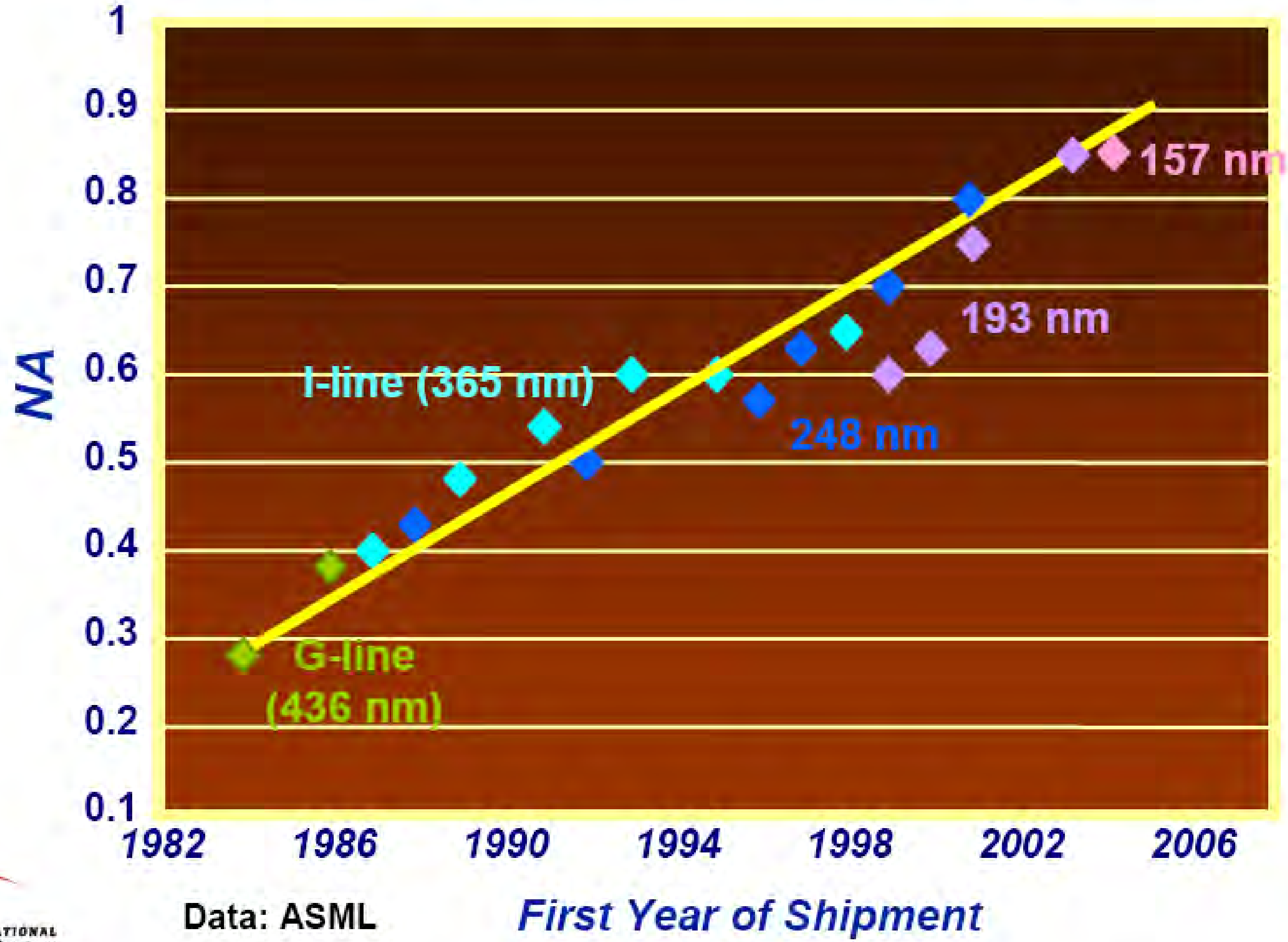
k_1 Reduction over Time



Source: ASML, ISMT

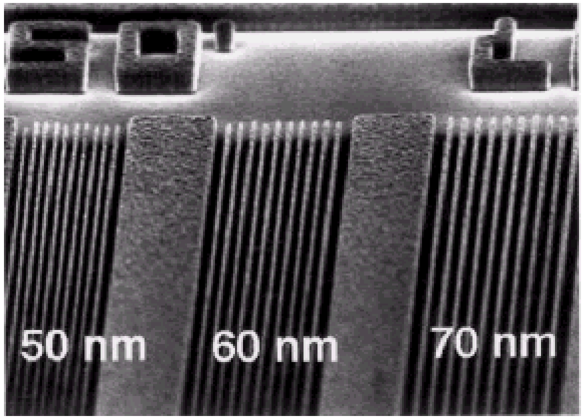
INTERNATIONAL SEMATECH

Numerical Aperture Increase over Time

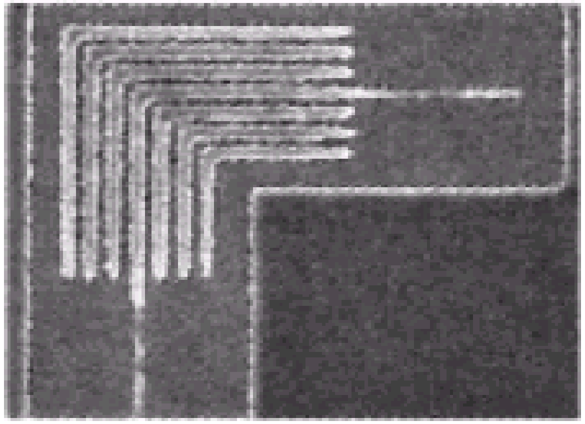


Data: ASML

Examples of EUV Lithography



