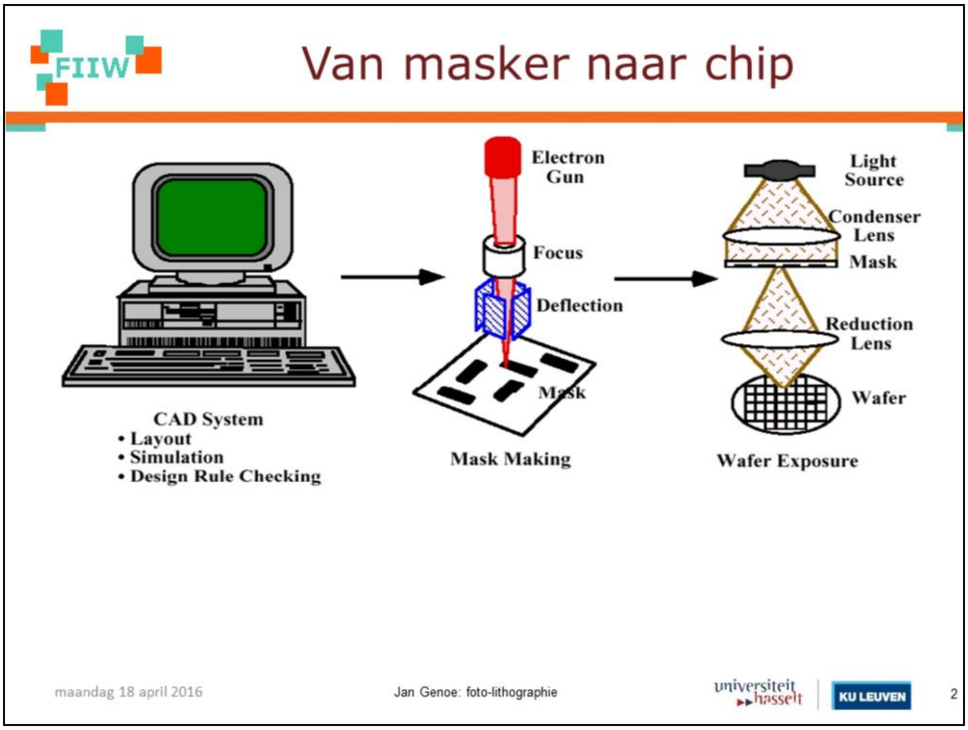
FIIW
Faculteit Industriële Ingenieurswetenschappen

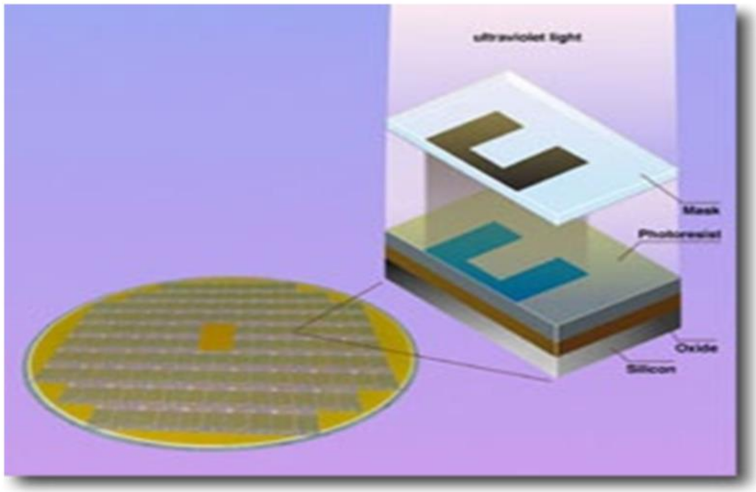
universiteit hasselt
KU LEUVEN

Jan Genoe
jan.genoe@kuleuven.be

Materialen in the foto-lithografie

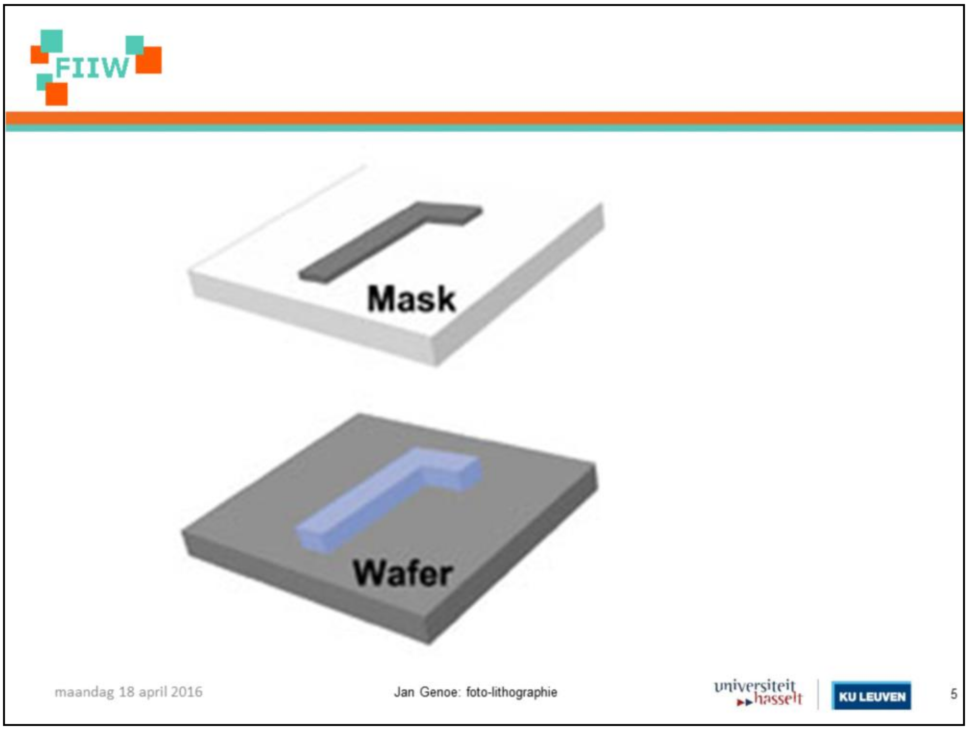

FIIW
Van masker naar chip
CAD System
• Layout
• Simulation
• Design Rule Checking
Electron Gun
Focus
Deflection
Mask
Mask Making
Light Source
Condenser Lens
Mask
Reduction Lens
Wafer
Wafer Exposure
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
2

Uitvoering van de belichting



Overzicht

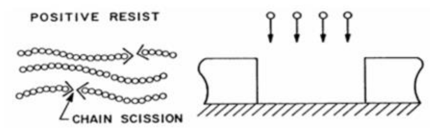
- Principe fotolithografie
- Masker types
  - Binaire maskers
  - Phase change maskers
- Keuze van de photoresist
- Keuze van de glasplaten
- Keuze van de metalen
  - Chroom
  - Molybdenum silicide (MoSi)


FIIW
Mask
Wafer
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
5

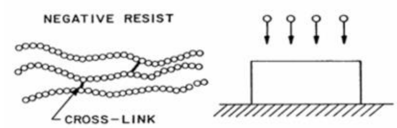
Resist Tone

Positieve: Het bekomen patroon is hetzelfde van het masker

Negatieve: Het bekomen patroon is het tegengestelde van het masker



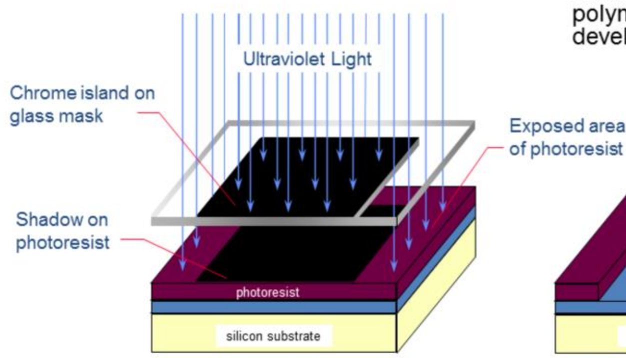
Verbreken van lange ketens door UV licht: belichte deel wordt oplosbaar in de ontwikkelaar

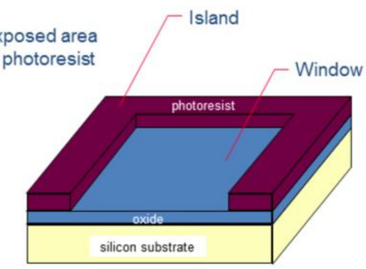


Maken van extra verbindingen tussen lange ketens door UV licht : belichte deel wordt **on**oplosbaar in de ontwikkelaar

Negative Lithography

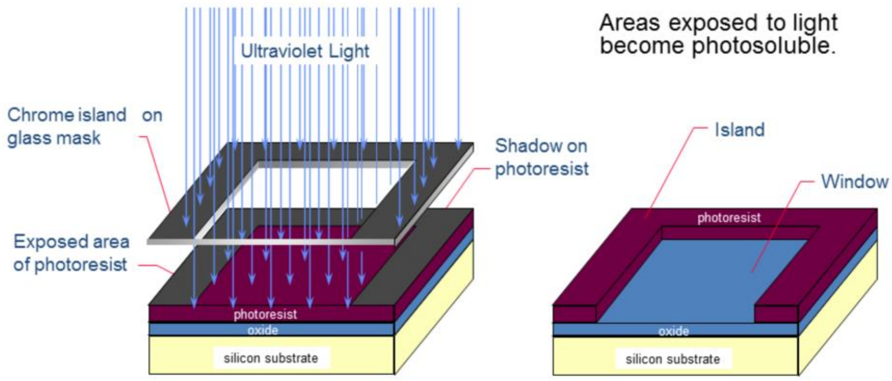
Areas exposed to light become polymerized and resist the develop chemical.





Resulting pattern after the resist is developed.

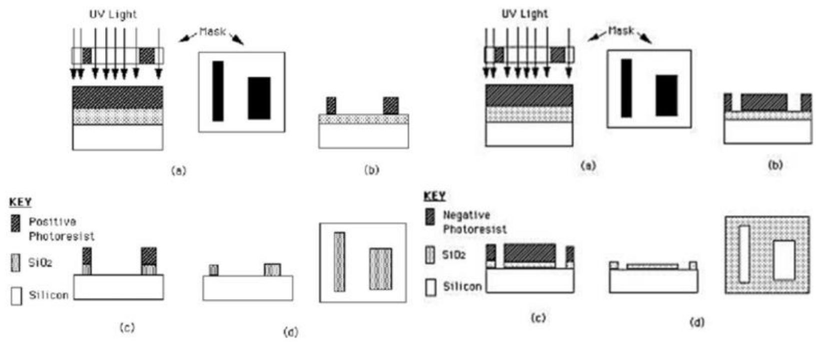
Positive Lithography



Areas exposed to light become photosoluble.

