Lithography für sub 100nm-Anwendungen in der Chip-Fertigung

Rolf Seltmann, AMD Saxony Limited Liability Company & Co. KG

References

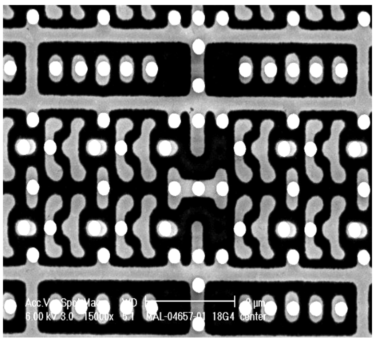
I would like to thank the following people/institutions for kindly giving me the allowance to use some of their data/foils:

- Gerhard Lembach (AMD/ASTA):
- Harry Levinson, Manager Startegic Lithography AMD:
- Thomas Zell (Lithography Principle at Infineon Technologies) Sommerschule Mikroelektronik, Lithography
- ASML Advanced Technology Review 2001 + 2003
- International SEMATEC raodshow 2003
- Siegfried Adam (Dresden artist): picture of lithography
- Valuable input from AMD-Litho: (Stefan Roling, Sven Muehle, Martin Mazur, Wolfram Grundke and others)

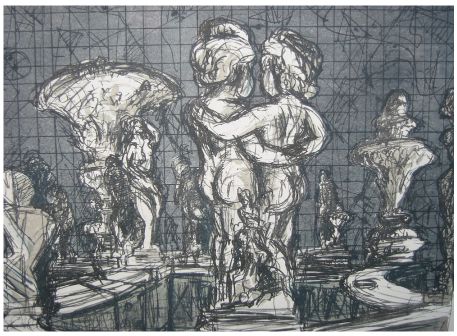
Outline

- Lithography basics
- Performance indicators for lithography
- Quick view on the history of lithography
- Principles of imaging
- Imaging and overlay examples
- The way toward 10nm-resolution
  - Going down the wavelength path?
  - Techniques to extend the optical lithography
  - EUV
  - Direct write lithography

Lithography: Science or art?*



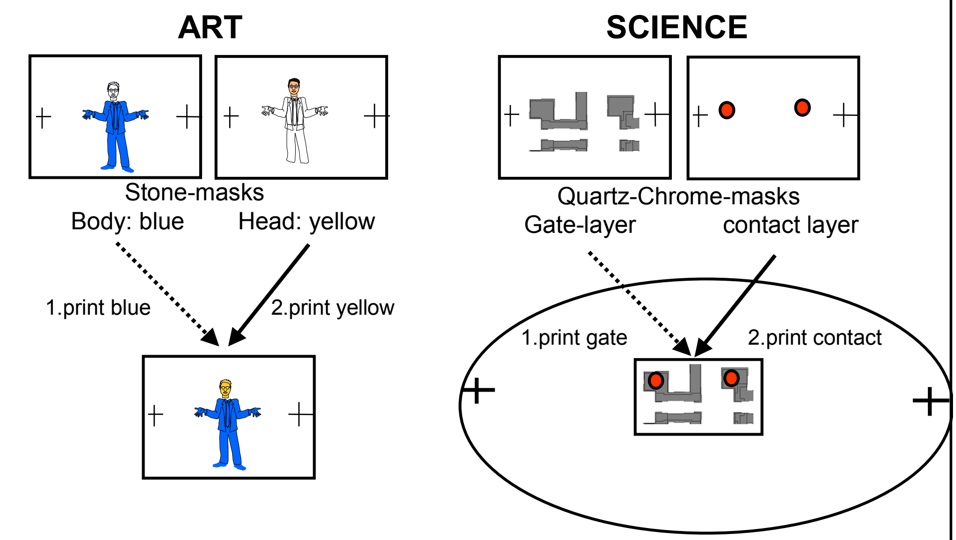
Metal and contact lithography



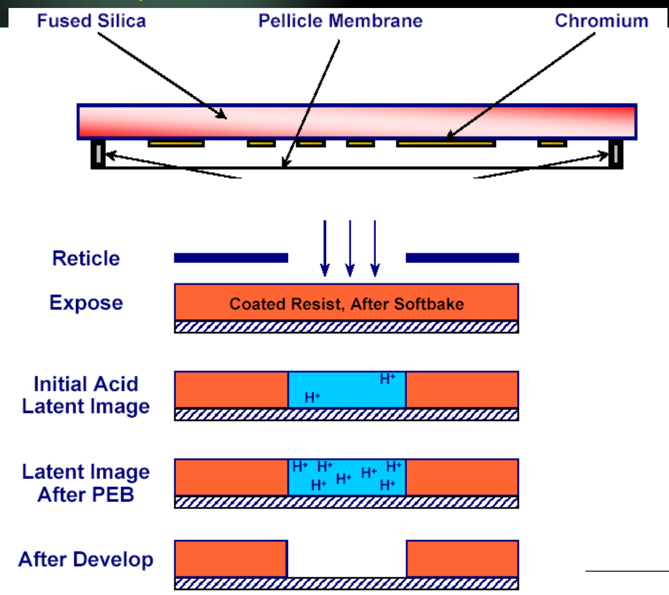
three-color-lithography "Figure I (Zwinger)" by Siegfried Adam

* Chris Mack, CEO of Finle Technologies

Lithography: Science and art ?

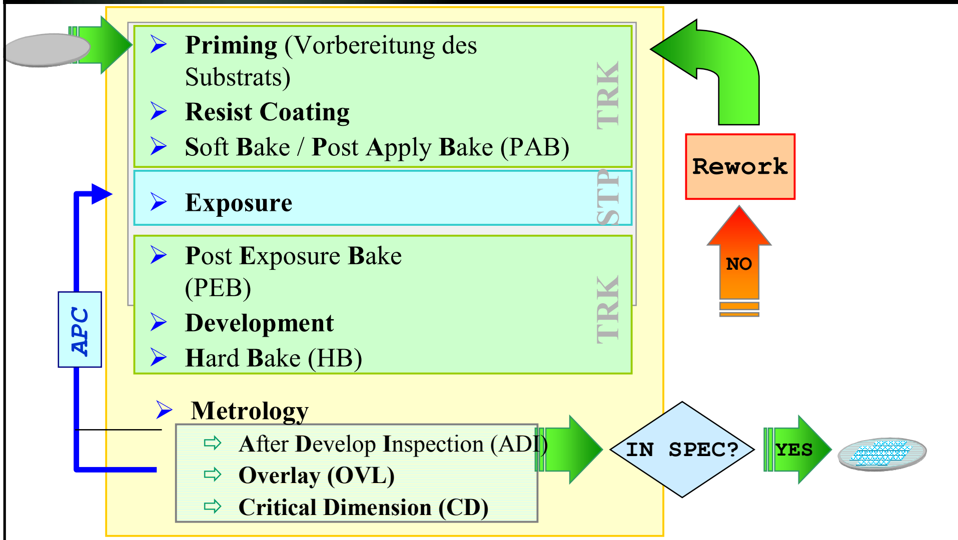


Exposure principle: chemically amplified resist for DUV



Prozessschritte in der Lithographie

AMD



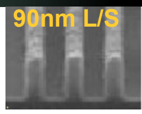
Outline

AMD

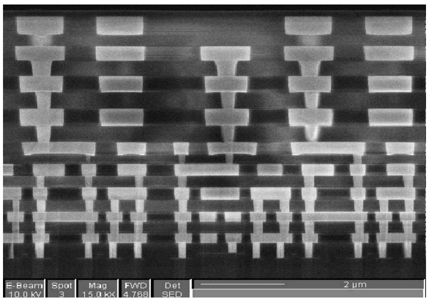
- Lithography basics
- **Performance indicators for lithography**
- Quick view on the history of lithography
- Principles of imaging
- Imaging and overlay examples
- The way toward 10nm-resolution
  - Going down the wavelength path?
  - Techniques to extend the optical lithography
  - EUV
  - Direct write lithography

