Lecture 9

Chemical Engineering for Micro/Nano Fabrication

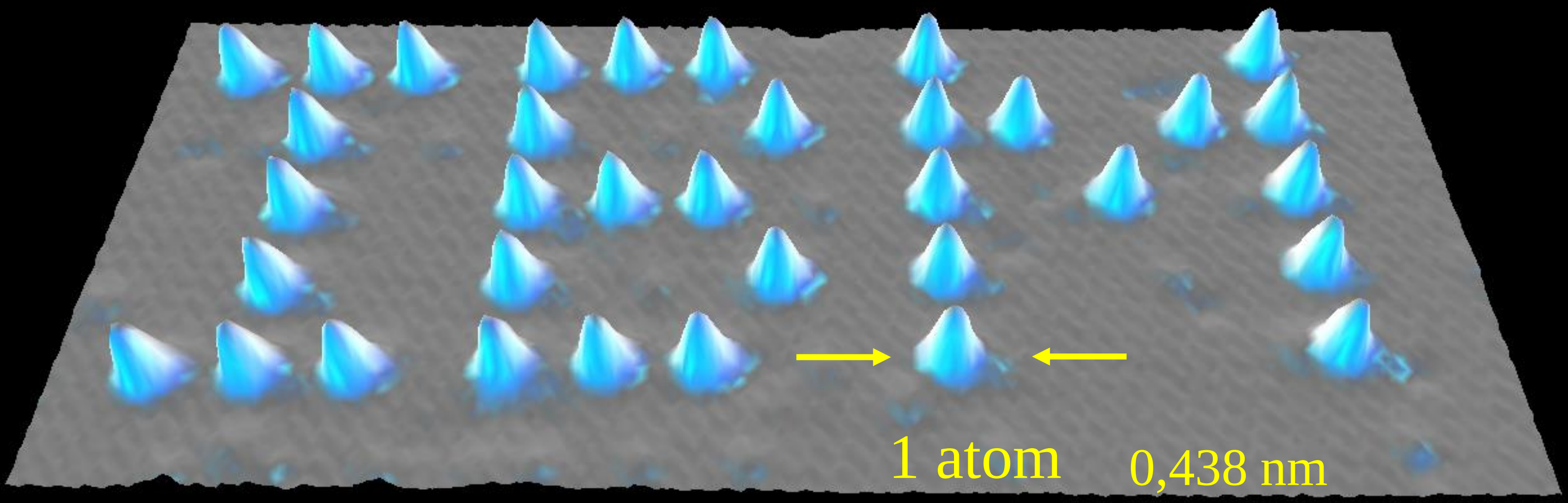
Matt Colburn

Steve Johnson

S.V. Sreenivasan

Nanoimprint Lithography NIL

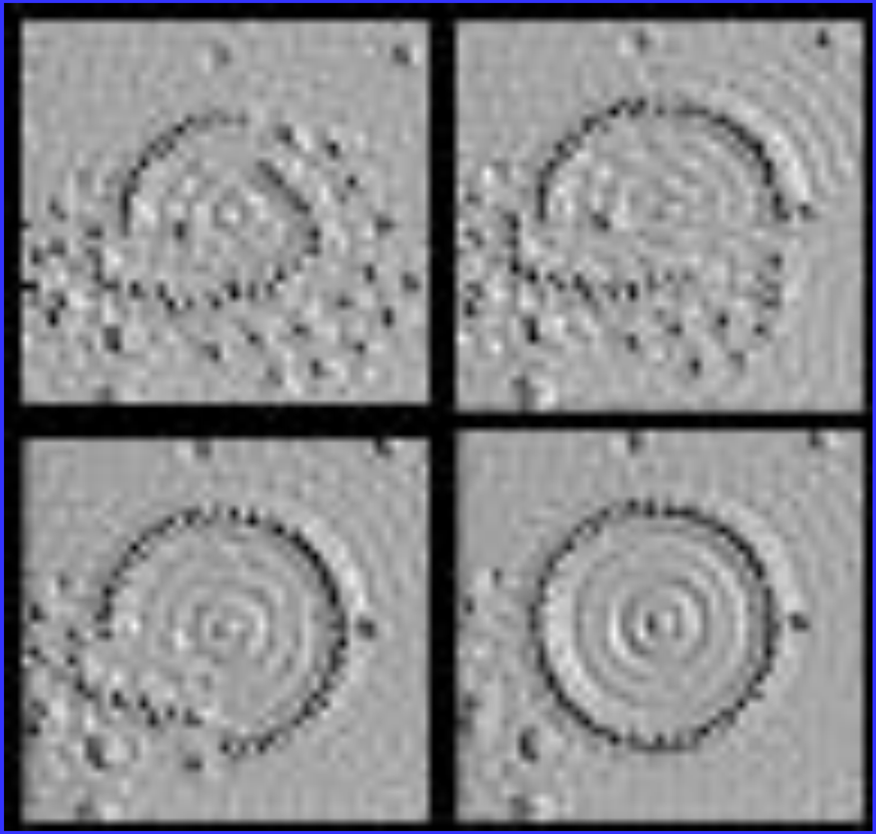
Ultimate limit of high resolution patterning!!



Eigler, et al IBM Almaden

Xe on Nickel

Atomic Resolution…atom by atom



Don Eigler

IBM Almaden Research Center

Resolution:

1 atom ~ 0.3–0.5nm

Throughput:

one atom per minute

~ 0.02 pixels/second

Great Science but not yet practical

Production Lithography

- 193nm step and scan exposure
- Chemically Amplified Resist
- Water immersion lithograpy
- Cost > $60 million/tool

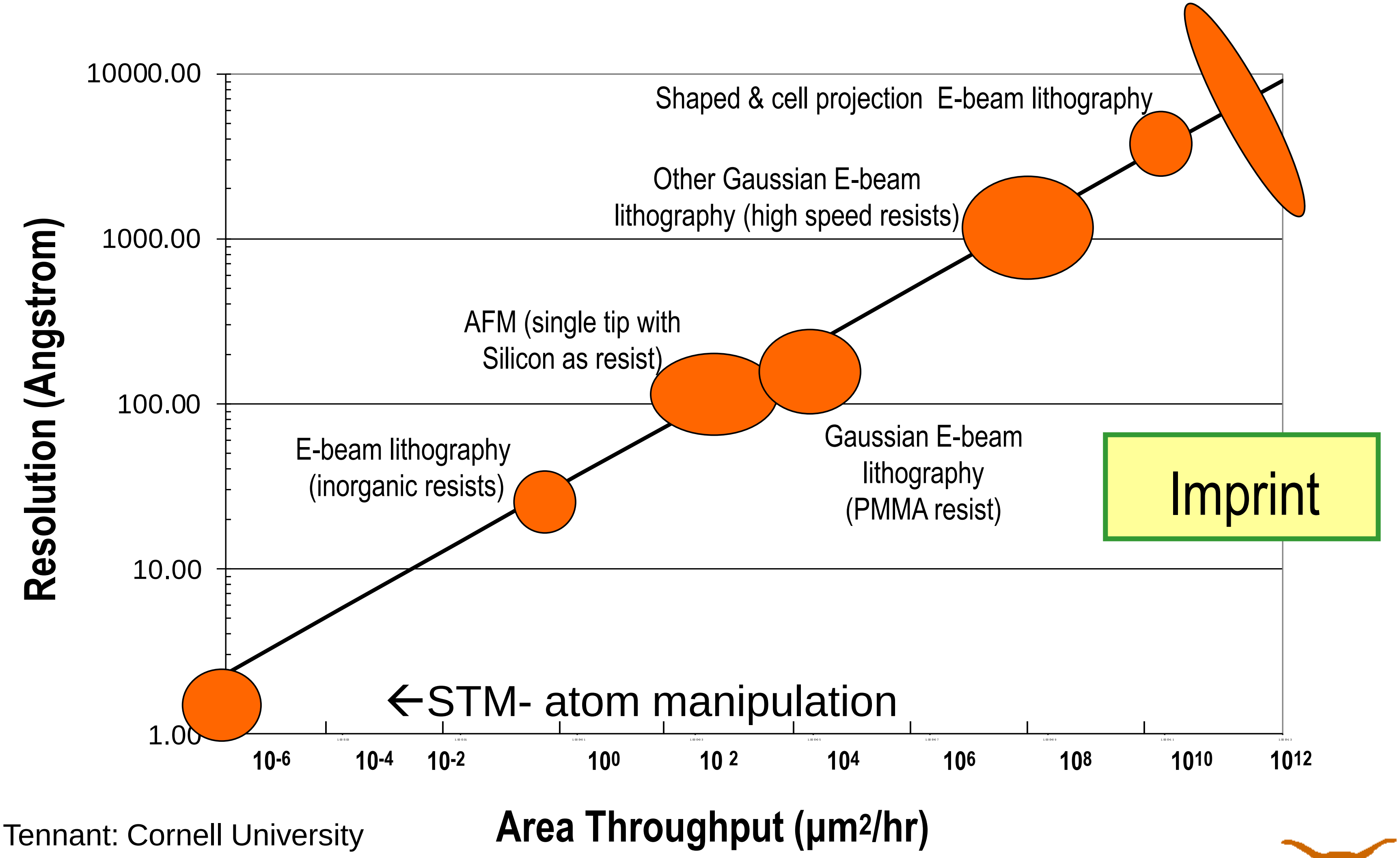
Resolution: 40 nm ≈ $\lambda/5$

Throughput: 100 wafers/hr

>300 gigapixels/sec!!!

OK…Serial Processes are Simply too Slow

Resolution vs. Throughput

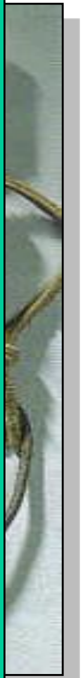


Don Tennant: Cornell University

600 AD Imprint Lithography

Minoan Signet Ring

From the Bronze Age



Tang

s

15th Century Imprint Lithography

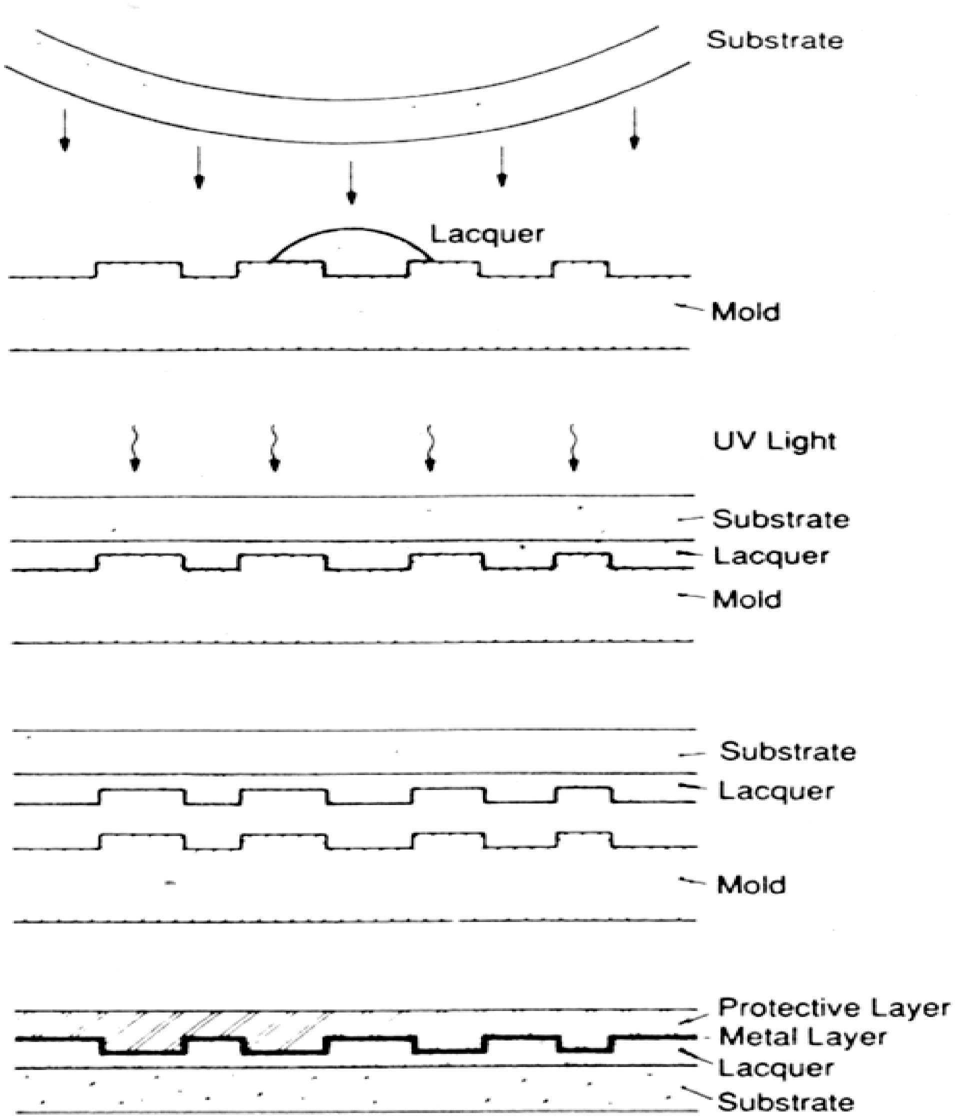
oquentie fonte ma-
hiſpanie galliarū
am veniſſe nobiles
ad cōtemplacōnem
erat: unius homi-
t. Habuit illa etas
bus ſeculis. celebrā-
m: ut urbem tātam

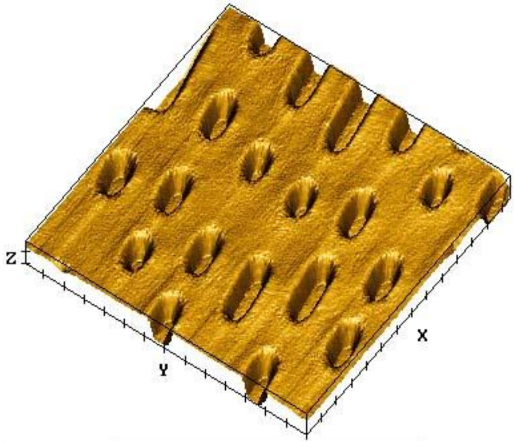
nos q
ba et
angel
aut a
tentis
auree
fuſa: f
rodi

JOHANNES GUTENBERG

1980's Nanoimprint for CDs

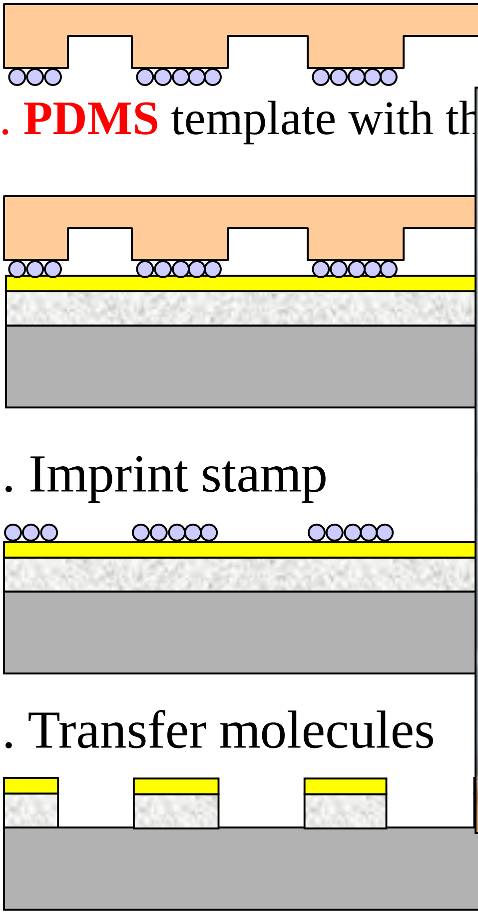
- **Phillips 2P process**
  - UV sensitive "lacquer" sandwiched between mold and thin polycarbonate substrate
  - UV light shown through substrate to cure lacquer





90's Soft Lithographyb

Soft Lithography

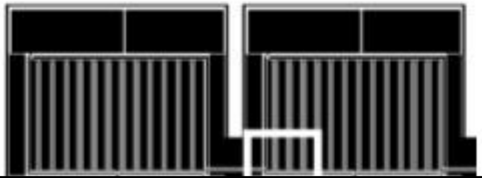


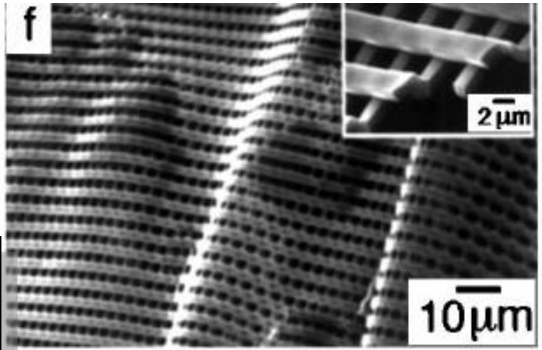
1. **PDMS** template with th

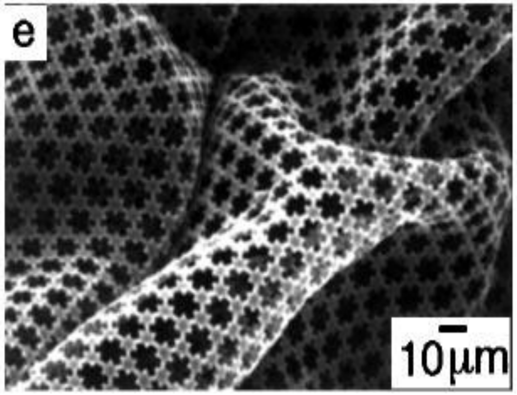
2. Imprint stamp

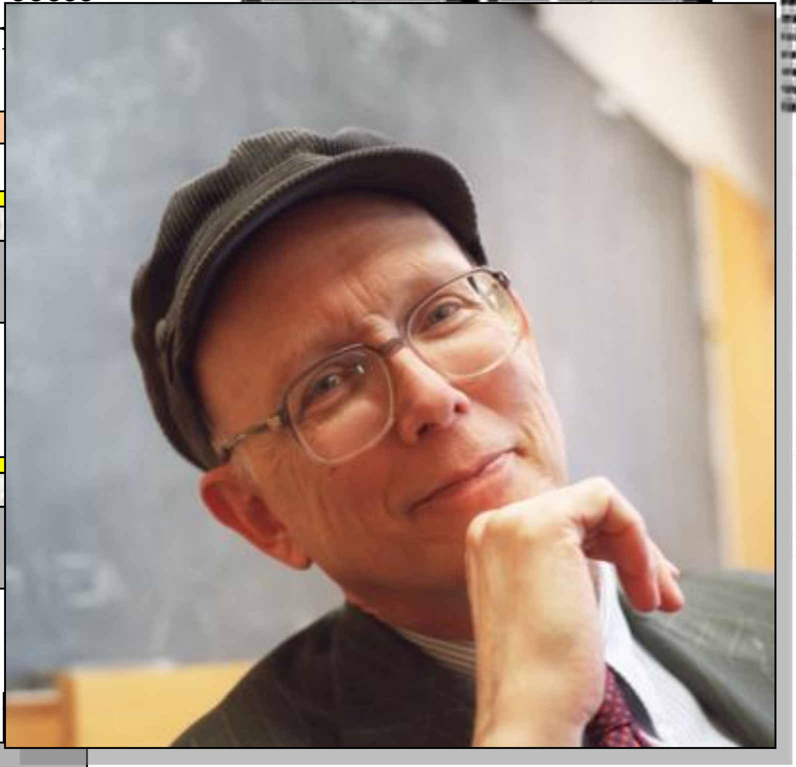
3. Transfer molecules

4. Pattern Transfer







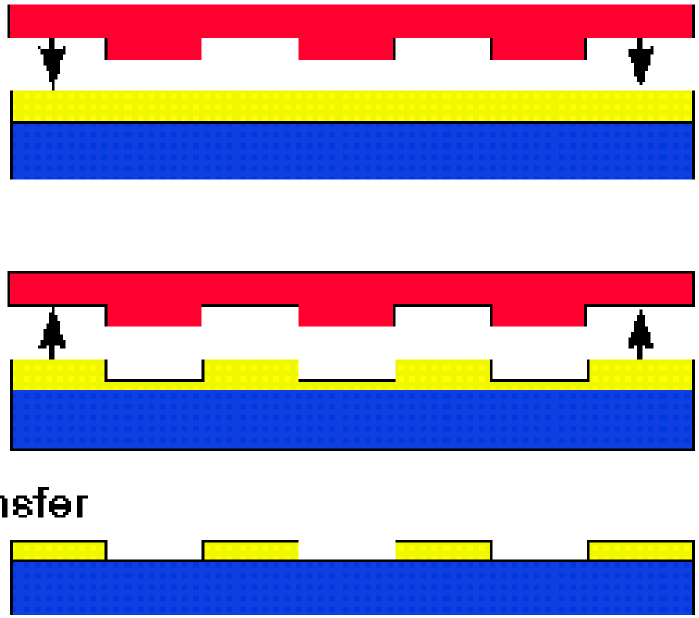


Younan Xia and George M. Whitesides

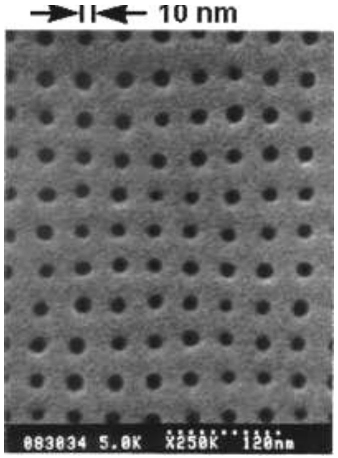
Annu. Rev. Mater. Sci. 1998. 28:153–84

90’s Thermal Imprint Lithography

NIL Process



1. Imprint
   - Press Mold
   - Remove Mold
2. Pattern Transfer
   - RIE

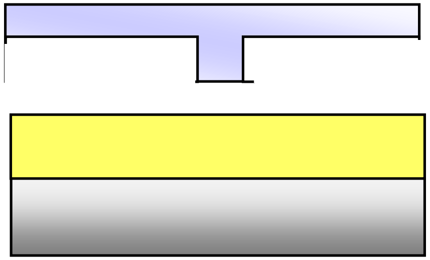


Science 5 April 1996:

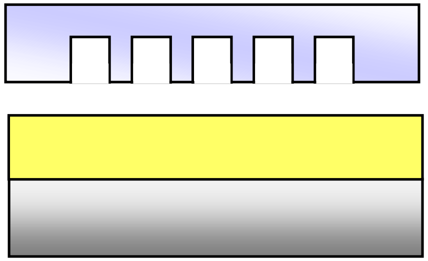
Stephen Y. Chou, * Peter R. Krauss, Preston J. Renstrom

Imprint Lithography with 10 -Nanometer Resolution

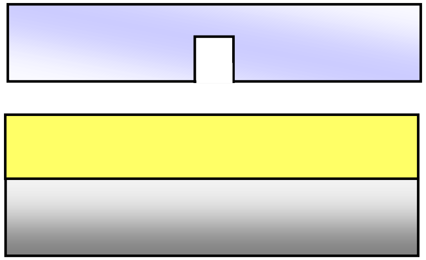
Pattern Density Effects



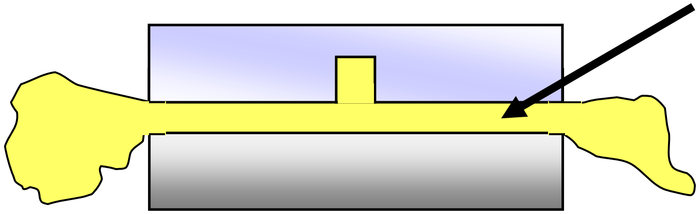
Easiest…



Easy…



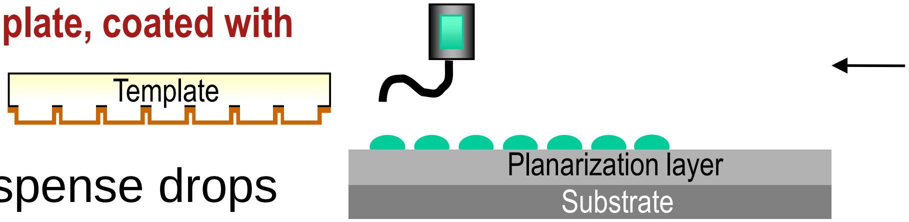
Very Difficult!



“Residual layer”

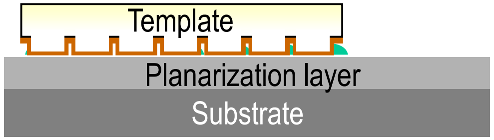
2000 Step and Flash Imprint Lithography

Fused silica template, coated with release layer



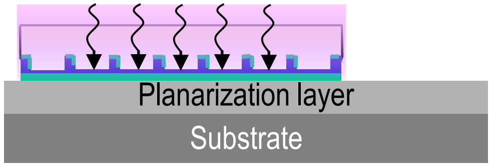
Step 1: Dispense drops

- **S-FIL fluid dispenser**
- **Ink jet system**

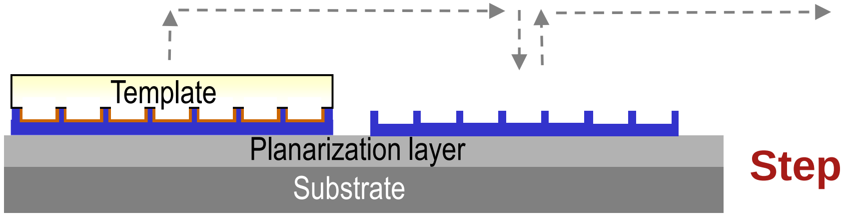


Step 2: Lower template and fill pattern

- **Template filling driven by capillary action**
- **low imprint pressure and room temperature process**



Step 3: Polymerize S-FIL fluid with UV exposure



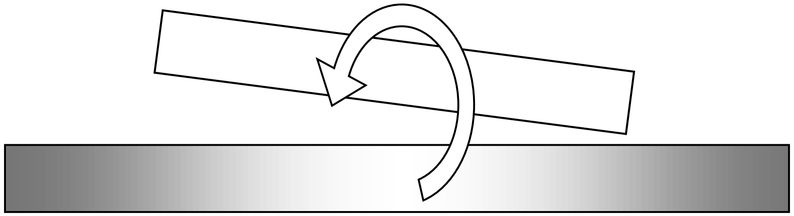
Step 4: Separate template from substrate

Step & Repeat

Molecular Imprints, Inc.