Resulting pattern after the resist is developed.

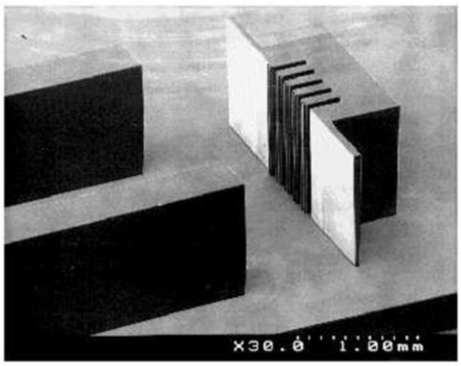
Resist Tone

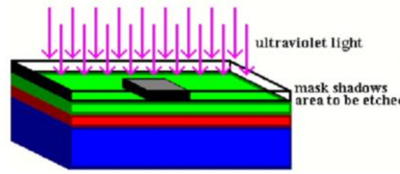


UV Light
Mask
(a)
(b)
KEY
Positive Photoresist
SiO2
Silicon
(c)
(d)
UV Light
Mask
(a)
(b)
KEY
Negative Photoresist
SiO2
Silicon
(c)
(d)

Resist Tone

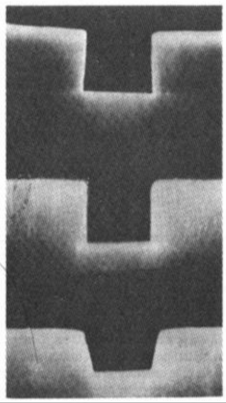
- Photoresist profielen
  - Overcut (LIFT-OFF)
  - Vertical
  - Undercut

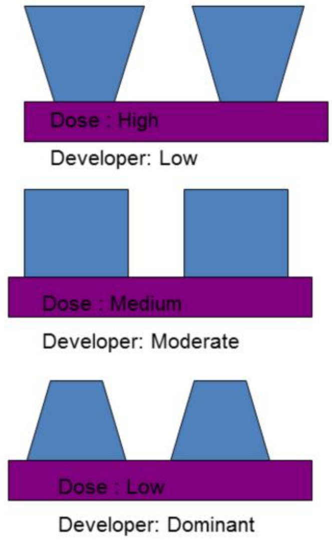


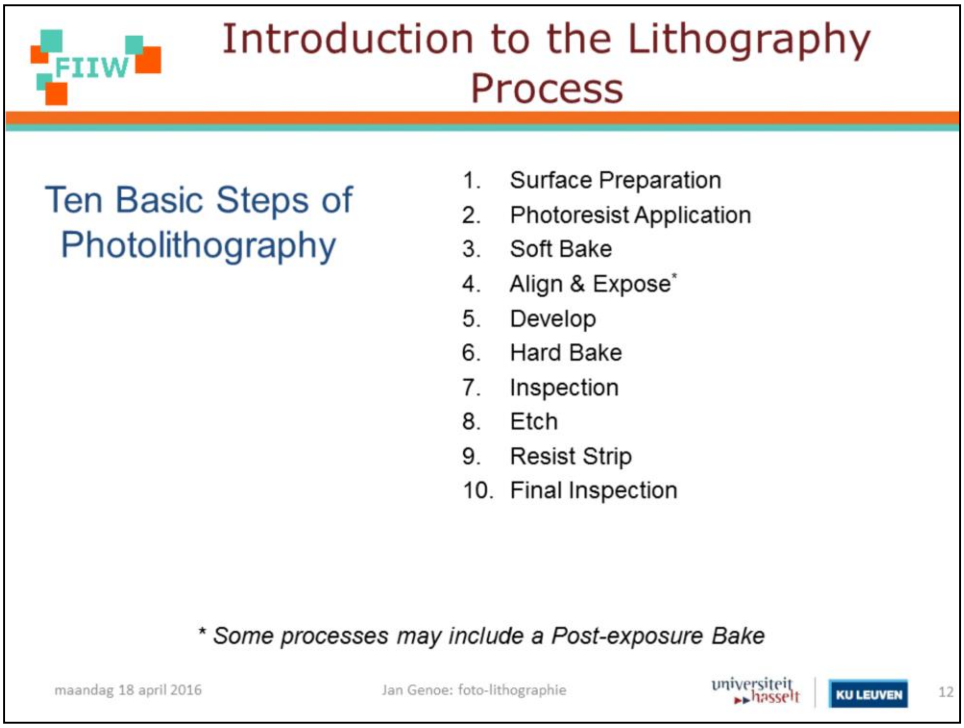


Resist Tone

- Photoresist profielen
  - Overcut (LIFT-OFF)
  - Vertical
  - Undercut



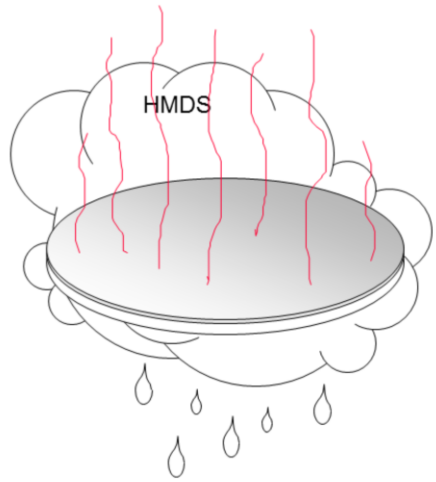




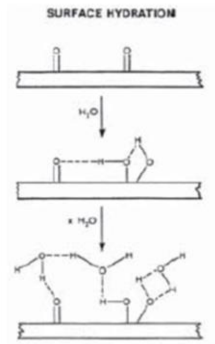
This following slides addresses Engineering Technology Content Standard 3 and 4 on Manufacturing and Materials.

1. Surface Preparation (HMDS vapor prime)

- Dehydration bake in enclosed chamber with exhaust
- Clean and dry wafer surface (hydrophobic)
- Hexamethyldisilazane (HMDS)
- Temp ~ 200 - 250° C
- Time ~ 60 sec.

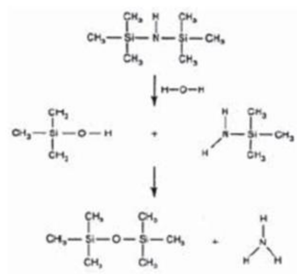


1. Surface Preparation (HMDS vapor prime)

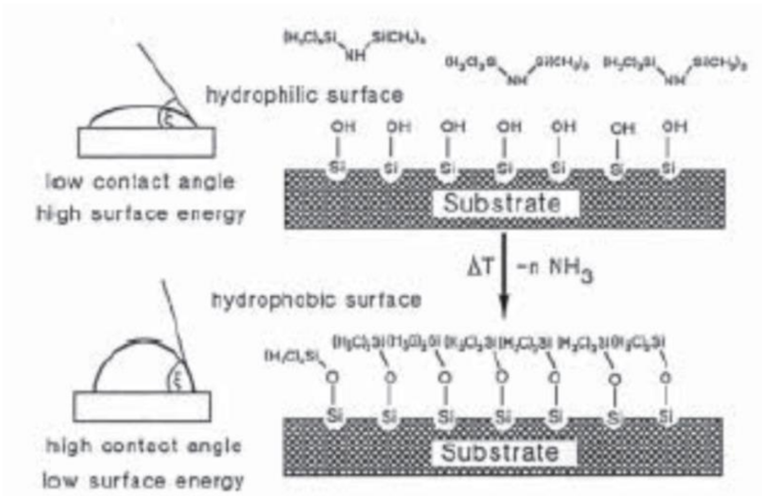


Shipley Tutorial Graphics

The figure below shows the chemistry of HMDS (hexamethyldisilazane), a primer which acts as an adhesion promoter for photoresist.

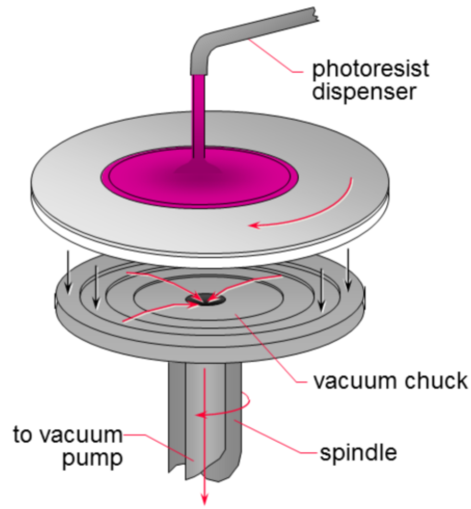


1. Surface Preparation (HMDS vapor prime)



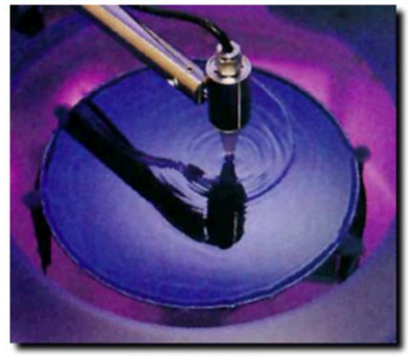
2. Photoresist Application

- Wafer held onto vacuum chuck
- Dispense ~5ml of photoresist
- Slow spin ~ 500 rpm
- Ramp up to ~ 3000 - 5000 rpm
- Quality measures:
  - time
  - speed
  - thickness
  - uniformity
  - particles & defects



2. Photoresist Application

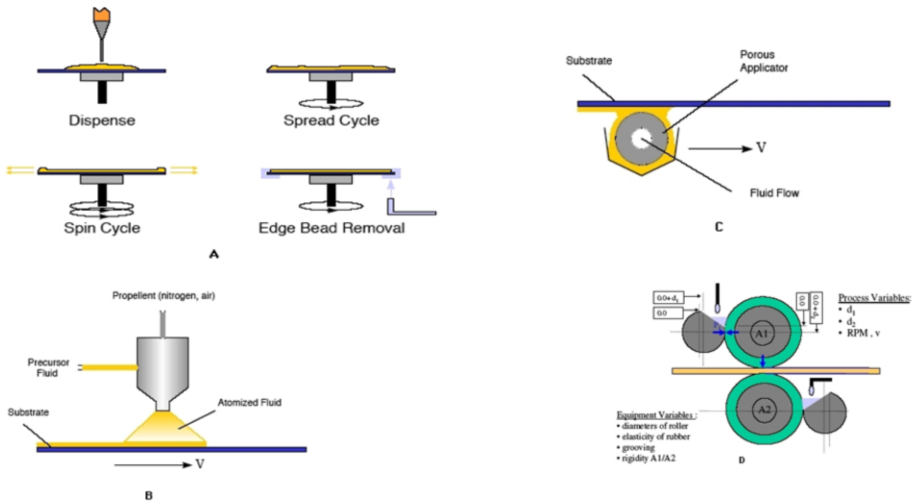
- Resist spinning thickness T depends on:
  - Spin speed
  - Solution concentration
  - Molecular weight (measured by intrinsic viscosity)
- In the equation for T, K is a calibration constant, C the polymer concentration in grams per 100 ml solution, η the intrinsic viscosity, and ω the number of rotations per minute (rpm)
- Once the various exponential factors (α,β and γ) have been determined the equation can be used to predict the thickness of the film that can be spun for various molecular weights and solution concentrations of a given polymer and solvent system