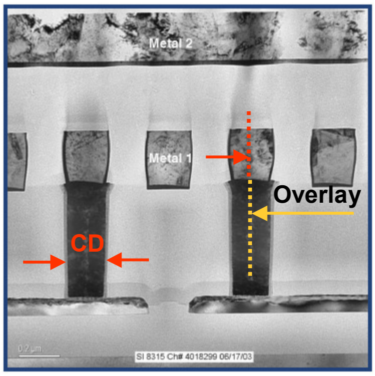
What counts in Lithography…

Resolution?
Yes, but that is not enough



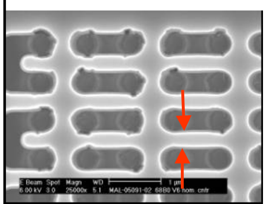
back-end metallization

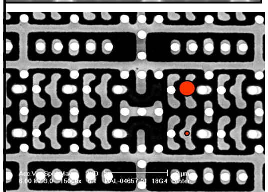




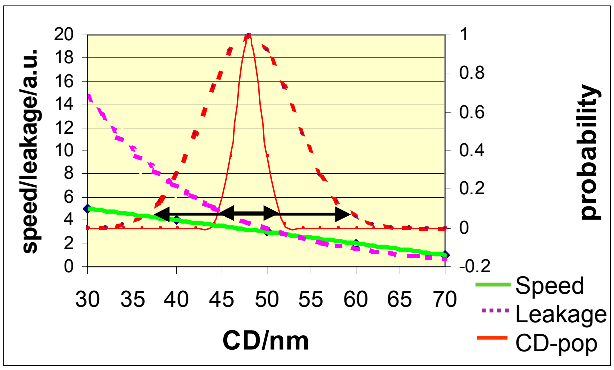
+ defect-free as everybody

Why tight CD-control?



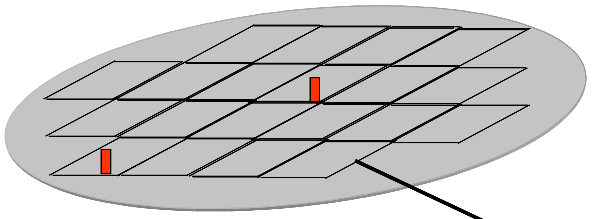


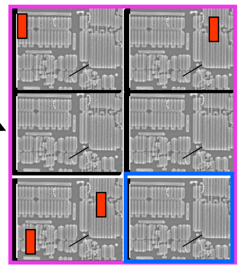
1. Isolation: Prevent bridging
2. Keep contact resistance low
3. **Improve Speed!**



Make CD-distribution as tight as possible!

Across chip linewidth variation: **ACLV** **goal: <5nm (3s)**
Across wafer linewidth variation. **AWLV**





- Lines of different pitches
- Line of different orientations
- Lines in different part of the processor (logic, RAM)
- Lines at different location at the reticle and on the wafer

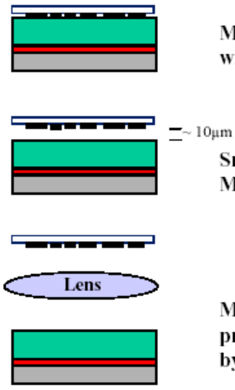
Outline

- Lithography basics
- Performance indicators for lithography
- **Quick view on the history of lithography**
- Principles of imaging
- Imaging and overlay examples
- The way toward 10nm-resolution
  - Going down the wavelength path?
  - Techniques to extend the optical lithography
  - EUV
  - Direct write lithography

History of lithography

AMD

Early Optical Lithography



Contact Printing — **Mask in direct contact with resist**
- Defects on Wafer and Mask
- Mask Lifetime

Proximity Printing — **Small Gap between Mask and Resist**
- Defects on Wafer
- Reduced Resolution

$\sim 1/\sqrt{Gap}$

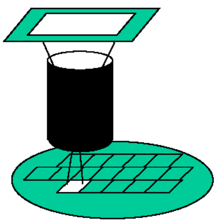
Projection Printing — **Mask Pattern projected by Lens on Resist**

Stepper versus scanner

AMD

1977 David Mann (GCA), 1979 (Carl Zeiss Jena)

Stepper Principal



Principal:

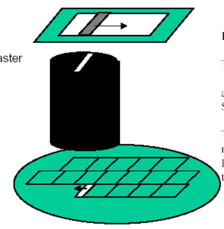
The whole Mask is exposed onto the Wafer at a time

Then the Wafer steps to the next Position and exposes the Mask at the new Position

1987 Perkin Elmer (SVGL)

Scanner Principal

le moves 4x faster than wafer



Principal:

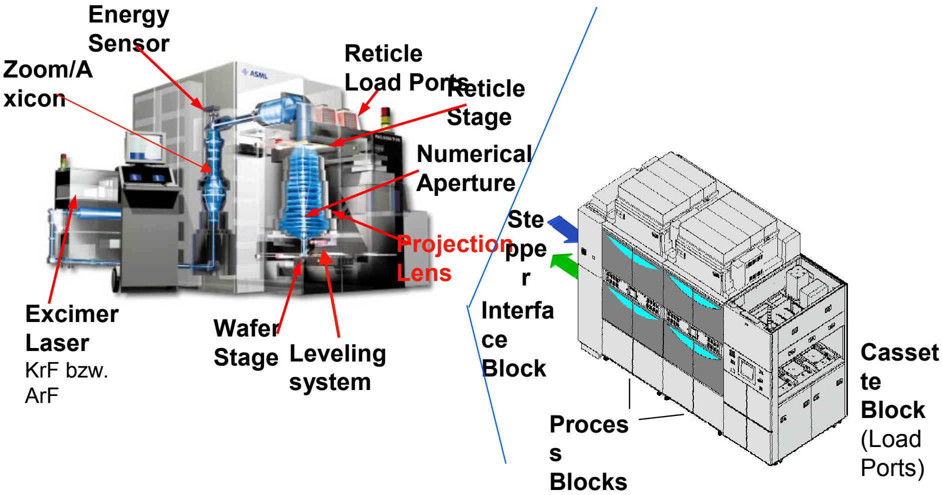
The Mask is exposed onto the Wafer by scanning Mask and Wafer past an imaging Slit

Then the Wafer steps to the next Position and the next Scan takes place

Advantages of the scanner
- Only small part of the lens needs to be optimum
- Averaging of aberrations along scan
- Dynamic focusing
- Larger field size (26 x 32mm)
- More degree of freedom to correct for errors

