Damage and Degradation of Optics and Sensors under intense EUV radiation from a table-top LPP source

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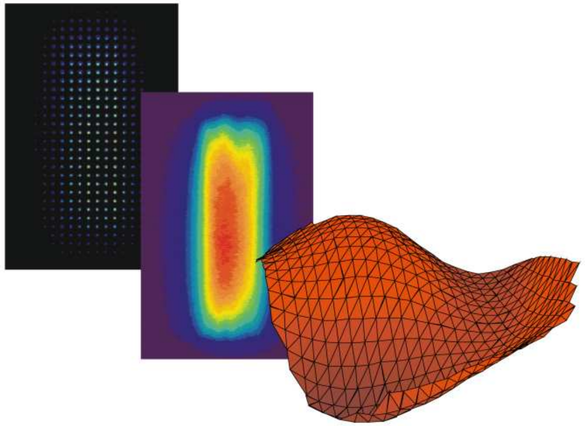
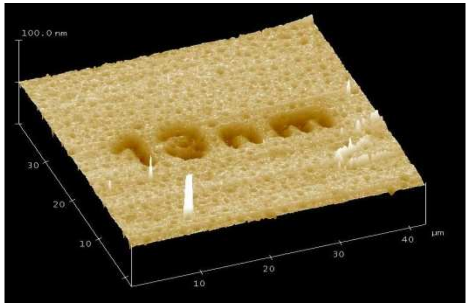
Dept.
“Optics / Short Wavelengths”

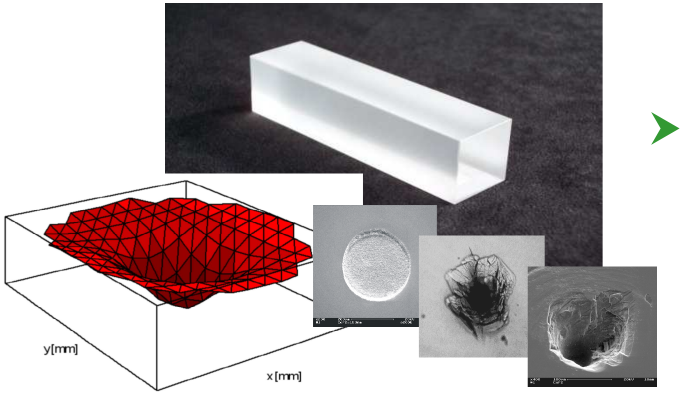
- Beam and Optics Characterization (**UV, EUV, XUV**)

- **Optics test** (351…**193 nm** **… 13.5 nm)**
  - *(Long term) degradation (10^9 pulses)*
  - *Non-linear processes*
  - *LIDT*
  - *Absorption / Scatter losses*
  - *Wavefront deformation*





- **Beam propagation**
  - *Wavefront*
  - *coherence*
  - *M²*

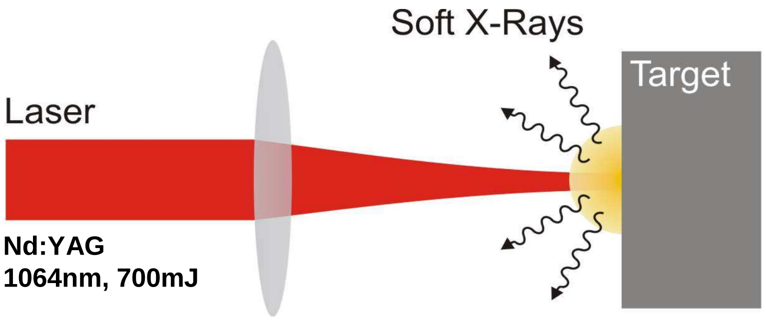


- **EUV/XUV technology**
  - *Source & Optics*
  - *Metrology*
  - *Material interaction*

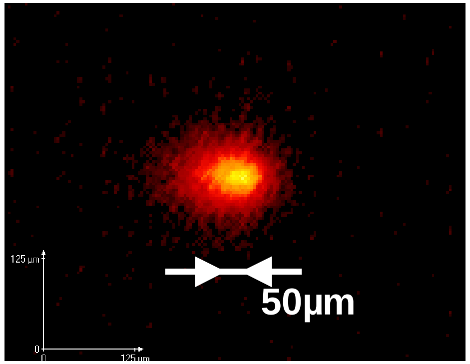
Outline

- Laser driven EUV/XUV Plasma-Source
- Overview: EUV Material Interaction Studies
- Damage to EUV sensors and optics
  - Photo-diodes
  - Grazing incidence mirrors (gold layers)
  - Multilayer mirrors (Mo/Si)
  - Mirror substrates (silicon, fused silica / CaF_2)
- Summary

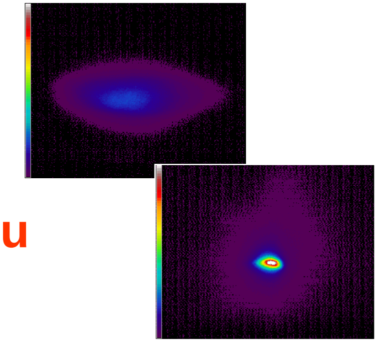
Laser driven
EUV / XUV plasma source

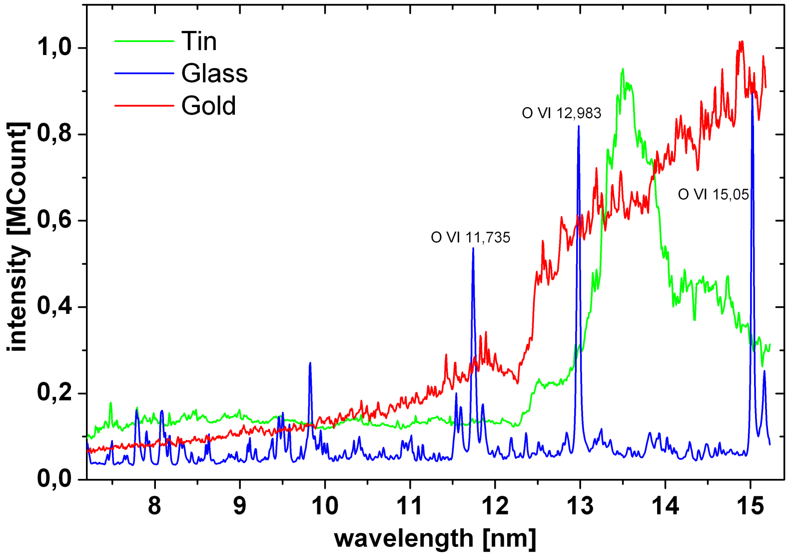


- **Au target**



- Pulse length: 8.8 ns
- Frequency: 1 – 10 Hz
- Gas Target
  - Ø ~ 300 µm
  - no debris
  - **low brilliance**
- **Solid State Target: Au**
  - Ø ~ 40 µm