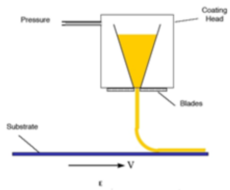
Photoresist Application
(Ontrak)

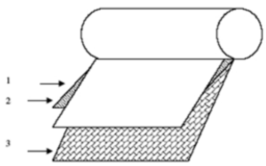
$$T = \frac{KC^{\beta}\,\eta^{\gamma}}{\omega^{\alpha}}$$

2. Photoresist Application

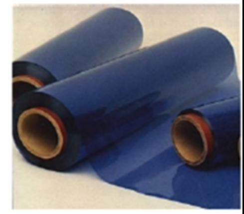


2. Photoresist Application



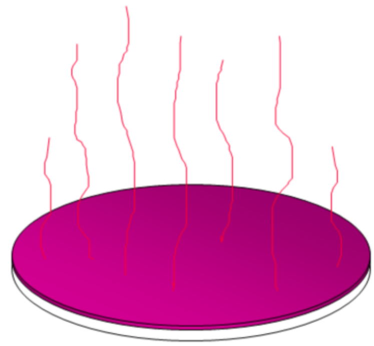


Three-layer structure of dry film photoresist.
1: polyethylene separation sheet; 2: photoresist and 3: polyester support.



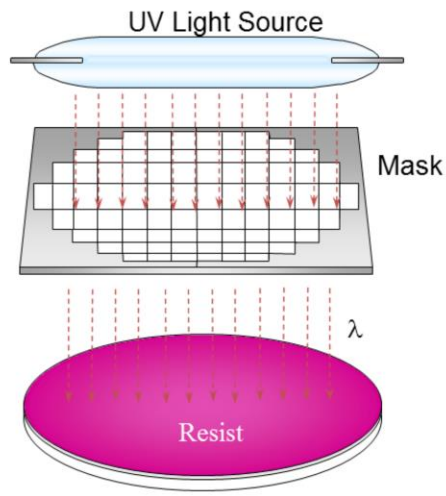
3. Soft Bake

- Partial evaporation of photo-resist solvents
- Improves adhesion
- Improves uniformity
- Improves etch resistance
- Improves linewidth control
- Optimizes light absorbance characteristics of photoresist



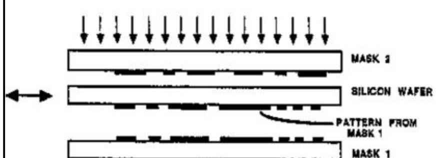
4. Alignment and Exposure

- Transfers the mask image to the resist-coated wafer
- Activates photo-sensitive components of photoresist
- Quality measures:
  - linewidth resolution
  - overlay accuracy
  - particles & defects



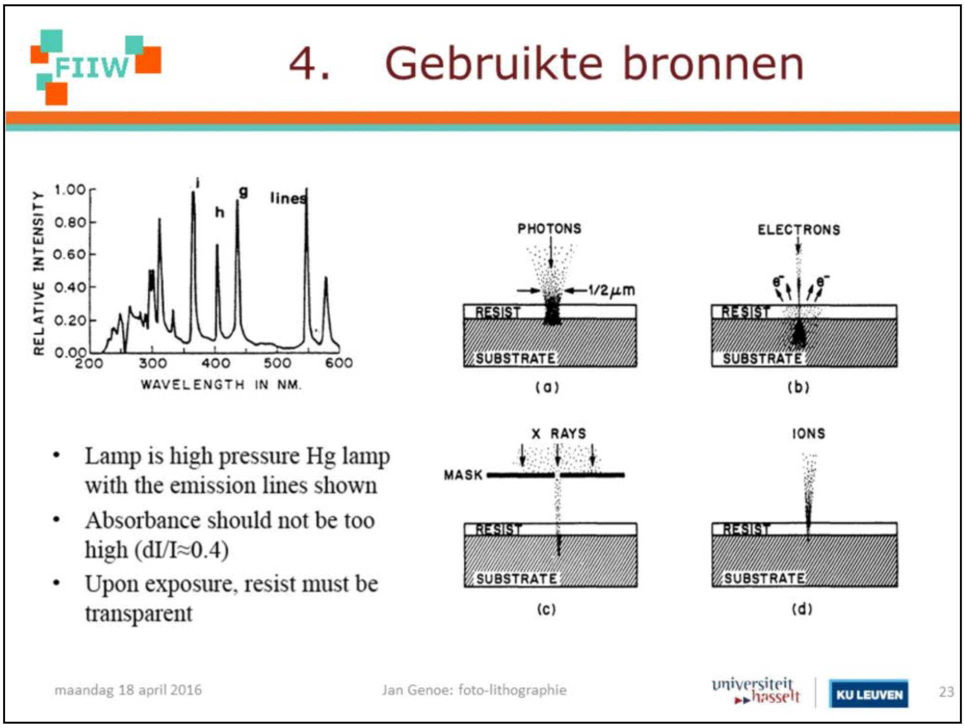
4. Alignment and Exposure

- Alignment errors (many different types)
- Mask aligner equipment
- Double sided alignment especially important in micromachines



Voorbeeld alignatie van 2-zijden

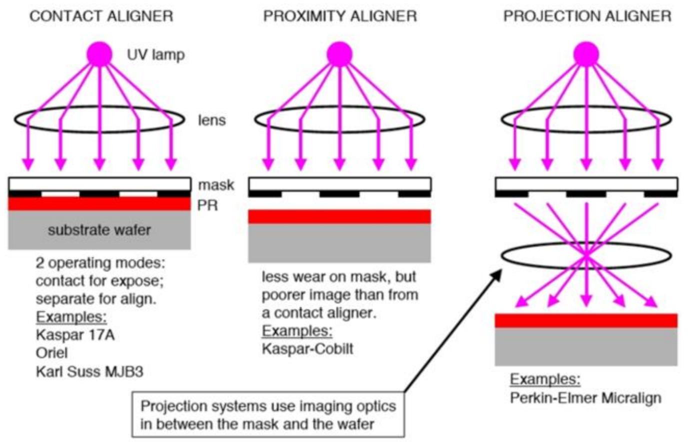
Oude mask aligner (~1988)
Moderne toestellen: volautomatisch



In principe zijn er 4 mogelijke bronnen voor de belichting:

- Licht (fotonen), meestal UV licht, bv van een kwiklamp. Dit is de enige methode die voor massaproductie nuttig is. Momenteel is mijn heel sterk aan het werken aan een EUV bron voor massa productie.
- Elektronen: deze kunnen veel nauwkeuriger gefocusseerd worden. Vooral nuttig voor eenmalig gebruik, bv voor het maken van de maskers.
- X-stralen: geeft ook een zeer hoge resolutie, maar is zeer duur
- Ionen

4. Alignment and Exposure



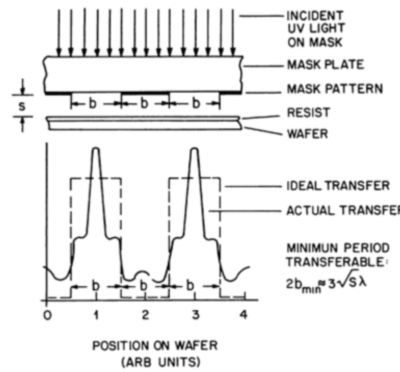
4. Alignment and Exposure

- Contact printing
- Proximity printing
- Self-aligned (see next)
- Projection printing : R = **$2b_{min}$ = 0.6 λ/NA**

$$R = 2b_{min} \sim 3\sqrt{\lambda\left(s+\frac{z}{2}\right)}$$

$$R = 2b_{min} \sim 3\sqrt{\lambda\frac{z}{2}}$$

$$2b_{min} \approx 3\sqrt{\lambda s}$$



4. Alignment and Exposure

Current DUV generation:

•DUV 193 nm
By combinations of phase-shift masks and off-axis illumination, 193 nm DUV can be extended beyond 100 nm, probably 70 nm!

•DUV 157 nm.
A solution for 50-70 nm but large absorption makes refractive systems extremely difficult to design. Further, no resist technology exists.

Printing system	Magn.	Resolution (mm)	Use
Contact	1:1	0.1 - 1	Research
Proximity	1:1	2 - 4	Low cost processes
Projection	4/5:1	0.1 - 1	Stepper litho - mainstream in VLSI

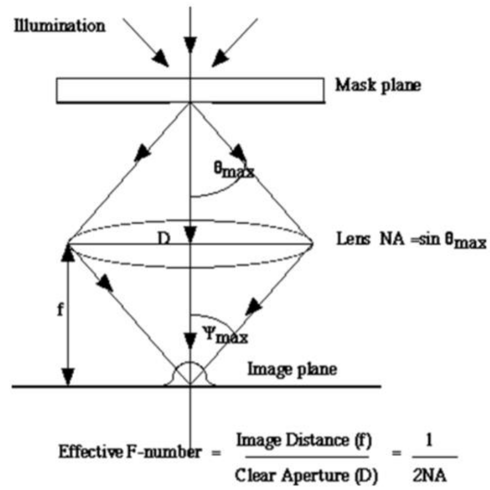
4. Alignment and Exposure

- The defocus tolerance (DOF)

$$\mathrm{DOF} = \pm \frac{k_2 \lambda}{(\mathrm{NA})^2}$$

$$\mathrm{DOF} = \pm \frac{k_2 R^2}{k_1^2 \lambda}$$

- Much bigger issue in miniaturization science than in ICs



[1] http://www.newport.com/tutornew/optics/Optics_Reference_Guide.html

FIIW

4. Alignment and Exposure

Reduce λ

$$W_{min} = k_1 \bullet \frac{\lambda}{NA}$$

Reduce k_1

Increase NA

Decreases as $\lambda\downarrow$

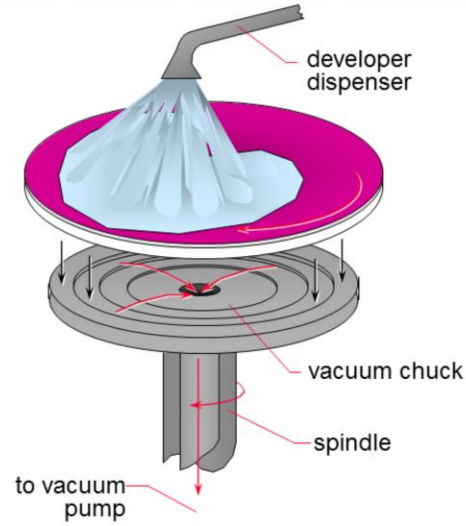
$$DOF = k_2 \bullet \frac{\lambda}{NA^2}$$