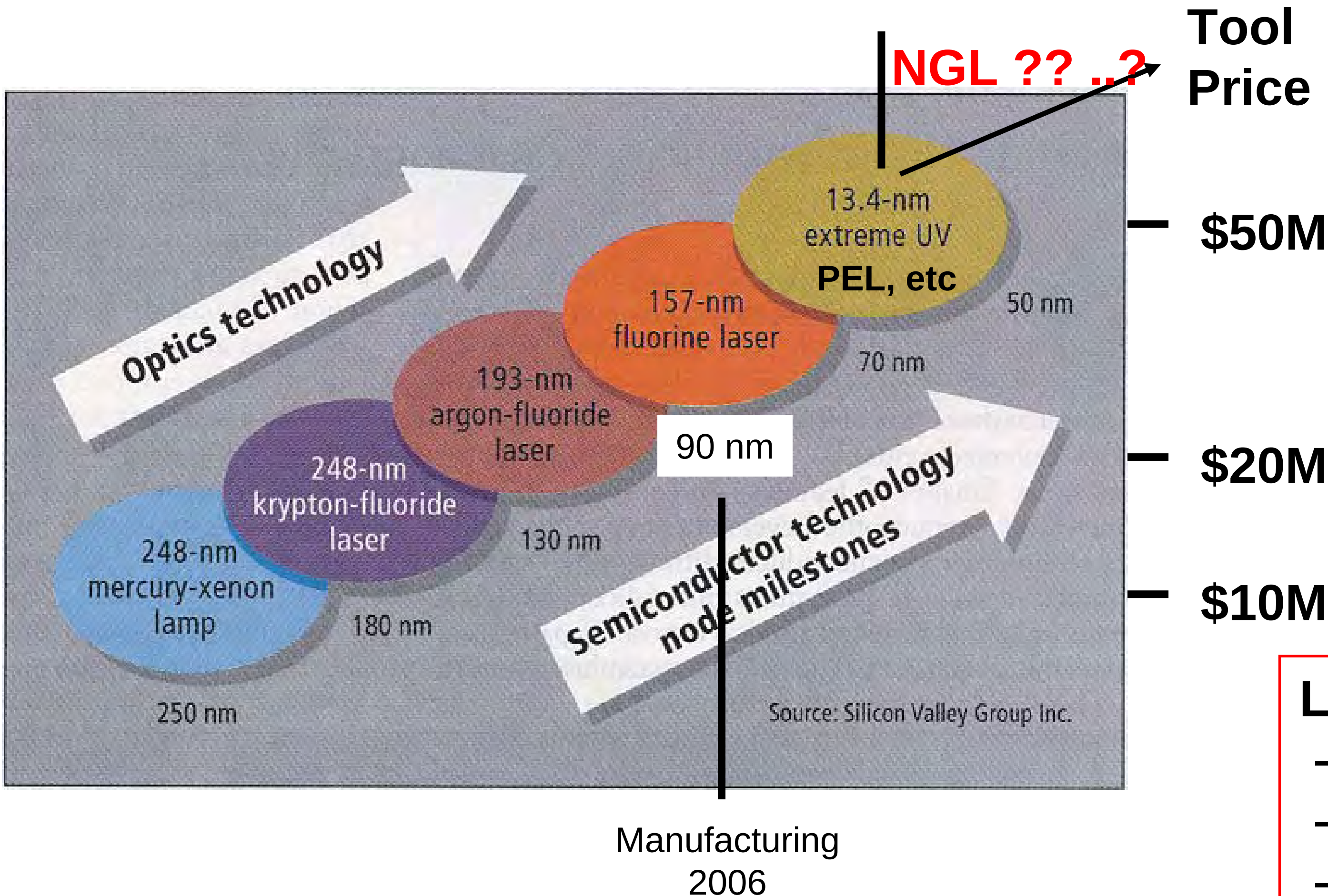
Stulen, at al., IEEE J. of Quan, Elec., 1999



100 nm elbow patterns

Chapman, et al., J. Vac. Sci. Tech. B, 2001

Conventional Lithography Can Not Offer the Resolution, Cost, and Exposure Area Needed for Nanomanufacturing