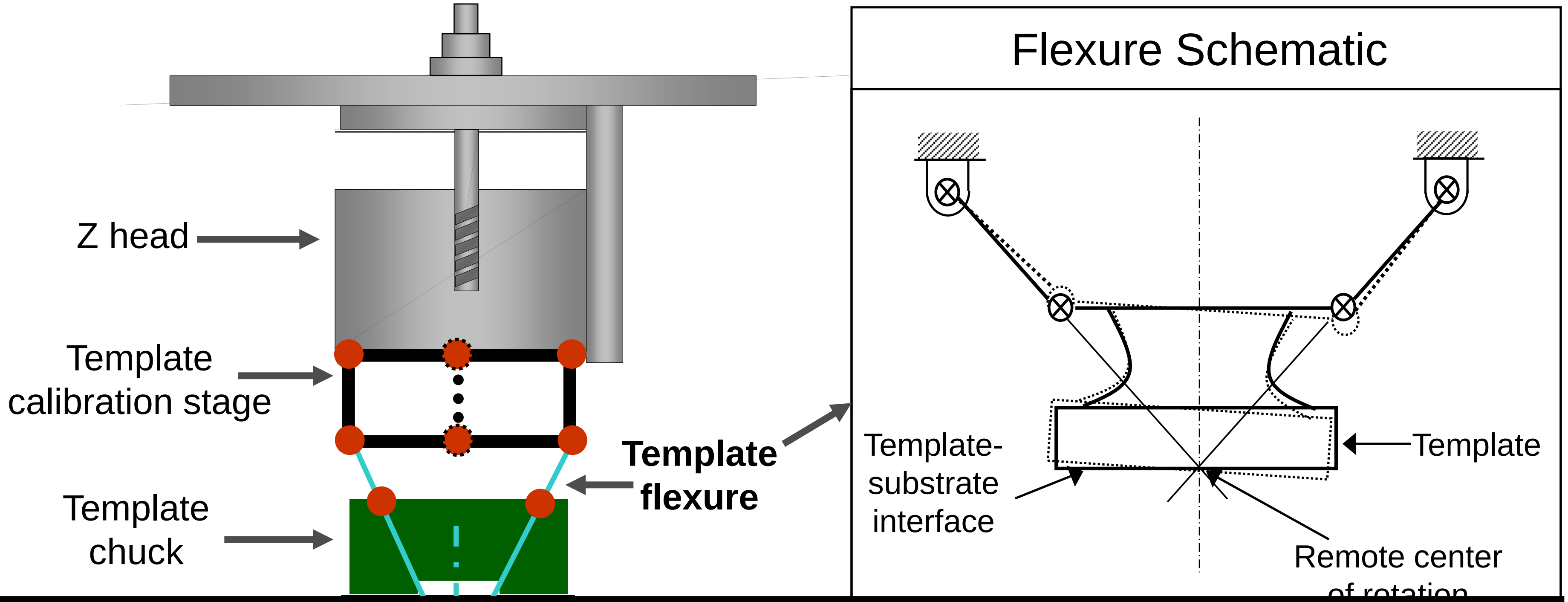
“Issues” with SFIL are:

- Templates
  - Orientation control
  - Making 1X templates
- Residual layer control
- Defects
  - Template wear
- Alignment
- Throughput



S.V. Sreenivasan

Self-Leveling Scheme using Template Flexure

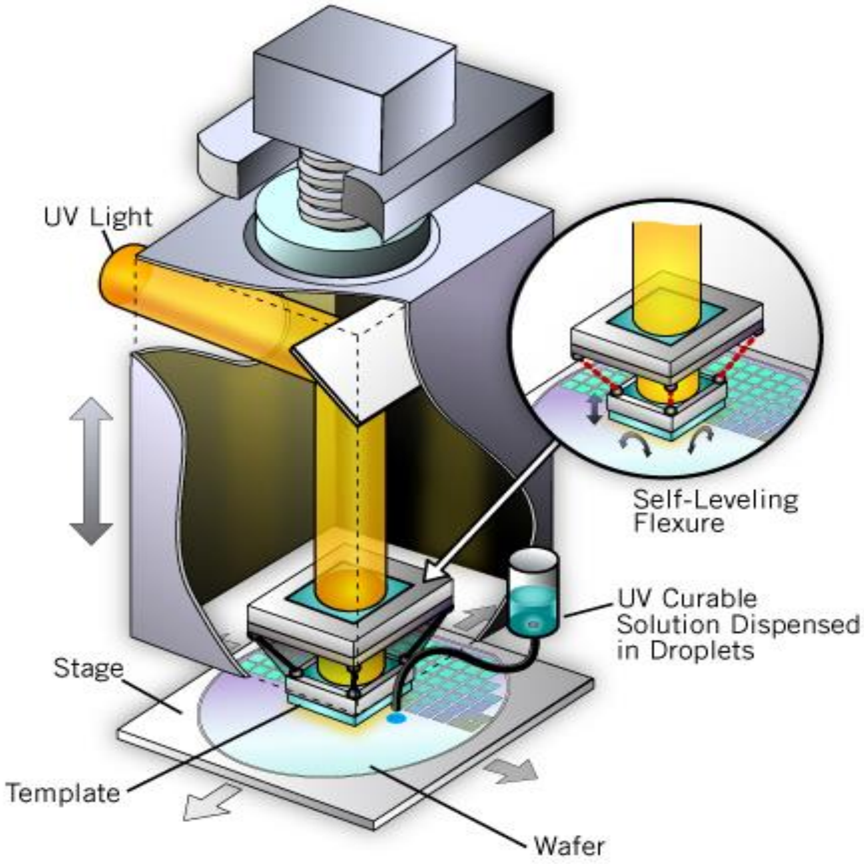


B. J. Choi, S. Johnson, M. Colburn, S.V. Sreenivasan, C. G. Willson, “Design of Orientation Stages for Step and Flash Imprint Lithography,” *Journal of Int. Societies for Precision Engineering and Nanotechnology*, Volume 25, No. 3, pp. 192-199, July, 2001.

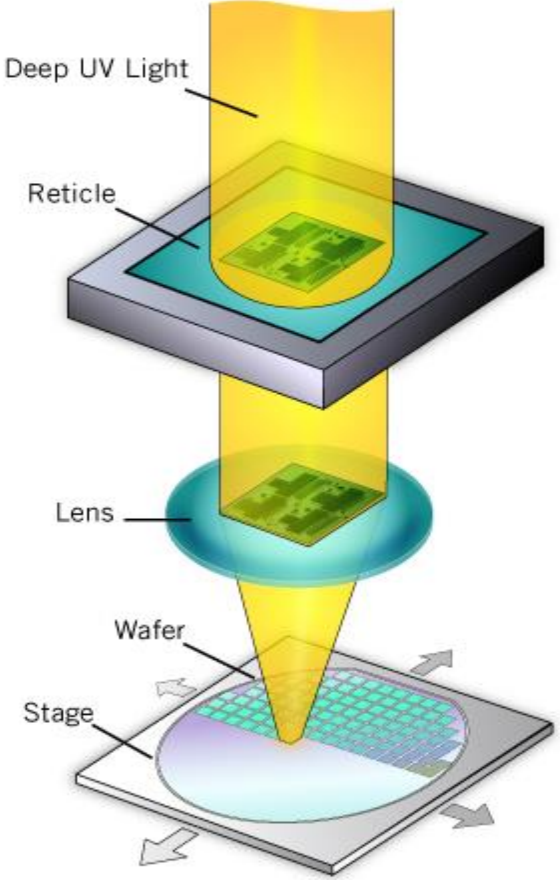
S-FIL vs. Optical Lithography Schematic

Greatly simplified and lower cost process

Imprint Lithography

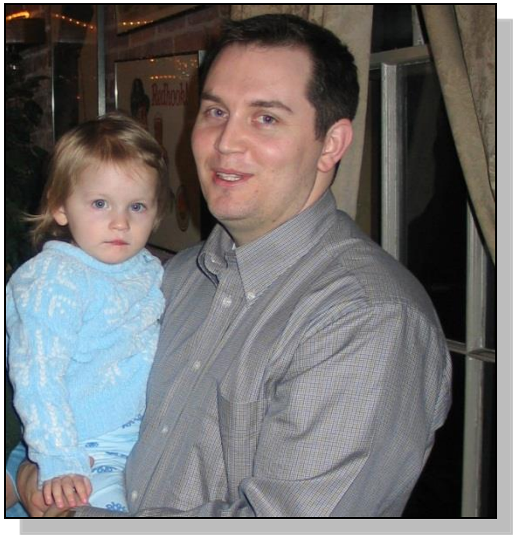


Standard Optical Lithography

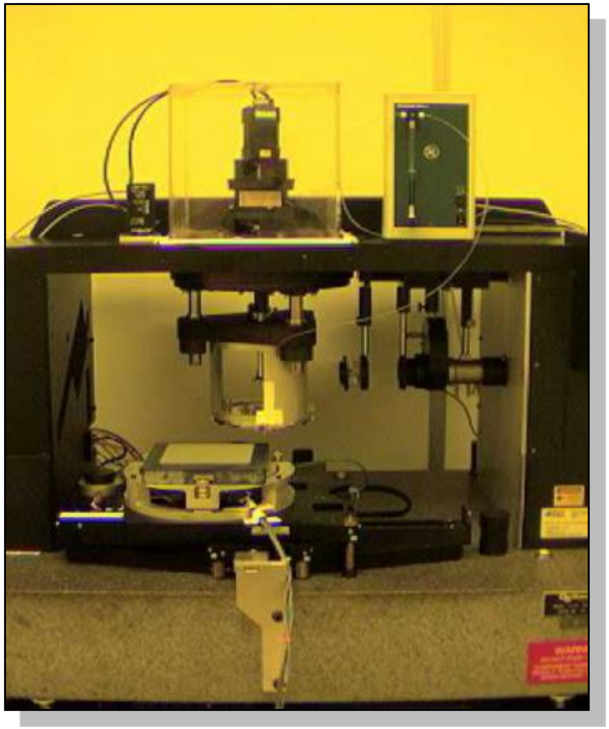


First Publication of SFIL

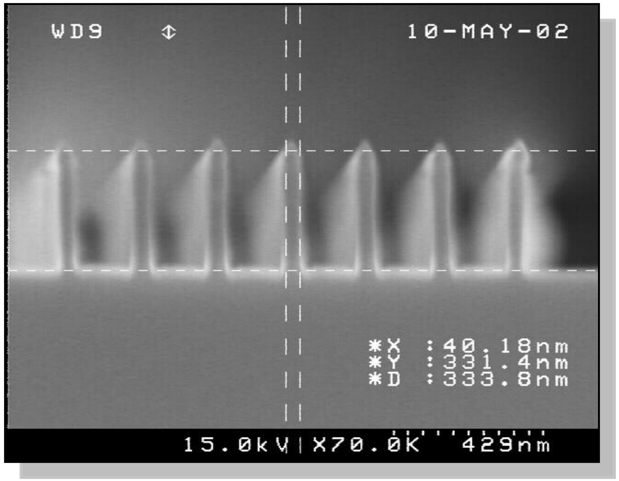
Colburn, et.al “Step and Flash Imprint Lithography: A New Approach to High-Resolution Patterning,” *Proc. SPIE* **3676** 379-389 (1999)



Matt Colburn, et. al



First SFIL tool

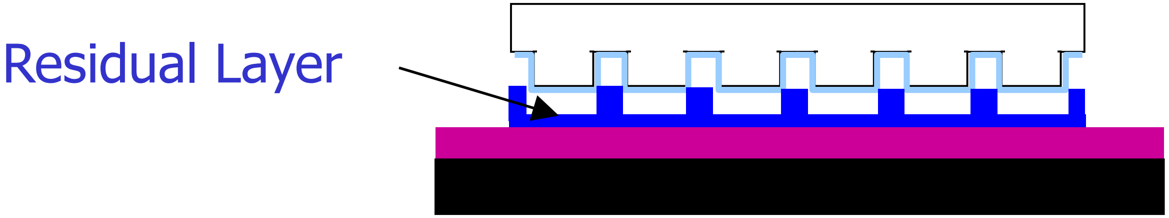


40 nm images

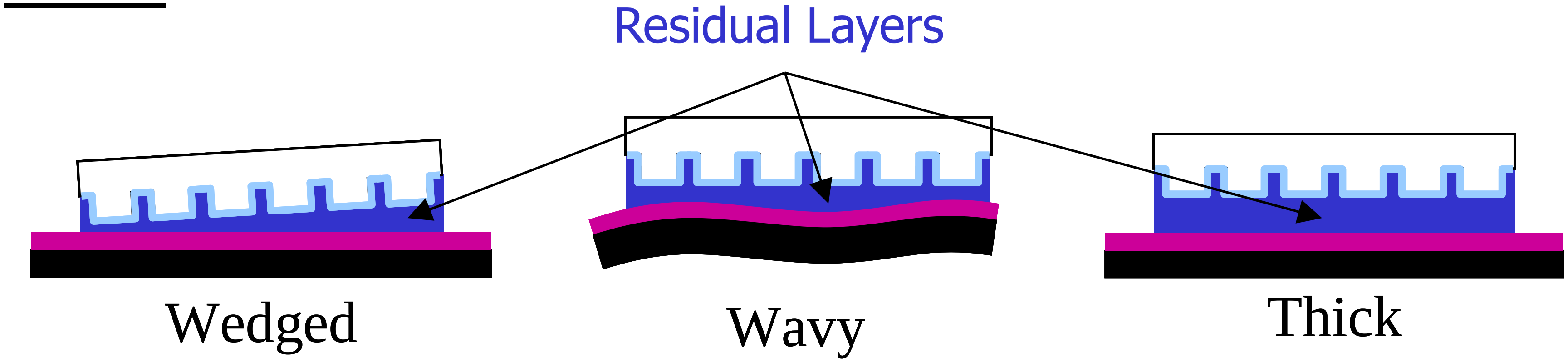
SFIL tool decade later

Residual Layer Thickness Control

Residual Layer is due to the **undisplaced** liquid

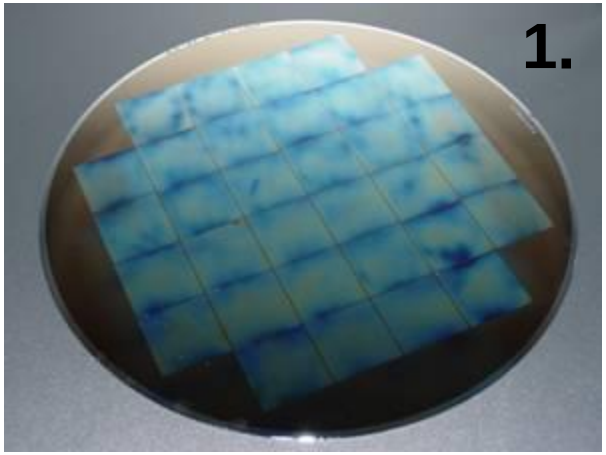


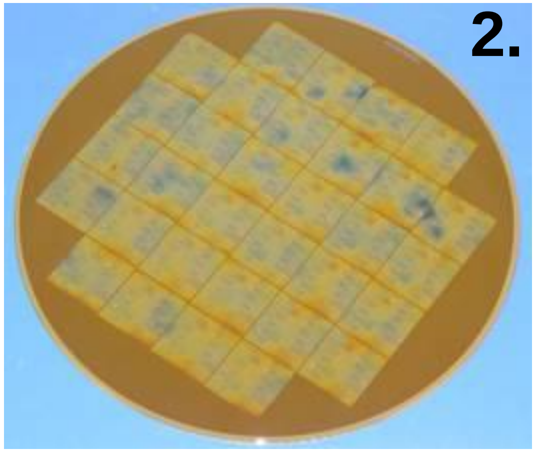
Avoid: **Non-uniformities**

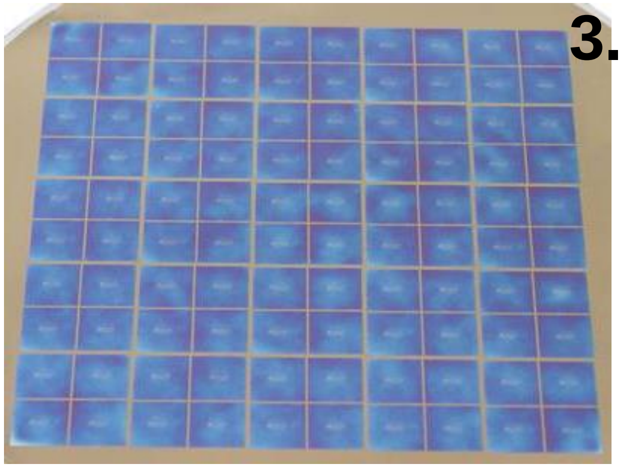


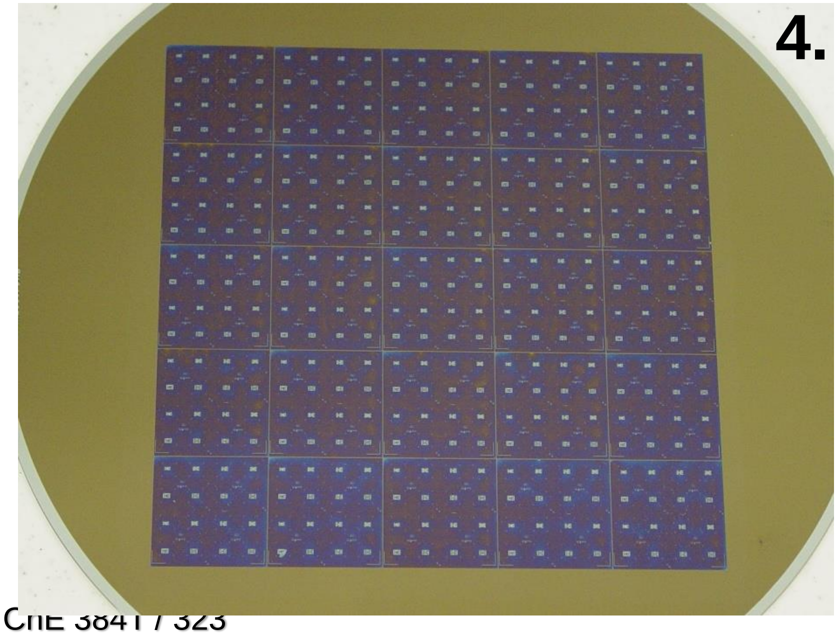
Residual layer needs to be thin and uniform

Focus on Continuous Process Improvement


1.


2.


3.

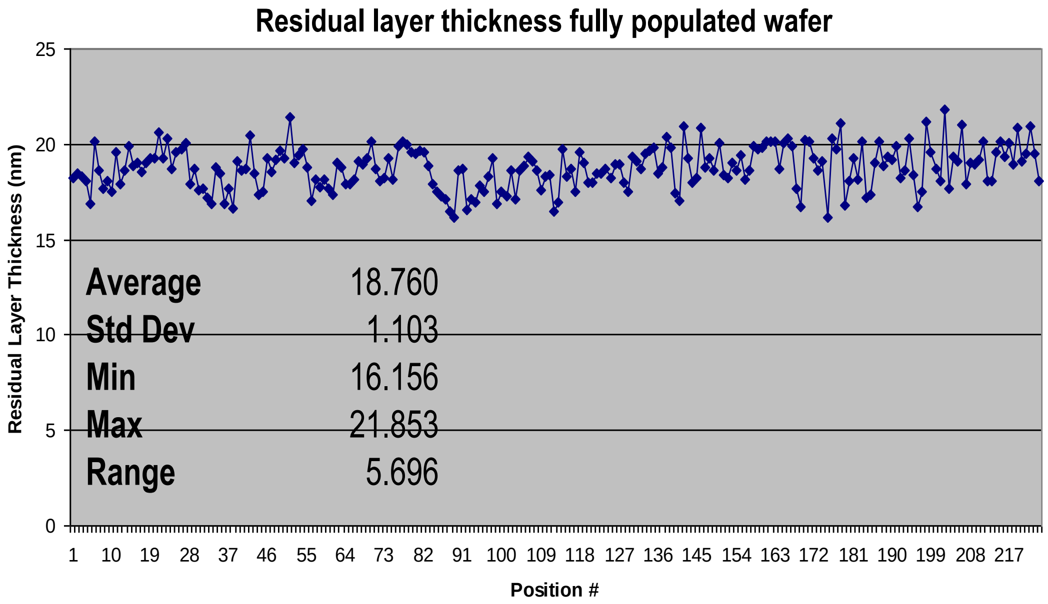

4.

- Minimize mean and standard deviation of residual layer
- Key drivers: chuck flatness, inkjet drop volume and location controls, evaporation.

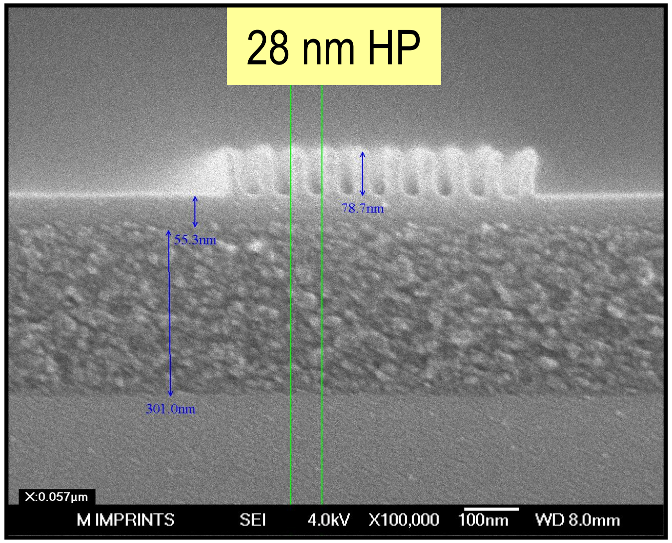
Residual Layer Thickness Measurements

Early Results

- **Residual layer mean <20nm and thickness variation to < 6 nm TIR**

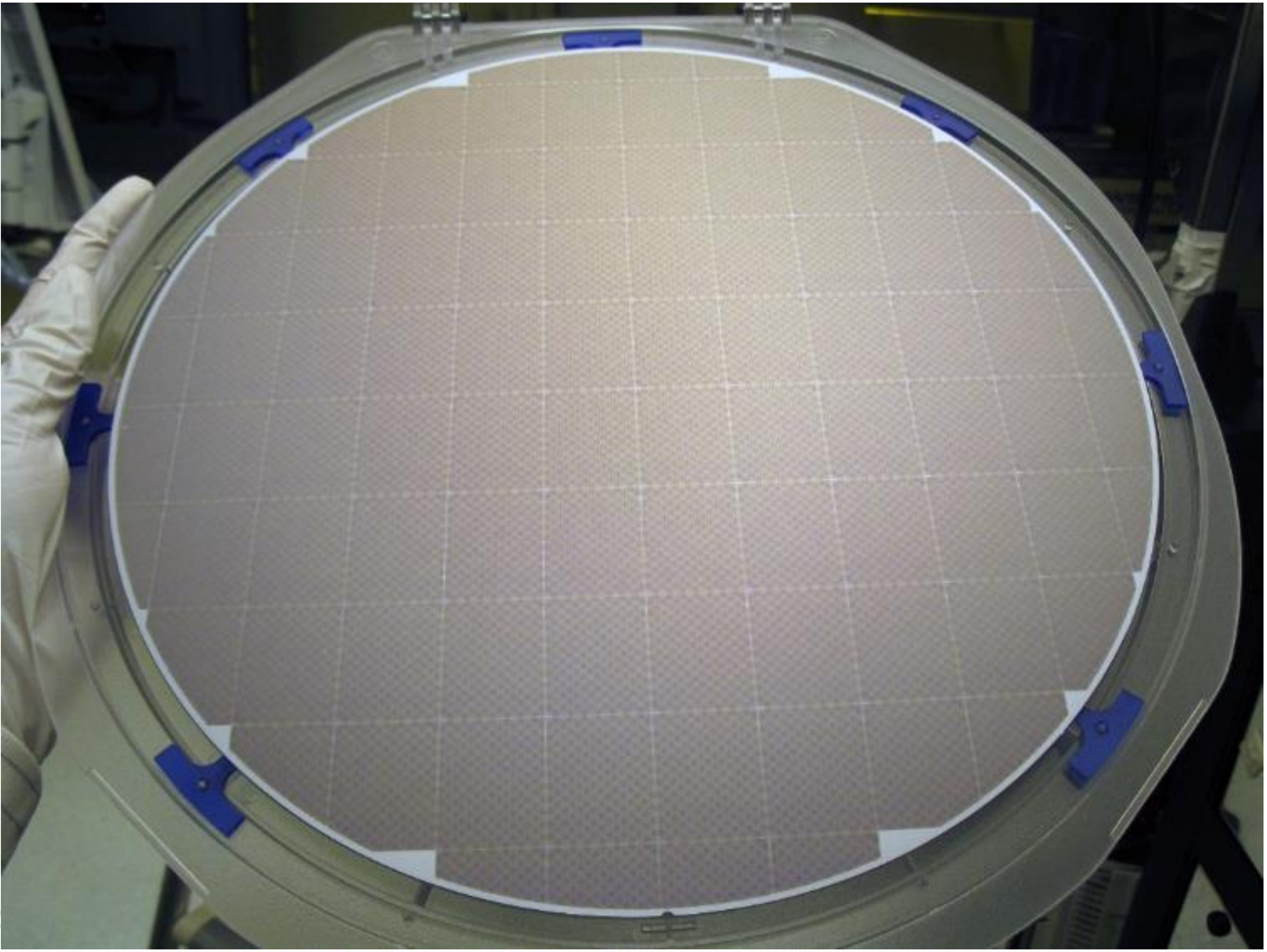


Average	18.760
Std Dev	1.103
Min	16.156
Max	21.853
Range	5.696



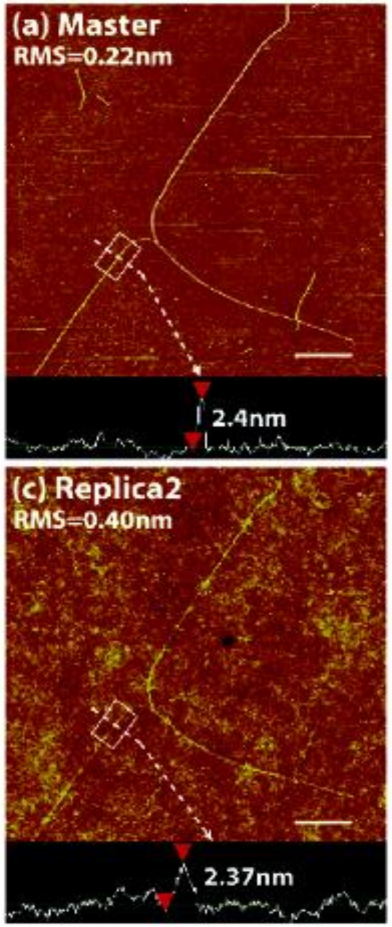
Residual Layer Control Today

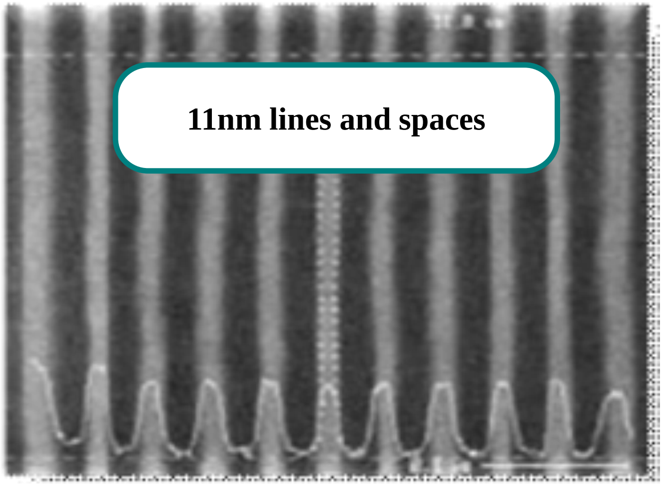
- Software and hardware has been developed to correctly jet resist, and control the spreading of the resist in a similar fashion to full fields