Decreases as k_2

Decreases as $NA\uparrow$

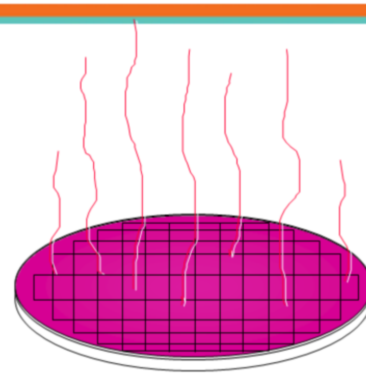
5. Develop

- Soluble areas of photoresist are dissolved by developer chemical
- Visible patterns appear on wafer
  - windows
  - islands
- Quality measures:
  - line resolution
  - uniformity
  - particles & defects



6. Hard Bake

- Evaporate remaining photoresist
- Improve adhesion
- Higher temperature than soft bake



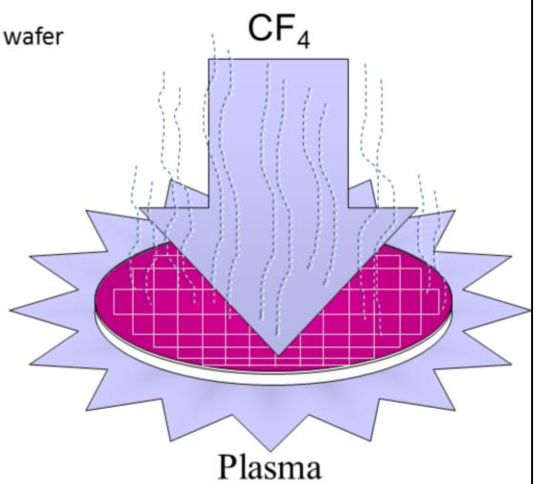
7. Development Inspection

- Optical or SEM metrology
- Quality issues:
  - particles
  - defects
  - critical dimensions
  - linewidth resolution
  - overlay accuracy

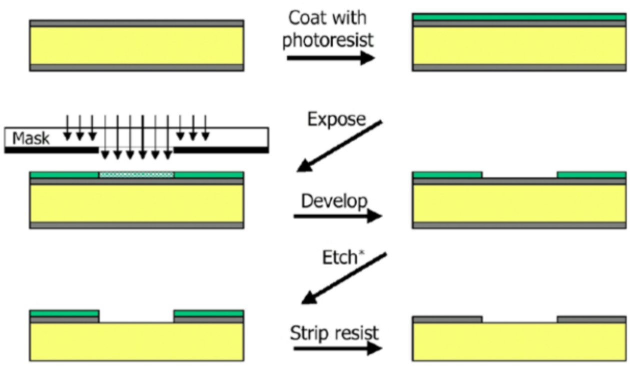
FIIW

8. Plasma Etch-Or Add Layer

- Selective removal of upper layer of wafer through windows in photoresist: subtractive
- Two basic methods:
  - wet acid etch
  - dry plasma etch
- Quality measures:
  - defects and particles
  - step height
  - selectivity
  - critical dimensions
- Adding materials (additive)
- Two main techniques:
  - Sputtering
  - evaporation

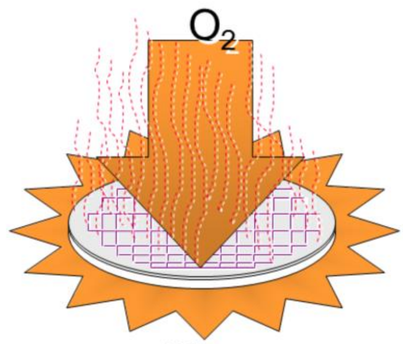


8. Plasma Etch-Or Add Layer



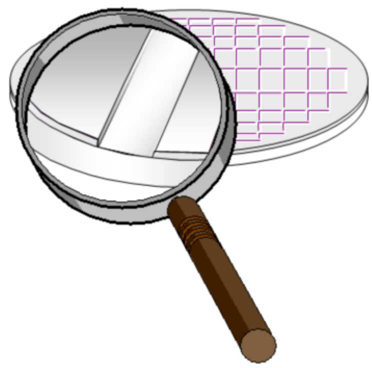
9. Photoresist Removal (strip)

- No need for photoresist following etch process
- Two common methods:
  - wet acid strip
  - dry plasma strip
- Followed by wet clean to remove remaining resist and strip byproducts



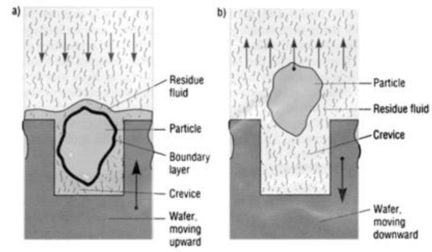
10. Final Inspection

- Photoresist has been completely removed
- Pattern on wafer matches mask pattern (positive resist)
- Quality issues:
  - defects
  - particles
  - step height
  - critical dimensions



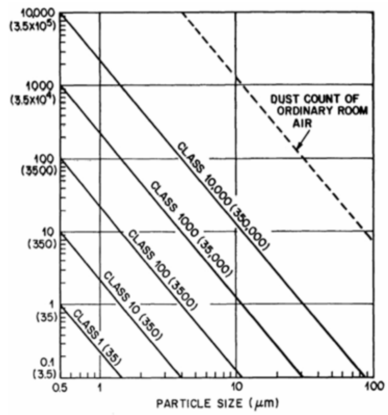
Clean-rooms, Wafer Cleaning

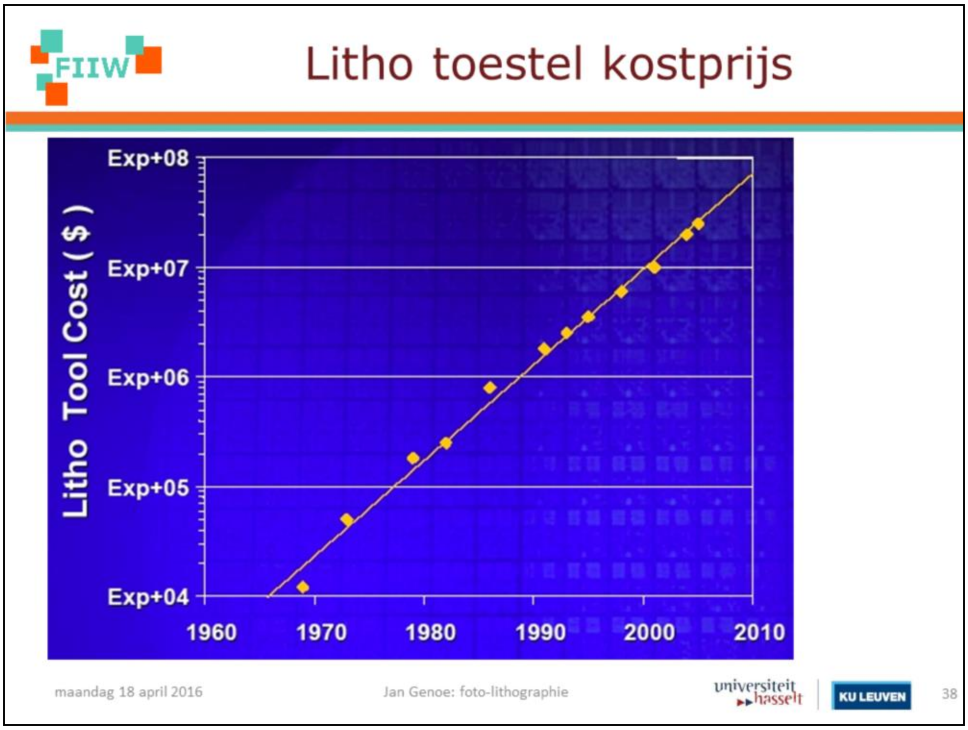
- Yellow light and low particle size/density curves
- Cleaning steps
  - RCA1-peroxides and NH_3-removes organics
  - RCA2-peroxide and HCl-removes metals
- Dry vs. wet cleaning
- Supercritical cleaning-no liquid phase



Clean-rooms, Wafer Cleaning

- Typical contaminants that must be removed prior to photoresist coating:
  - dust from scribing or cleaving (minimized by laser scribing)
  - atmospheric dust (minimized by good clean room practice)
  - abrasive particles (from lapping or CMP)
  - lint from wipers (minimized by using lint-free wipers)
  - photoresist residue from previous photolithography (minimized by performing oxygen plasma ashing)
  - bacteria (minimized by good DI water system)
  - films from other sources:
    - solvent residue
    - H_2O residue
    - photoresist or developer residue
    - oil
    - silicone



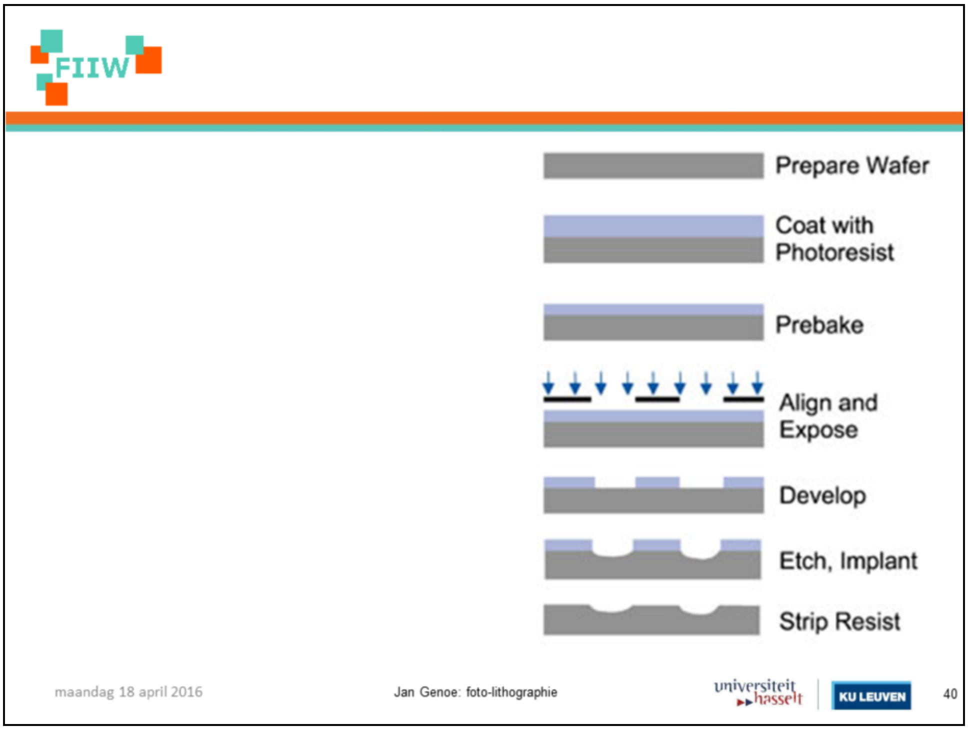


FIIW
Litho toestel kostprijs
Litho Tool Cost ($)
Exp+08
Exp+07
Exp+06
Exp+05
Exp+04
1960
1970
1980
1990
2000
2010
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
38