Limited to:
- -- 65 nm?
- -- 1 sq-in area
- -- $40M/tool

Nanoimprint Lithography (NIL) –a Solution to Nano-manufacturing

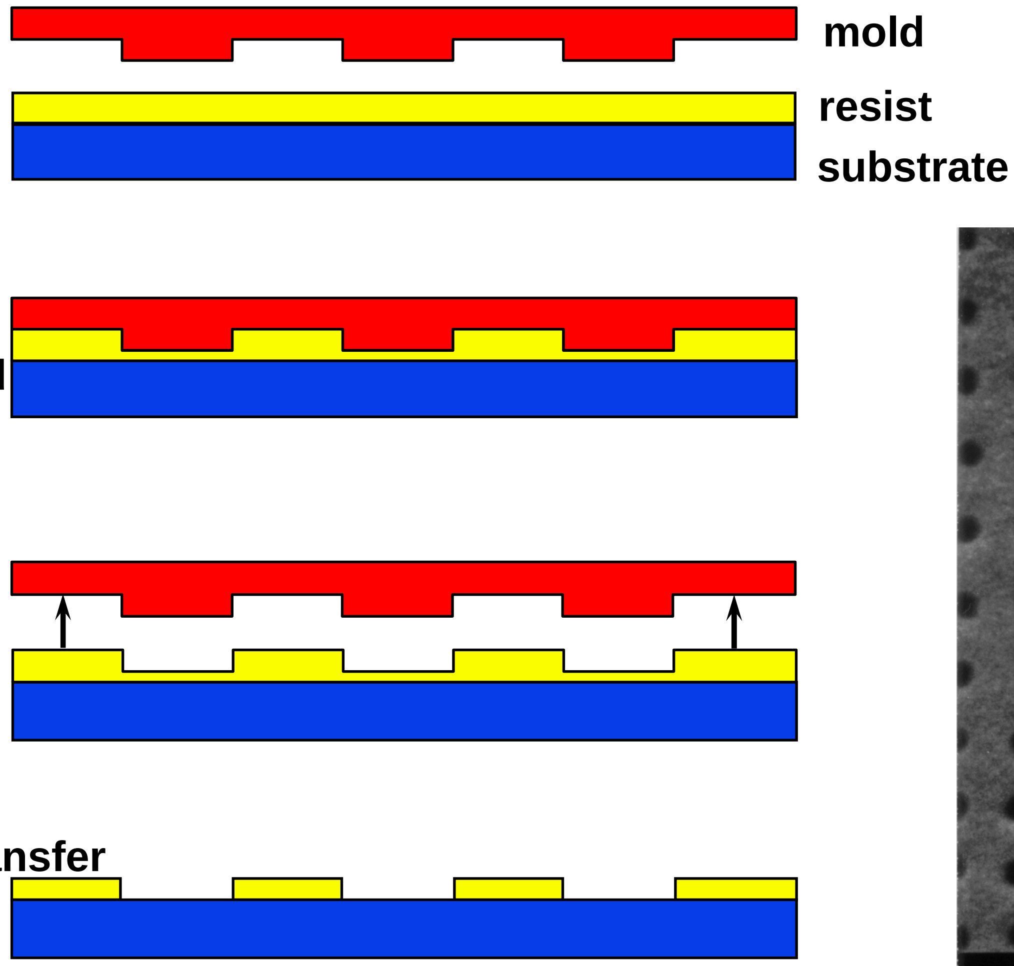
1. Imprint

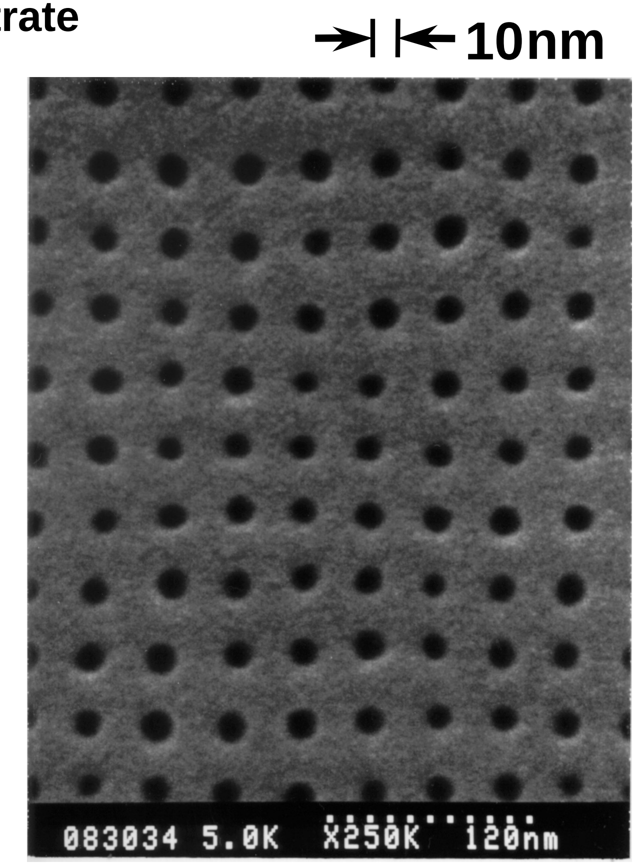
•Press Mold

•Remove Mold

2. Pattern Transfer