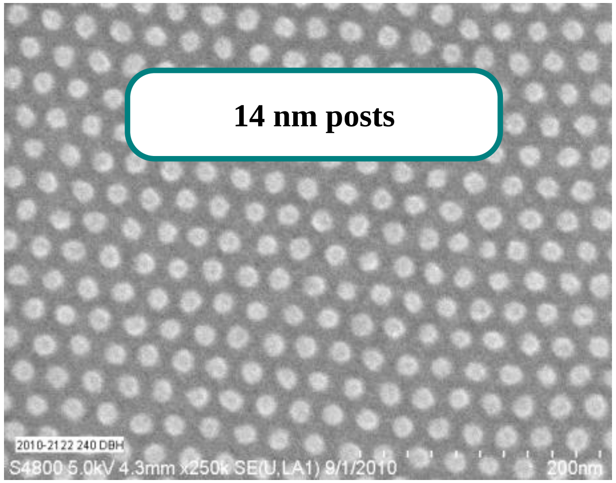
SFIL Lithography

2nm Replication
(Rogers et al, Illinois)

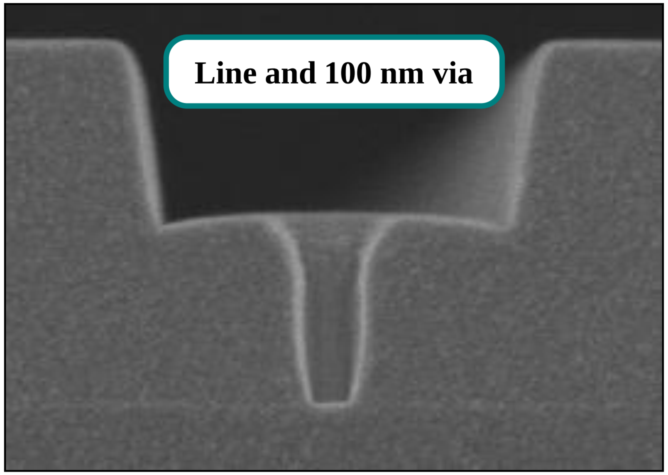




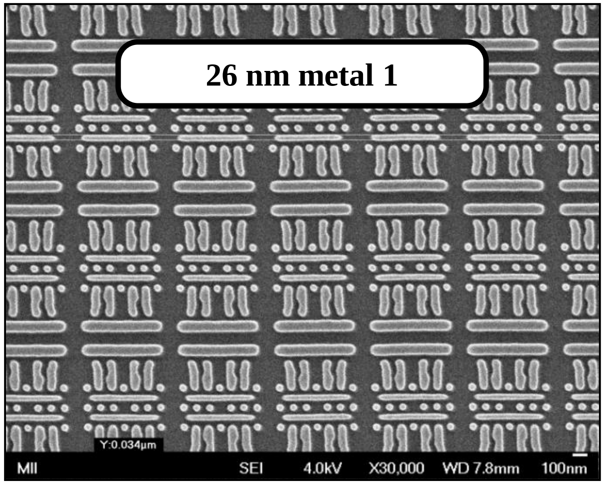
11nm lines and spaces



14 nm posts



Line and 100 nm via



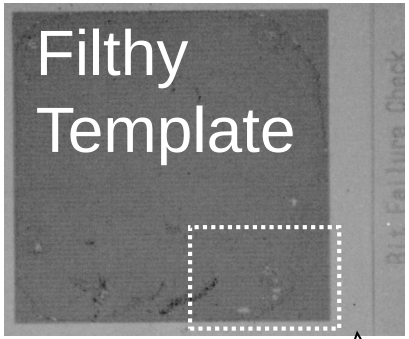
26 nm metal 1

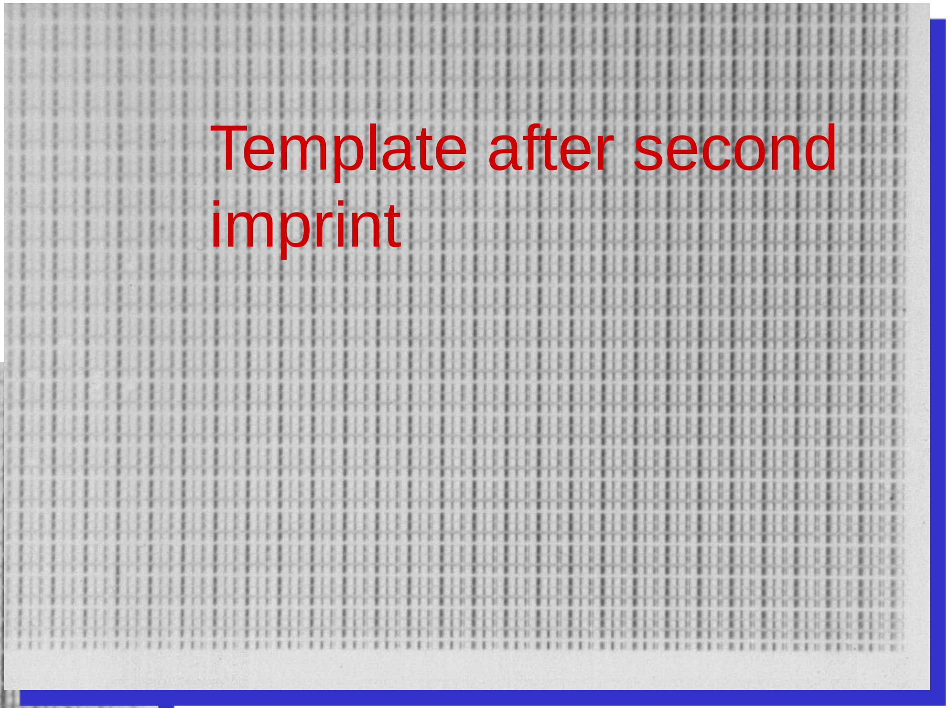
Defects

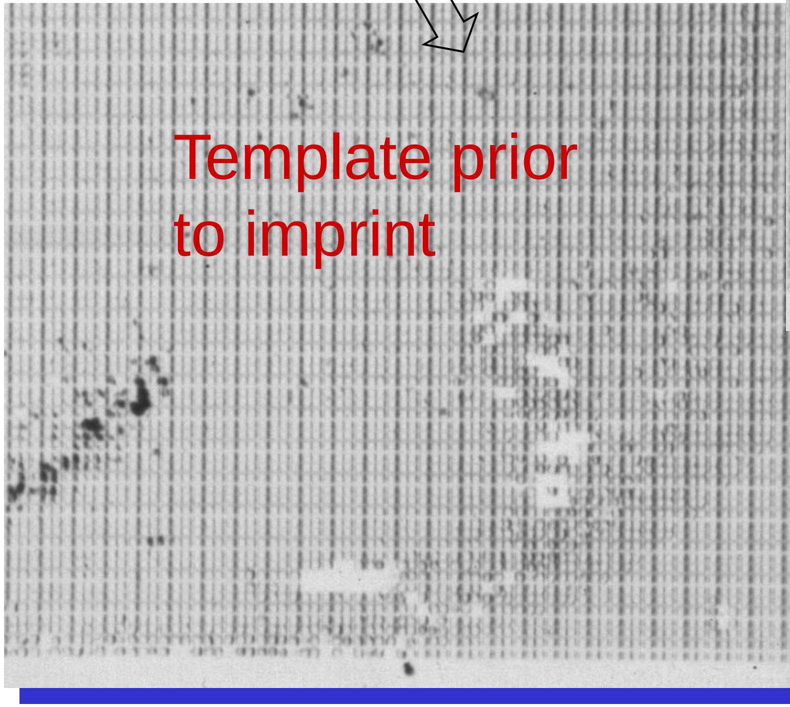
1) Why do you think 1X projection lithography replaced contact printing in the early 80’s?? Don’t you learn from history??

2) Do you propose attempt to do lithography without a pellicle??!!

Template Before and After Imprints







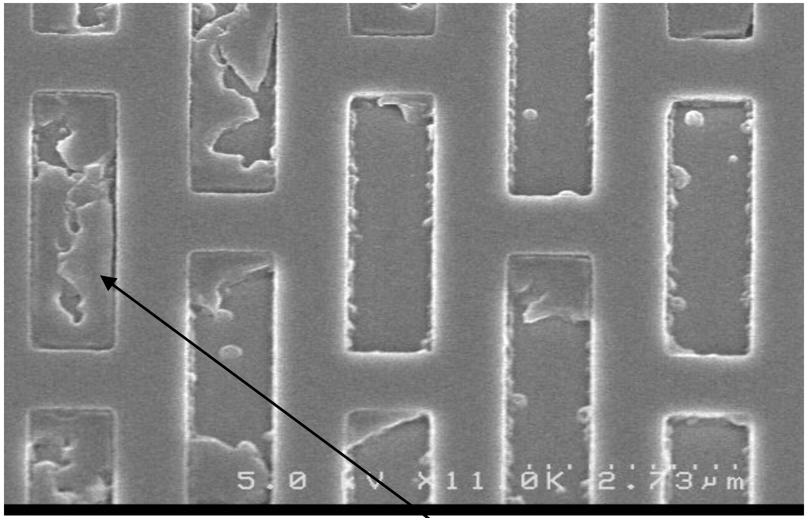
All visible defects disappear from the template.

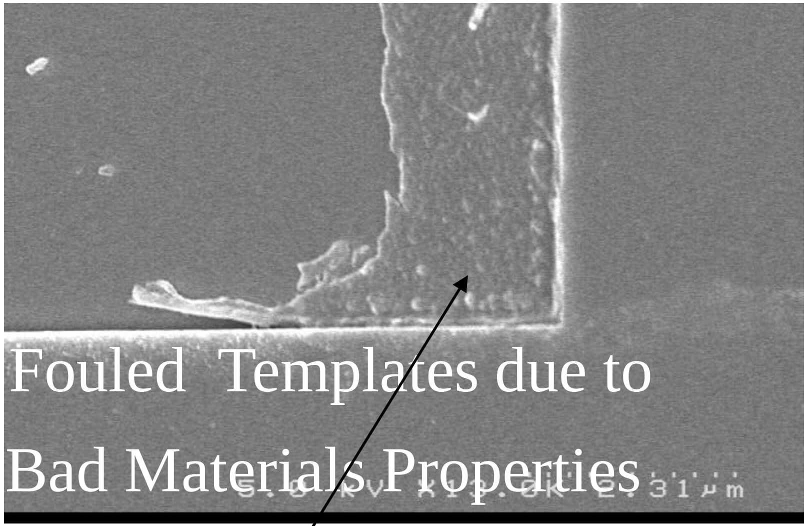
Printing is the best way to clean an SFIL template!

This is our “Pellicle”

Cohesive vs Adhesive Separation

Material with poor mechanical properties

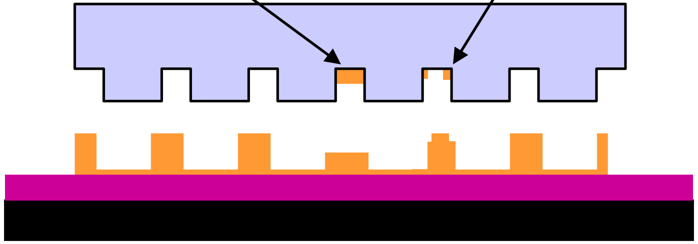




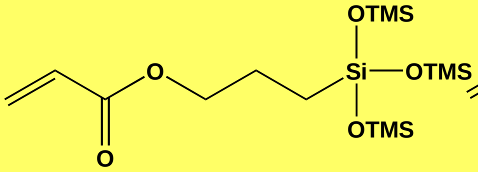
Fouled Templates due to

Bad Materials Properties

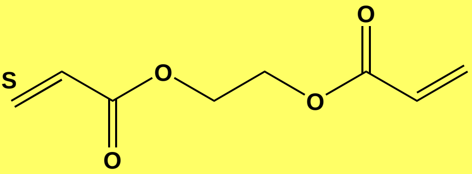
Cohesive Failures call for stronger materials



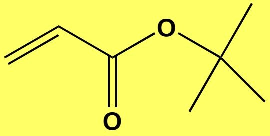
First Etch Barrier Formulation "E4"



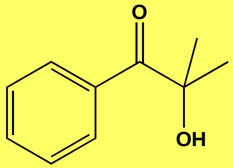
Si-containing monomer



EGDA

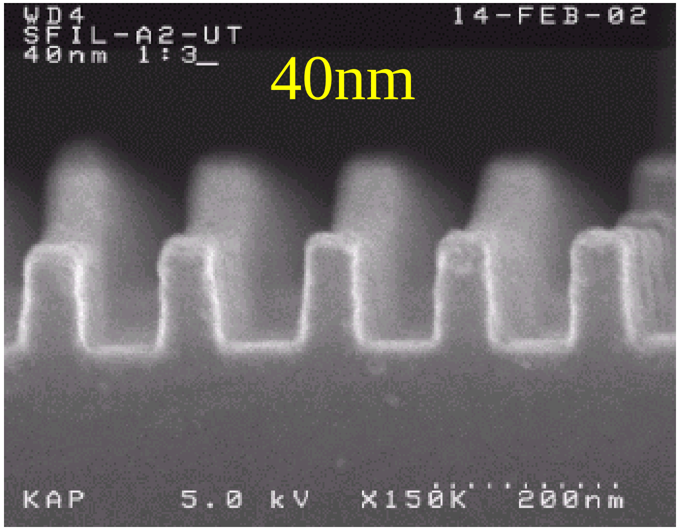


t-BuAc

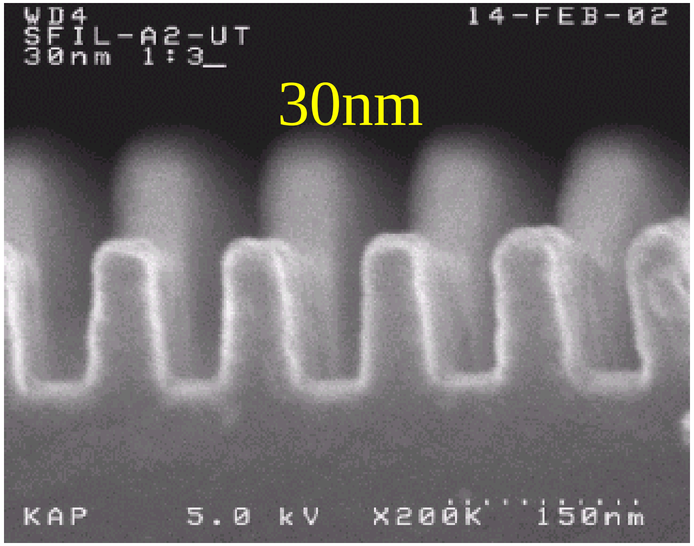


Darocur 1173

- *Well defined, stable structures:*
- *Rapid cure to high conversion:*
- *Low viscosity: 1.9cPs/20C*



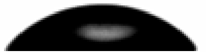
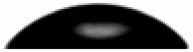
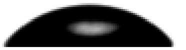
40nm



30nm

Role of Evaporation in Imprint Process

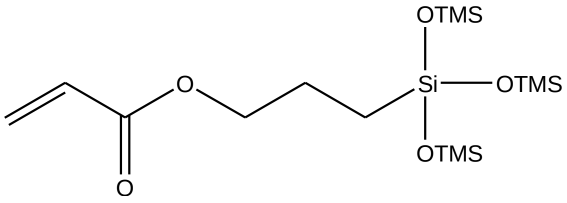
- **Thin residual layers and ease of filling require low viscosity & small drops.**
- **High evaporation can lead to:**
  - Variable mechanical properties of imprint material
  - Variation in film thickness

Evaporation of an 80pL Drop of Monomer					
Initial Drop	10 seconds	20 seconds	30 seconds	40 seconds	50 seconds
 70µm					