FIIW

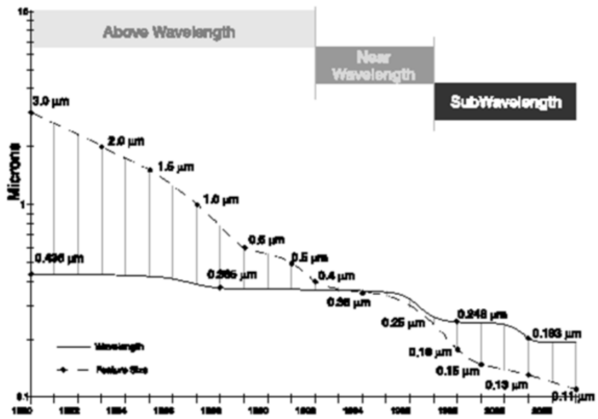
Year of 1st DRAM Shipment	1997	1999	2003	2006	2009	2012
DRAM Bits/Chip	256M	1G	4G	16G	64G	256G
Minimum Feature Size nm						
Isolated Lines (MPU)	200	140	100	70	50	35
Dense Lines (DRAM)	250	180	130	100	70	50
Contacts	280	200	140	110	80	60
Gate CD Control 3σ (nm)	20	14	10	7	5	4
Alignment (mean + 3σ) (nm)	85	65	45	35	25	20
Depth of Focus (μm)	0.8	0.7	0.6	0.5	0.5	0.5
Defect Density (per layer/m^2) @ Defect Size (nm)	100 @ 80	80 @ 60	60 @ 40	50 @ 30	40 @ 20	30 @ 15
DRAM Chip Size (mm^2)	280	400	560	790	1120	1580
MPU Chip Size (mm^2)	300	360	430	520	620	750
Field Size (mm)	22x22	25x32	25x36	25x40	25x44	25x52
Exposure Technology	248nm DUV	248nm DUV	248nm or 193nm DUV	193nm DUV or ???	193nm DUV or ???	???
Minimum Mask Count	22	22/24	24	24/26	26/28	28

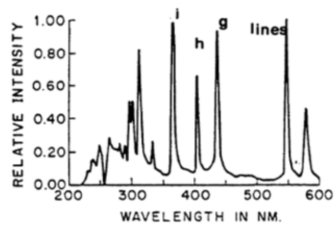
maandag 18 april 2016 Jan Genoe: foto-lithographie universiteit hasselt KU LEUVEN 39


FIIW
Prepare Wafer
Coat with Photoresist
Prebake
Align and Expose
Develop
Etch, Implant
Strip Resist
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
40

FIIW

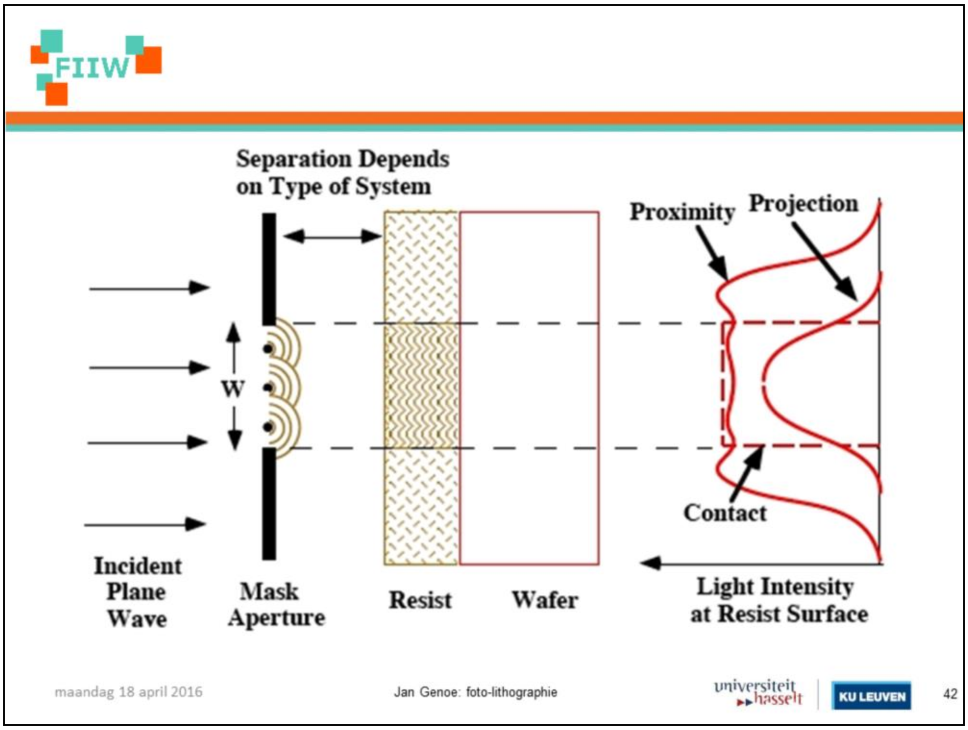
Naar kleiner dan de golflengte



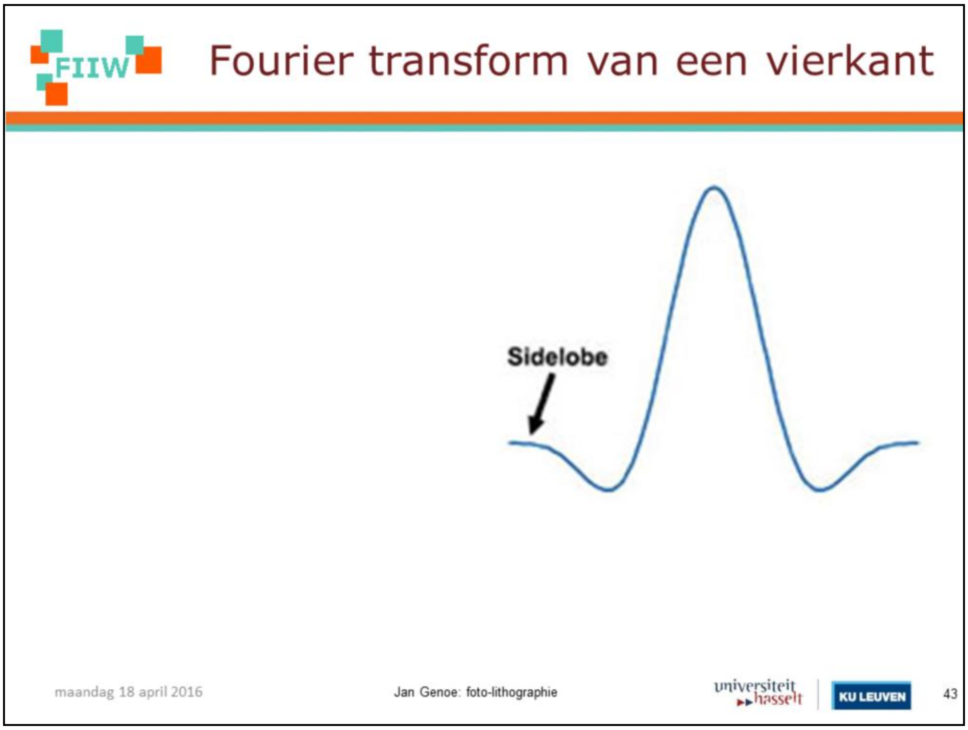


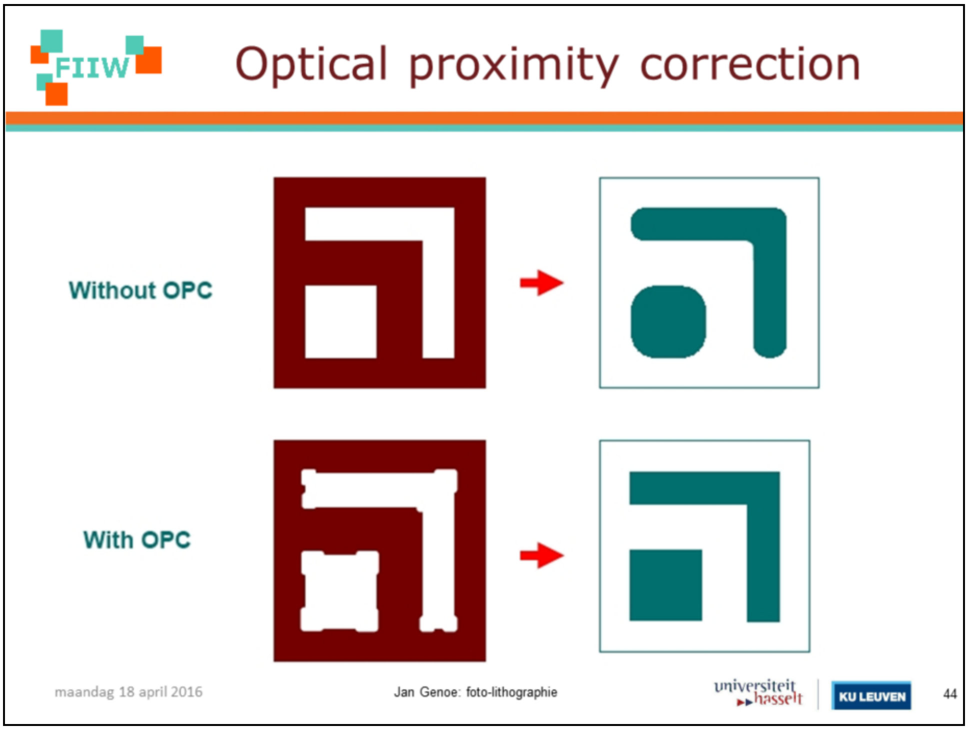
Kahng et. al., 1999 DAC

maandag 18 april 2016 Jan Genoe: foto-lithographie universiteit hasselt KU LEUVEN 41