•RIE

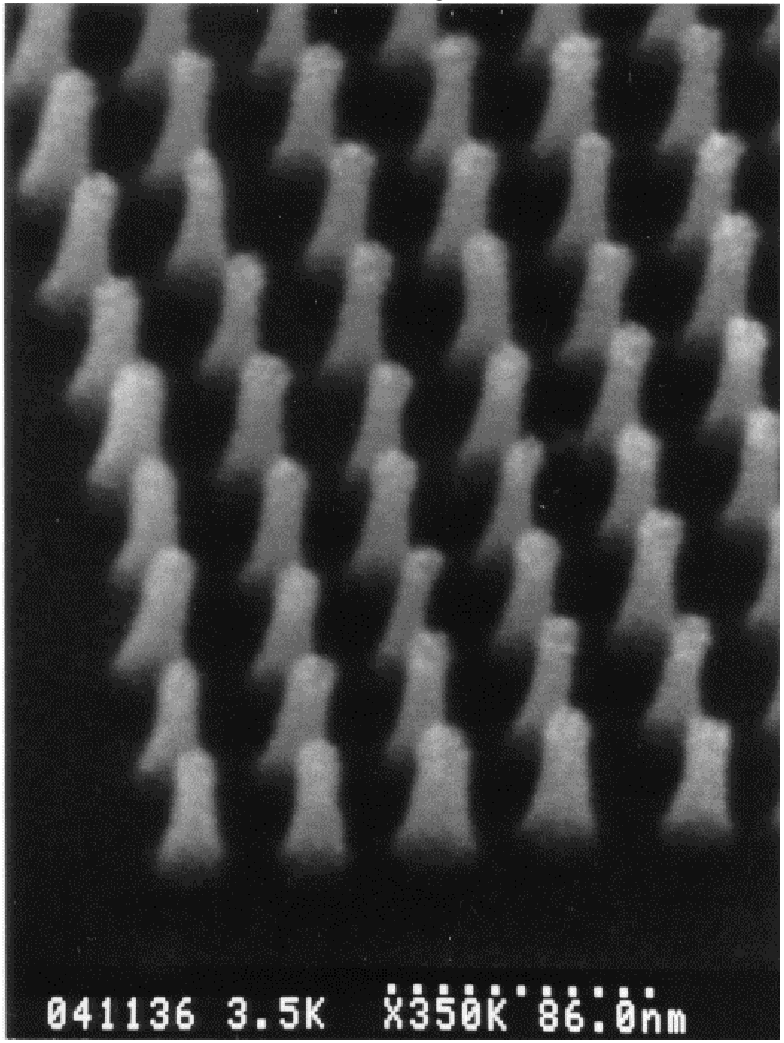




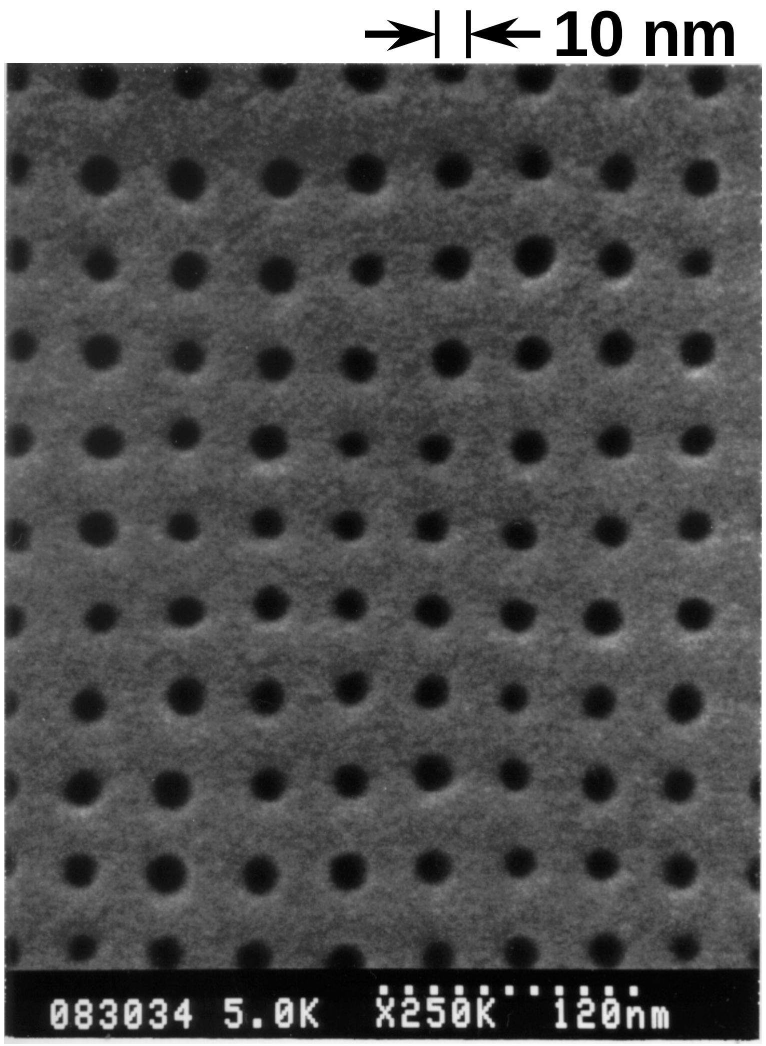
Chou, US Pat 5,772,905, 6,309,580, APL, Vol. 67, 3114 (1995); Science, Vol. 272, 85 (1996)

10 nm Diameter, 40nm Period Imprint Mold (After 12 Imprints)