Today:
1. ASML
2. Nikon
3. CANON

ASML Scanner and TEL coater-developer-track

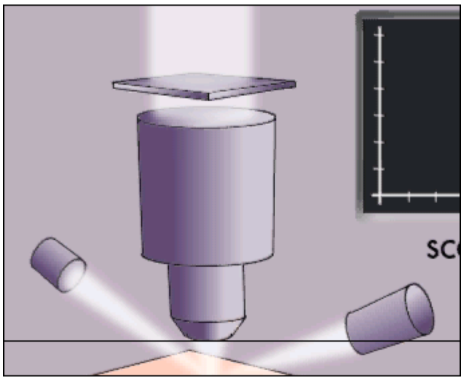


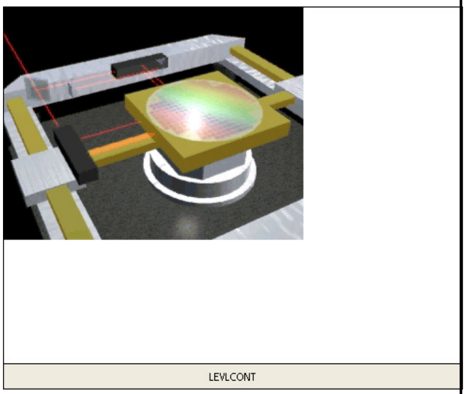
Reticle + wafer scanning

Stage synchronisation of <10nm (3s) necessary

Focus and leveling principle

AMD





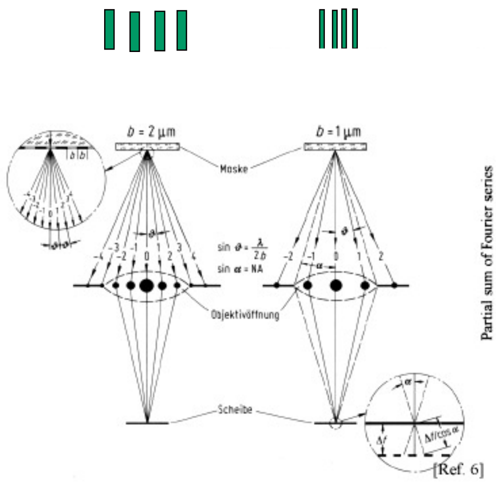
Outline

AMD

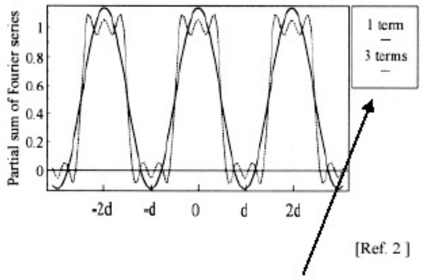
- Lithography basics
- Performance indicators for lithography
- Quick view on the history of lithography
- **Principles of imaging**
- Imaging and overlay examples
- The way toward 10nm-resolution
  - Going down the wavelength path?
  - Techniques to extend the optical lithography
  - EUV
  - Direct write lithography

Imaging principle

AMD



As more diffraction orders we sample as more the image matches the original.....
In real world we have only 1.order!



Number of Diffraction Orders determine
Quality of reassembled Image

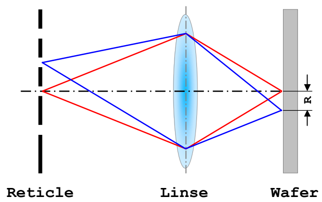
Diffraction Orders captured by the numerical Aperture
are used to generate the Image in Resist

Rayleigh Equations

AMD

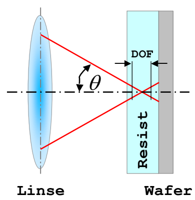
„Resolution"

$$R = k_1 \cdot \frac{\lambda}{NA}$$



k_1: 0.4 ... 0.7

Empirical constant which describes the process fidelity (lens, stage, reticle chuck, resist,....)



„Depth of Focus"

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

k_2: 0.3 ... 1.0

Numerische Appertur: $NA = n \cdot \sin\theta$

↑ NA λ ↓ k1↓

Lightsources for Lithography I

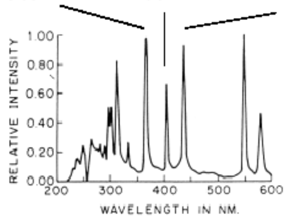
High Pressure Mercury Lamp

- Broad Band — several nm — (for **reflective** Systems)
- Spectral Peaks — few nm — (for **refractive** Systems)

I - Line: 365 nm

H -Line: 406 nm

G - Line: 436 nm



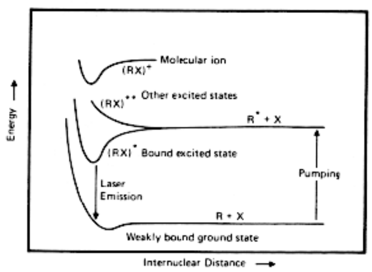
[Ref. 1]

Chromatic correction of lenses is necessary, done by different refractive material

Lightsources for Lithography II

Laser (Excimer)

- Bandwidth narrowed — picometer — (necessary due to limited Availability of Lens Materials)



[Ref. 7]

Typical Gases

KrF	248 nm
ArF	193 nm
F_2	157 nm

Outline

- Lithography basics
- Performance indicators for lithography
- Quick view on the history of lithography
- Principles of imaging
- **Imaging and overlay examples**
- The way toward nm-resolution
  - Going down the wavelength path?
  - Techniques to extend the optical lithography
  - EUV
  - Direct write lithography

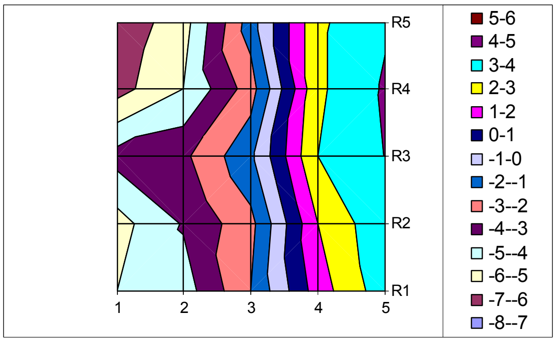
Parameters which impact CD-performance (ACLV)

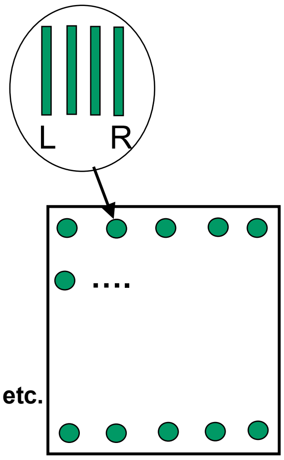
Lens aberrations
Focus and leveling (tool, wafer, technology/ step height)
Dose control
Stray-light
Homogeneity of the design
Proximity to other pattern
Resist properties
Layer reflectivity

…

Example of the Impact of COMA-aberration on across field CD-performance (L-R)

AMD

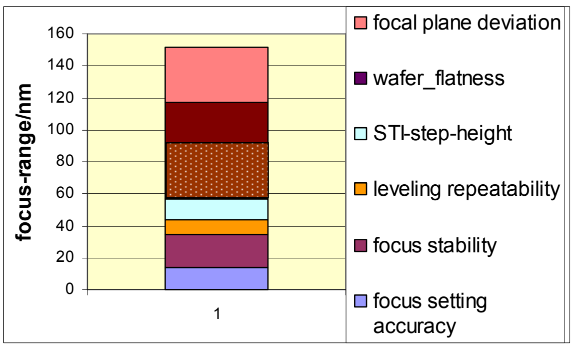




- **The design contains a lot of line pairs, groups etc.**
- **Keep COMA <2nm**
- **Apply dummy gates where possible**

Example for focus-budget

AMD

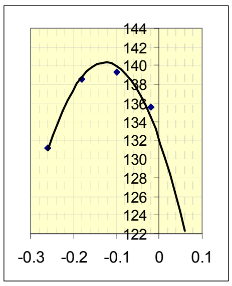


Focus budget < UDOF

Examples:

Gate 130nm: ±150nm < ±160nm

Via 1- 90nm: ±150nm >±130nm

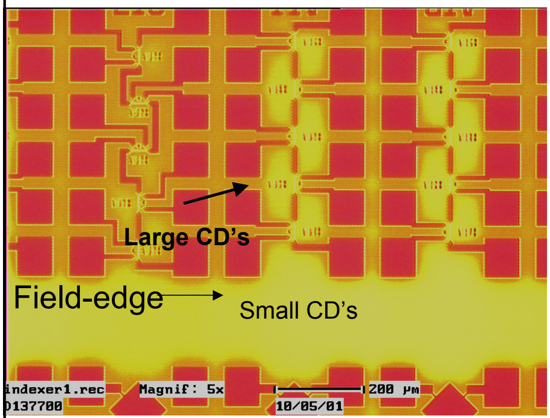


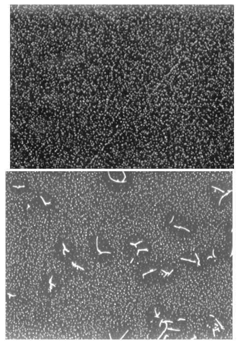
CD versus focus

- Wafer flatness major contributor
- Backside polished wafers have lower contribution
- Newer tools will have reduced focal plane deviation
- Any reduction of any contribution is appreciated

Lens contamination and its impact on CD-performance

AMD





Keep the air free of ammoniums, sulfur and water !