FIIW
Separation Depends on Type of System
Proximity
Projection
W
Contact
Incident Plane Wave
Mask Aperture
Resist
Wafer
Light Intensity at Resist Surface
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
42


FIIW
Fourier transform van een vierkant
Sidelobe
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
43

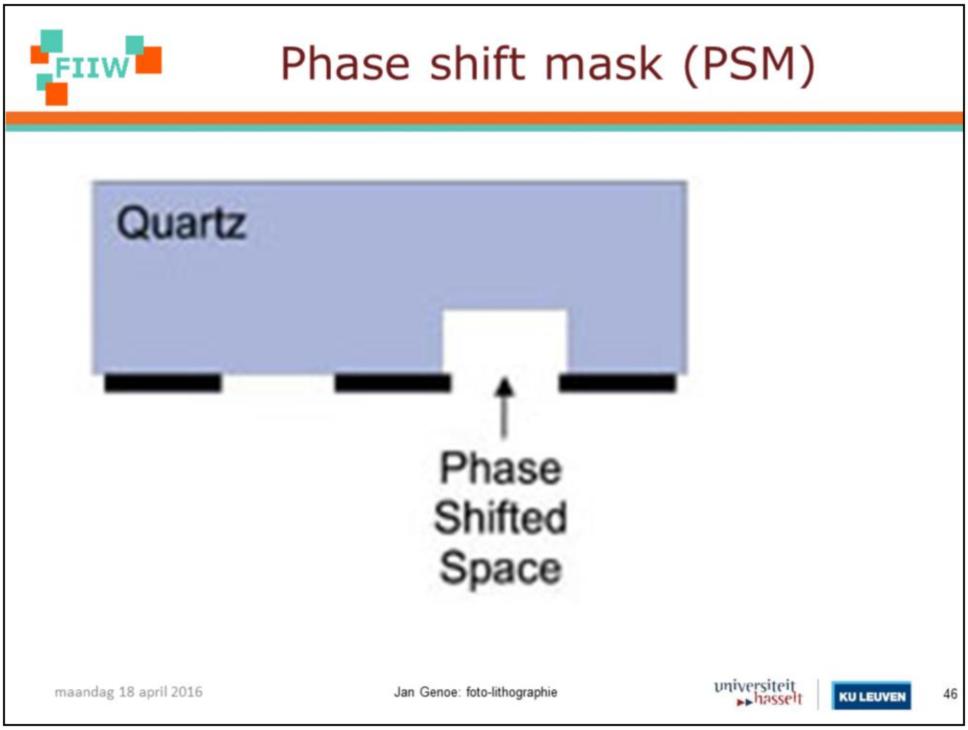

FIIW
Optical proximity correction
Without OPC
With OPC
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
44

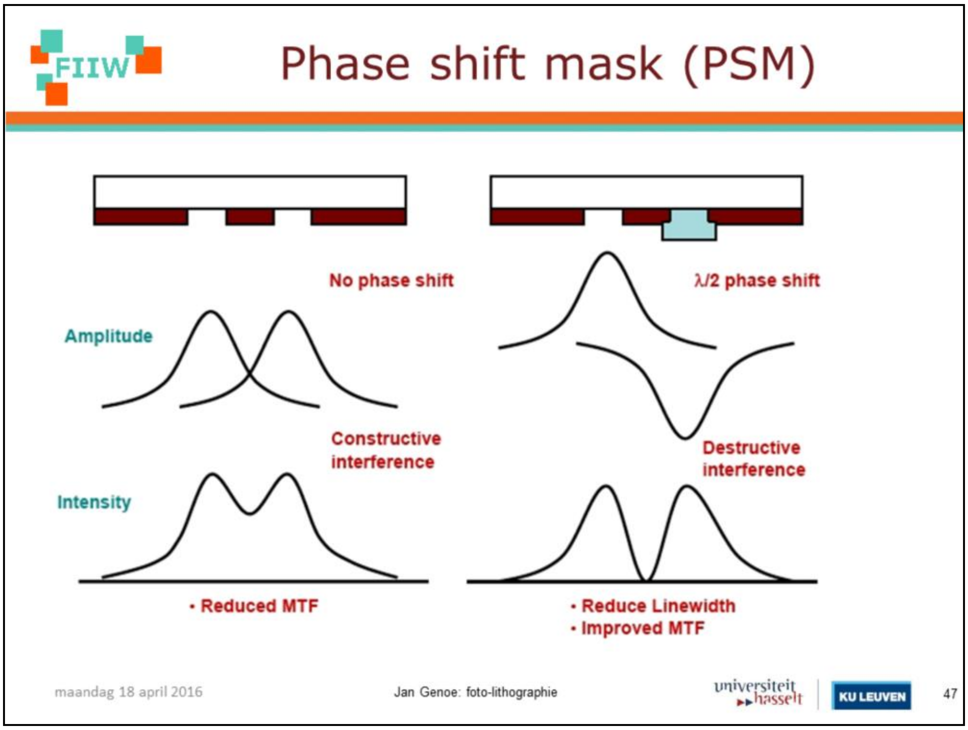
Phase shift mask (PSM)

$$\Delta\phi = 2\pi(n-1)d/\lambda$$

n = glass index of refraction

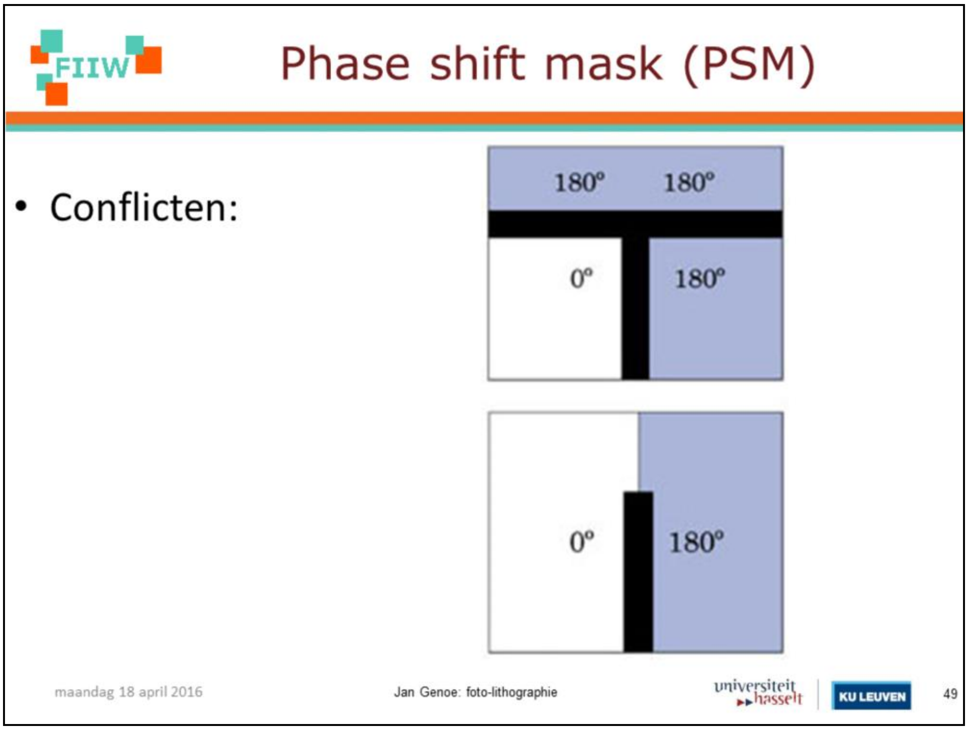
d = shifter thickness


FIIW
Phase shift mask (PSM)
Quartz
Phase
Shifted
Space
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
46


FIIW
Phase shift mask (PSM)
No phase shift
λ/2 phase shift
Amplitude
Constructive
interference
Destructive
interference
Intensity
• Reduced MTF
• Reduce Linewidth
• Improved MTF
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
47

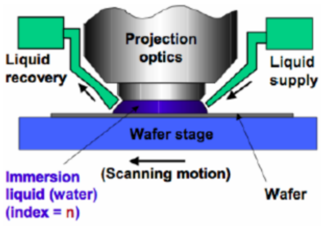
Alternating Phase-Shift Masks

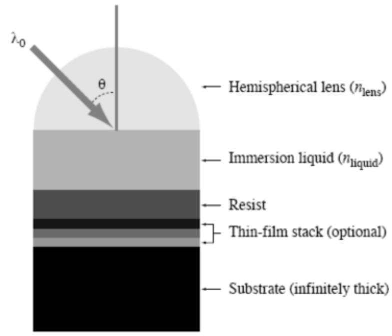
Alternating phase-shift masks (AltPSM) are used to print narrow lines in positive photoresist by making the clear areas on either side of the line of opposite phase. Thus, the phase cancellation effect of light diffracted from either side of the line will keep the line dark and narrow, even when out of focus. AltPSM is a “strong” PSM that can maximize resolution and depth of focus.



[1] C. A. Mack, *Field Guide to Optical Lithography*, SPIE Press, Bellingham, WA (2006)

Immersion lithography





	medium	n	λ/n	ratio
ArF dry	Air	1.0	193nm	1.00
F2 dry	N_2	1.0	157nm	0.81
ArF immersion	H_2O	1.44	134nm	0.69
F2 immersion	PFPE	1.37	115nm	0.60

maandag 18 april 2016 Jan Genoe: foto-lithographie universiteit hasselt KU LEUVEN 50

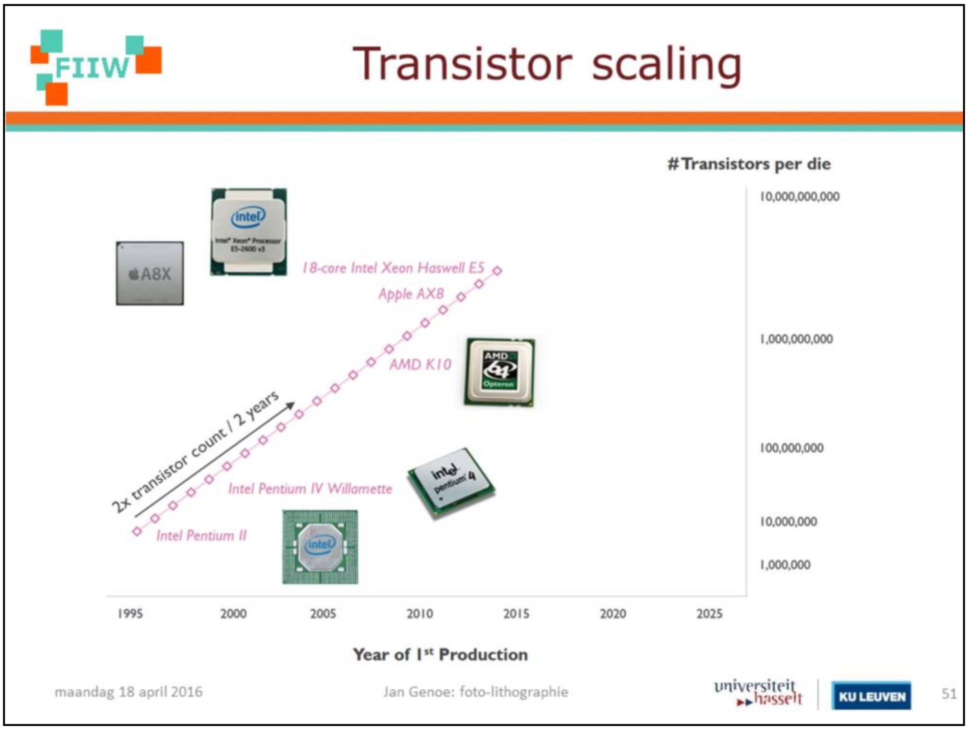
Door vloeistoffen met hoge brekingsindex te gebruiken gaat de effectieve golflengte omlaag en kunnen er fijnere patronen gelegd worden en kan er hogere focusdiepte bekomen worden.