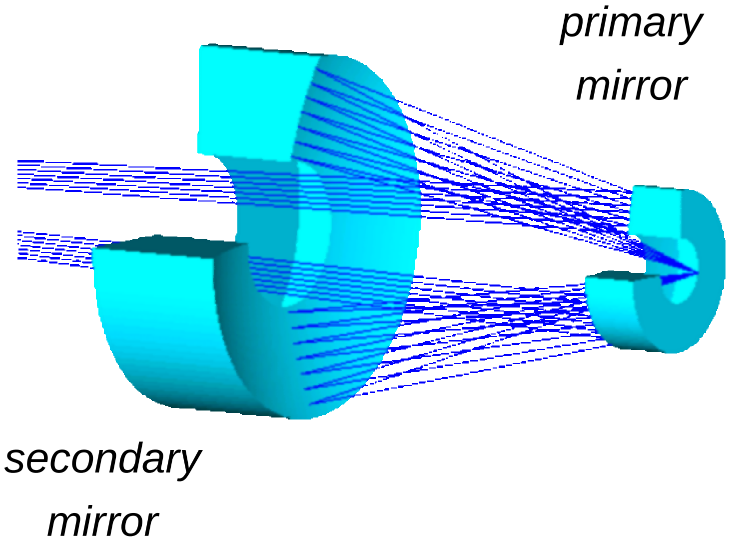


Schwarzschild Objective @ 13.5 nm

- Modified design
- Mo/Si multilayer coating
- Imaging of plasma

$\Rightarrow$ Micro-focus with high EUV fluence

Peak wavelength	13.5nm (± 2%BW)
Magnification	0.102
Numerical aperture	0.4
Acceptance angle (Ω)	5.33 msr



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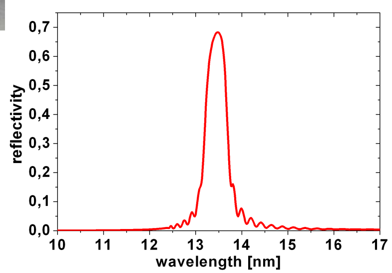
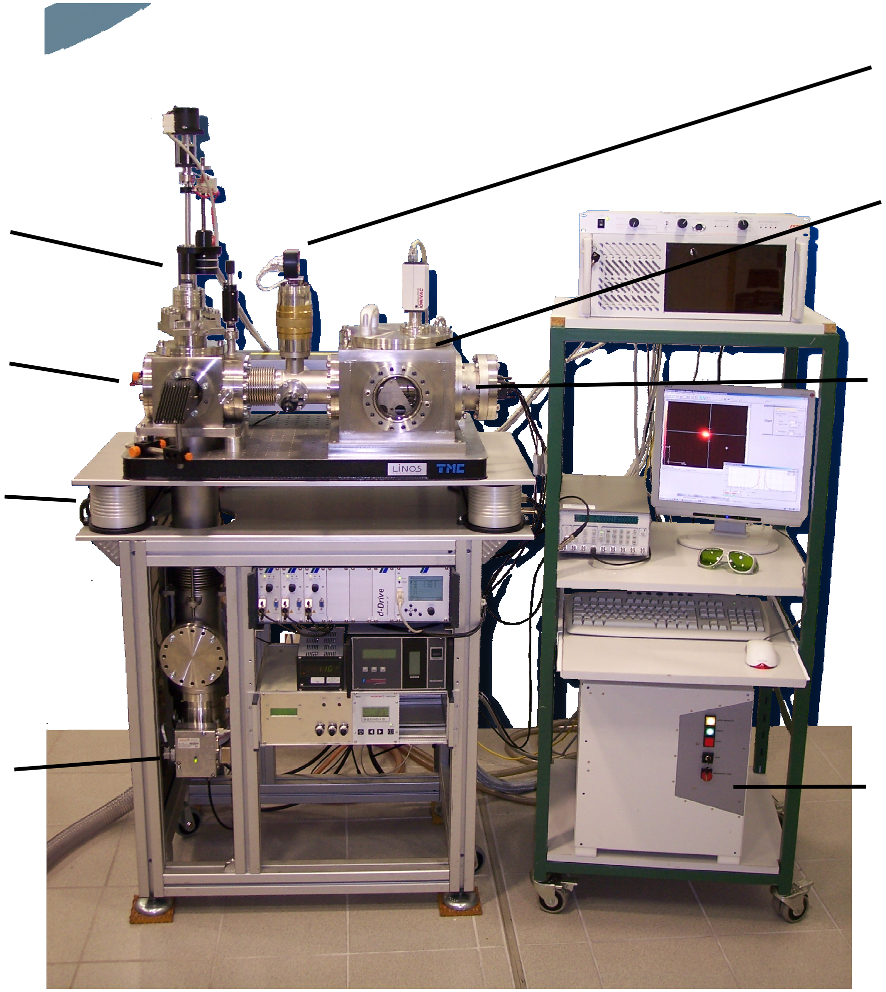