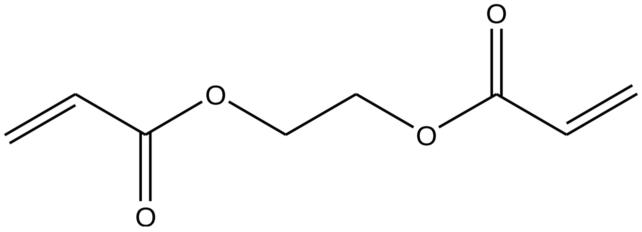
~ 42% material loss

~ 56% material loss

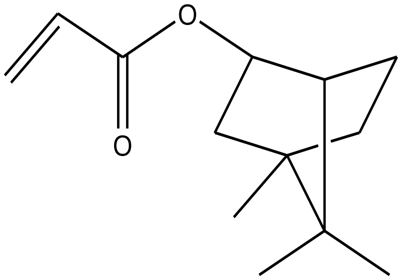
Working etch barrier formulation



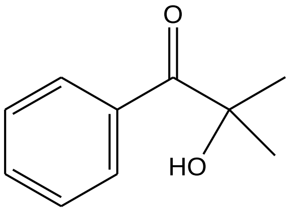
SIA0210 44%



EGDA 15%



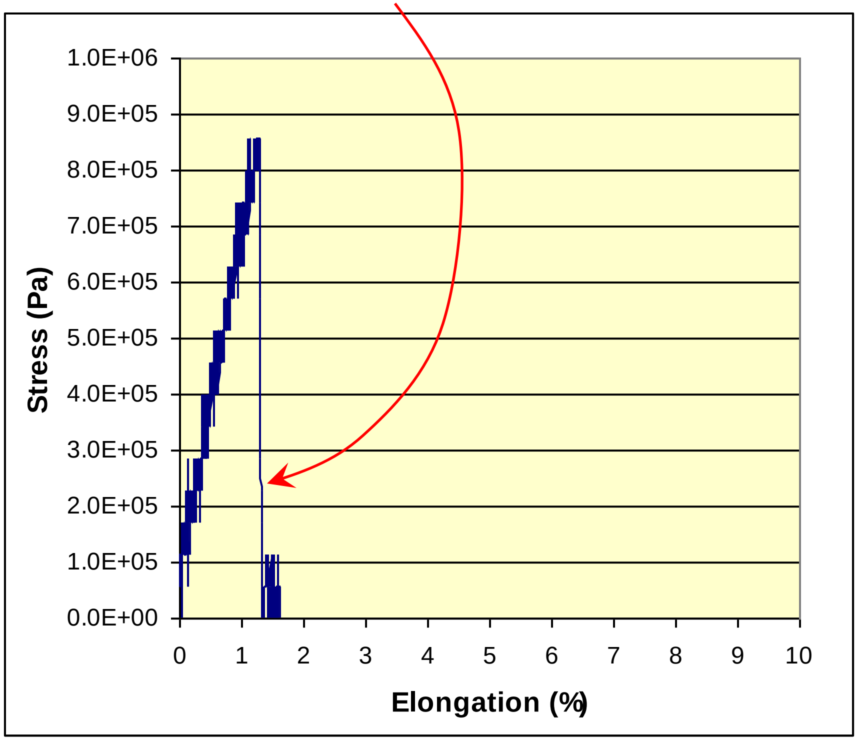
iBA 37%



Irgacure 4%

Old Stuff

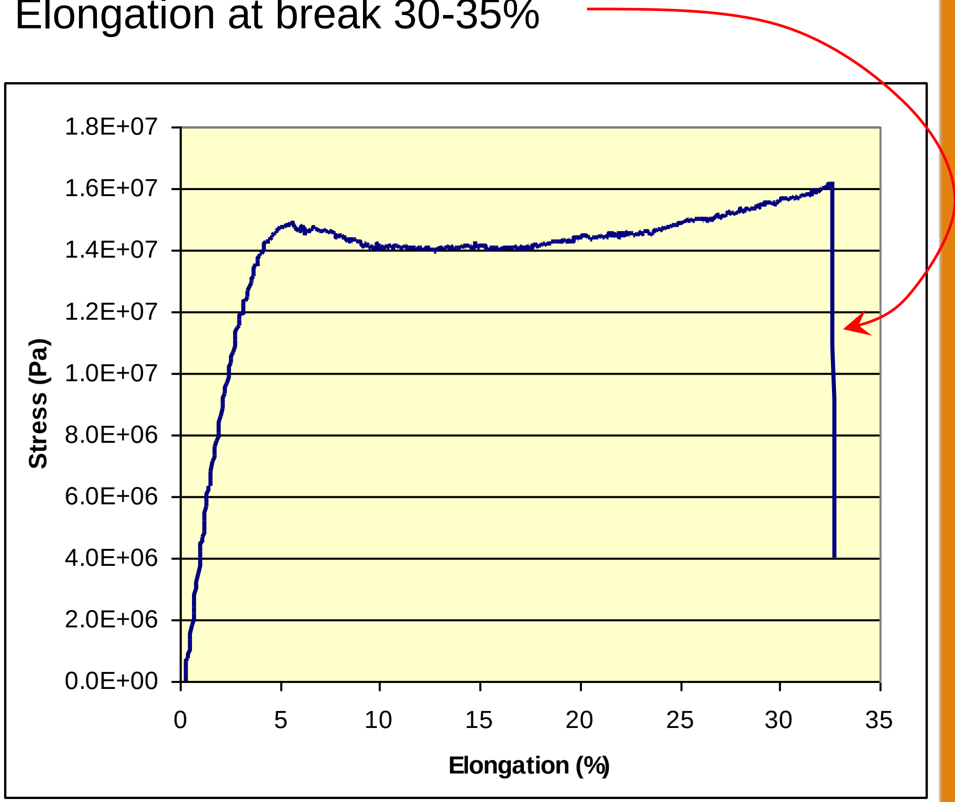
Elongation at break 1-2%



Tensile Modulus 80 MPa

New Stuff

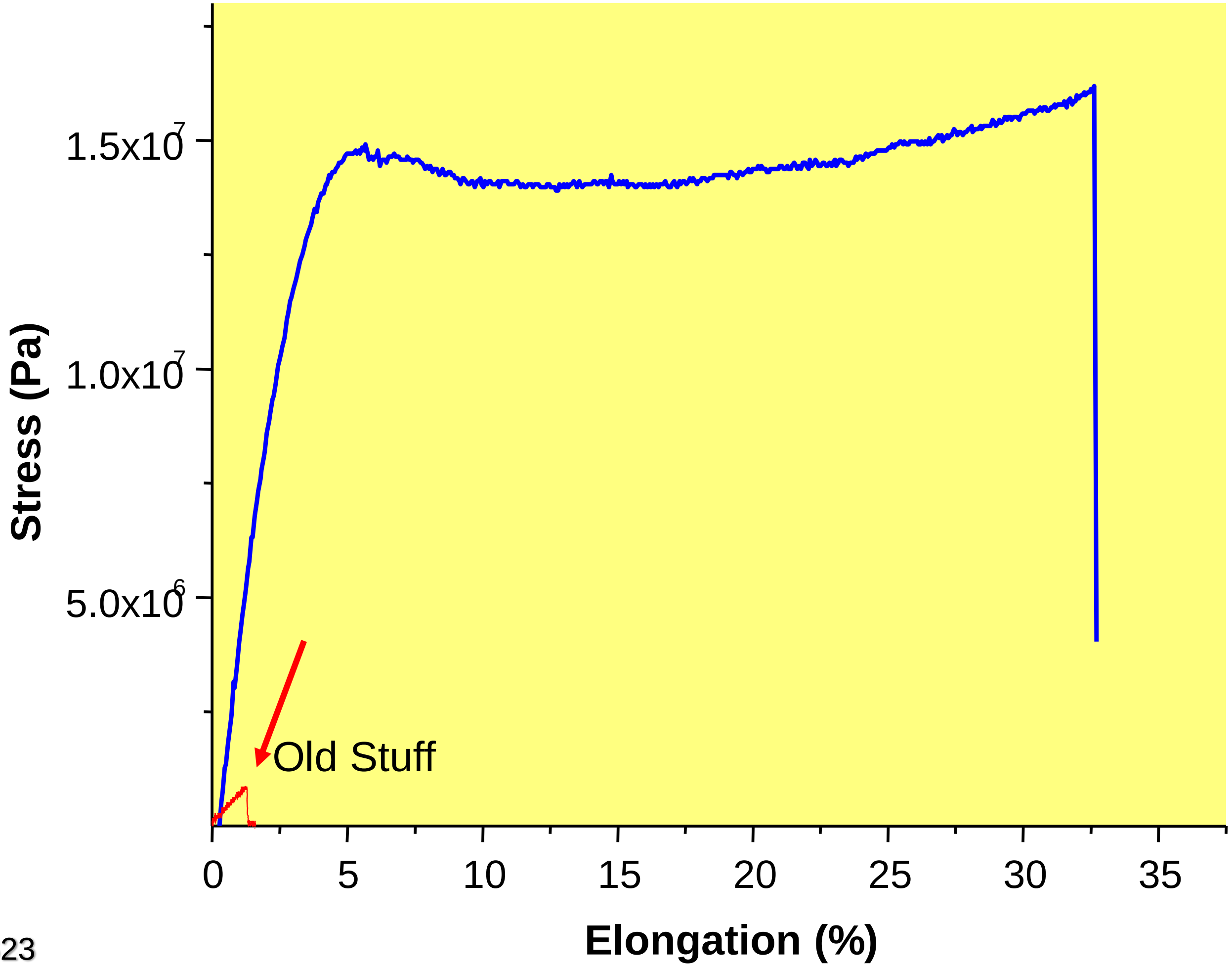
Elongation at break 30-35%



Tensile Modulus 500 MPa

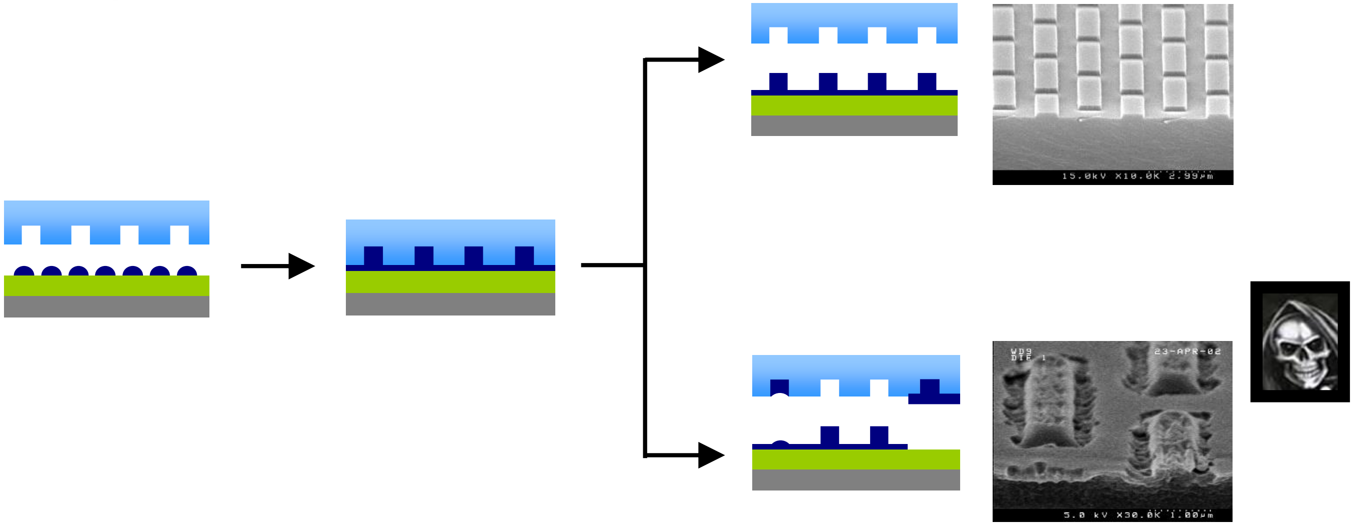
Many fold improvement in Mechanical Properties

- Break stress of new stuff is **16 MPa**

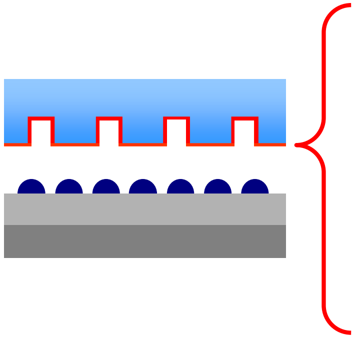


Separation Failures

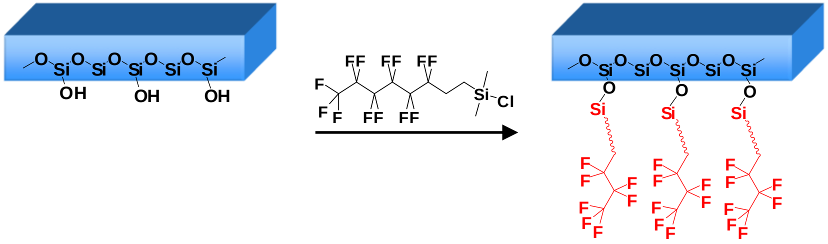
Separation process

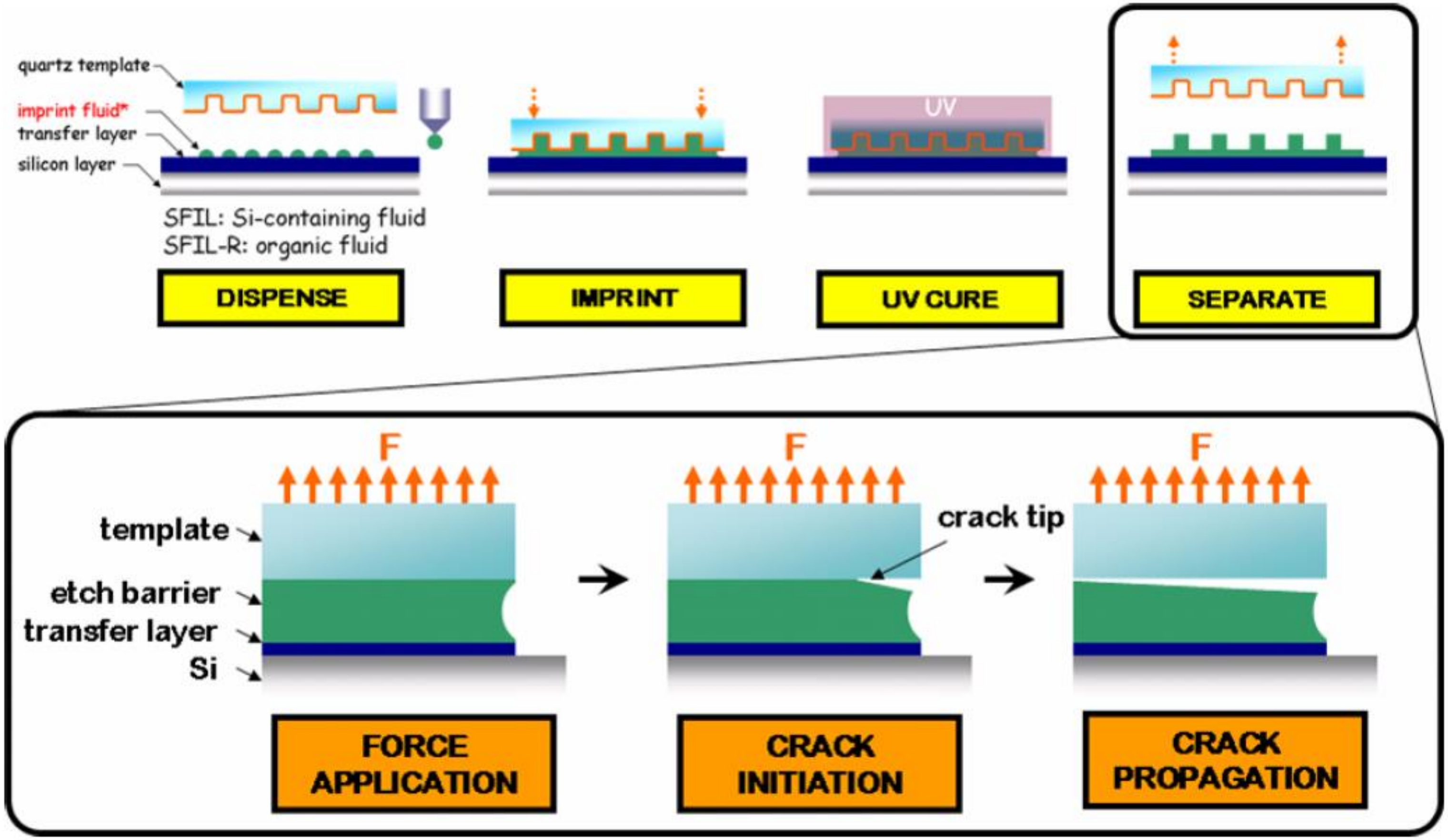


Solution?

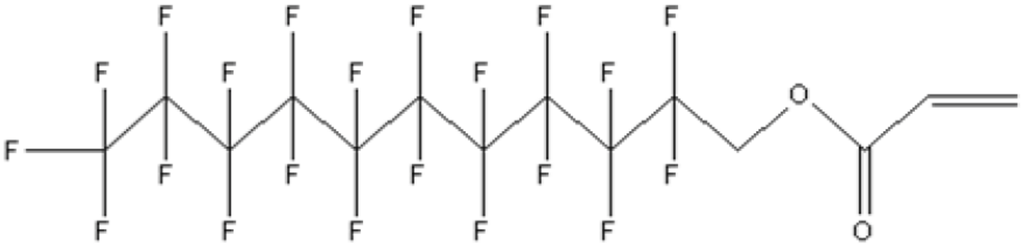


Fluorinated Self Assembly Monolayer (F-SAM)

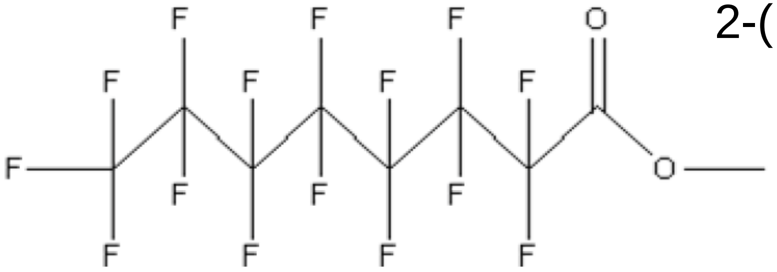



quartz template
imprint fluid*
transfer layer
silicon layer
SFIL: Si-containing fluid
SFIL-R: organic fluid
DISPENSE
IMPRINT
UV
UV CURE
SEPARATE
F
template
etch barrier
transfer layer
Si
F
crack tip
F
FORCE APPLICATION
CRACK INITIATION
CRACK PROPAGATION

Fluorosurfactants

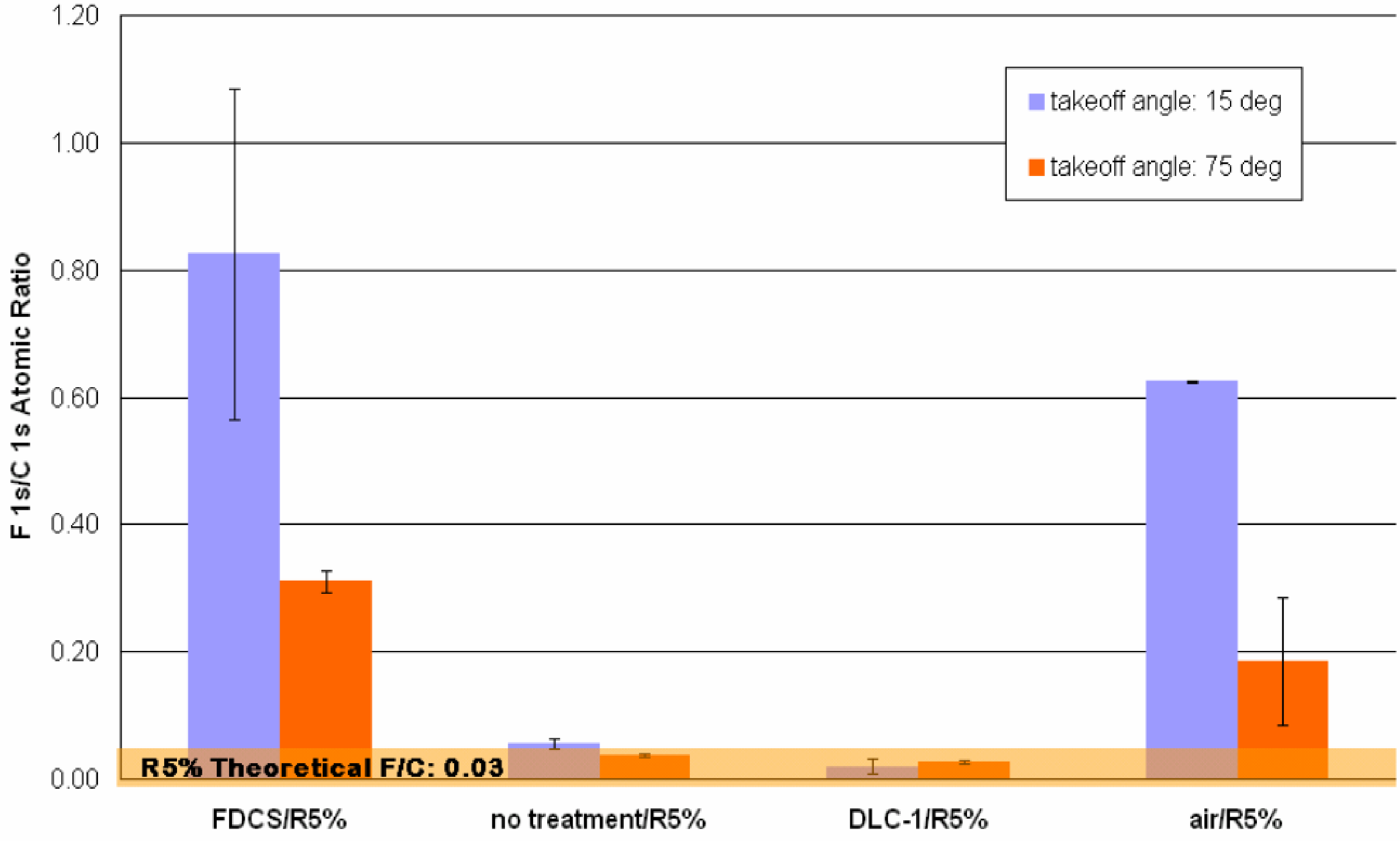


2-(Perfluorodecyl)ethyl acrylate (R)

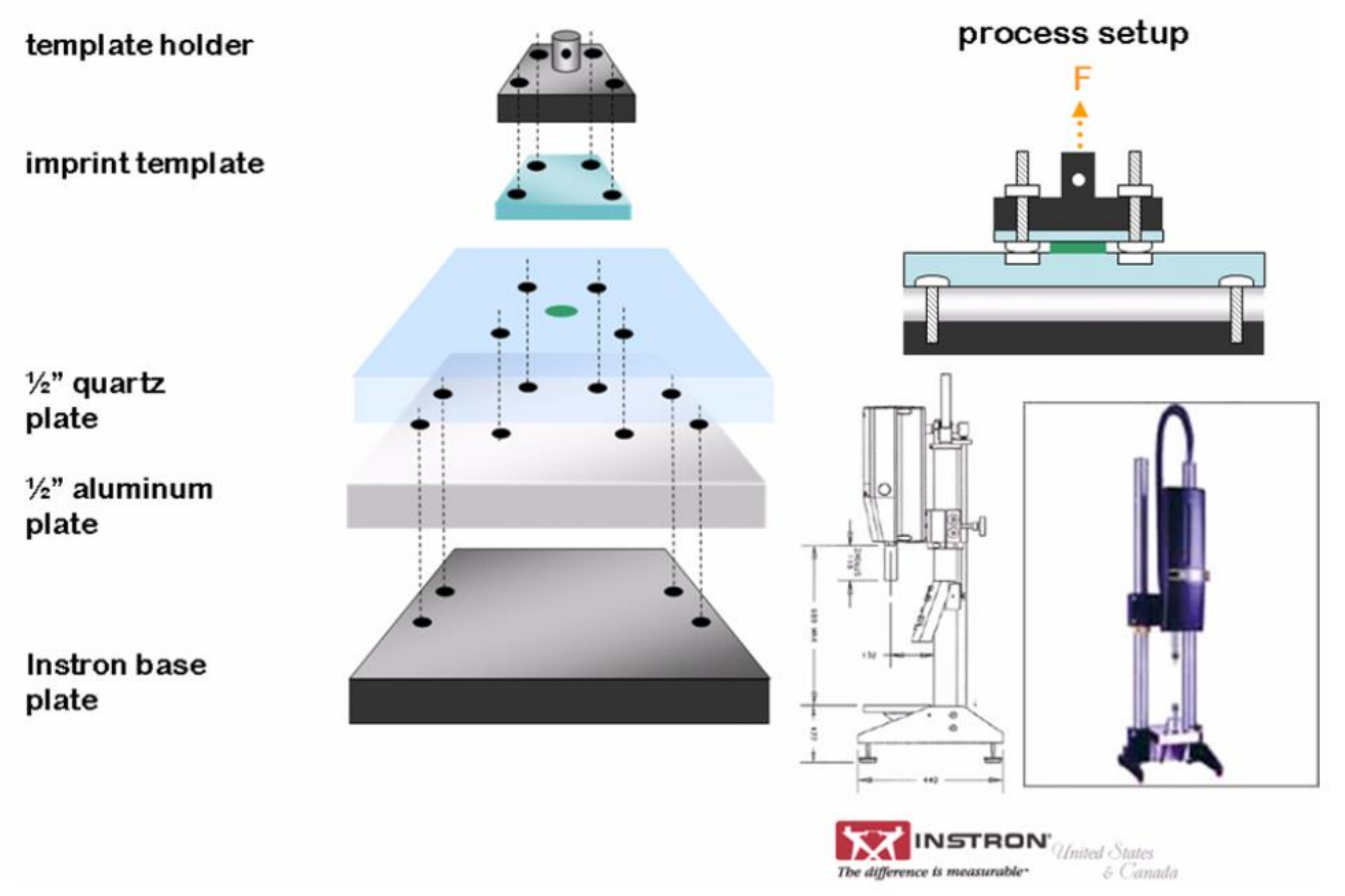


Methyl perfluorooctanoate (NR)

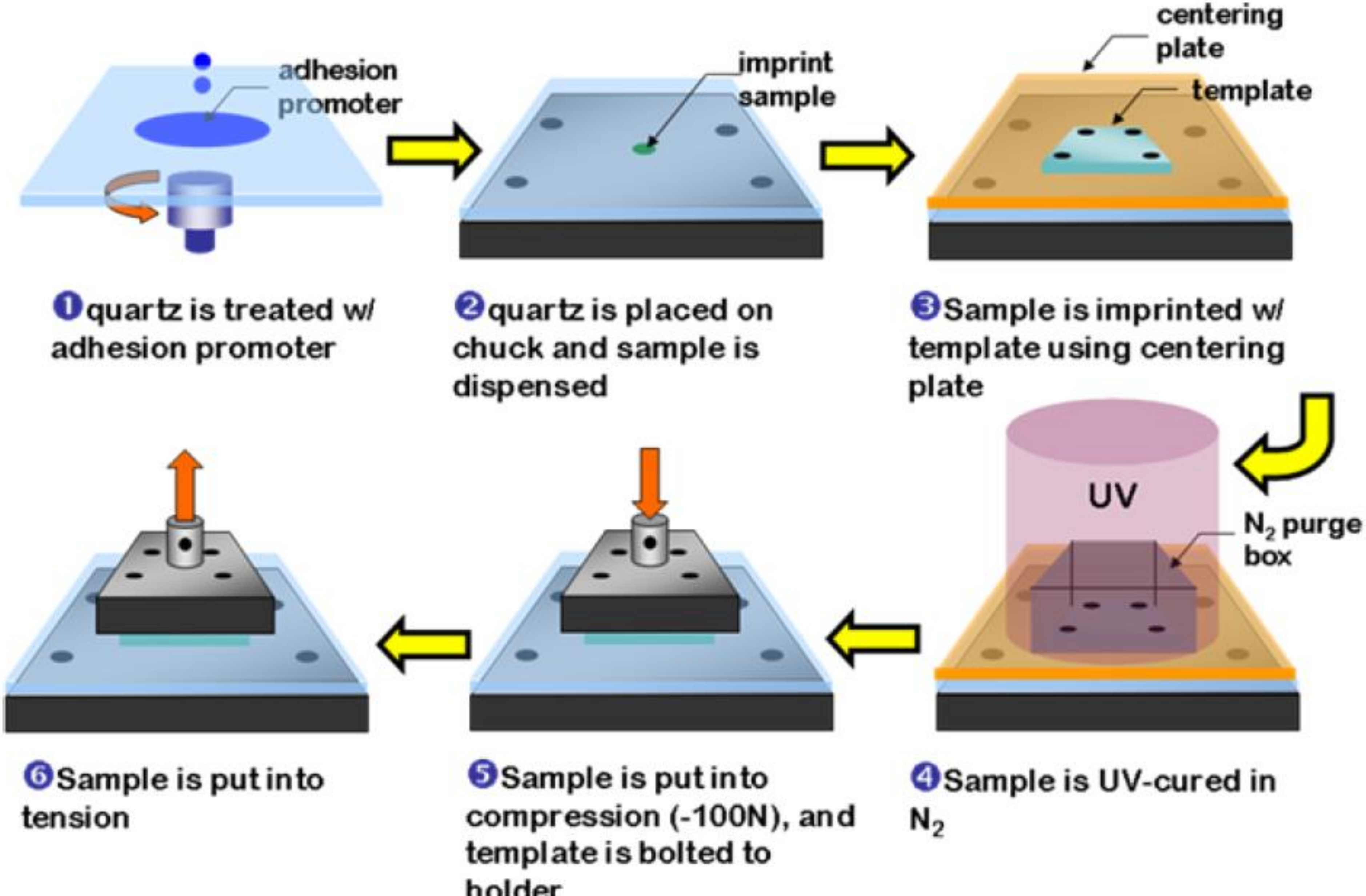
Surfactant Migration Study: Reactive Surfactant



Adhesion Test Tool



o set up and conduct an imprint on the Instron.