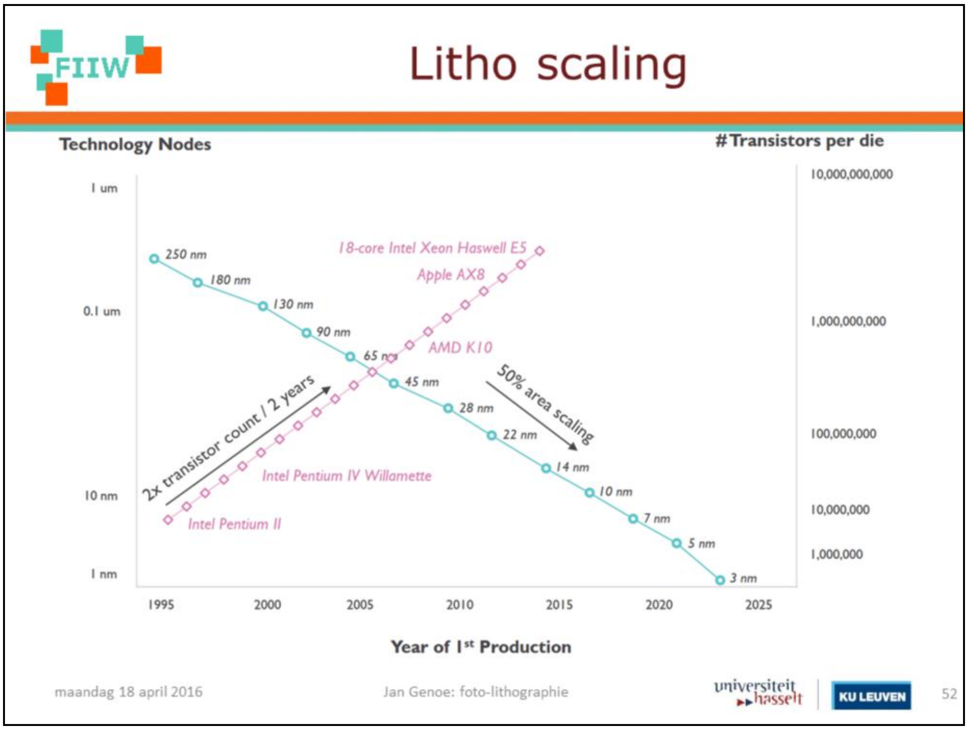
Gebruikte vloeistoffen voor immersie litho:

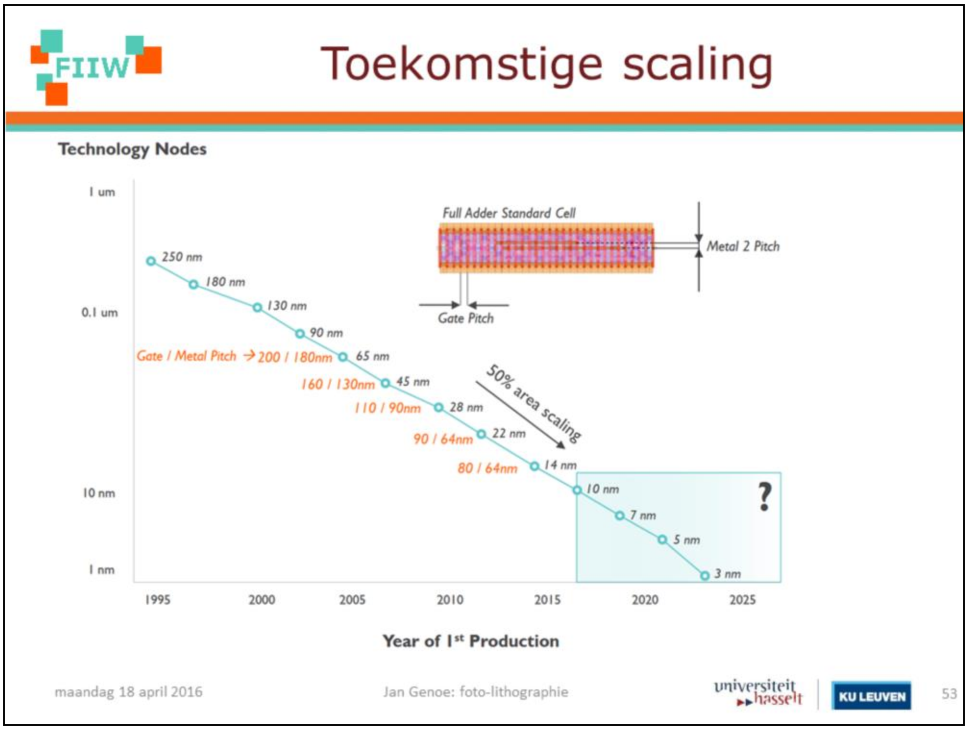
193nm water

157nm polyfluoropolyether

https://en.wikipedia.org/wiki/Immersion_lithography


FIIW
Transistor scaling
Transistors per die
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
18-core Intel Xeon Haswell E5
Apple AX8
AMD K10
2x transistor count / 2 years
Intel Pentium IV Willamette
Intel Pentium II
A8X
1995
2000
2005
2010
2015
2020
2025
Year of 1st Production
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
51

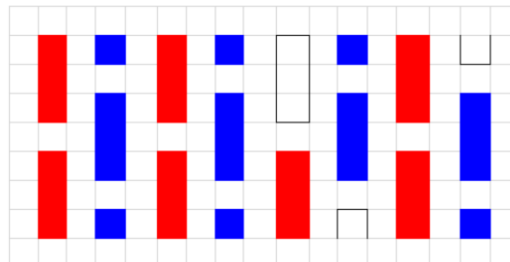

FIIW
Litho scaling
Technology Nodes
Transistors per die
1 um
0.1 um
10 nm
1 nm
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
250 nm
180 nm
130 nm
90 nm
65 nm
45 nm
28 nm
22 nm
14 nm
10 nm
7 nm
5 nm
3 nm
18-core Intel Xeon Haswell E5
Apple AX8
AMD K10
Intel Pentium IV Willamette
Intel Pentium II
2x transistor count / 2 years
50% area scaling
1995
2000
2005
2010
2015
2020
2025
Year of 1st Production
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
52


Toekomstige scaling
Technology Nodes
1 um
0.1 um
10 nm
1 nm
250 nm
180 nm
130 nm
90 nm
65 nm
45 nm
28 nm
22 nm
14 nm
10 nm
7 nm
5 nm
3 nm
Gate / Metal Pitch → 200 / 180nm
160 / 130nm
110 / 90nm
90 / 64nm
80 / 64nm
Full Adder Standard Cell
Metal 2 Pitch
Gate Pitch
50% area scaling
?
1995
2000
2005
2010
2015
2020
2025
Year of 1st Production
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
53

FIIW

Meervoudige belichting

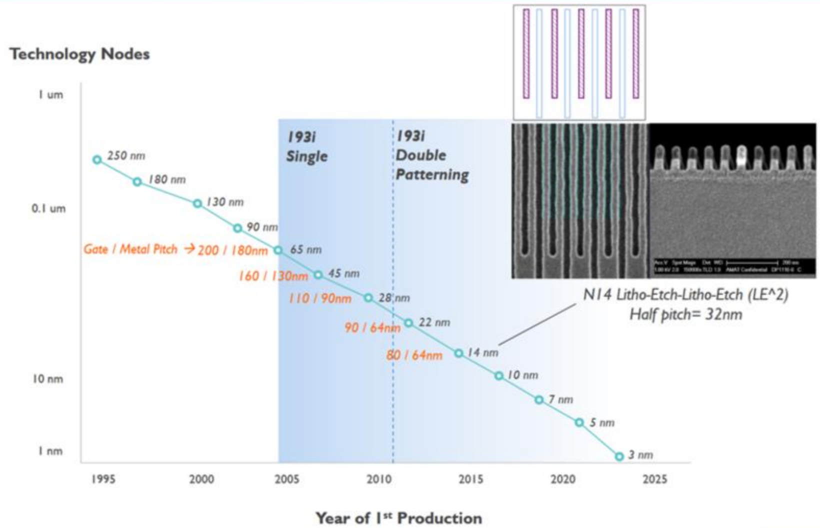
- Een patroon van veel hogere resolutie kan bekomen worden door meerdere belichtingen na elkaar uit te voeren
- 2 belichtingen
- 3 belichtingen
- …



[1] http://en.wikipedia.org/wiki/Multiple_patterning

FIIW

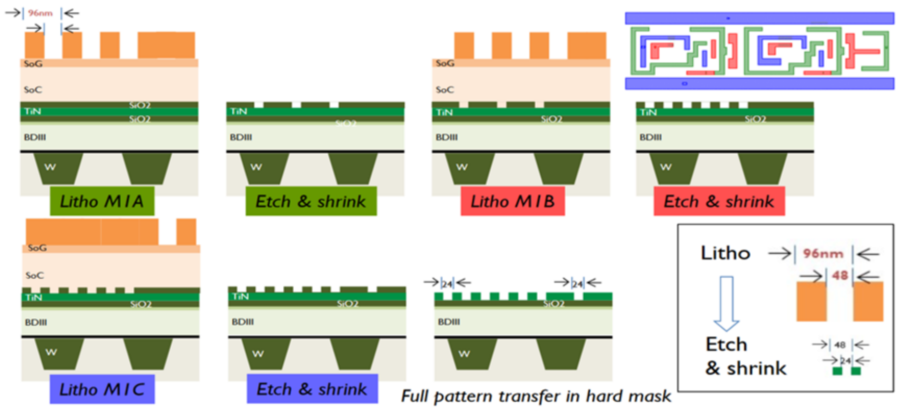
Dubbele belichting (N14)