F. Barkusky, K. Mann, T. Feigl, Rev. Sci. Instr., **76**, 105102 (2005)

Photograph of EUV setup



CCD-Camera

Solid target positioning

Optics Chamber with Schwarzschild objective

Source chamber

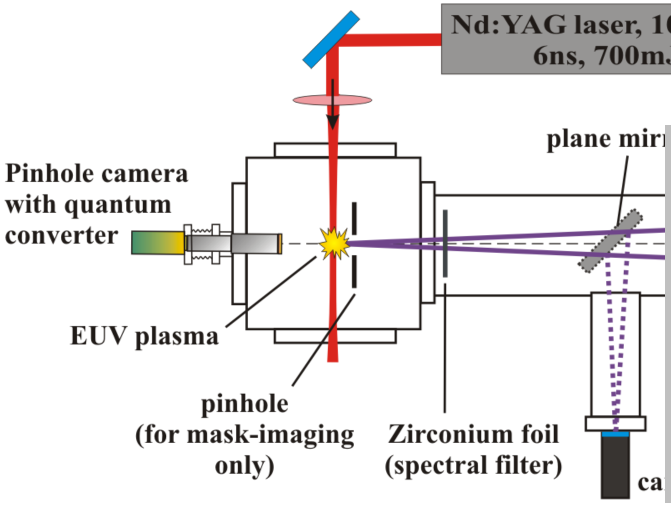
Sample positioning

Vibration isolation system

Vacuum pump

Laser power supply

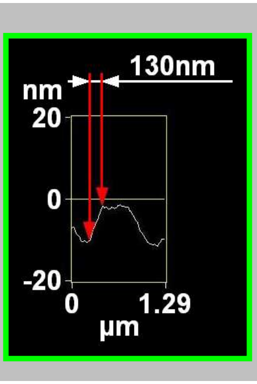
Gas-puff target EUV Setup

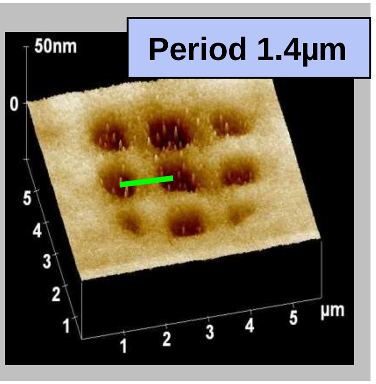


▶ Up to 70mJ/cm²

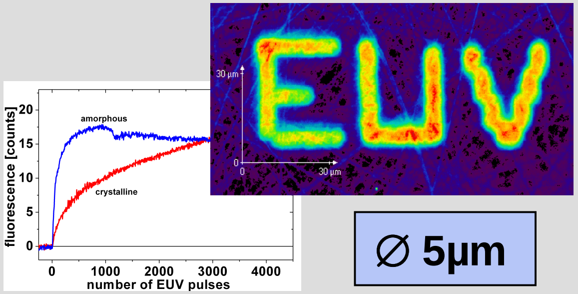
Resolution: 130nm

(NA 0.25)





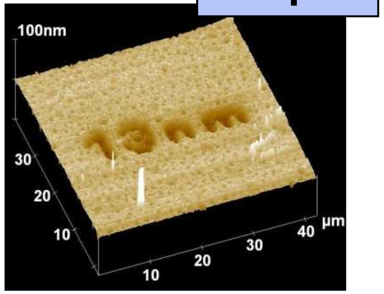
Color Centers in LiF



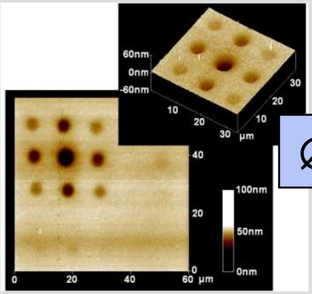
F. Barkusky, K. Mann, et.al., Rev. Sci. Instr., 76, 105102 (2005)