❶ quartz is treated w/ adhesion promoter

❷ quartz is placed on chuck and sample is dispensed

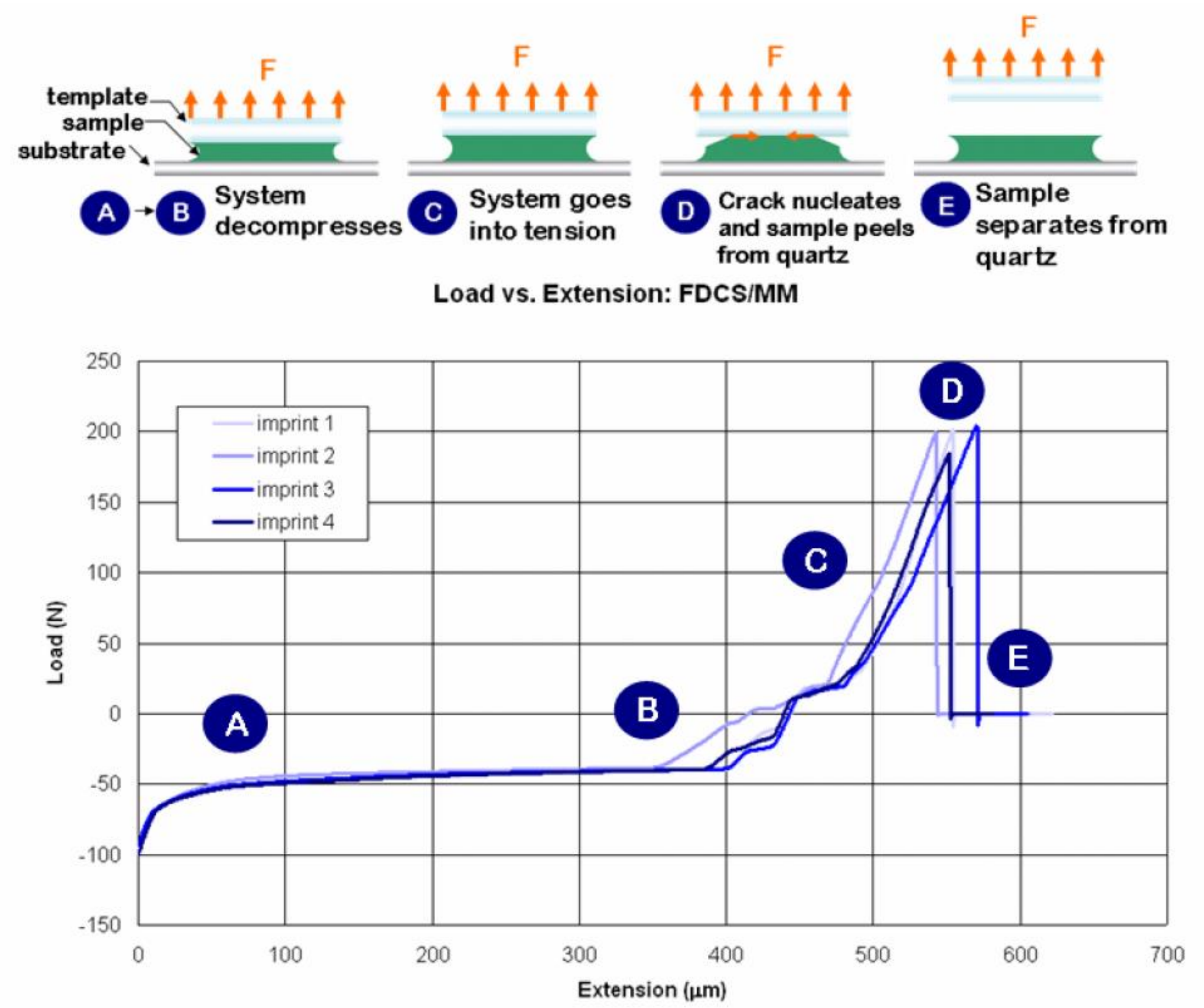
❸ Sample is imprinted w/ template using centering plate

❹ Sample is UV-cured in N_2

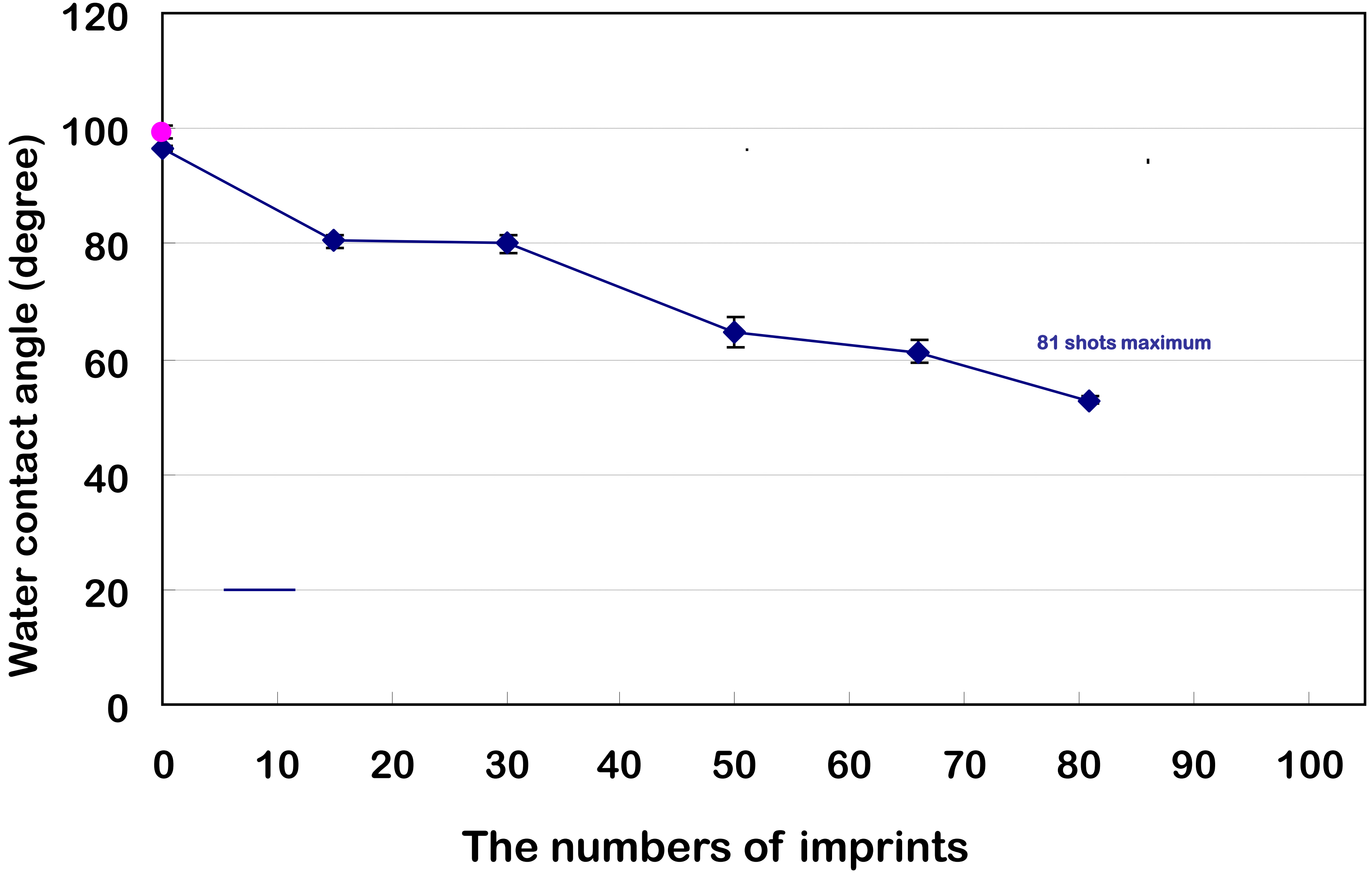
❺ Sample is put into compression (-100N), and template is bolted to holder

❻ Sample is put into tension

Instron Experiment

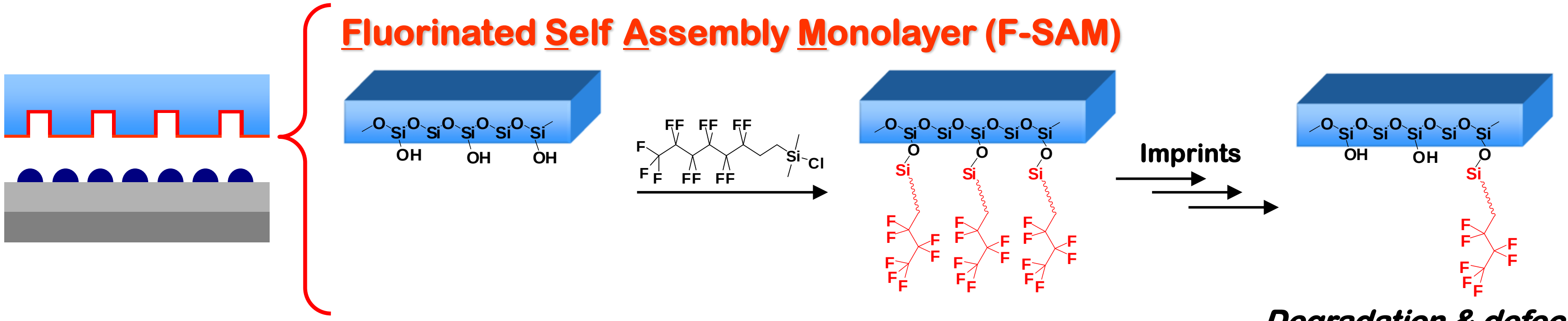


Bad News!


120
100
80
60
40
20
0
Water contact angle (degree)
0
10
20
30
40
50
60
70
80
90
100
The numbers of imprints
81 shots maximum

We have a “wear” problem

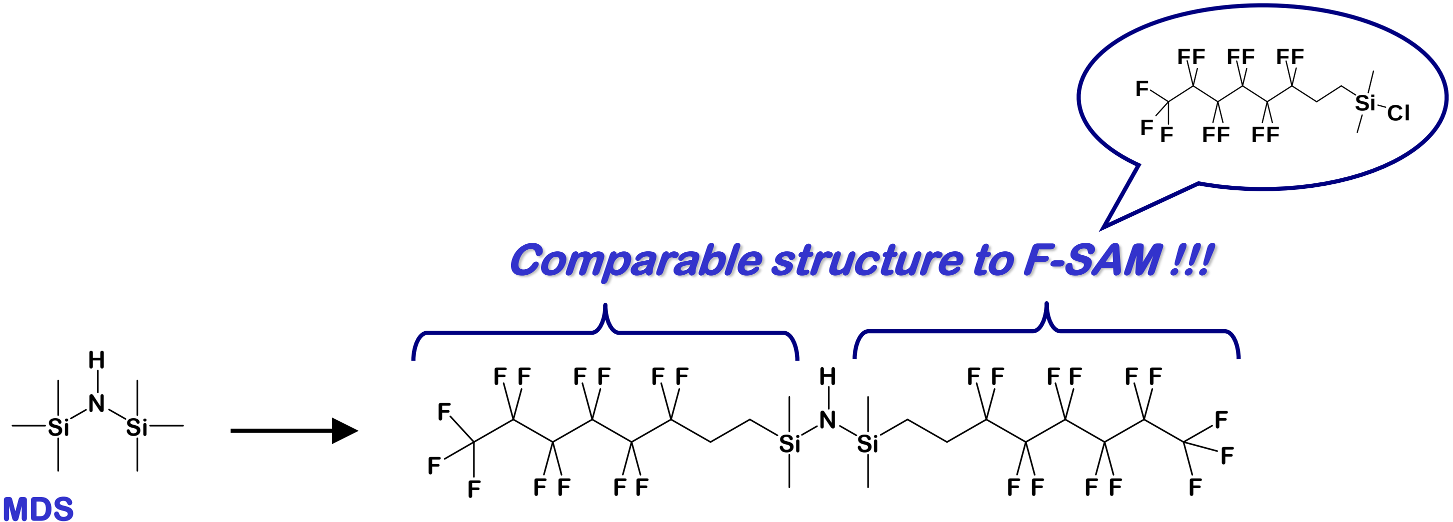
Current solution & a problem



<u>F</u>luorinated <u>S</u>elf <u>A</u>ssembly <u>M</u>onolayer (F-SAM)

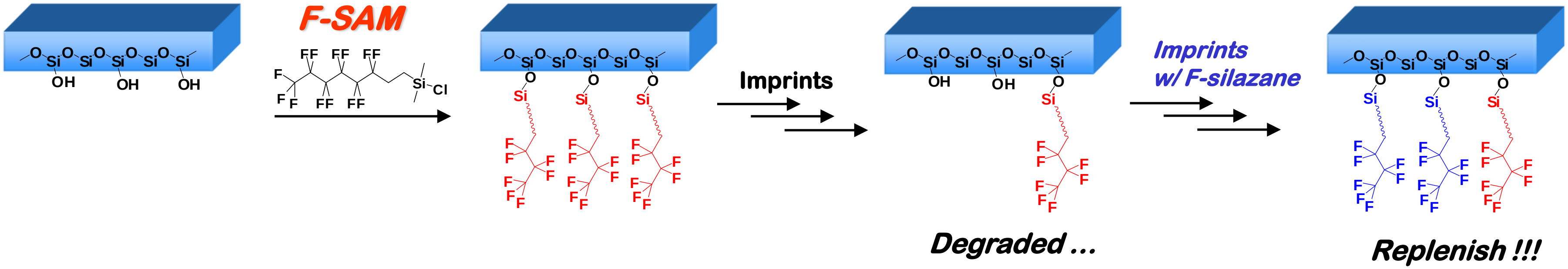
Degradation & defects !!

Potential Solution to the "wear" problem

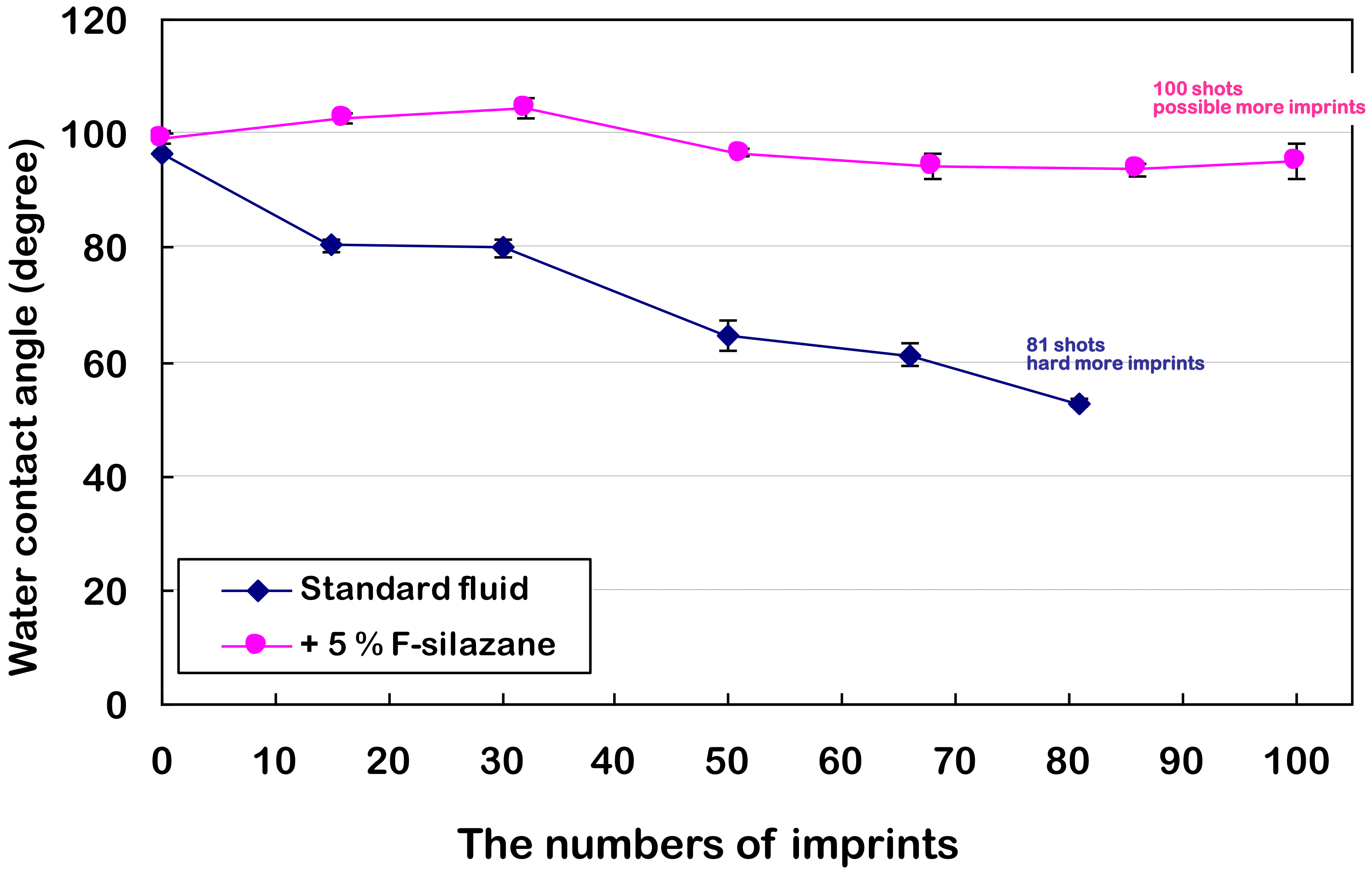


CENTRAL GLASS CO., LTD.

Concept



Multiple Imprints Results



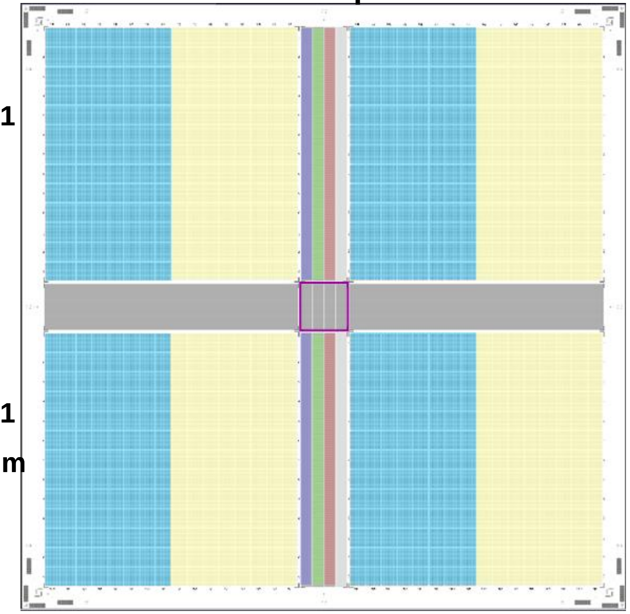
10,000 non-stop Imprints for one Template

- **Imprinted 82,200 mm wafers with 124 fields per wafer**
- **Wafers were imprinted with 13 mm X 13 mm mask fields**
- **The imprints had no unprinted streets between the imprints**
- **No process disruptions due to particles were observed**
- **Do not know of any limitations, we could have printed more fields**

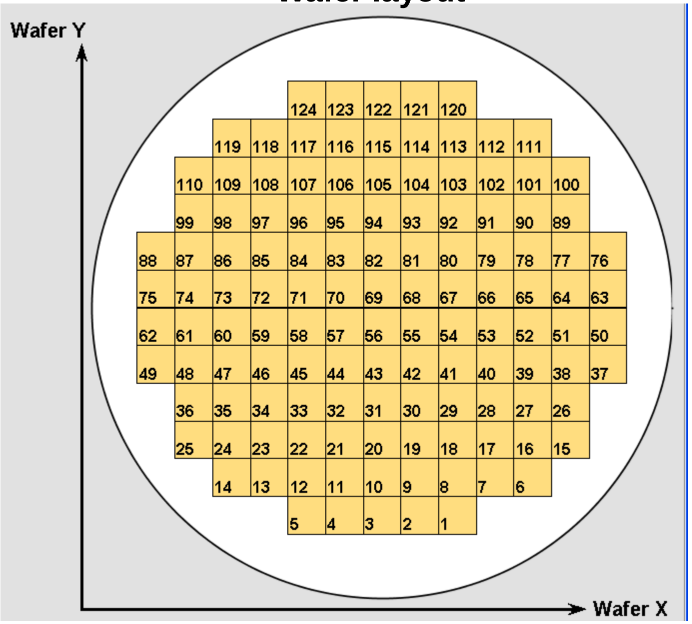
- **Features: Metal-1 and Contact arrays**

  - ■ **350 nm minimum CD M1**
  - ■ **400 nm contacts**
  - ■ **90 nm minimum CD M1**
  - ■ **80 nm minimum CD M1**
  - ■ **70 nm minimum CD M1**
  - ■ **120 nm contacts**
  - ■ **100 nm minimum CD M1**
  - □ **Program defects: 100 nm minimum CD M1**

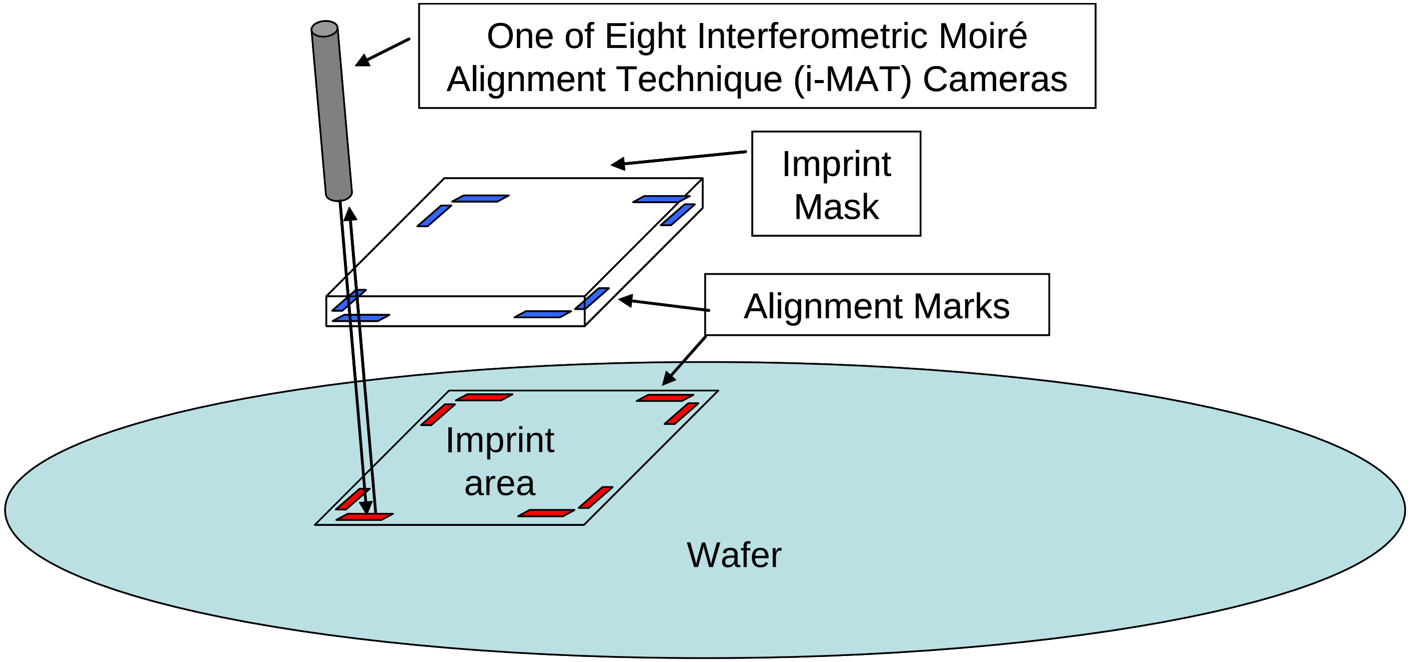
Defect Template



Wafer layout

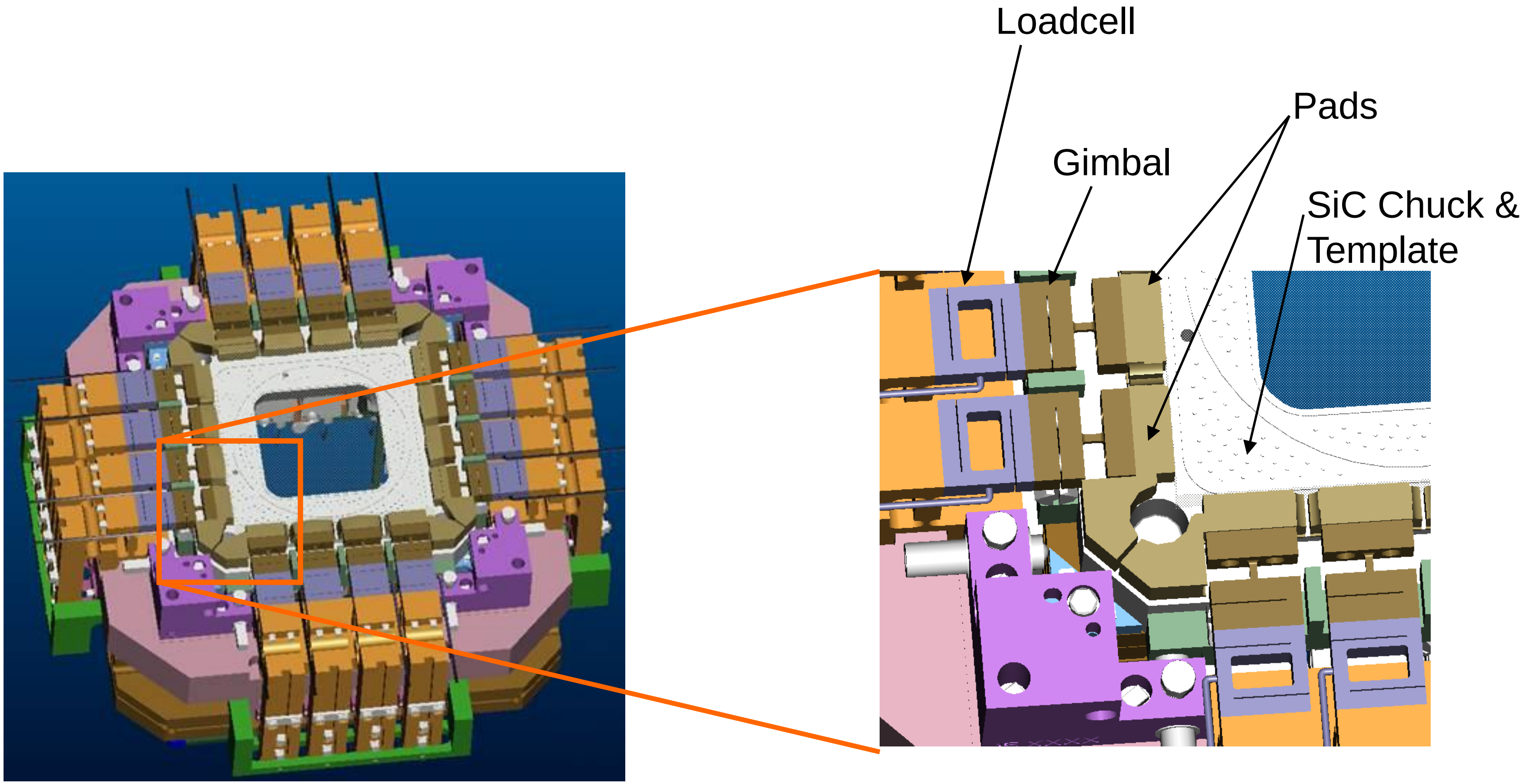


Field-To-Field Alignment



- **Moiré metrology originally developed for X-Ray litho (Smith, Moon)**
  - Sub-nanometer resolution, inclined optics
  - Insensitive to film thickness variations
- **Alignment and scale/shape correction are performed “in-liquid” which is typically a 15nm residual layer**

Overlay: Scale/Shape Correction Mechanism



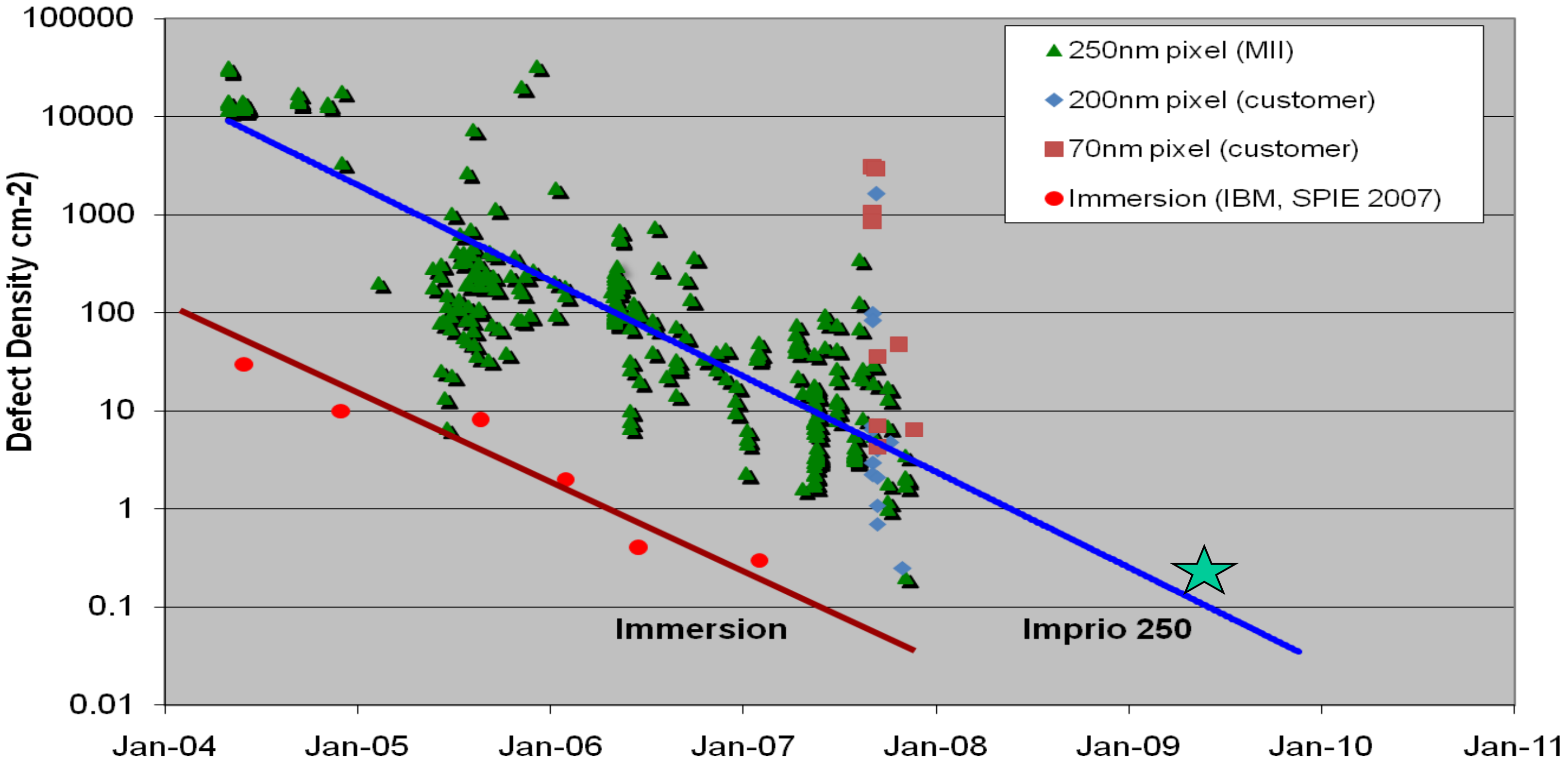
Defects

1) Why do you think 1X projection lithography replaced contact printing in the early 80’s?? Don’t you learn from history??