10 nm

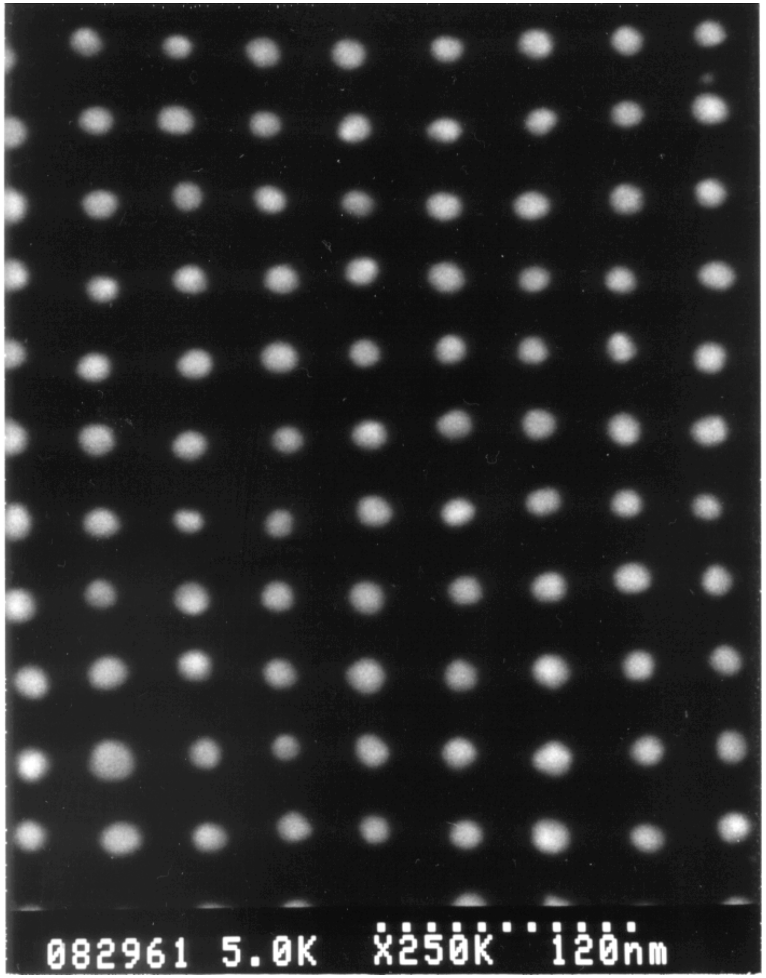


10 nm Diameter, 40 nm Period and 60 nm Deep Holes Imprinted into PMMA

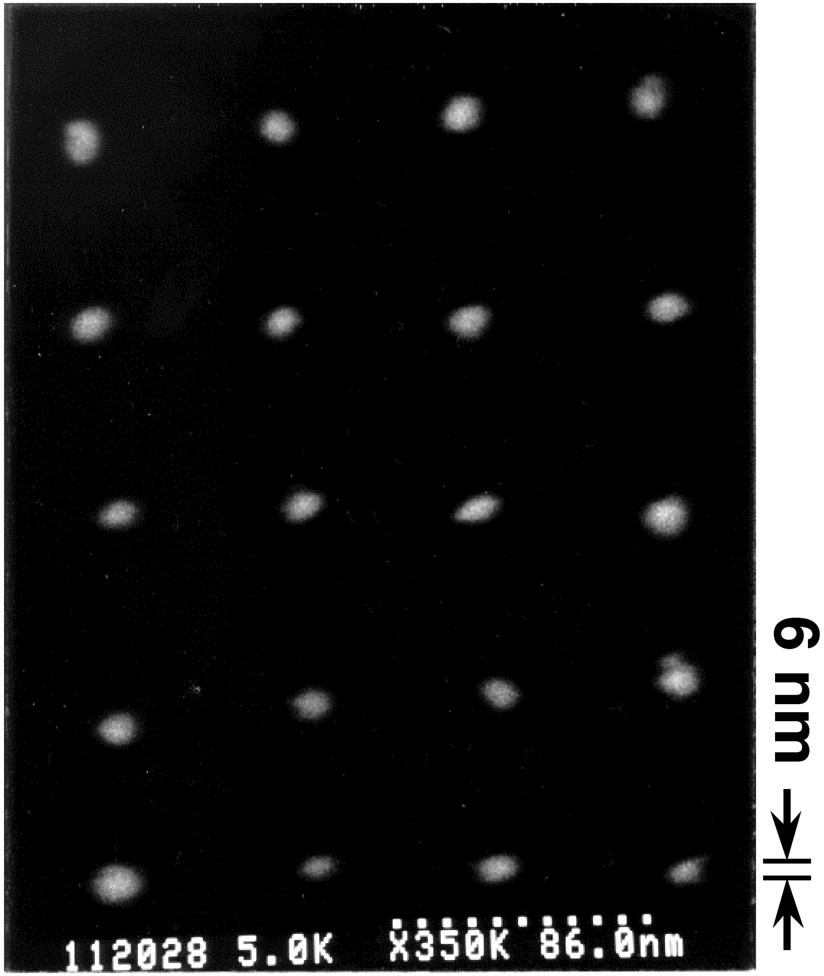


10 nm Diameter & 40 nm Period Ti/Au Dot Array by NIL and Lift-Off

10 nm