PMMA

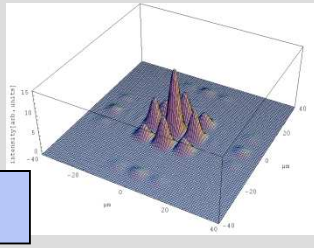
Ø 1µm



EUV Diffraction



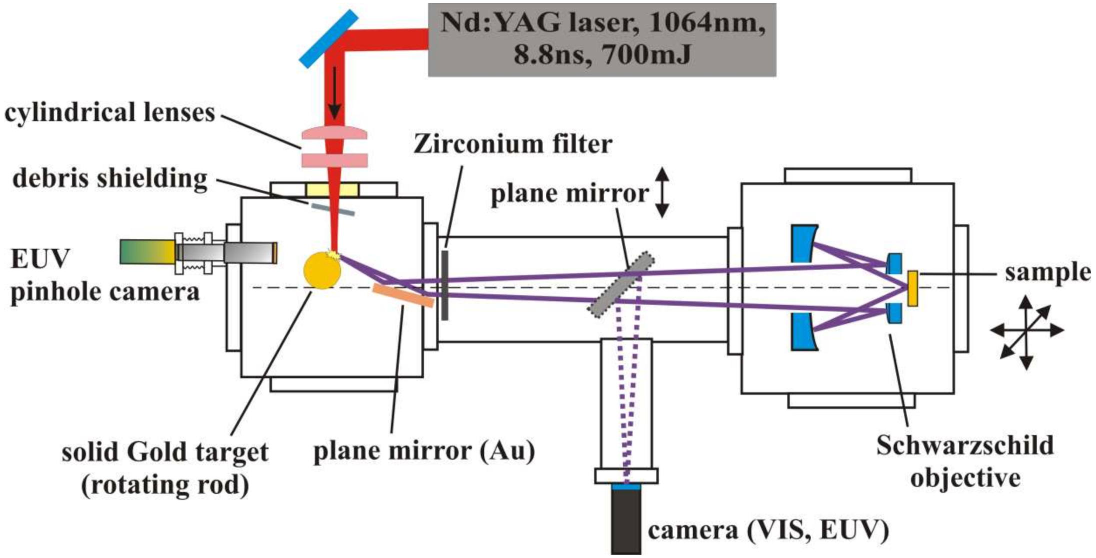
Ø 5µm



⇒ pure 13.5 nm radiation

F. Barkusky, K. Mann, et.al., J. Appl. Phys. 101, 124908 (2007)

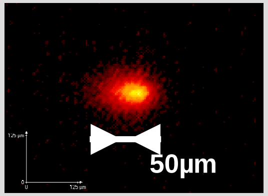
Solid-target EUV setup



- Solid Target: Au
- Rotating rod
- Au thickness: 200µm

Energy density in focus

- Energy → calibrated photodiode
- Area → etching in PMMA

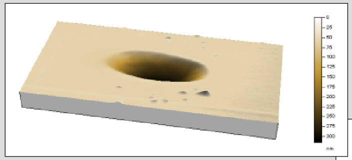


Au plasma image sequence

1.2 J/cm² **(filtered by Mo/Si + Zr)**

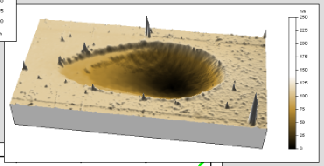
7.4 J/cm² @ 13.5 nm , 8.8ns **(filtered only by Mo/Si)**

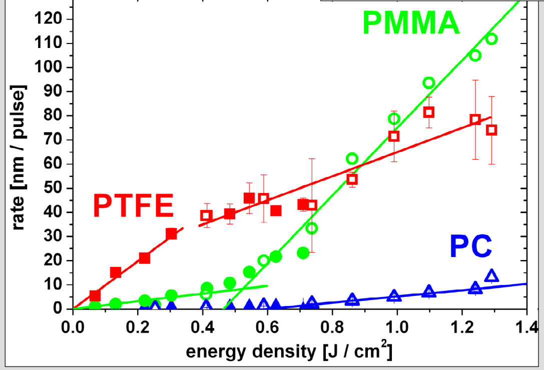
Polymer ablation



PMMA, 0.5 J/cm²
10 EUV pulses

PMMA, 1.3 J/cm²
1 EUV pulse





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- Damage to EUV sensors and optics
  - Photo-diodes
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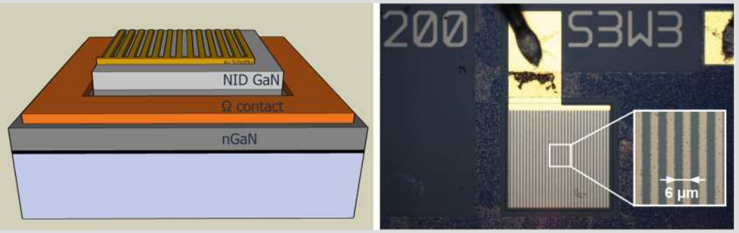
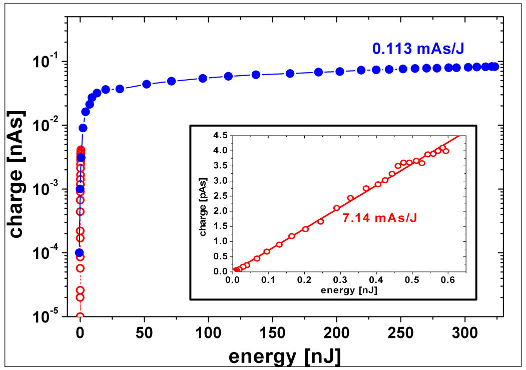
Degradation test of AlGaN diodes

- AlGaN Diode
- Not sensitive to wavelengths above 200 – 365 nm

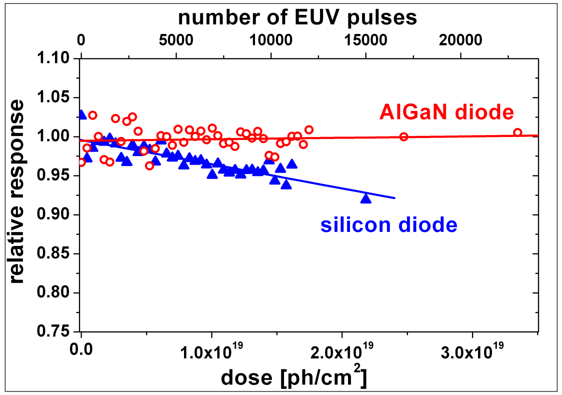


Responsivity



- first linear range
  - diode regime **7.14 mAs/J**
  - **German PTB: 8 mA/W**
- saturation
  - 0.6 - 50 nJ
- second linear range
  - Photo-effect on golden contact fingers

Radiation damage resistance



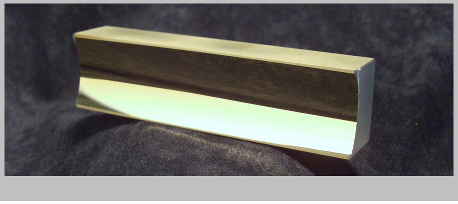
- Silicon diode
  - responsivity decreases
  - 8 % after 2.2×10^{19} ph/cm^2
- AlGaN diode
  - no change in responsivity after 3.2×10^{19} ph/cm^2

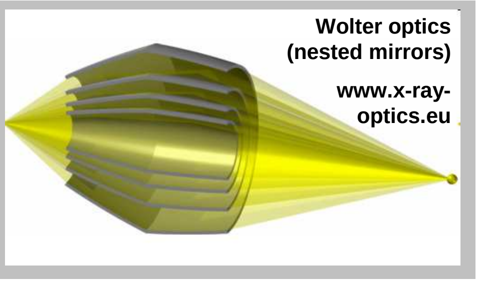
$\Rightarrow$ Application: reference monitor for EUV

F. Barkusky, K. Mann, J. John, P. Malinowski, Rev. Sc. Instr. 80, 9 (2009)

Damage / Ablation of Gold layers

- Used as EUV grazing incidence mirrors
  - Collector mirrors for EUV-Lithography
  - Mirrors for FEL