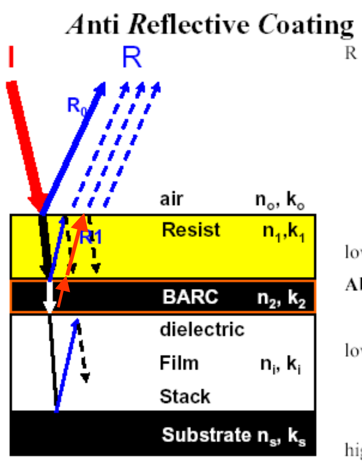
CD's depend heavily on design homogeneity!

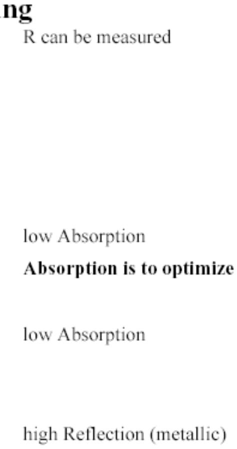
Organophosphates < 1-4ppt!

Principle of anti-reflective coating

AMD

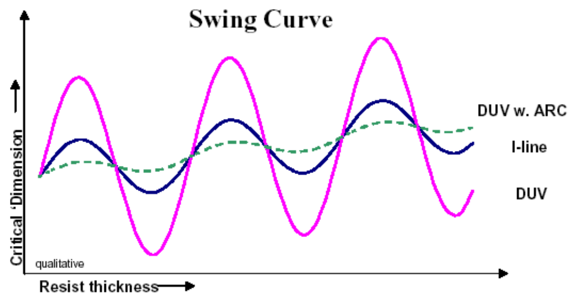
Ideally.:
Red and blue reflected wave have the same amplitude but different phase (P/2)





Impact of imperfect ARC on CD-variation

AMD



Antiflective Coatings help to control CD Variation

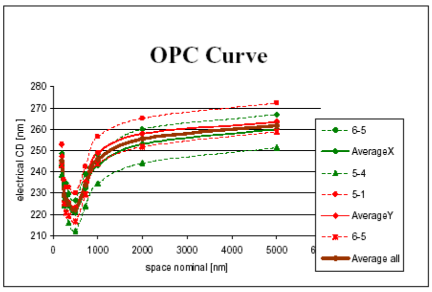
CD-variation due to step-height + imperfect ARC

Examples:

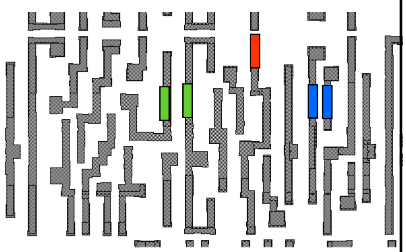
- implant layer CD-dependency on STI-oxide thickness
- Via iso-dense-bias dependency on ILD-thickness

Optical proximity effect

AMD

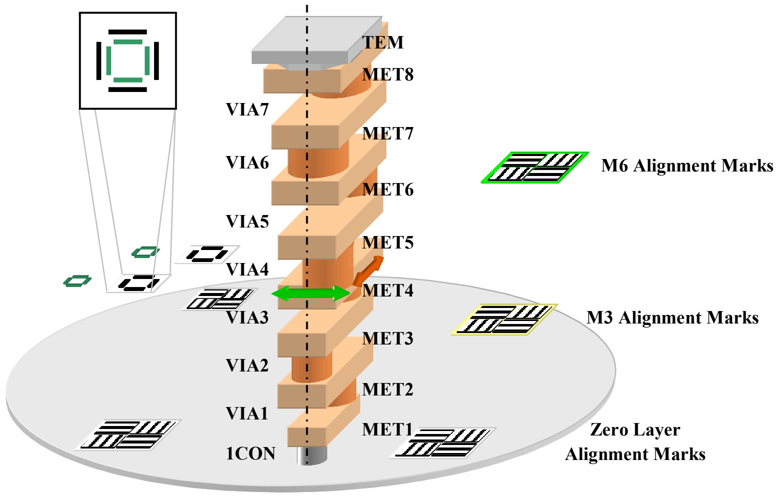


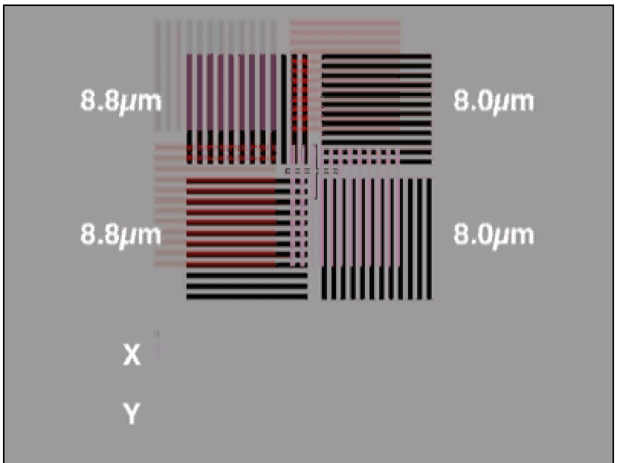
Real layout



What to do ?

Overlay / Alignment





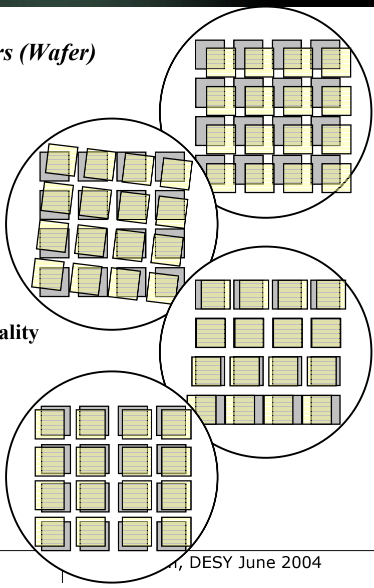
grating

Overlay-terms: A complex task for APC (Advanced process control)

AMD

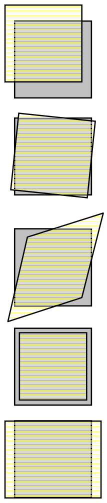
Interfield Errors (Wafer)

- Translation
- Rotation
- Non Orthogonality
- Expansion



Intrafield Errors (Reticle)

- Reticle Translation
- Reticle Rotation
- Asymmetric Reticle Rotation
- Reticle Magnification
- Asymmetric Reticle Magnification



Outline

AMD

- Lithography basics
- Performance indicators for lithography
- Quick view on the history of lithography
- Principles of imaging
- Imaging and overlay examples
- **The way toward nm-resolution**
  - **Going down the wavelength path?**
  - **Techniques to extend the optical lithography**
  - **EUV**
  - **Direct write lithography**

Where is the industry today?