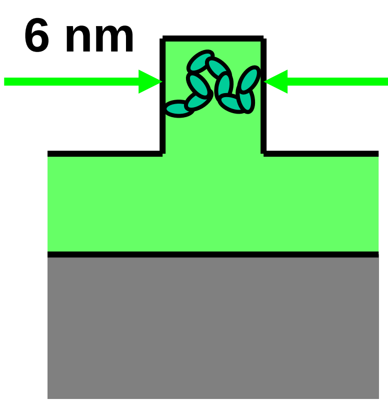


6 nm Diameter & 65 nm Period Ti/Au Dot Array by NIL and Lift-Off

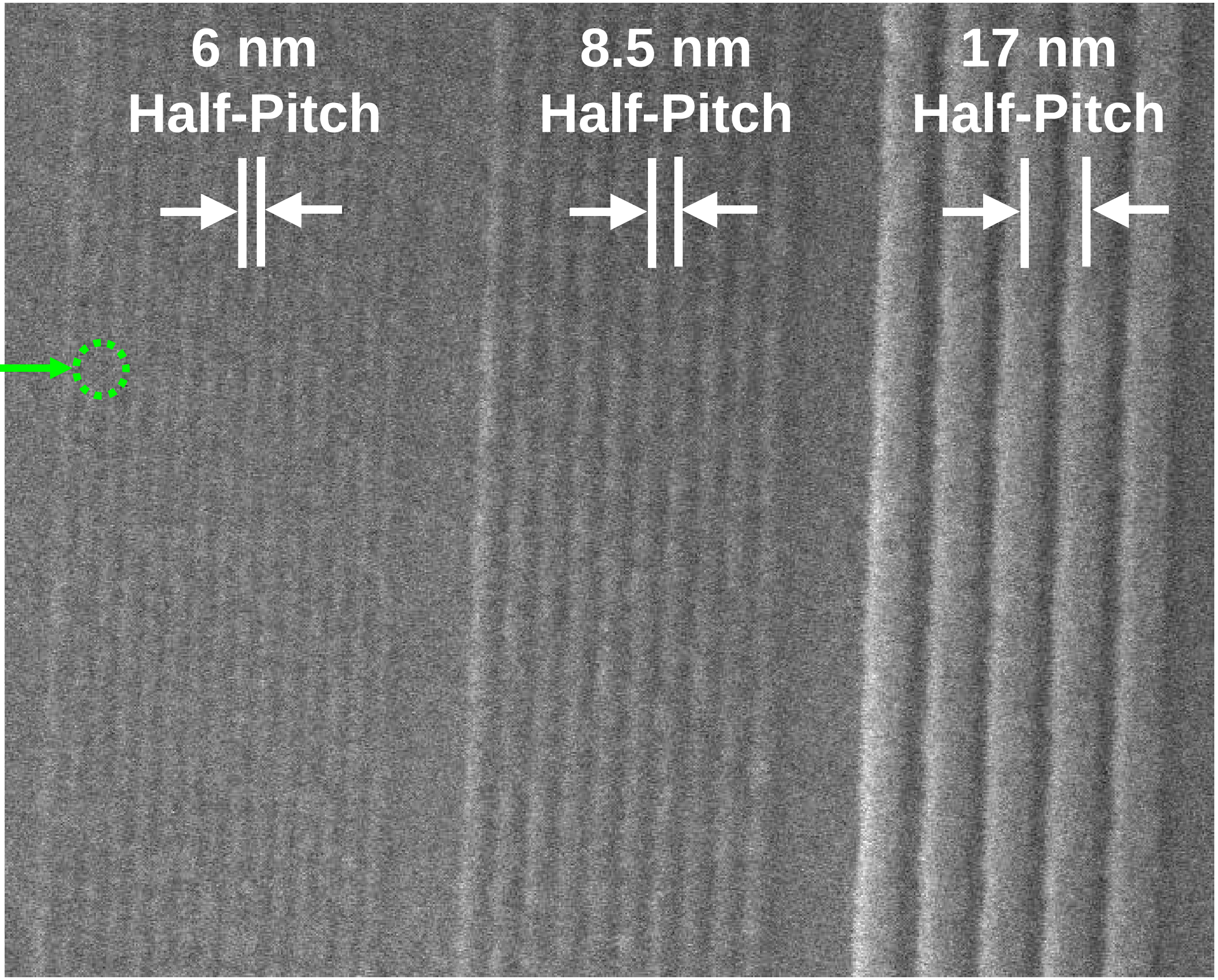


6 nm Half-Pitch Resist Lines by NIL

- NIL resist (cured)
- Quartz
- Monomer (1.4 nm)