2) Do you propose attempt to do lithography without a pellicle??!!

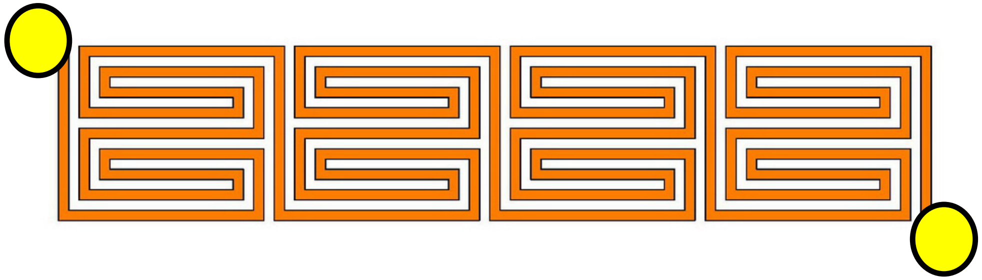
Defect Density Trend Similar to Immersion

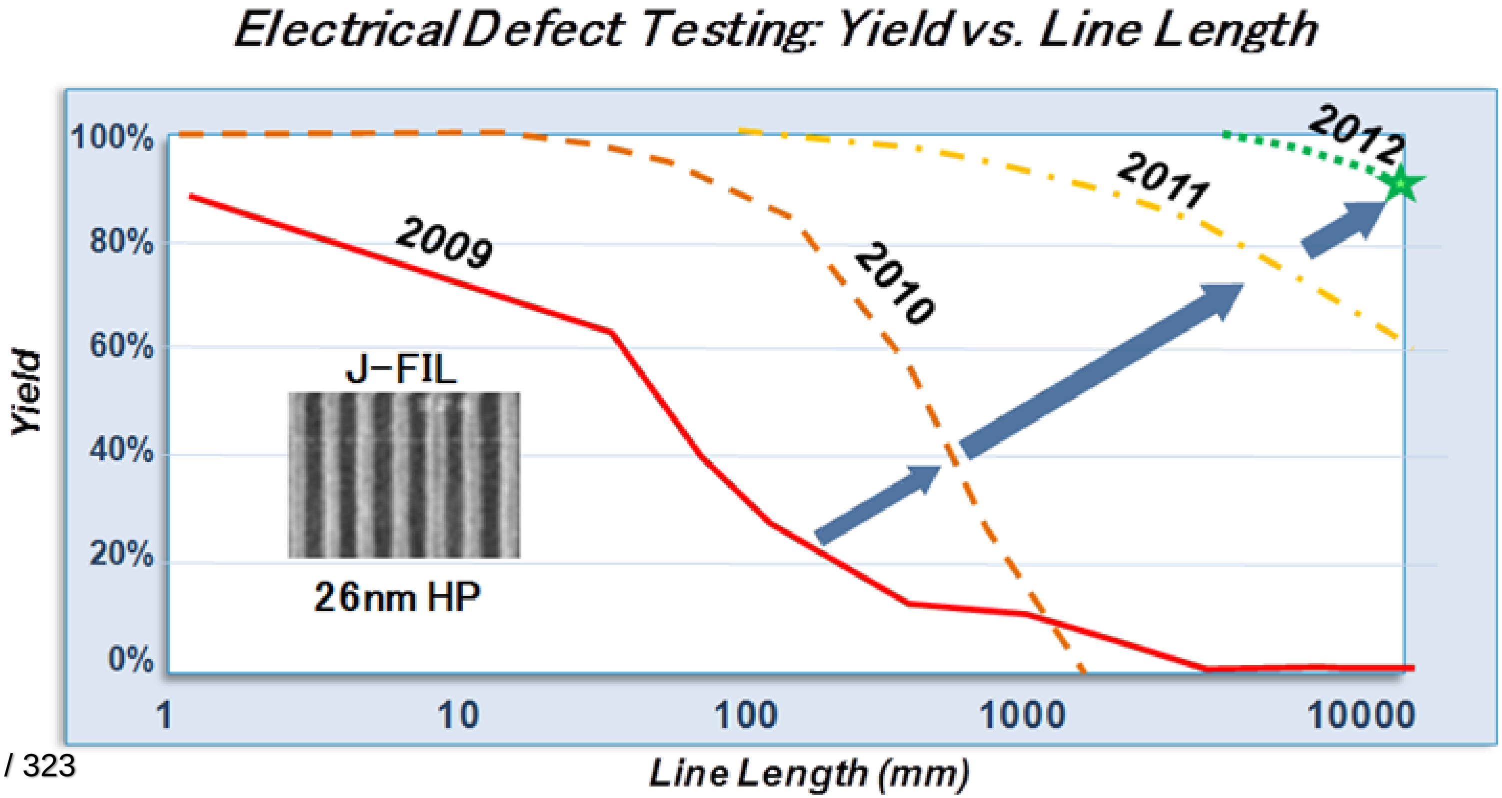
- Data measured on imprinted wafers – includes all sources of defects
- Steady improvement in defect density –
- Rate approximately one order of magnitude per year
  - *very similar to immersion lithography learning curve*



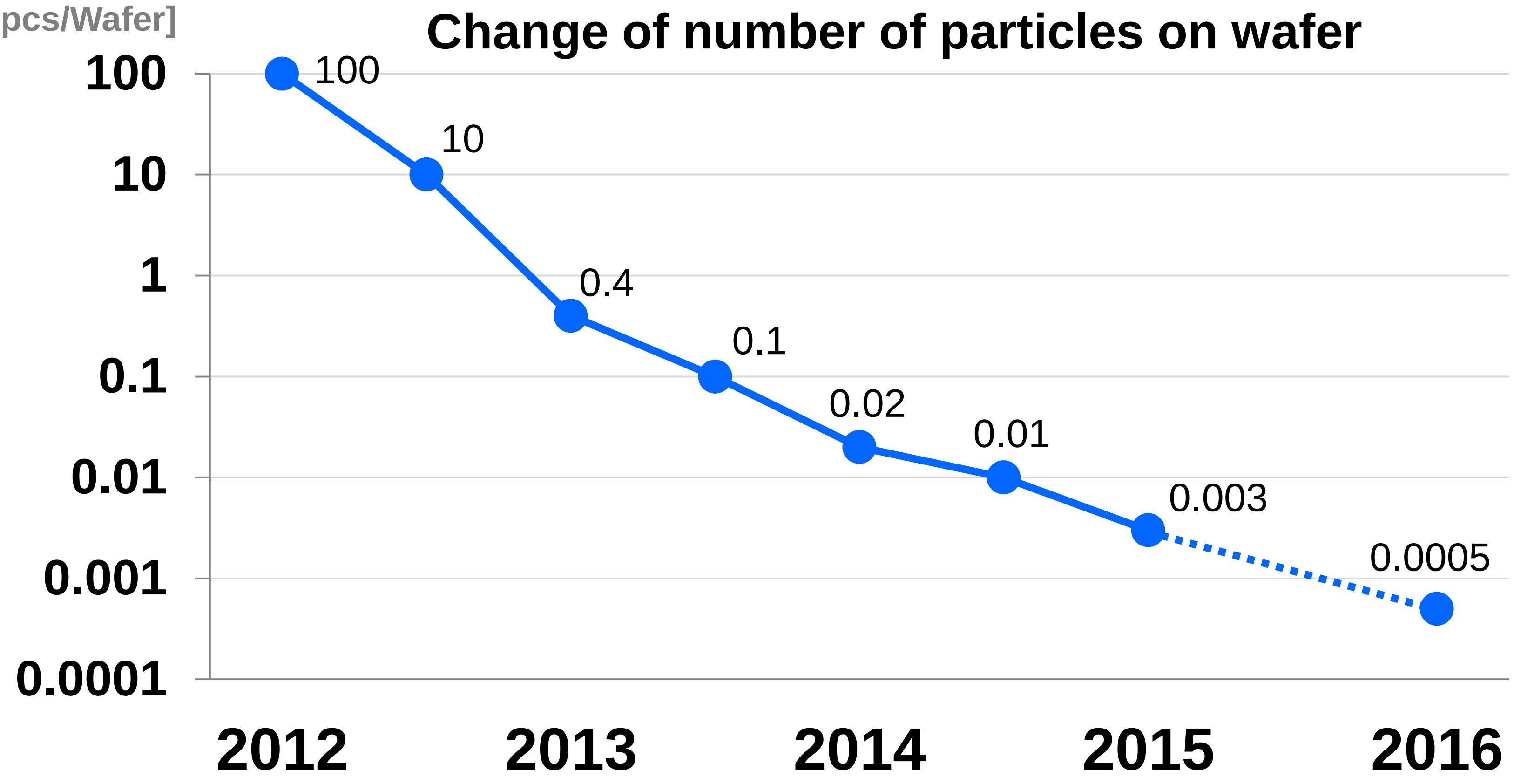
The Claims of the Detractors/Competitors

- **The stated "facts"…..SFIL cannot:**
  - Control RLT
  - Align
  - Defectivity, etc.…

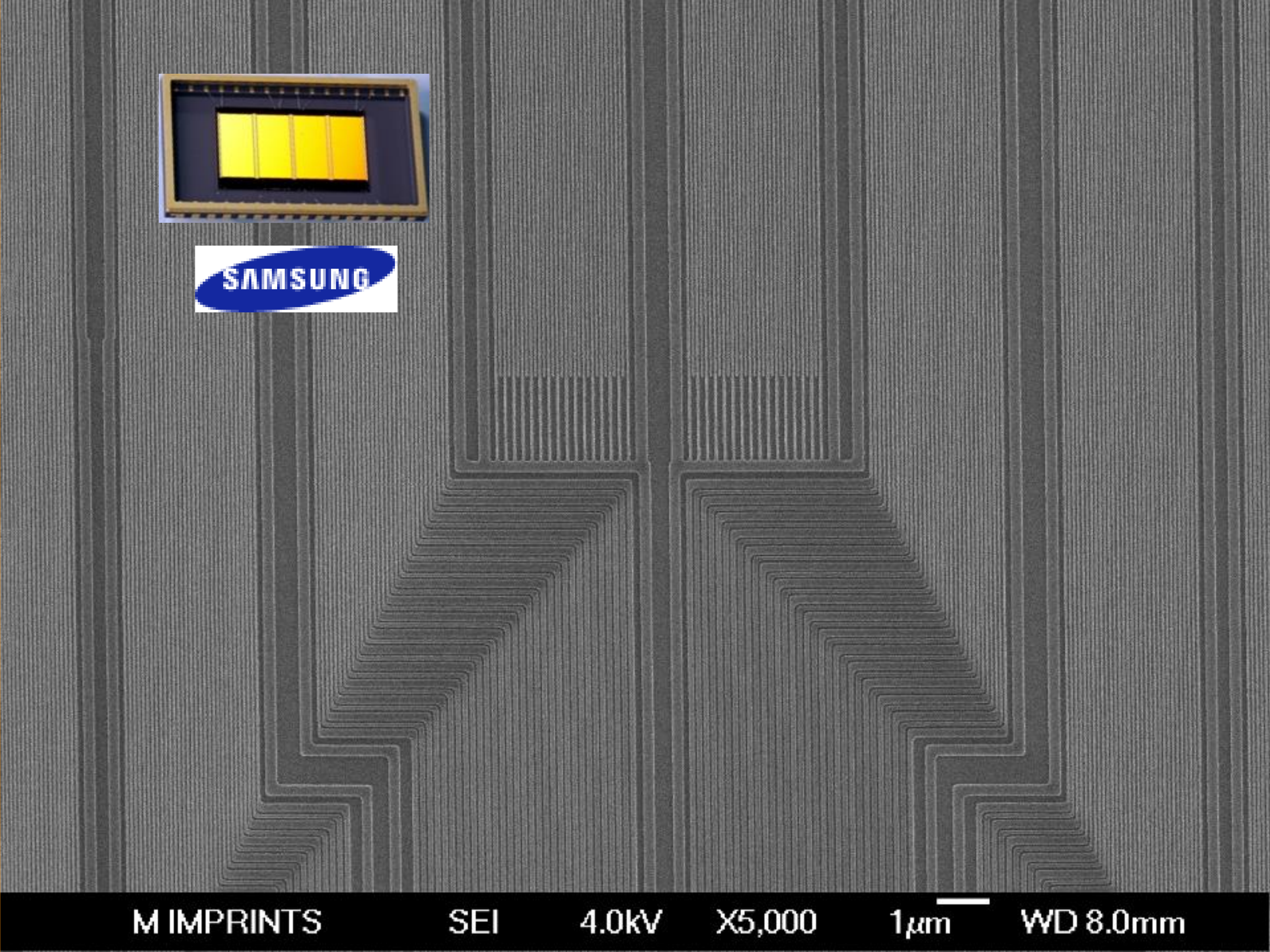




Mask Life: Wafer Fall-On Particle Trend



Hard particle reduction prolongs mask life


SAMSUNG
M IMPRINTS
SEI
4.0kV
X5,000
1μm
WD 8.0mm

Canon, Toshiba and SK hynix going forward with SFIL

Report: Toshiba adopts imprint litho for NAND production

June 07, 2016 // By Peter Clarke

Toshiba will adopt nanoimprint lithography (NIL) as a way of reducing the cost of production of NAND flash memory, according to a Nikkei report. Toshiba plans to allocate part of an 860 billion yen (about $8 billion) budget for spending on semiconductors over the next three years on introducing NIL into flash memory production lines, the report said. Production is set to begin in fiscal 2017 in Yokkaichi.

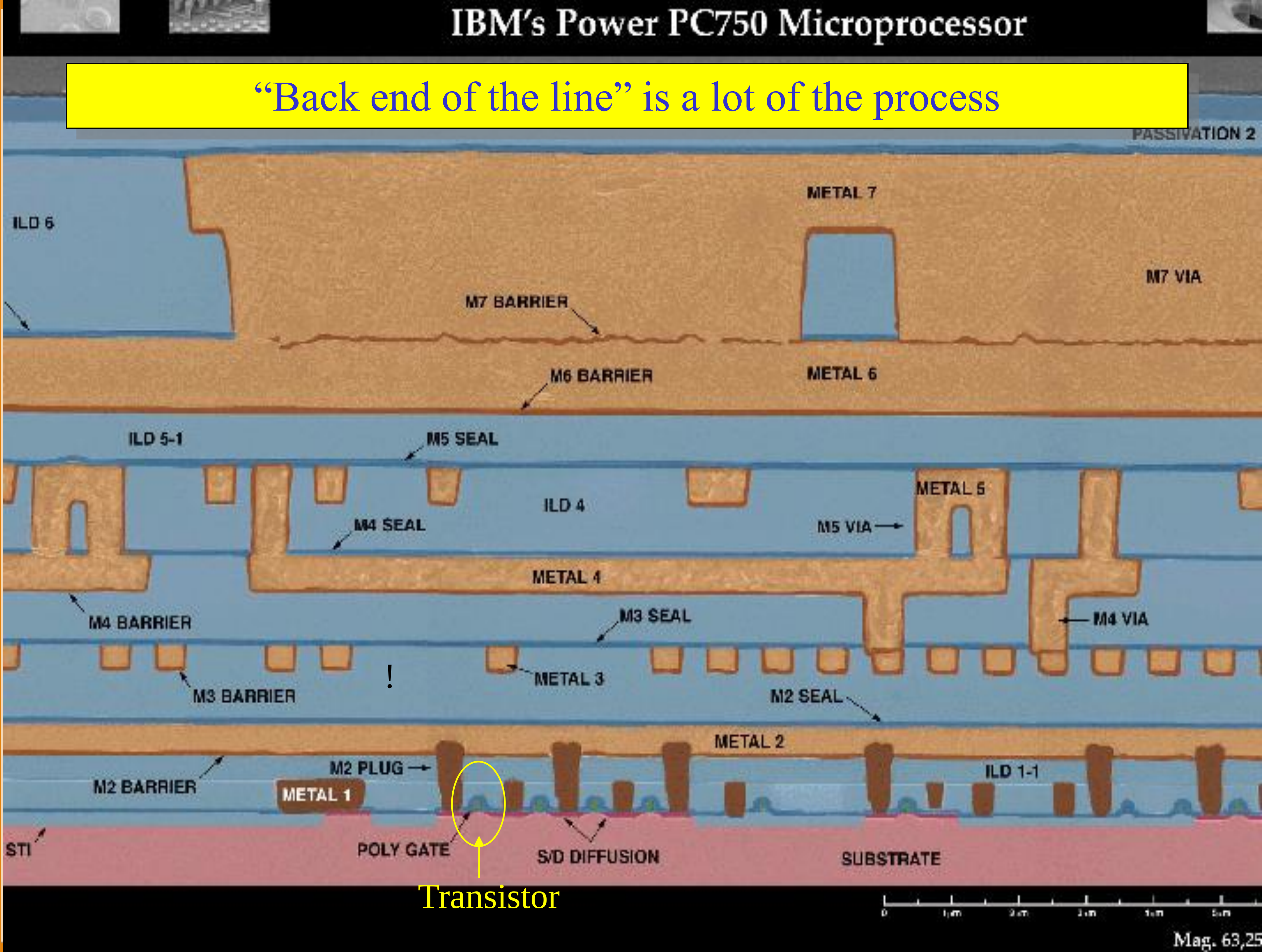
Canon TOSHIBA Leading Innovation FUJIFILM DNP SK hynix

News Release

Canon provides nanoimprint lithography manufacturing equipment to Toshiba Memory's Yokkaichi Operations plant

TOKYO, July 20, 2017—Canon Inc. announced today that the company has provided the FPA-1200NZ2C, semiconductor lithography equipment that utilizes nanoimprint lithography (NIL) technology which Canon has been continuously developing since 2004, to leading provider of semiconductor memory solutions Toshiba Memory Corporation's Yokkaichi Operations plant. The provision of this equipment represents significant progress toward semiconductor device mass production that employs nanoimprint technology.

“Back end of the line” is a lot of the process

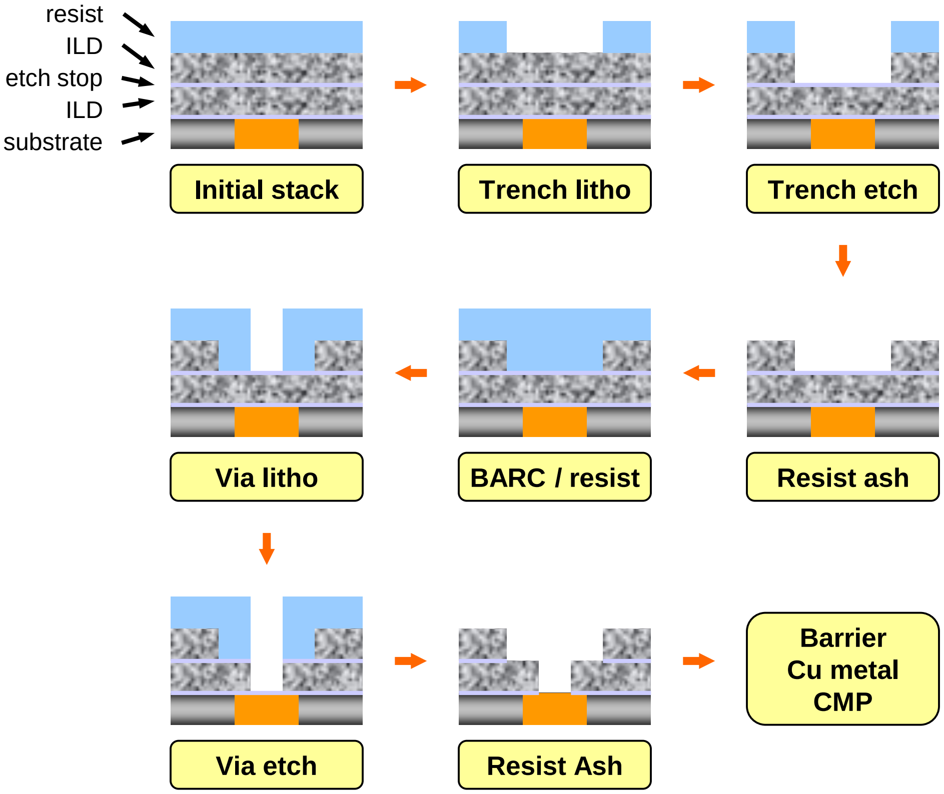


!