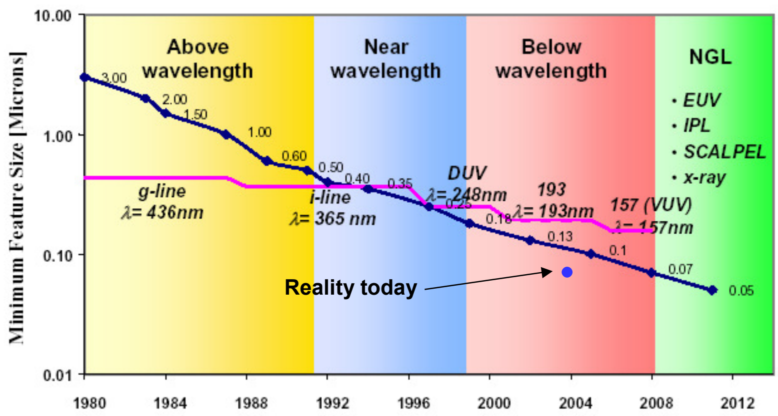
AMD

	Development	Production
NA	193nm	193nm
wavelength	0.85	0.75
Resolution	70nm	90nm
Overlay	20nm	30nm
CD-uniformity	**6nm**	**8nm**

The Lithography Dilemma

AMD

Lithography Roadmap:The Sub-Wavelength Gap



Going down the wavelength path?

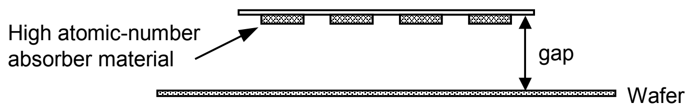
AMD

- Evolutionary by finding new Excimer-gas-mixtures:
  - 157nm F2
  - ~~113nm~~ : no transparent material, contamination,…
- Revolutionary: using x-ray and corpuscular-beams
  - EUV = soft x-ray (13nm)
  - Hard x-ray
  - E-beam
  - Ion-beam

X-ray-lithography: principle

AMD

- At these wavelengths there are no materials that are either highly reflective or refractive.
  - Limited optics.
  - No reduction lenses.
  - Ultra-high-requirements on the masks
- Diffraction effects can be reduced by shortening the wavelength < 1nm



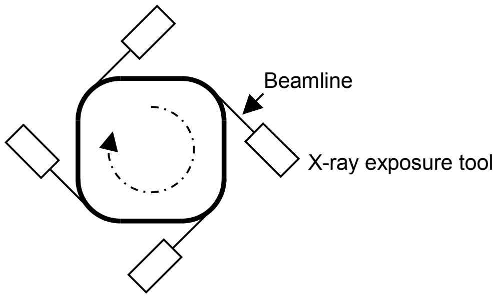
$$W_{min} = \sqrt{\frac{g\lambda}{\alpha}}$$

Gap (microns)	W_{min} (nm)
1	26
5	58
10	82
20	115

X-ray light sources

AMD

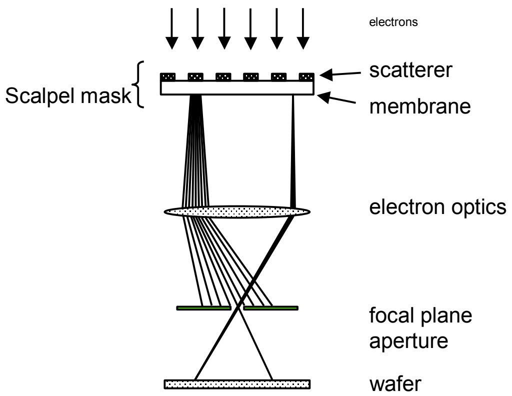
- There are two types of x-ray light sources.
  - Synchrotron.
  - Point sources.
- Synchrotron light sources deliver highly collimated light with significant short wavelength content.



Electron projection lithography (EPL)

AMD

- Why not combine the resolution advantages of e-beam with the productivity advantages of a lithographic technology that uses masks?

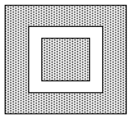


SCALPEL =

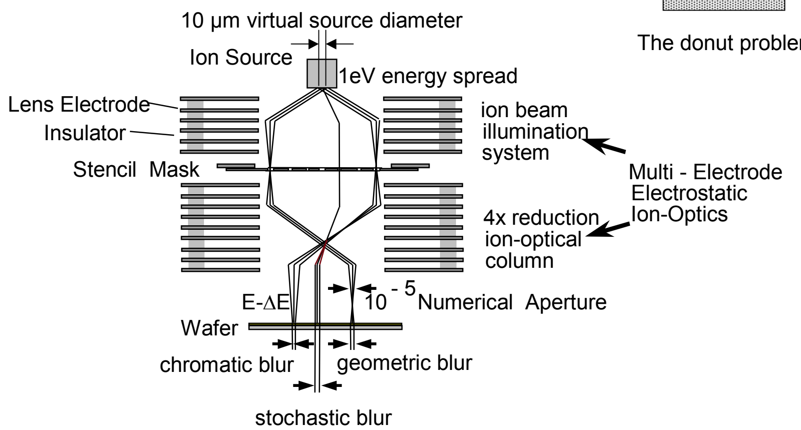
SCattering with Angular Limitation-Projection Electron-beam Lithography

Ion-beam projection lithography

- A stencil mask must be used.
  - Holes are made in a membrane to allow the ions to pass through.



The donut problem



Current status of the short-wavelength-techniques

No-one survived for mainstream lithography!

Multiple reasons:

- Unbelievable extension of optical lithography
- Costs
- Technical difficulties (mask, overlay)
- Not enough support by industry (e.g. ion-beam)

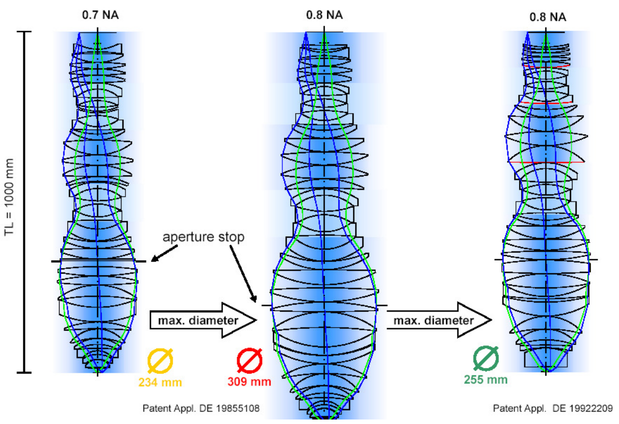
- X-ray-lithography
  - X-ray was supported more than a decade by many big-players (IBM, Japanese companies) but also German government (Fraunhofer Berlin: Heuberger)
  - Overall, x-ray received between 1 and 2B$ investment!
  - Masks (registration, defects, CD) but also infrastructure
  - Will be used for niche applications, e.g. micro-mechanics

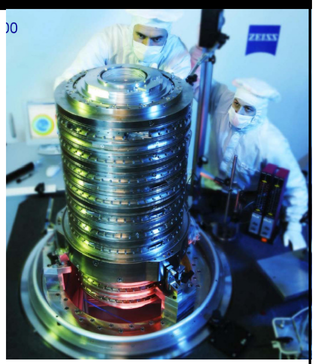
Outline

- Lithography basics
- Performance indicators for lithography
- Quick view on the history of lithography
- Principles of imaging
- Imaging and overlay examples
- **The way toward nm-resolution**
  - Going down the wavelength path?
  - **Techniques to extend the optical lithography**
  - EUV
  - Direct write lithography

The way to higher NA: use of a-spheres

248nm: all quartz optics
193nm: low amount of CaF_2
157nm: CaF_2-optics!