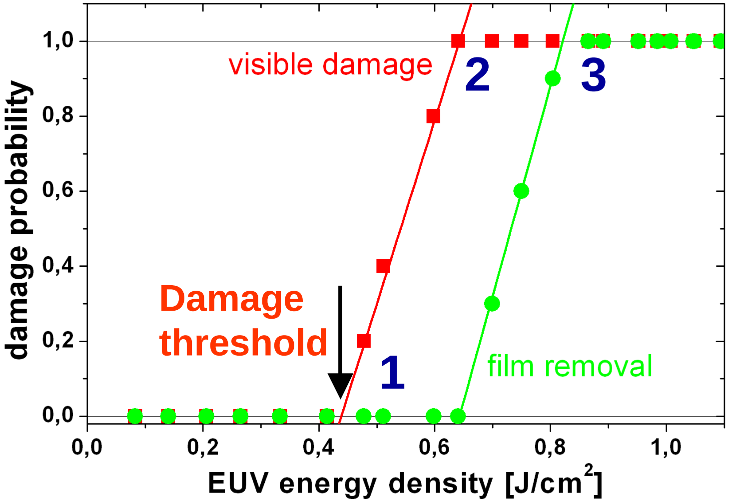

Toroidal mirror

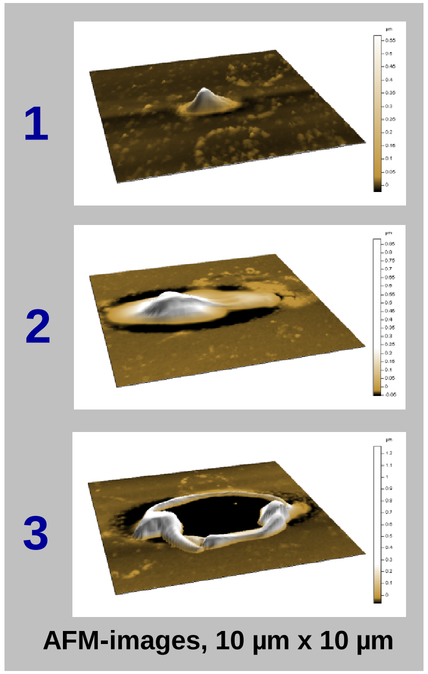

Wolter optics (nested mirrors)

www.x-ray-optics.eu

69 nm Au thickness

- Gold layer on glass
- 1-on-1 damage test
  - 10 positions, fixed fluence
  - damage probability plot





AFM-images, 10 µm x 10 µm

⇒ **damage threshold 420 mJ/cm²**

(69nm Gold film, 13.5 nm wavelength, 8.8ns pulse duration)

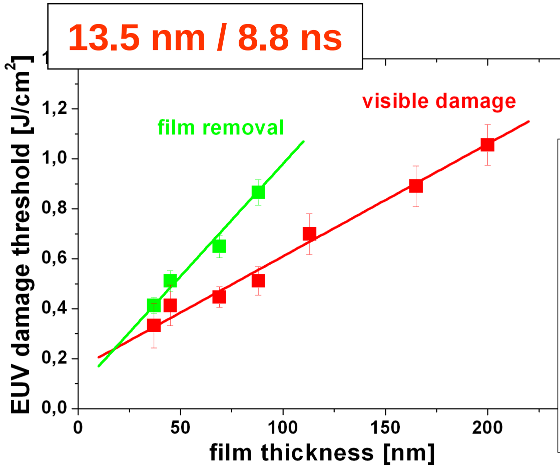
⇒ **Indication for thermal behaviour**

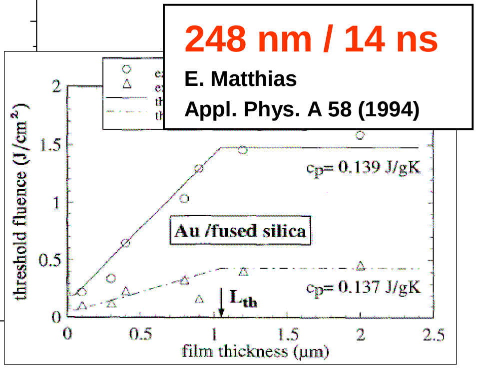
Varying Gold film thickness

- Film thickness dependence
  - Threshold fluence ∝ film thickness
  - Different slopes for damage and removal
  - Offset 0.1 - 0.2 J/cm^2

⇒ **comparable to Excimer-laser ablation**

13.5 nm / 8.8 ns

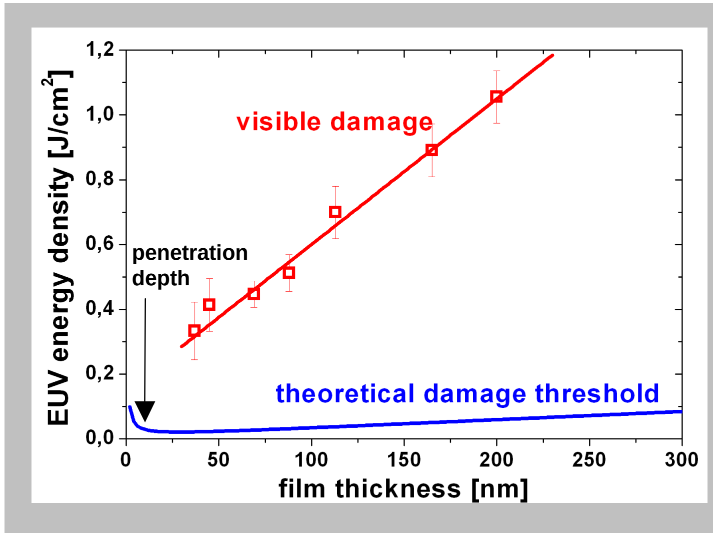




248 nm / 14 ns

E. Matthias

Appl. Phys. A 58 (1994)



- **Calculation of thickness-dependent threshold**

$$I_{tm} = \frac{T_{\text{phase-transition}} - T_{\text{sample}}}{(1-e^{-\alpha d})\cdot(1-R)} \cdot \left(\left[\rho_f c_f - \left(\frac{L_{th,s}}{L_{th,f}} \right) \rho_s c_s \right] l_f + L_{th,s} \rho_s c_s \right)$$