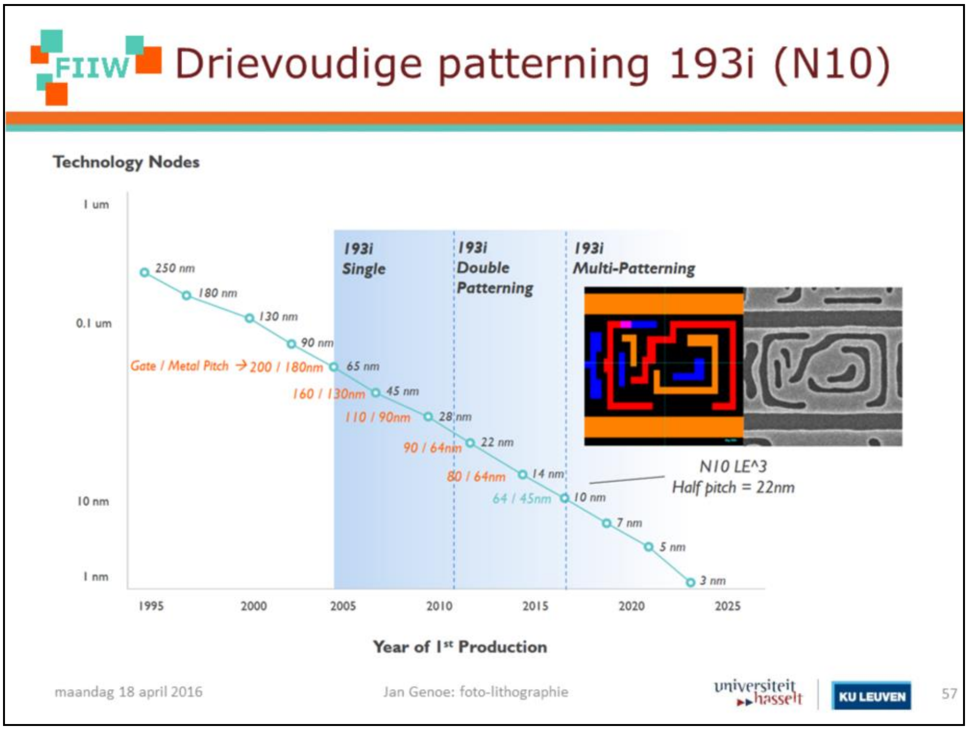
maandag 18 april 2016 Jan Genoe: foto-lithographie universiteit hasselt KU LEUVEN 55

Drievoudige patterning 193i (N10)

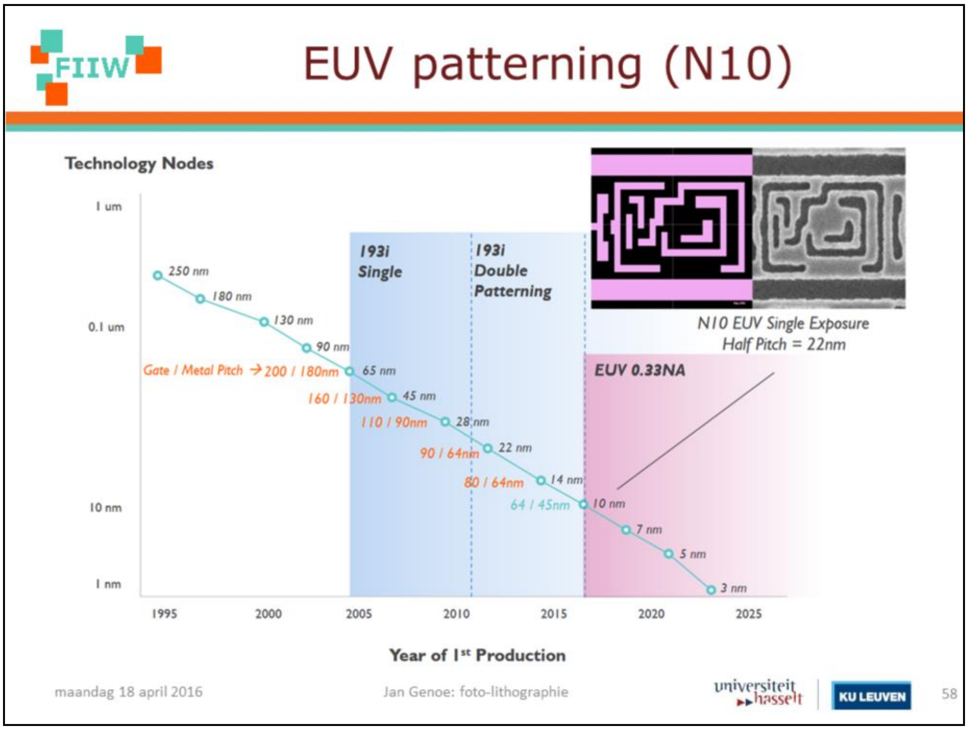
- Hardmask en "etch and shrink"
- Triple patterning (split in M1A, M1B en M1C)



maandag 18 april 2016 Jan Genoe: foto-lithographie 56



FIIW
Drievoudige patterning 193i (N10)
Technology Nodes
1 um
0.1 um
10 nm
1 nm
193i Single
193i Double Patterning
193i Multi-Patterning
250 nm
180 nm
130 nm
90 nm
65 nm
45 nm
28 nm
22 nm
14 nm
10 nm
7 nm
5 nm
3 nm
Gate / Metal Pitch → 200 / 180nm
160 / 130nm
110 / 90nm
90 / 64nm
80 / 64nm
64 / 45nm
N10 LE^3
Half pitch = 22nm
1995
2000
2005
2010
2015
2020
2025
Year of 1st Production
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
57

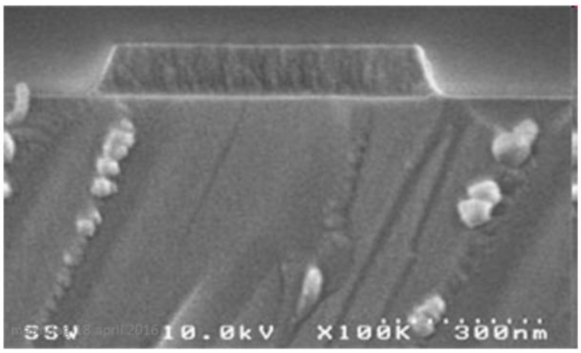

EUV patterning (N10)
Technology Nodes
1 um
0.1 um
10 nm
1 nm
250 nm
180 nm
130 nm
90 nm
65 nm
45 nm
28 nm
22 nm
14 nm
10 nm
7 nm
5 nm
3 nm
Gate / Metal Pitch → 200 / 180nm
160 / 130nm
110 / 90nm
90 / 64nm
80 / 64nm
64 / 45nm
193i Single
193i Double Patterning
EUV 0.33NA
N10 EUV Single Exposure
Half Pitch = 22nm
1995
2000
2005
2010
2015
2020
2025
Year of 1st Production
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
58

Materiaal van de maskers

- Masker platen
  - Quarts glas(laat UV licht door)
    - Gewoon glas laat zichtbaar licht door maar houdt veel UV licht tegen
- Masker metaal
  - Chroom
  - Molybdenium Silicide

Chroom

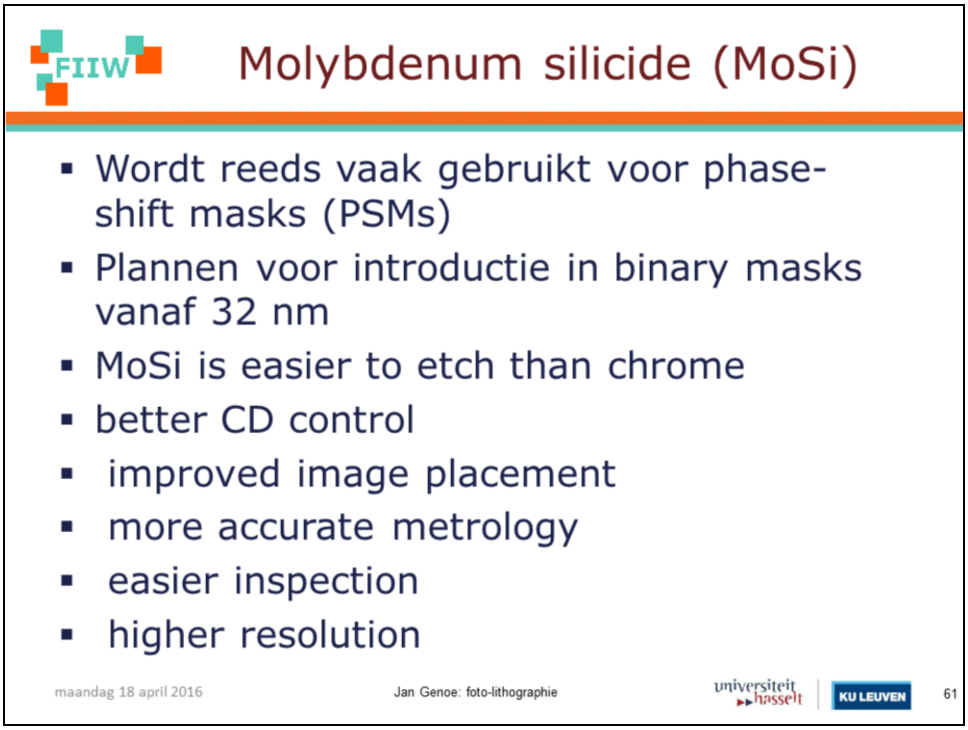
- Is gedurende 25 jaar gebruikt
  - Technologie is goed gekend, moeilijk te vervangen.
- Chrome is difficult to etch in a modern dry etch reactor



Chroom ets [1]

60

[1] Brian J. Grenon, **Grenon Consulting**


FIIW
Molybdenum silicide (MoSi)
Wordt reeds vaak gebruikt voor phase-shift masks (PSMs)
Plannen voor introductie in binary masks vanaf 32 nm
MoSi is easier to etch than chrome
better CD control
improved image placement
more accurate metrology
easier inspection
higher resolution
maandag 18 april 2016
Jan Genoe: foto-lithographie
universiteit hasselt
KU LEUVEN
61