Transistor

Dual Damascene Process

Traditional Dual Damascene Process

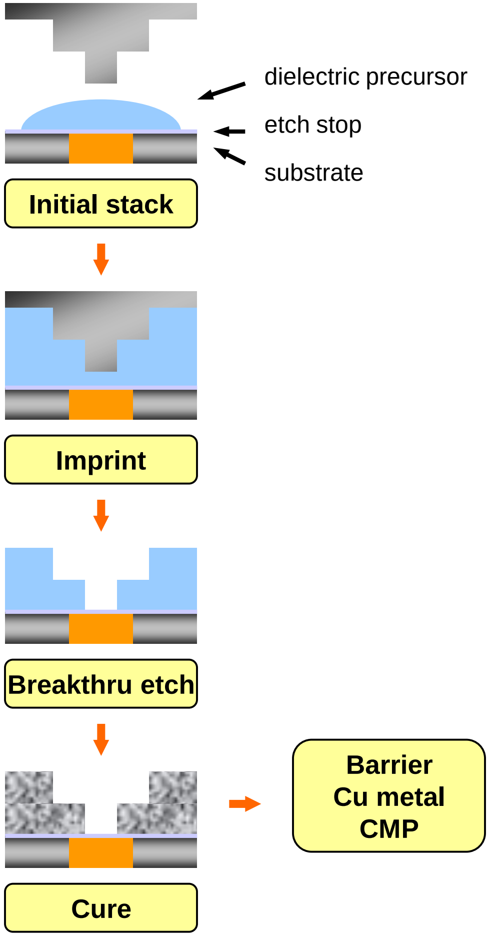


resist
ILD
etch stop
ILD
substrate

- Initial stack
- Trench litho
- Trench etch
- Resist ash
- BARC / resist
- Via litho
- Via etch
- Resist Ash
- Barrier
  Cu metal
  CMP

184 steps for 8 levels of Cu

Dual Damascene Process with Imprint Litho

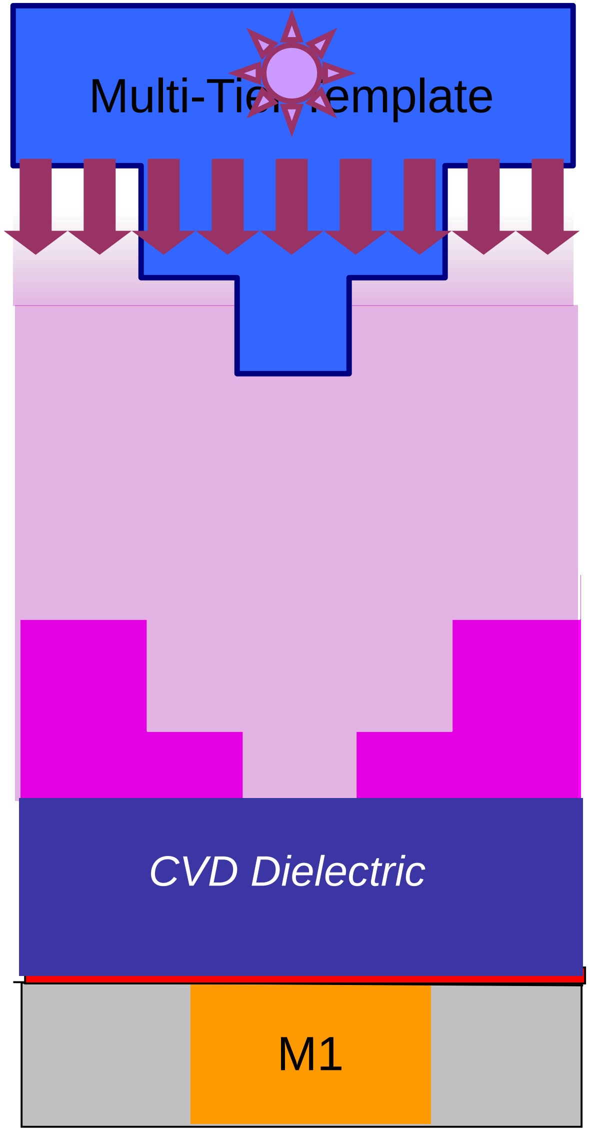


dielectric precursor
etch stop
substrate

- Initial stack
- Imprint
- Breakthru etch
- Cure
- Barrier
  Cu metal
  CMP

72 steps for 8 levels

SFIL Damascene Process (SIM)



# of process steps: 3

SFIL IMPRINTING

Release

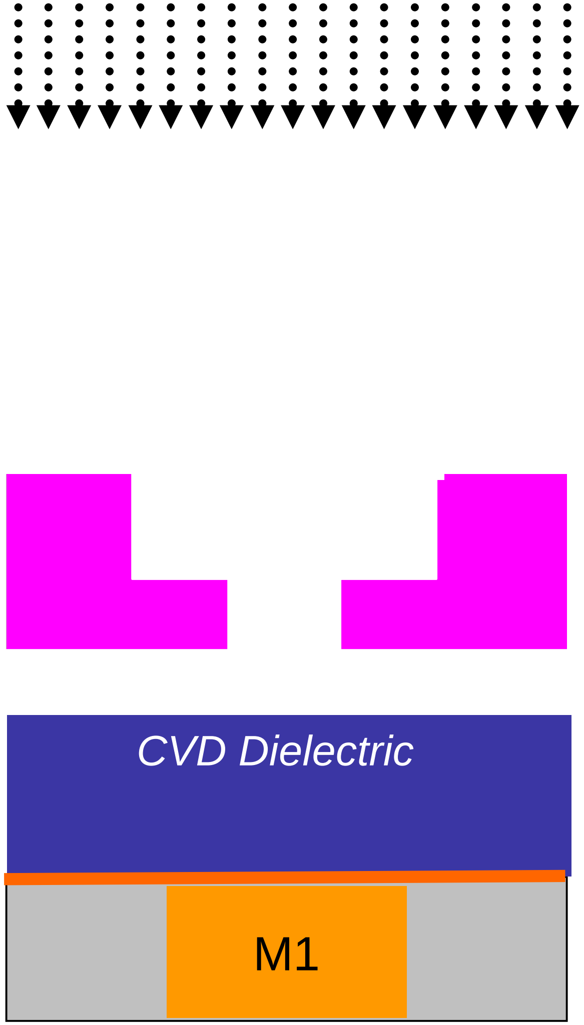
Deposit CVD dielectric (BD)

Deposit barrier

SFIL Damascene Process

Etch Transfer

# of process steps: 5



Sacrificial Imprint Material (SIM)

Strip (SIM)

SFIL Damascene Process

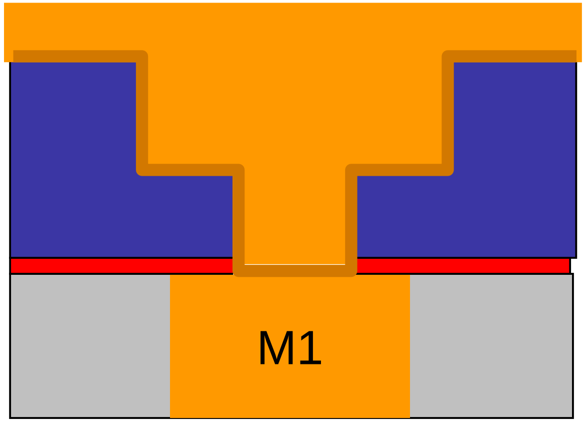
\# of process steps: 9

x 8

72

184 – 72 = 112

Saved steps ?



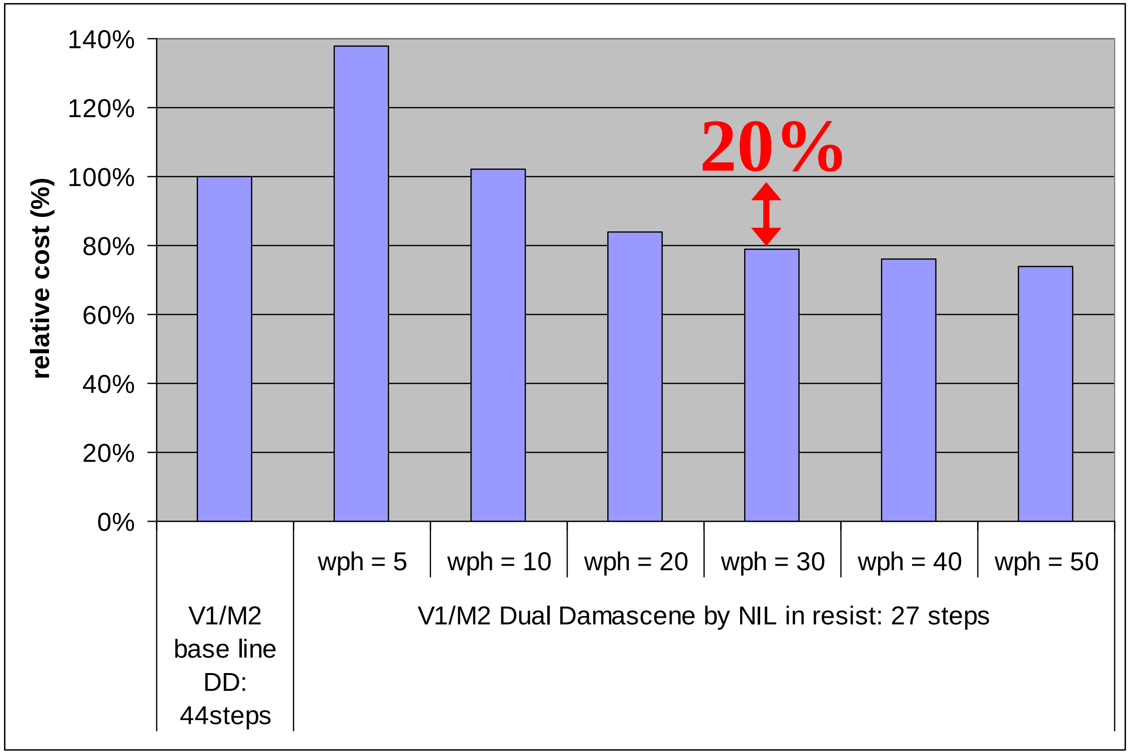
CMP

Copper Plate

Copper Seed

Etch Diffusion Barrier

BEOL Multilevel Imprint Cost Saving



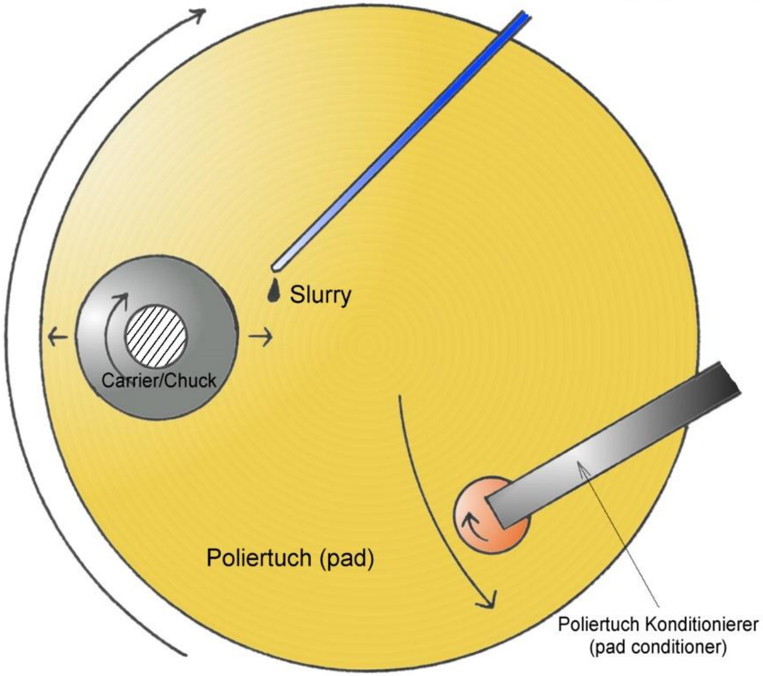
- **20% *overall* saving at 30 wph**
- **Cost analysis courtesy of Sergei V. Postnikov, Infineon Technologies; presented at Semicon Europa 2007, Stuttgart, Germany**

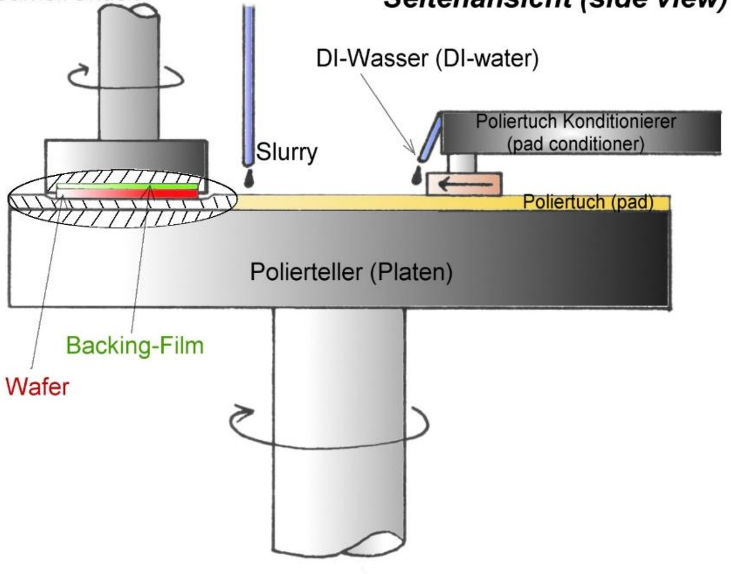
Damascene Swords and Jewelry

Damascene Swords and Jewelry

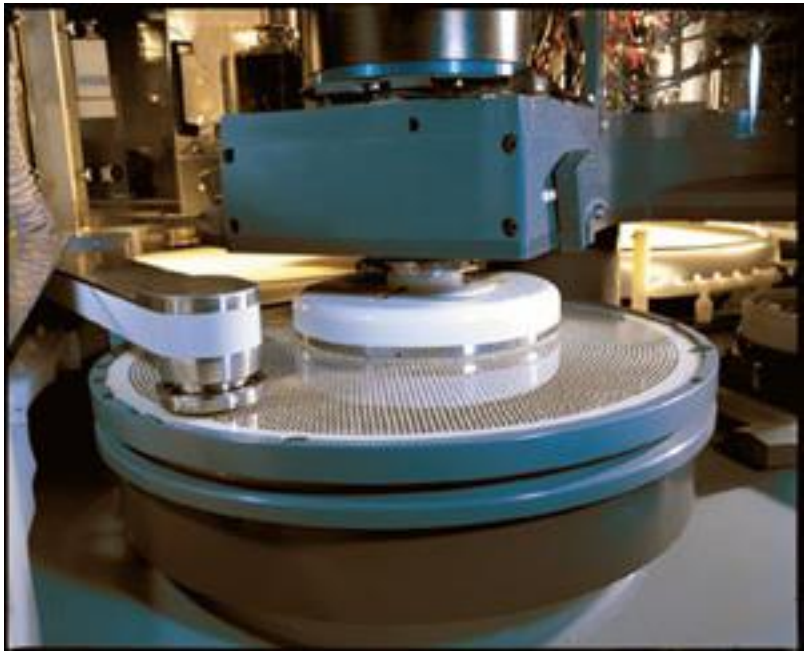
Damascene Swords and Jewelry

Chemical Mechanical Polishing

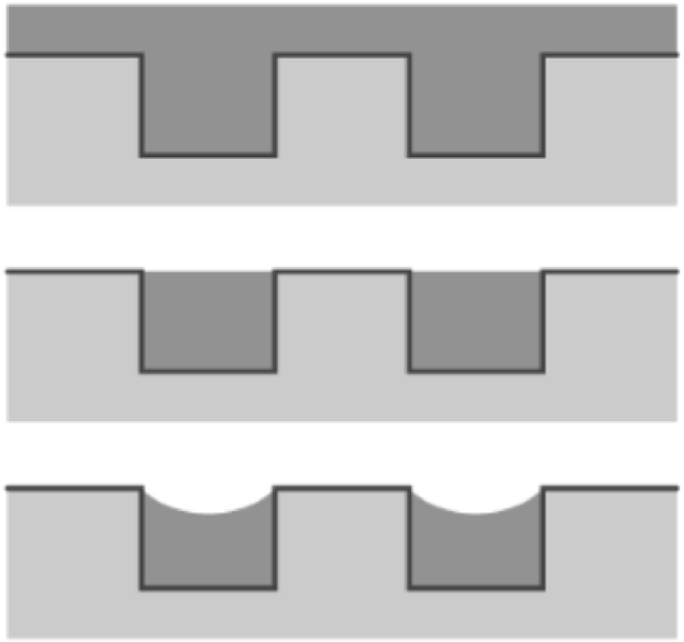

Draufsicht (top view)


Seitenansicht (side view)

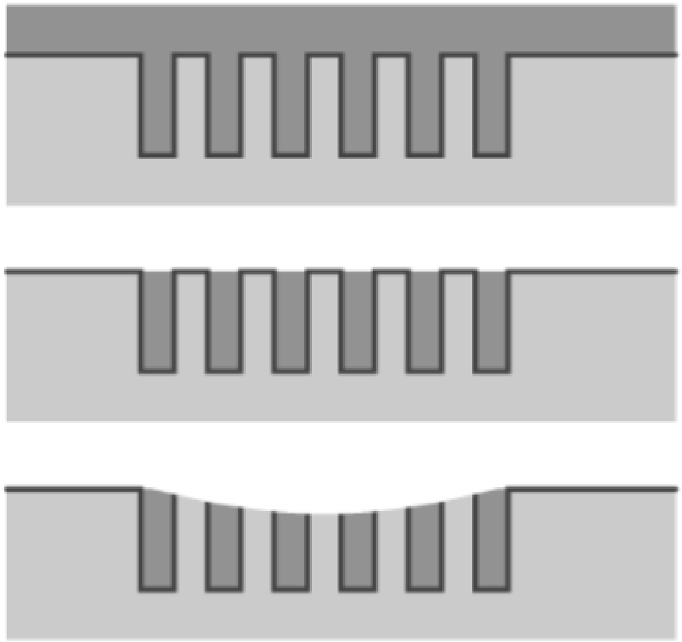
CMP Tools



Dishing and erosion

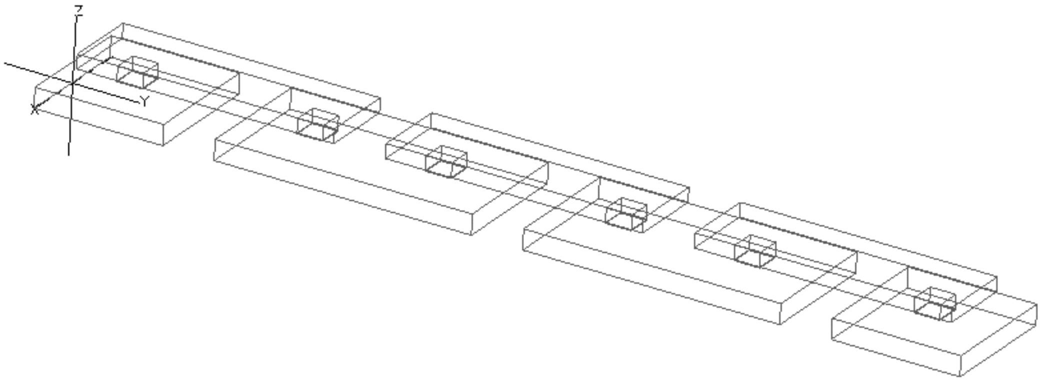


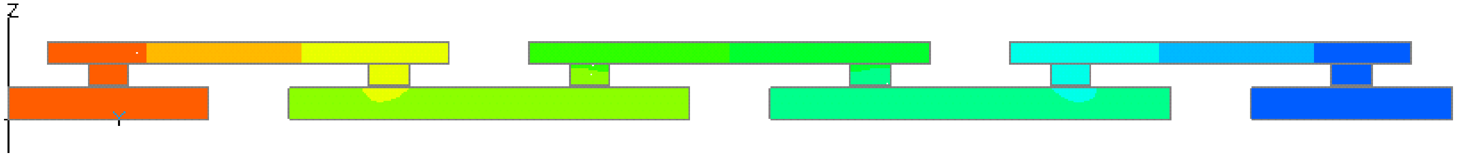
Dishing affecting wide metal lines (Cu polishes faster than dielectric)