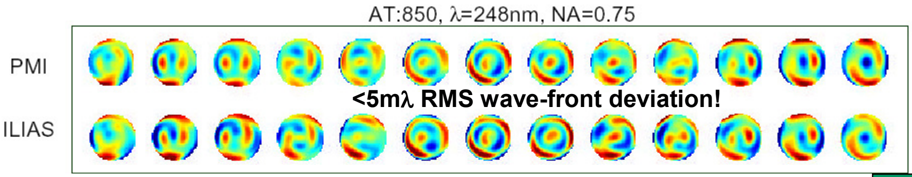


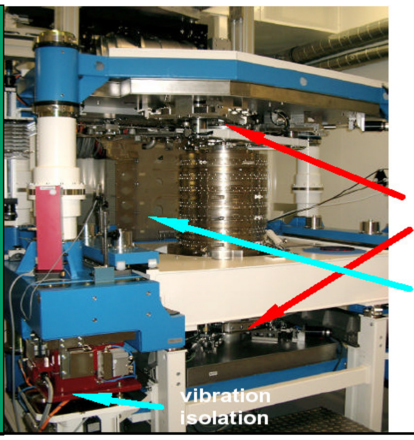


Ultra low laser bandwidth necessary (<1pm)

Lens aberrations are minimized to <5mλ

AMD





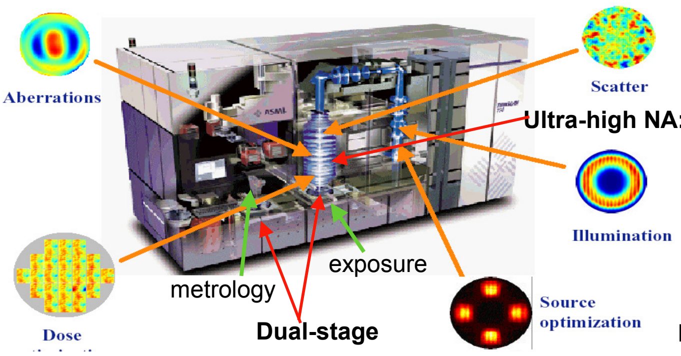
ATOS (in operation for /1200)

- new metrology device for improved performance and non rotational symmetric projection lenses
- interferometrically controlled sensor and reticle stages (long/short stroke actuators)
- metrology frame (zerodur) for improved drift control
- offers **additional calibration** possibilities (necessary for actual and future specifications)

The way to 65nm (90nm): Twinscan at 193nm (XT1250)

AMD

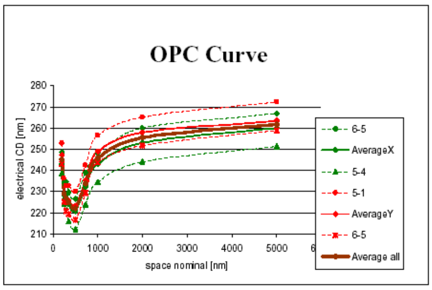
Mask and system integration is needed to enable low k1



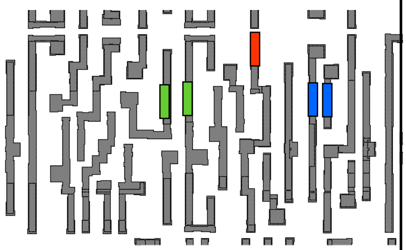
Dual stage advantage

- Wafer surface modeling
- Multiple alignment
- No throughput loss

Optical proximity effect



Real layout

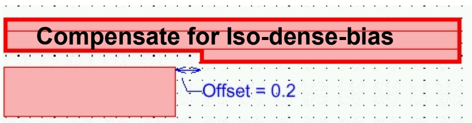


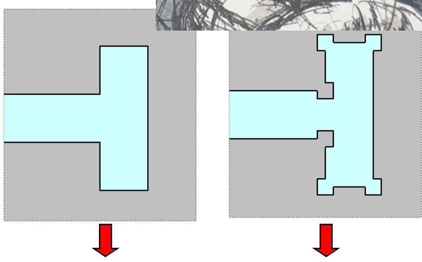
What to do ?

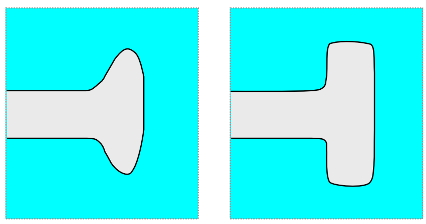
Rule based OPC = like art?

The artist tries to make the best match with his target (impression, expression, reality (original))

The scientist tries to make the best match of the original (designed feature)



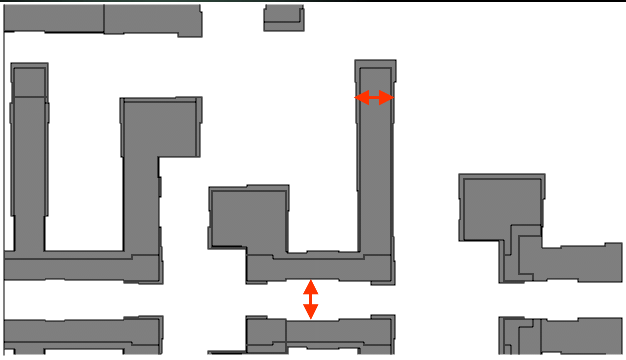




Beispiel:
“ Wenn eine Linie keinen nachbarn hat, dann zeichne Sie 20nm größer. Beginne mit der Vergrößerung 0.2µm, nachdem die Nachbarlinie endet ”

Interaction of Litho and design: Model based OPC

AMD



Goal: all lines have to have the same CD on the wafer!
some iterations between OPC-application and wafer tests are needed before we get a satisfactory result!

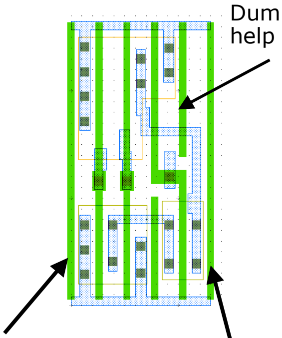
- Ultra-high complexity of the design
- To write such a reticle takes more than a day!

Design for manufacturability

AMD

Make lithography friendly design, e.g. by:

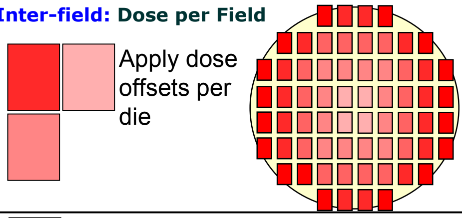
- Same pitch everywhere
- Dummy gates (see picture)
- Same orientation of all critical gates
- Homogeneous pattern density
- Regard lithographic corner rounding
- ….



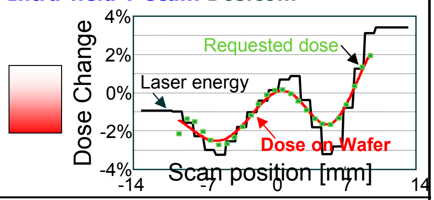
Tuning exposure dose across wafer and field