E. Matthias, Appl. Phys. A 58

- 100 % absorptance (R = 0)
- Radiative energy → thermal energy (no losses)
- Constants of bulk material

⇒ **Quantitative discrepancy between calculation and measurement**

Correction of EUV energy density

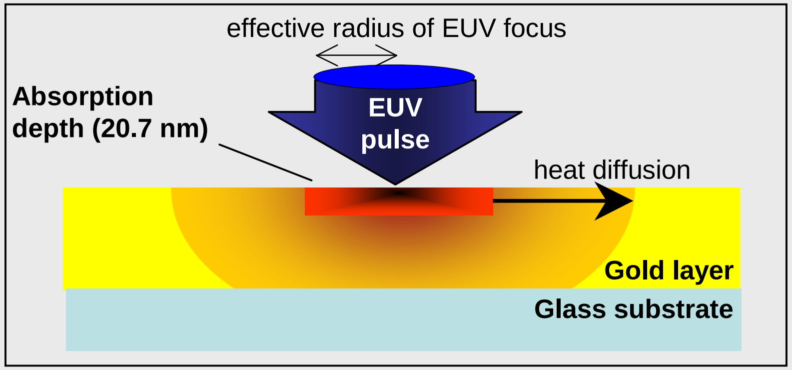
- Heat diffusion during EUV pulse

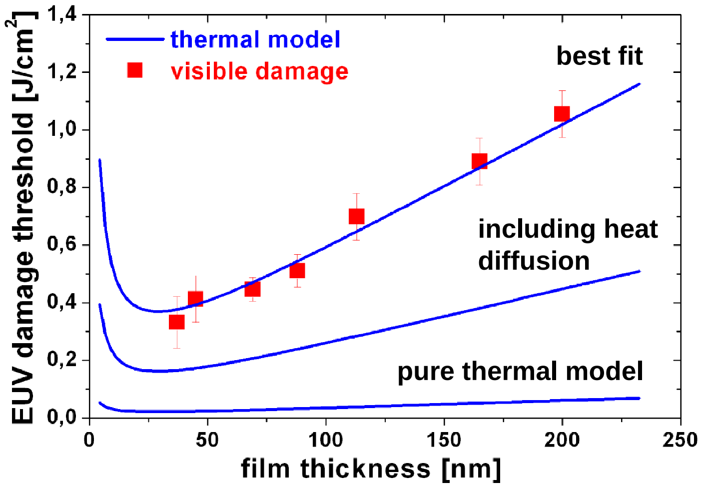
$$L_{th} = \sqrt{2 \cdot \kappa \cdot \tau} = \sqrt{2 \cdot \frac{\lambda}{\rho \cdot c} \cdot \tau}$$

κ	**temperature conductance**
λ	**heat conductance**
ρ	**density**
c	**heat capacity**
τ	**pulse duration**

⇒ **Heat diffusion length ~ 1.9 µm** (14 ns; $1/e^2$)

(effective radius of EUV focus ~ 2.3 µm)





- **better agreement to simulation**
- remaining errors
  - partial loss of EUV energy
    - photo electrons (~ 10 %)
    - Photo – Fluorescence
  - Properties of film differ from bulk

⇒ **data support thermal model for Au ablation @ 13.5 nm**

Damage of
Mo/Si multilayer mirrors

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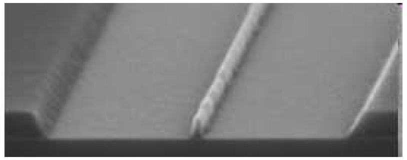
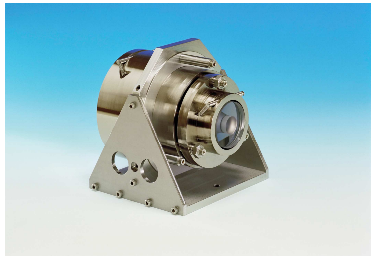
- Molybdenum / Silicon (Mo/Si) multilayer mirrors
- $R_{max} \sim 70\ \%$
- Applications:
  - EUV lithography
  - FEL
  - Laboratory sources

imec

30 nm isolated line, generated with EUV lithography



CARL ZEISS SMT



TEM-Micrograph of Mo/Si mirror

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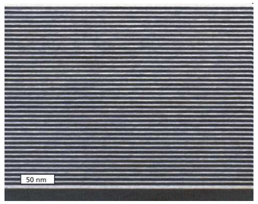
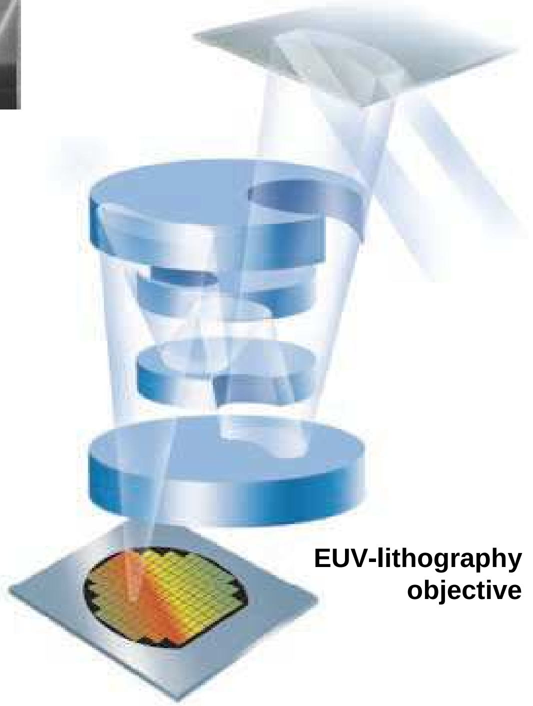


- Mo/Si mirror damage test
  - Silicon substrate / $[Mo/Si]^{60}$
  - 20° @ 13.5 nm