- 6 nm = 9 monomers

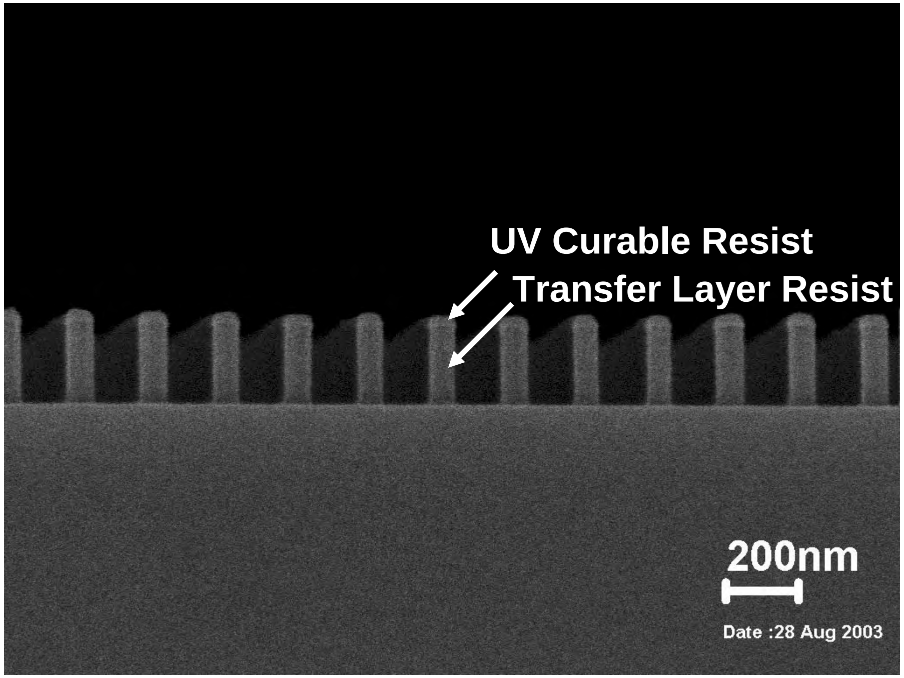


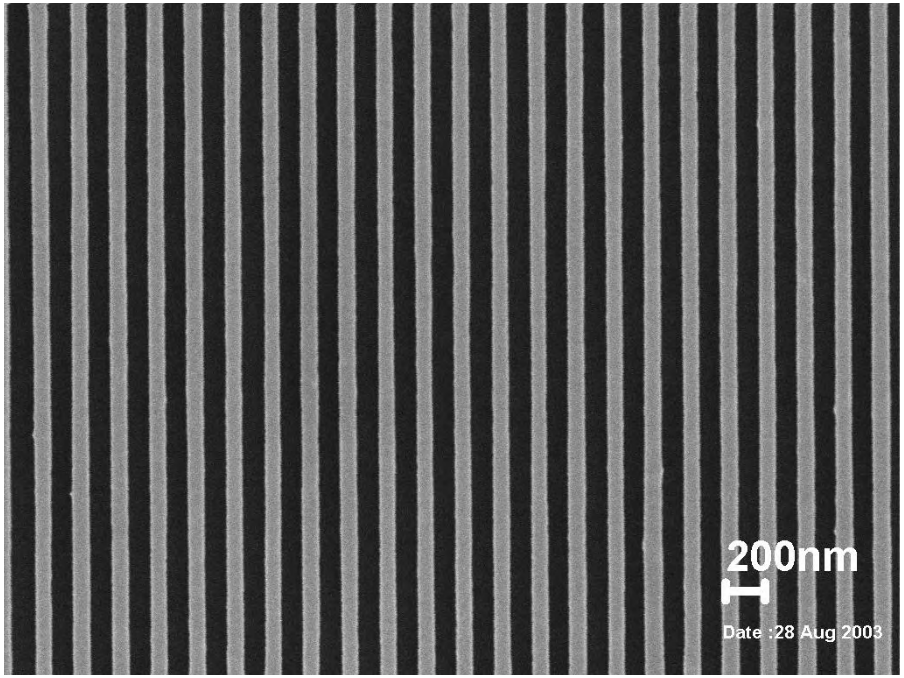
Polymerization within a constrained geometry



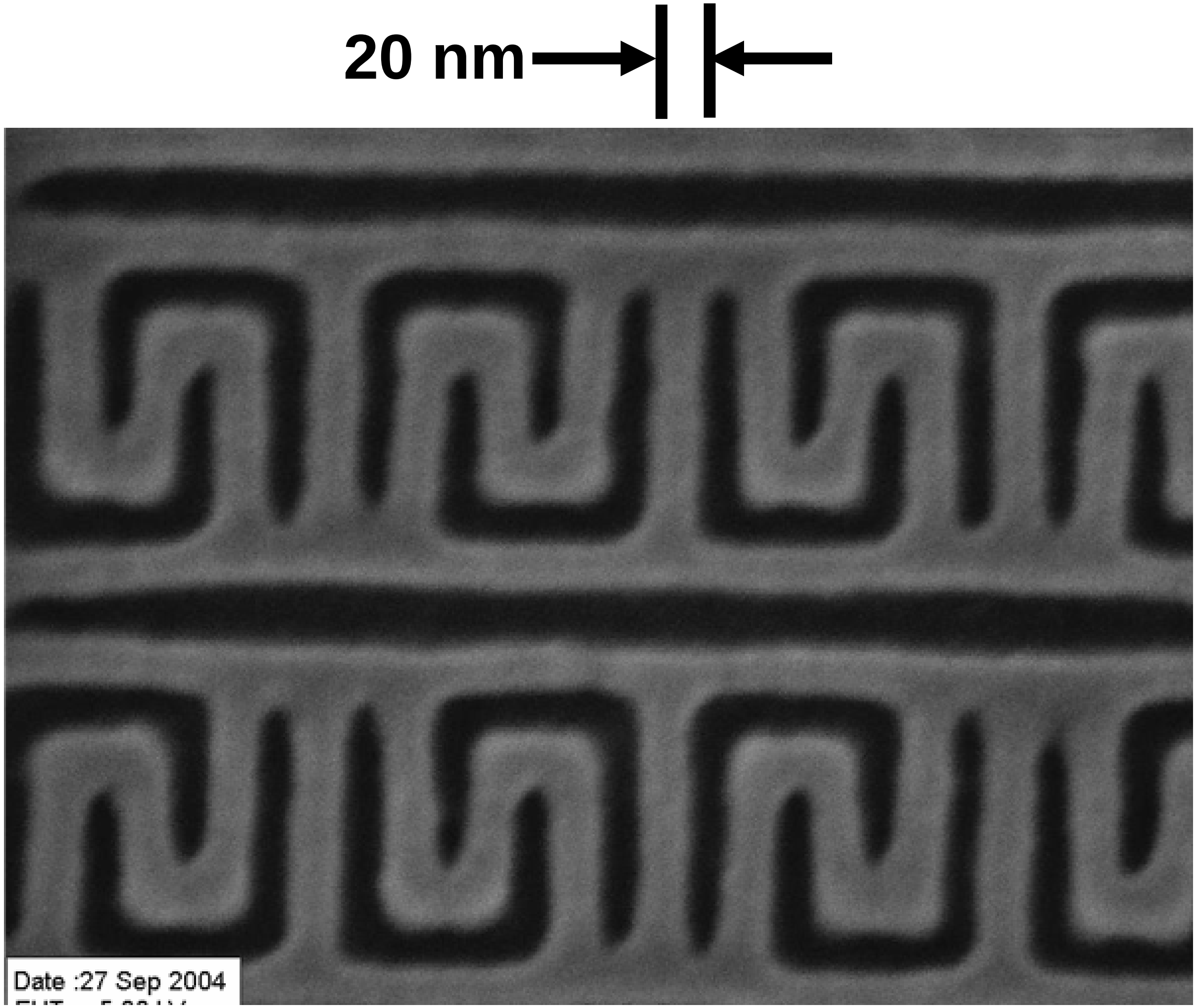
Austin and Chou, J of Nanotechnology 2005