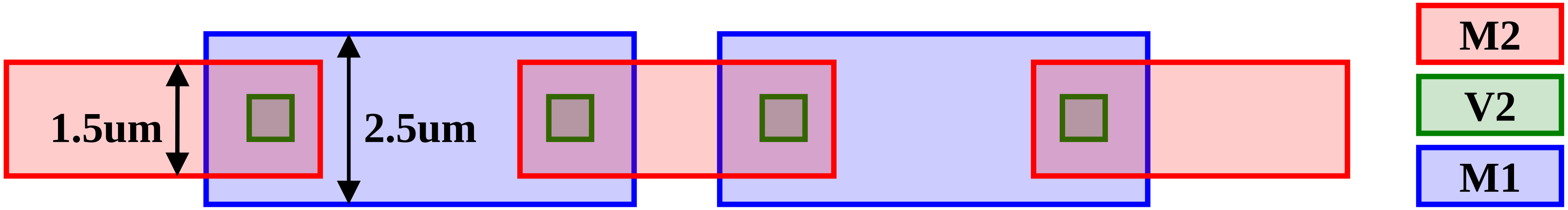


Erosion affecting high density metal pattern

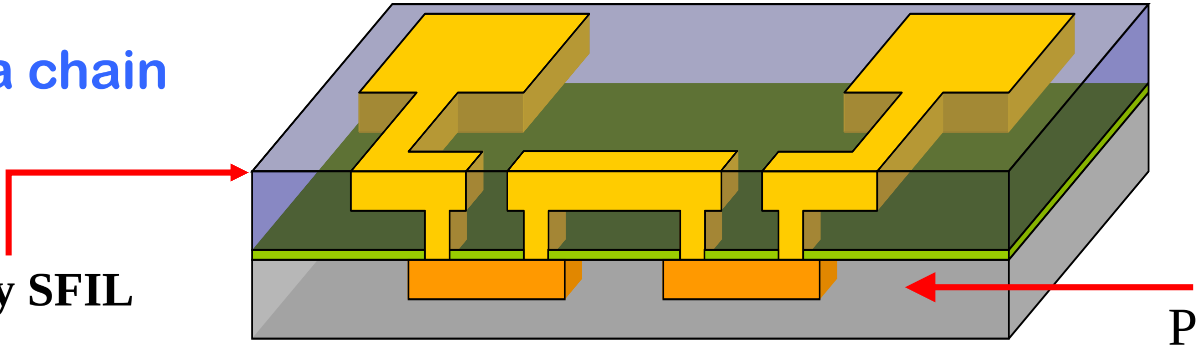
Via Chain Test Structure







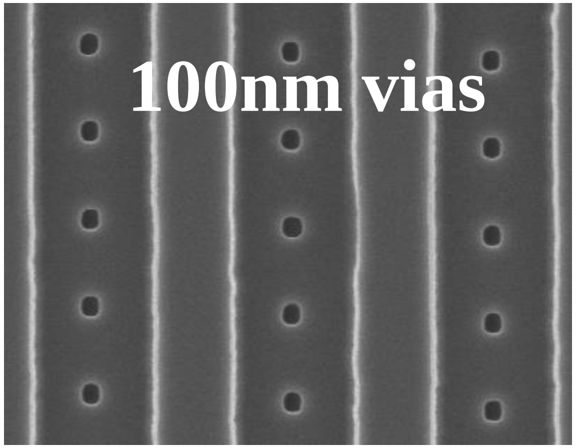
Via Chain Structures

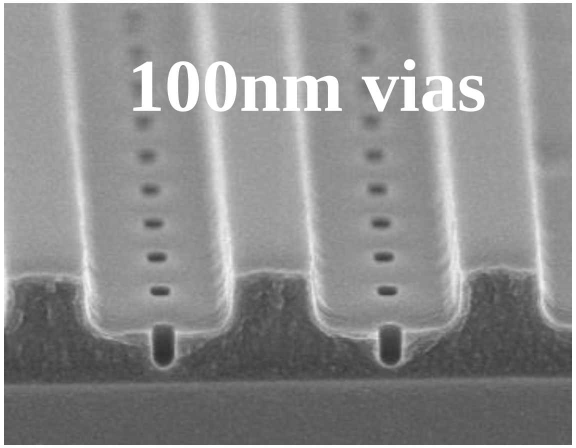


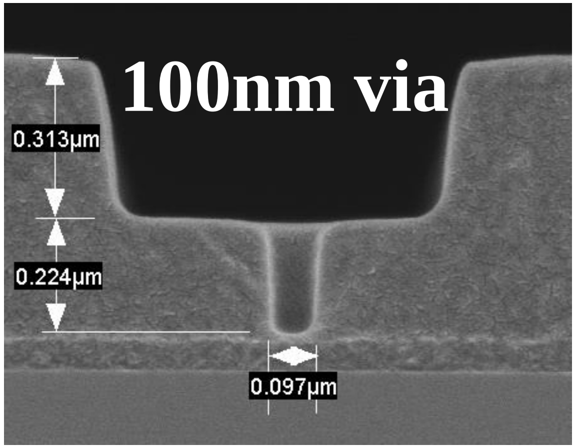
Via chain

M2 by SFIL

M1 by
Photolithography

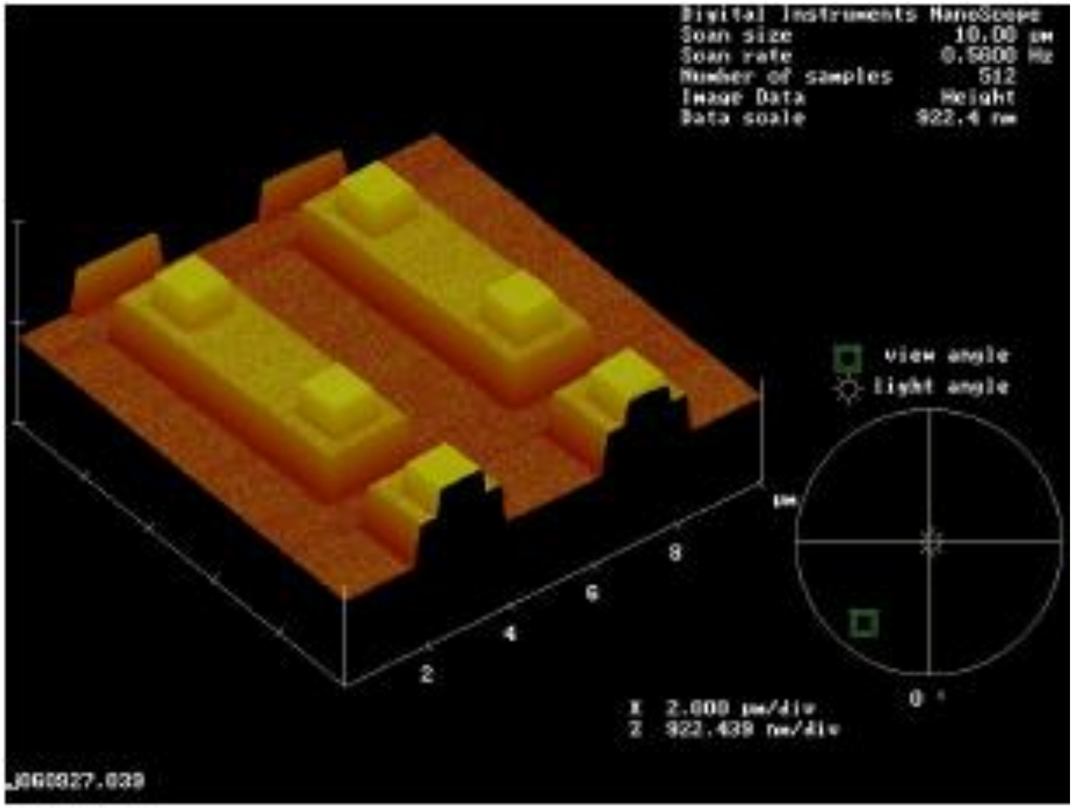




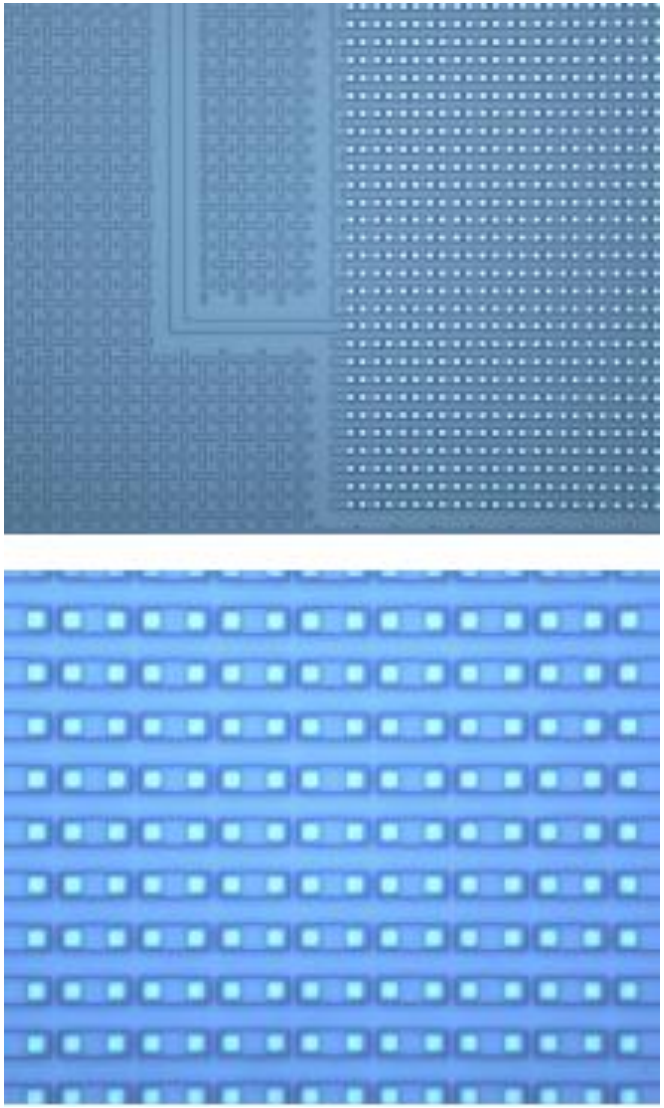


Template

now a commercial product

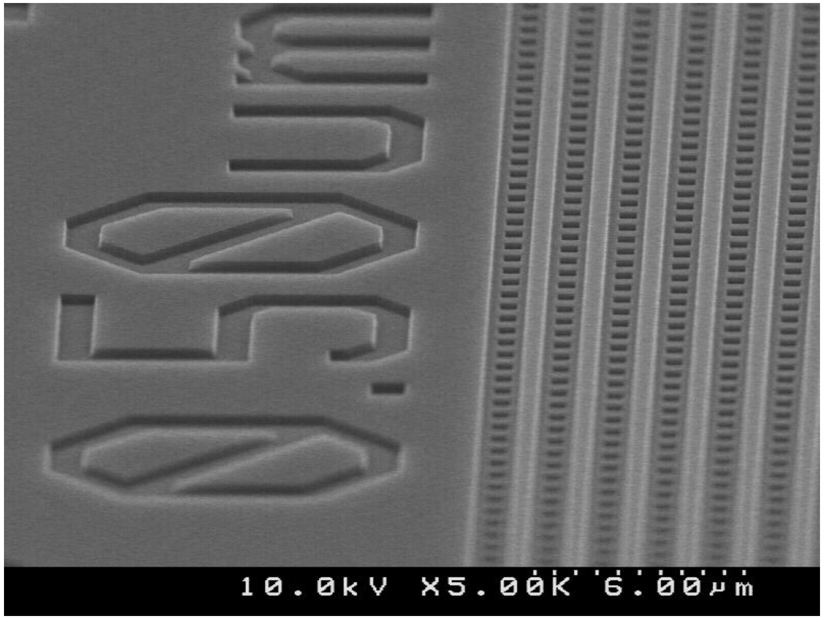


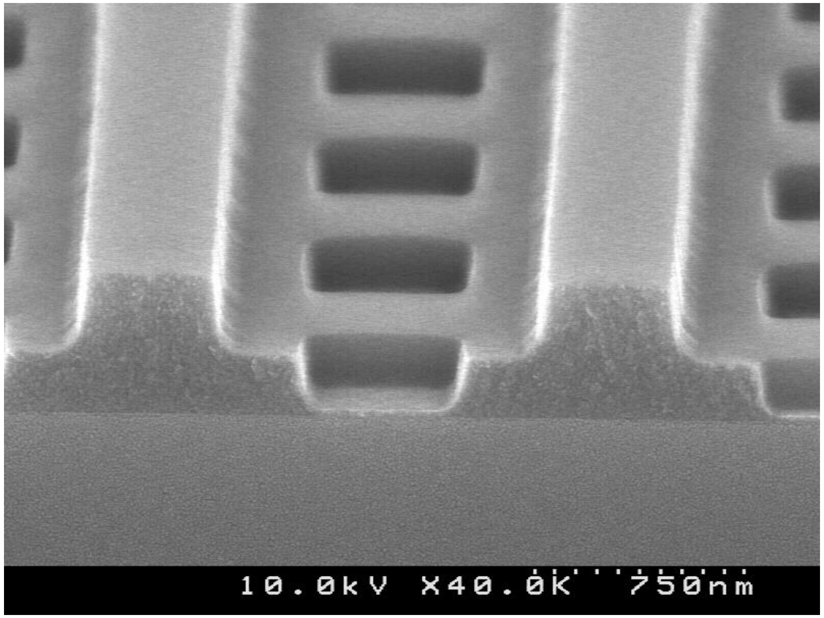
```
Digital Instruments NanoScope
Scan size                10.00 µm
Scan rate               0.5800 Hz
Number of samples          512
Image Data              Height
Data scale             922.4 nm
```

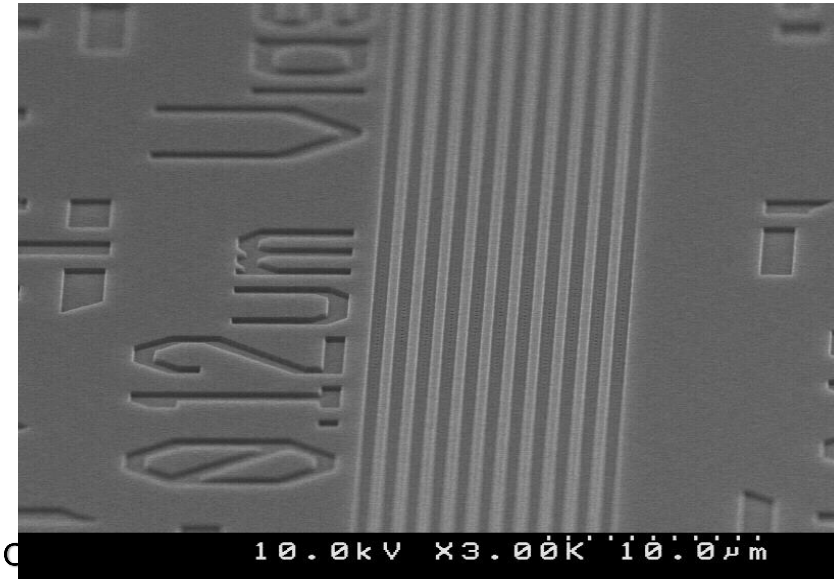


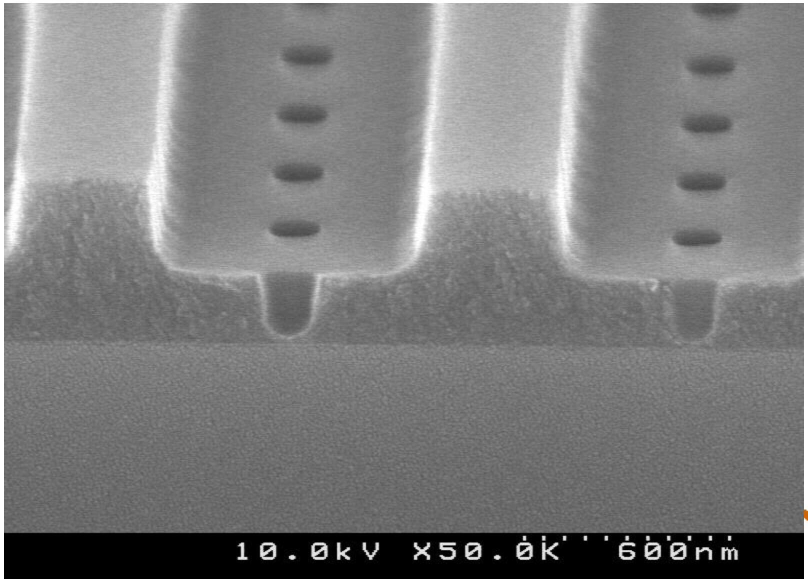
Via chain test site

Imprinting


10.0kV X5.00K 6.00µm


10.0kV X40.0K 750nm

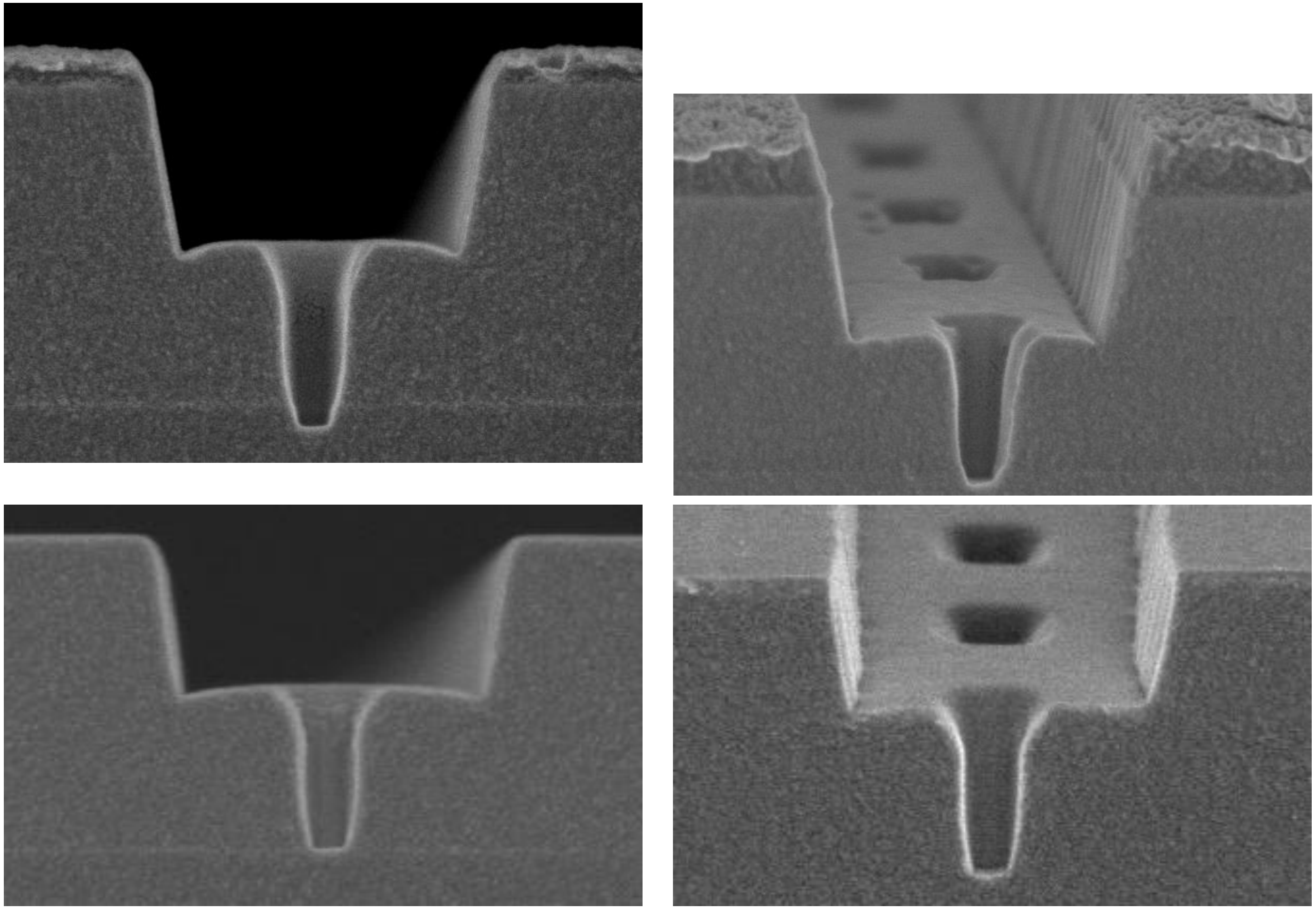

10.0kV X3.00K 10.0µm


10.0kV X50.0K 600nm

Pattern Transfer Demonstration

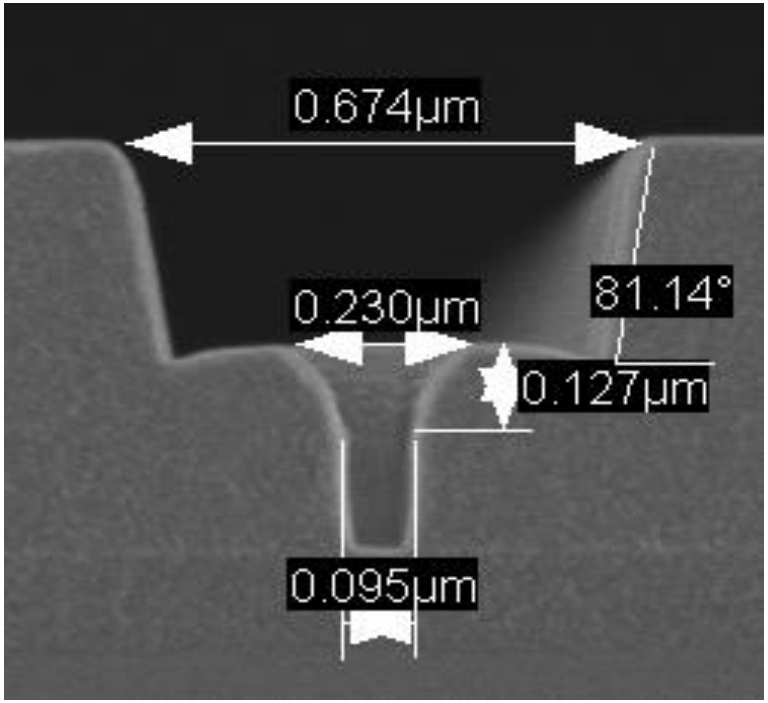
Trench Etch
$CF_4/C_4F_8/N_2$

Ash
N_2/H_2

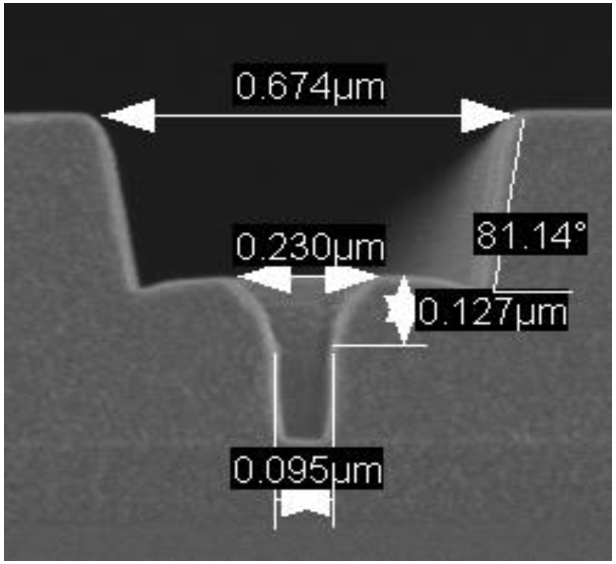


Both Coral® and Black Diamond® were processed

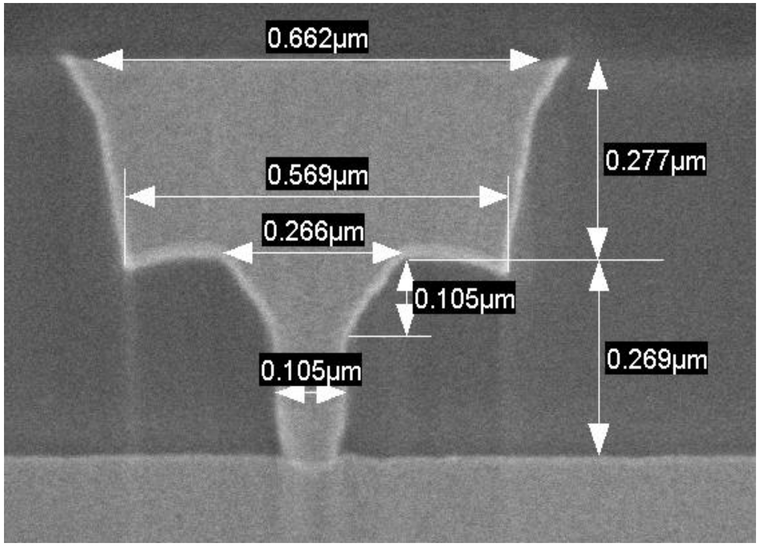
If this works, it saves more than 100 unit process steps from the manufacturing of a modern microprocessor and provides a saving of 20-50% (per studies by Infineon and SEMATECH)



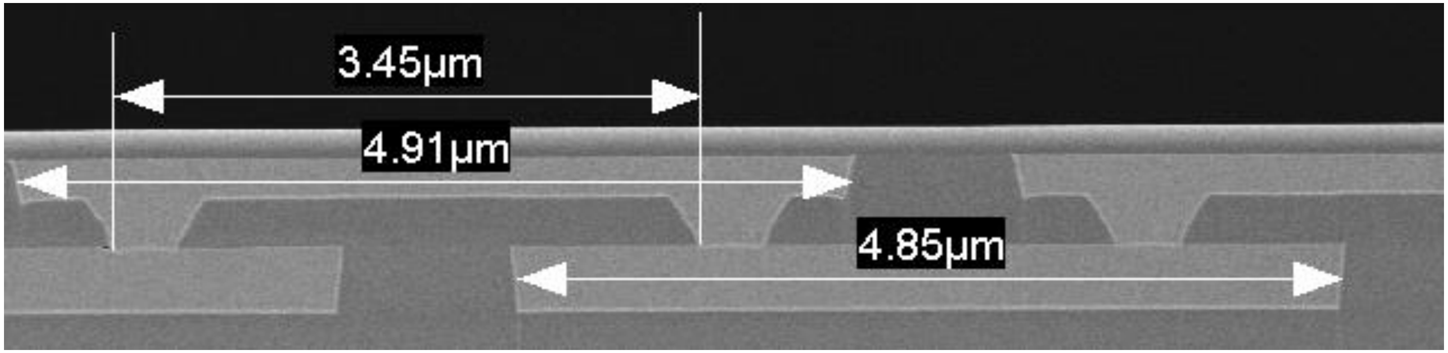
Wiring Level Complete



After etch

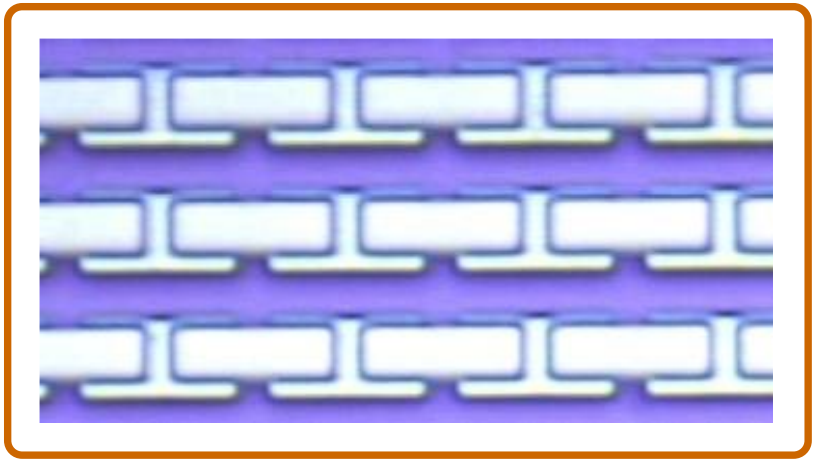


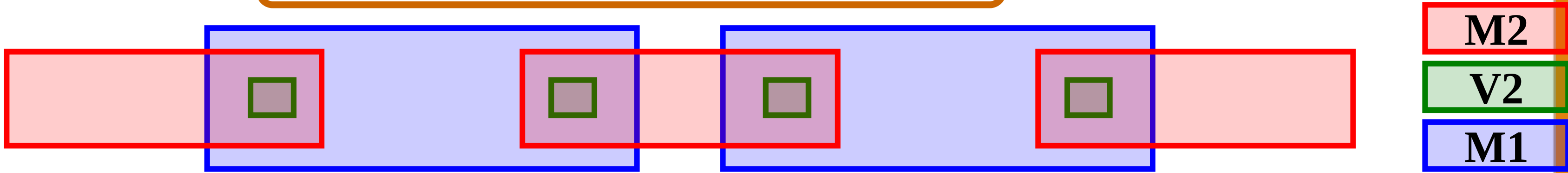
After metal

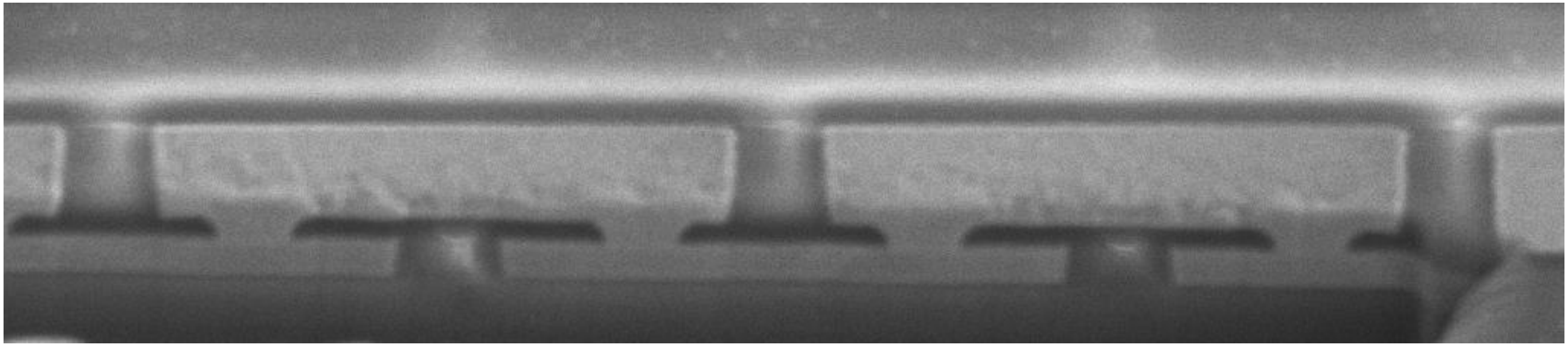


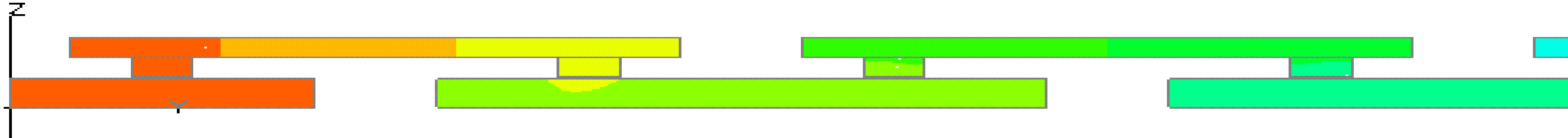
After metal

Completed Via Chains

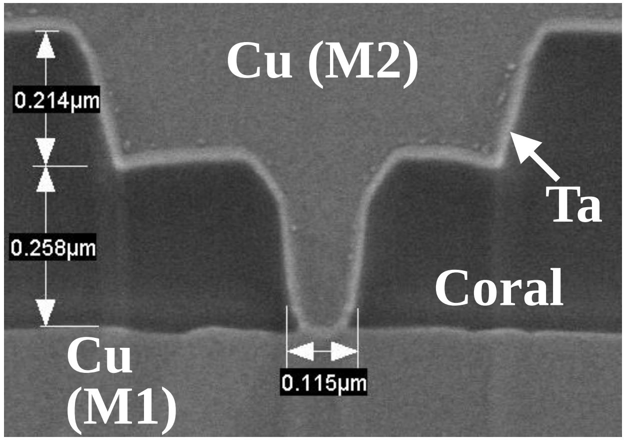




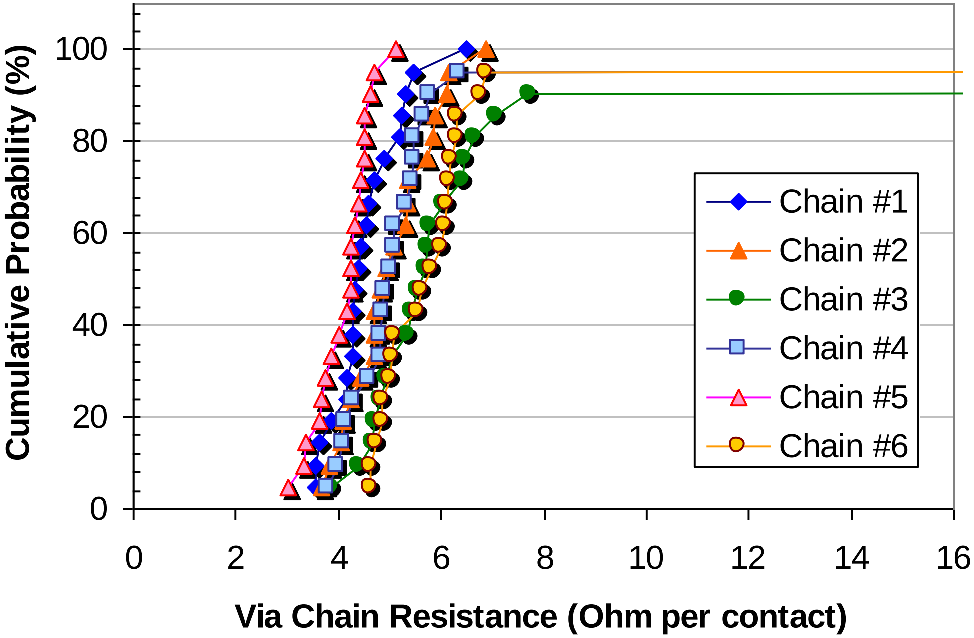




Via Chain – 120 nm 1000 Contacts



Template CD = 120 nm
Final CD = 115 nm



- **Yield statistics (6 valid and identical chains tested)**
  - Overall yield of 1000-contact chains with ***via CD 120 nm (nominal)*** / ***115 nm (final)*** – **96.83%**
  - Individual contact yield – **99.9968%**