1 EUV pulse
$3.1\ J/cm^2$

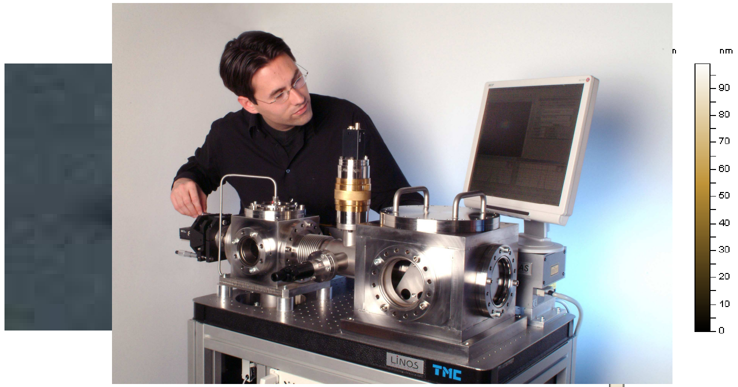


EUV-lithography objective

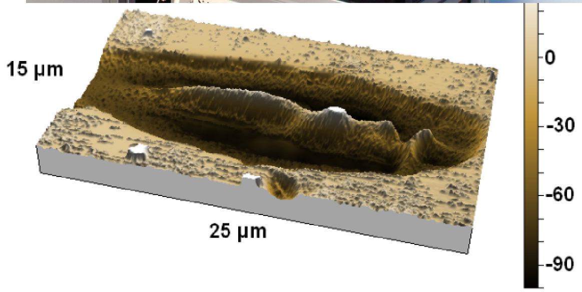
Comparison ns – fs
EUV pulses

8.8 ns, 13.5 nm (LLG)

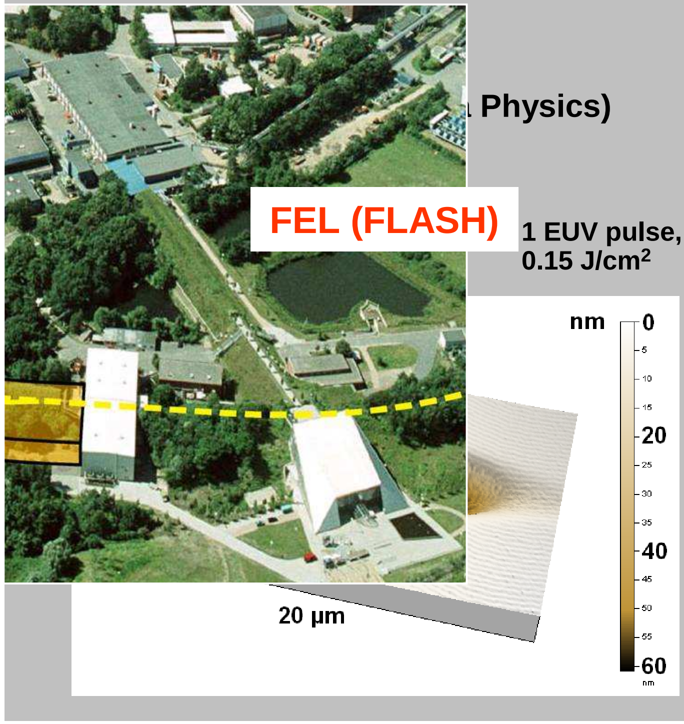
1 EUV pulse
3.1 J/cm^2



1 EUV pulse
6.5 J/cm^2



15 fs, 13.5nm (FLASH)