Inter-field: Dose per Field

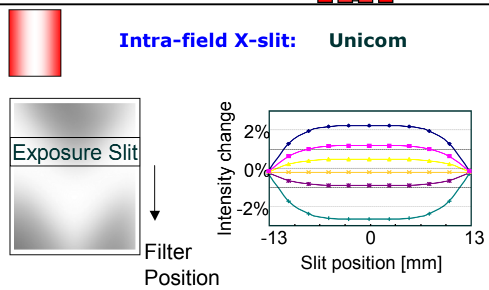
Apply dose offsets per die

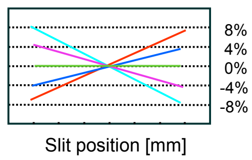


Intra-field Y-scan: Dosicom

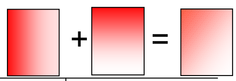


Intra-field X-slit: Unicom

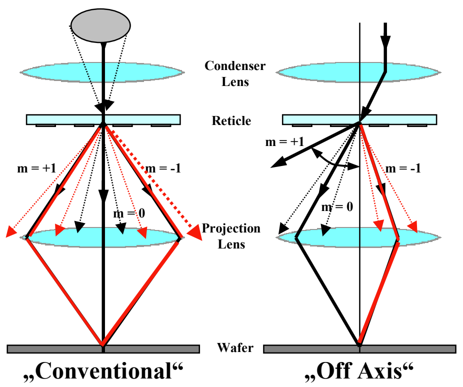




Unicom + dosicom

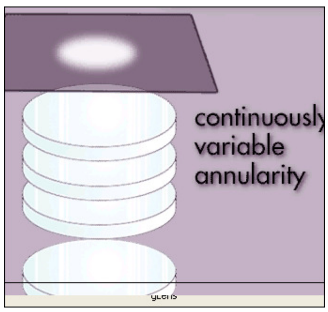


„Off-Axis“ Illumination: impove resolution and DOF

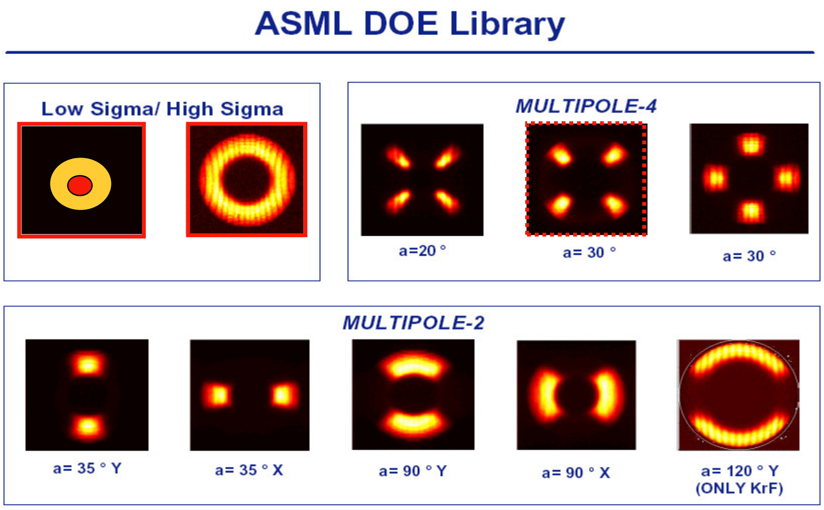


Vorteile:

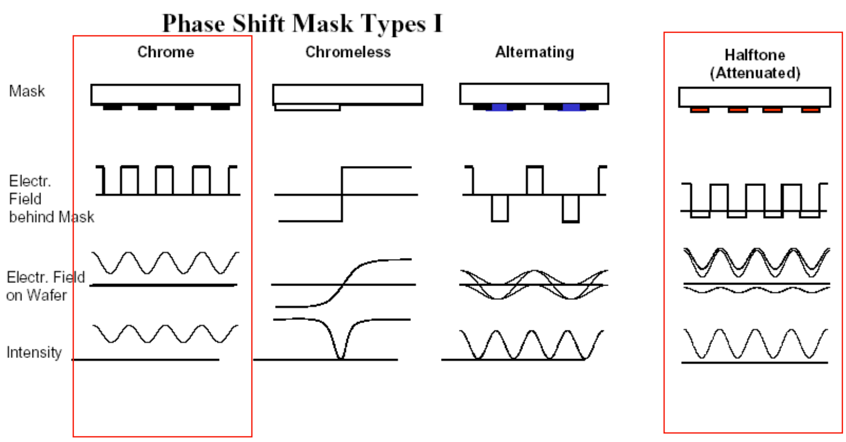
- Ermöglicht kleineren Pitch für ein vorgegebenes NA und eine feste Wellenlänge λ.
- Verbessert die Fokustiefe (DOF)



Illumination profiles to improve resolution and DOF



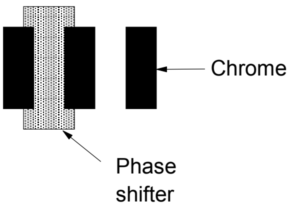
Reticle enhancement techniques



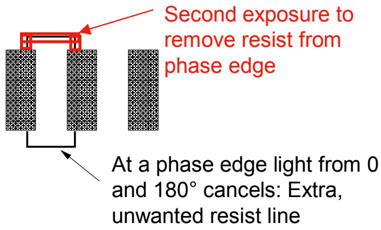
Alternating Phase-shift-mask: principle

AMD

On the mask



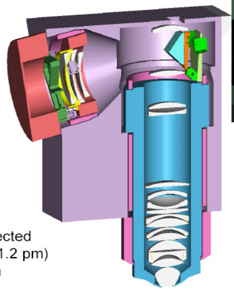
On the wafer



- Difficult mask manufacturing, more expensive masks
- Difficult task to de-composite design into two masks
- Slow exposure process, exposure time is twice as large
- High requirements on

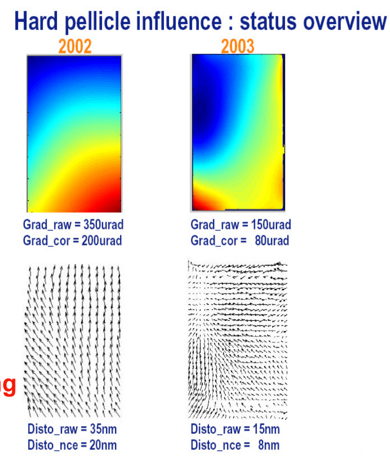
157nm-lithography

AMD



Specs:

NA = 0.85 - 0.60
σ = 0.93 - 0.23
Slit = 26 mm
Mag = 4x
Laser = F2 line selected
(FWHM = 1.2 pm)
Resolution = 70 nm
k1 = 0.38

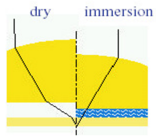


- **Optics and machine concept ready**
- **Laser light-source in good shape**

- **Resist status**
- **Hard pellicle (0.8mm thick) introduces distortion (example)---can be handled by scanner**
- **High nitrogen consumption due to purging (no O2 allowed!)**
- **Contamination and VUV-reticle cleaning**
- **Only one technology node?**
- **Not enough support anymore !?**

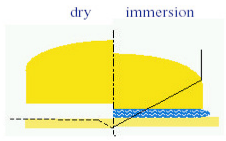
New approach: extend the 193nm-wavelength by immersion

Immersion: liquid between lens and wafer



Option 1) modify existing lens
- Resolution remains same
- Increased Depth of Focus

Short time-to-market, limited expenses.
Enables process development

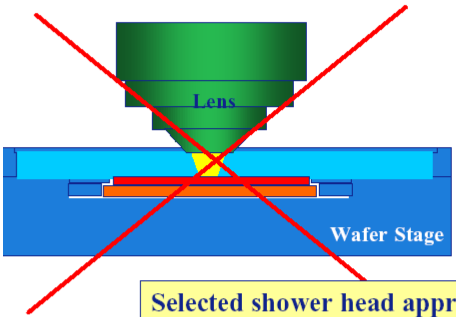


Option 2) new hyper NA immersion lens
- Increased resolution

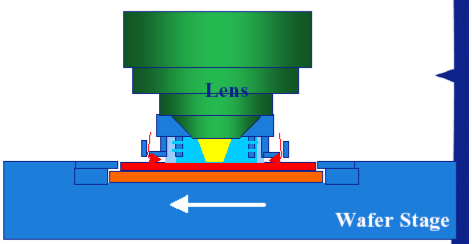
Significant effort in lens
Delay wavelength transition

Liquid containment / handling

Swimming Pool approach



Shower approach



Selected shower head approach:

- Most compatible with TWINSCAN architecture
  - only fluid where it is needed
  - no conflict with alignment and leveling metrology
  - no impact on wafer handling system
- Ensures highest throughput and lowest fluid consumption

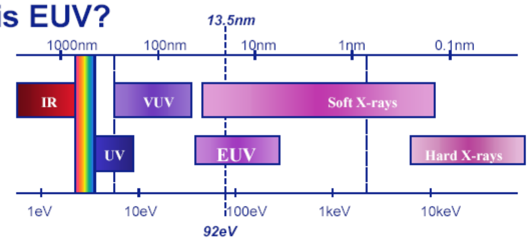
Immersion status

- DOF-improvement by a factor of 2 demonstrated, Resolution enhancement is not in question
- First demonstrator tool at ASML is available for industry
- Particle formation (micro-bubbles) and Focus-problems at the edge of the wafer are still an issue
- However there is a strong believe in the industry that immersion will succeed within the next two years

- Estimation of extension of 193nm-immersion into the 30nm-resolution-range if coupled with strong reticle enhancement techniques
- 193nm –lithography will be the only high-end production solution within this decade!