Vertical Sidewall of 70 nm Resist Lines by Photo Curable/Transfer Nanoimprinting





20 nm Half-Pitch & 0.04 μm^2 SRAM Contact Layer by NIL



CD control measurements:

- Mean: 21.5 nm
- σ (sigma): 1.3 nm

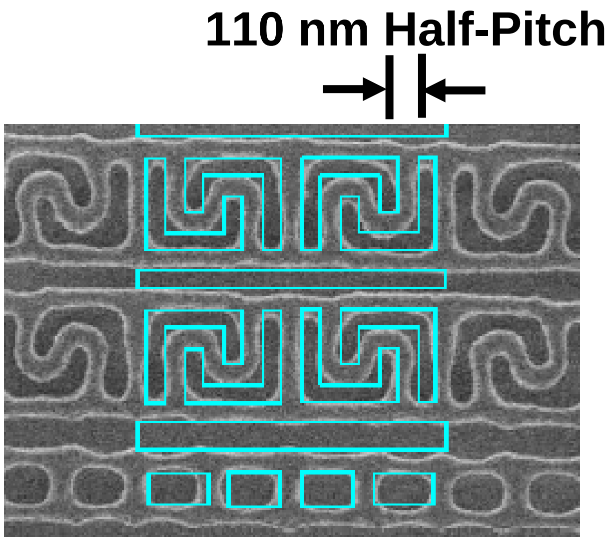
ITRS roadmap spec: 2016!

Austin and Chou, J of Nanotech, Aug. 2005
Nanonex NX-2000 NIL machines
Nanonex NXR-2010 resist

Comparison of SRAM Metal Layers by 65 nm Node Photolithography & Nanoimprint lithography

Intel

1.13 μm^2 cell by 193 nm lithography & phase masks (2002)



ftp://download.intel.com/research/silicon/BorodovskyPhotomaskJapan0402pres.pdf

Reduction:
-- 6X in linear
-- 30X in area

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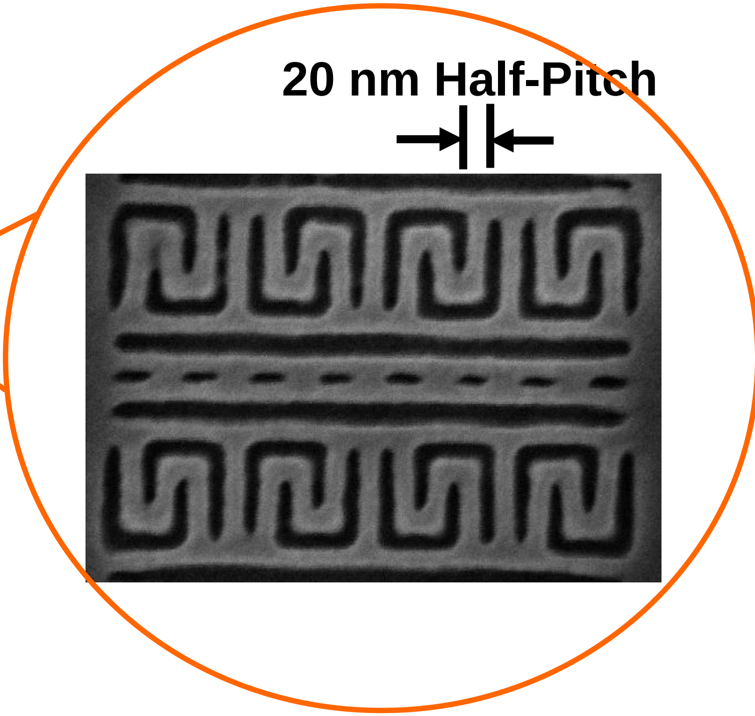
0.04 μm^2 cell by nanoimprint lithography



Austin and Chou, J Nanotech. 2005
Nanonex NX-2000 NIL machines
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