New generation lithography: EUV

What is EUV?



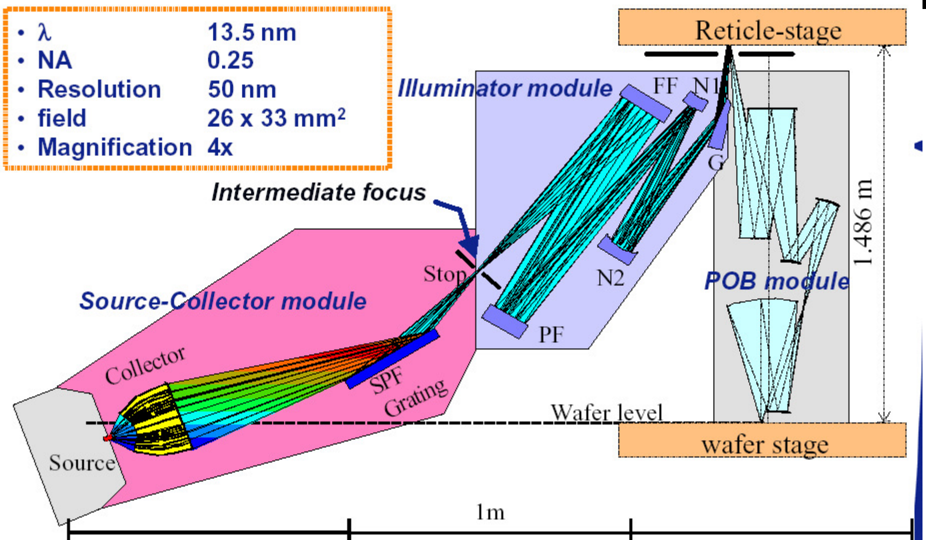
Extreme UltraViolet (EUV) is EM radiation at ~13.5 nm, which falls into X-ray band. EUV was 'marketing name' to separate the program from hard X-ray lithography.

EUV radiation is absorbed by almost all materials and gases, so the optics must be reflective and fully contained in vacuum.

The reticle too must be reflective. Chrome is most likely used as the absorbing layer. Production technology is known; the challenge is to accomplish zero defect density during fabrication and after completion (no pellicle!).

Alpha demo optical system

- λ 13.5 nm
- NA 0.25
- Resolution 50 nm
- field 26 x 33 mm²
- Magnification 4x



Mask-less lithography

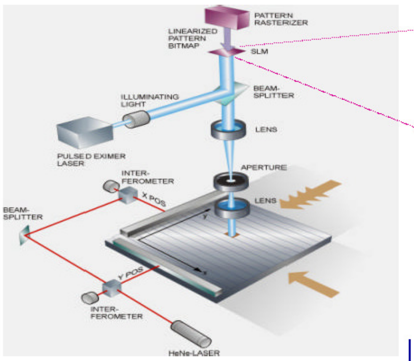
AMD

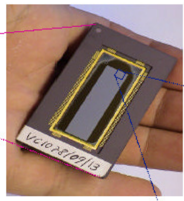
- Masks become more and more expensive, e.g. one single mask easily can exceed 40000$!
- ASIC manufacturer and foundries have sometime batches with just few wafers of its kind.
- They cannot afford to pay this high mask costs anymore
- Why not directly pattern wafers + take advantage of shorter wavelength if using e-beams
- The problem is productivity.
  - Optical lithography is a highly parallel process, direct writing is a serial process.
  - Even with new super-parallel principles, throughputs of few wafers per hour are a terrific challenge
  - Data and pixel rate of some Tera-bytes per second are necessary!

there is a high need for mask less lithography →

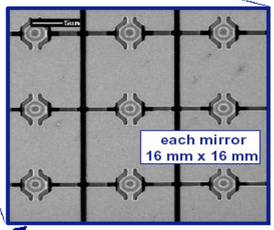
- E-beam projection
- Multi-beam e-beam
- Micro-mirror-laser-lithography

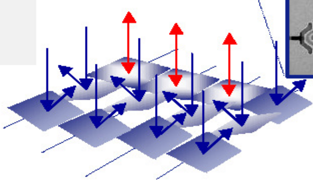
SLM Imaging Basics: SLM in Maskless Scanner





Micronic SLM chip
8 mm x 33mm active area
(512 x 2048 pixels)
1.048 MPixels

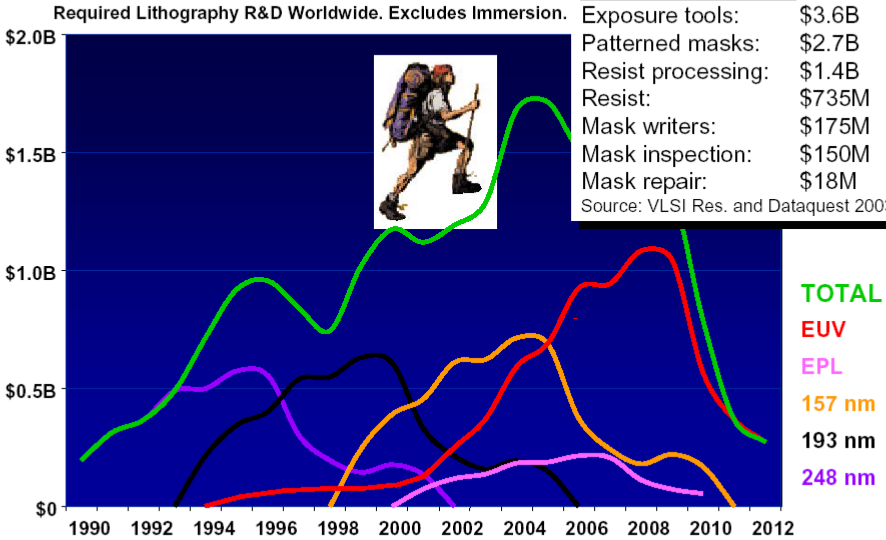




Lithography pattern generation is controlled by reflecting laser light from individual pixels towards or away from the wafer

The Lithography Mountain

Required Lithography R&D Worldwide. Excludes Immersion.



Estimated 2003 TAM:

Exposure tools:	$3.6B
Patterned masks:	$2.7B
Resist processing:	$1.4B
Resist:	$735M
Mask writers:	$175M
Mask inspection:	$150M
Mask repair:	$18M

Source: VLSI Res. and Dataquest 2003

Lithography: Art or science?

Lithography application in high-end semiconductor manufacturing is based on scientific principles, however…

- We convinced ourselves the artist uses the same steps as the technician
- To select the right technology is not just based on technical knowledge but also on feeling of the lithographic community
- To make a circuit layout manufacturable requires artist-like handling of critical layout areas
- The lithographic problem often is multi-dimensional without enough resources to go down the whole path to its roots: feeling and creativity is needed at a high extend

However, I don't want to work in high energy physics: This seems me to be even less predictable than the future in lithography

Vielen Dank!

Trademark Attribution