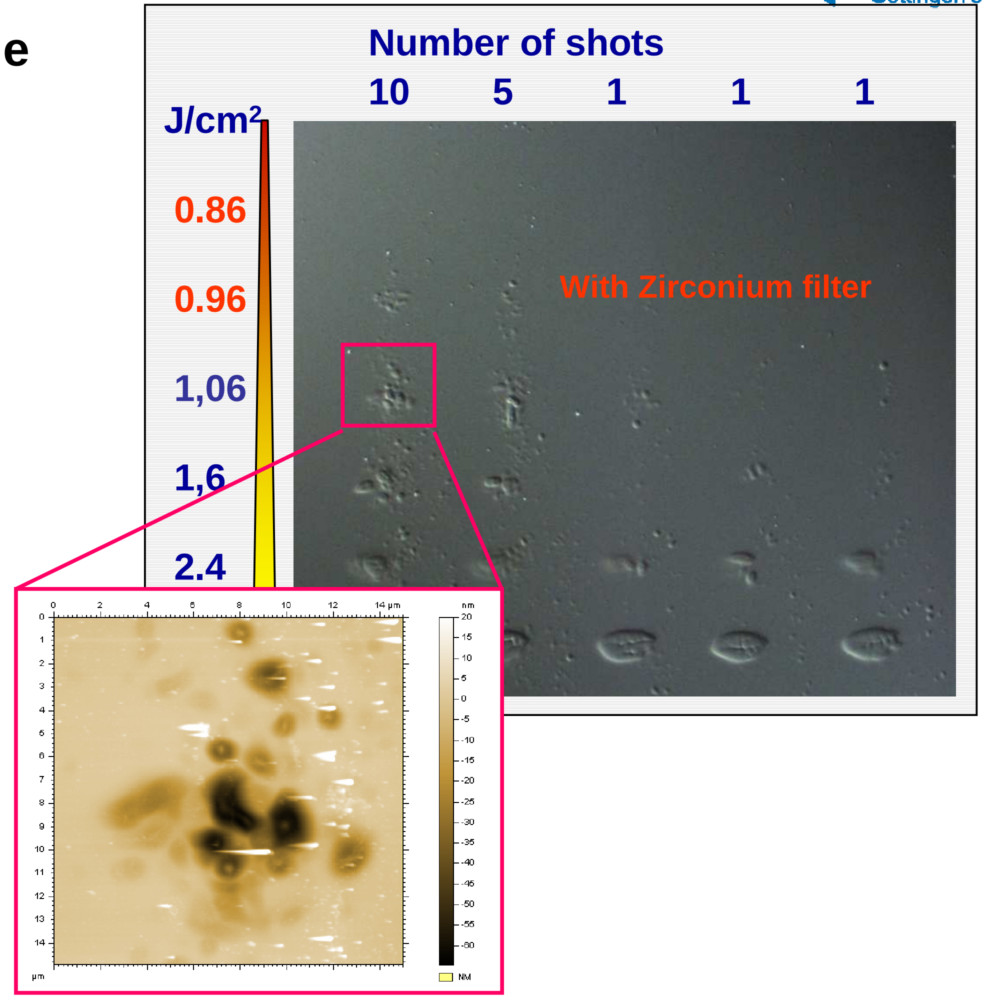
1 EUV pulse,
0.15 J/cm^2

- ⇒ **Smooth surface**
- ⇒ **Elongated bump in middle of crater**

Damage Morphology

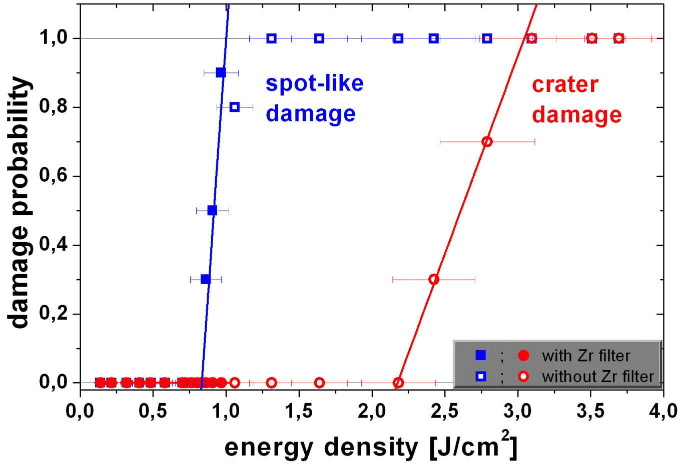
- **inhomogenity-induced damage**
  - many small craters (spots)
  - Locally higher absorption
    - local impurities
    - defects in multilayer system
  - Independent from intensity distribution

- **Crater damage**
  - mainly one crater

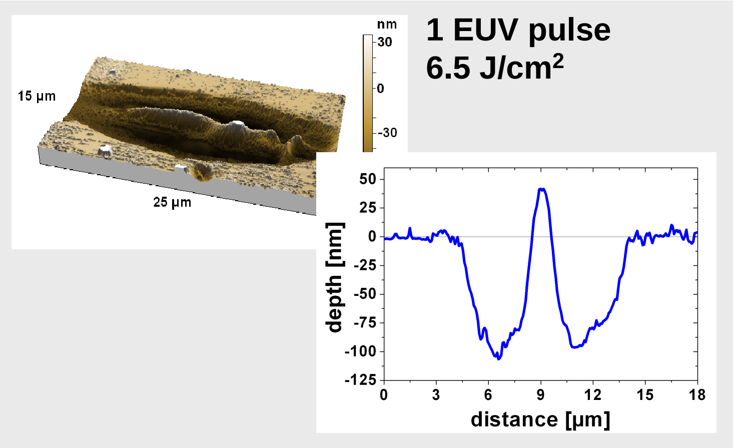


- Bulge in middle of each spot

1-on-1 damage test



- **Damage probability**
  - 10 positions at fixed fluence
  - Fluence variation
- **Two damage regimes**
  - **Spot-like damage ~ 0.8 J/cm2**
  - **Crater damage ~ 2.2 J/cm2**



1 EUV pulse
6.5 J/cm^2

⇒ high fluence: crater depth ~100 nm

(1/4 of multilayer thickness)

⇒ complete damage of multilayer system

Damage of mirror substrates

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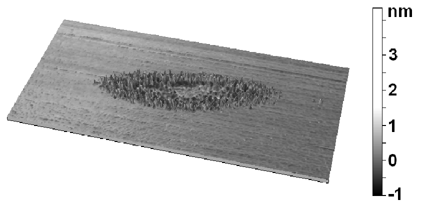
Damage threshold of reflective coatings

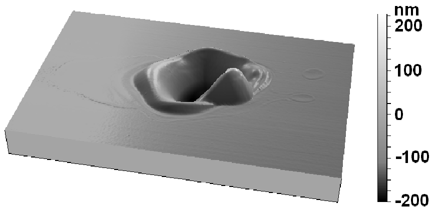
- **Part of incident light reaches the substrate**
- **Determination of damage threshold for substrate materials**

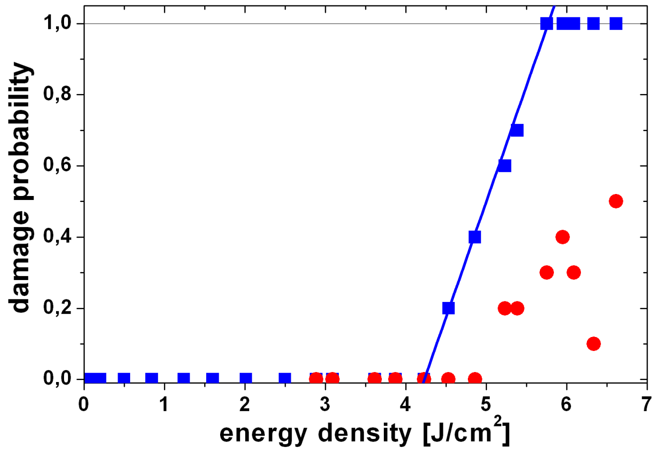
Silicon wafer

- Surface near damage 4,1 J/cm²
  - roughening
  - depth 2 - 4 nm
  - Caused by natural oxidized silicon



- Crater damage 5 J/cm²
  - Depth 100 – 200 nm
  - Molten material



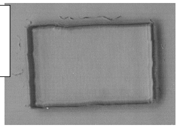


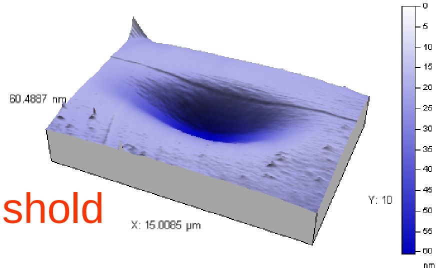
Damage of
mirror substrates

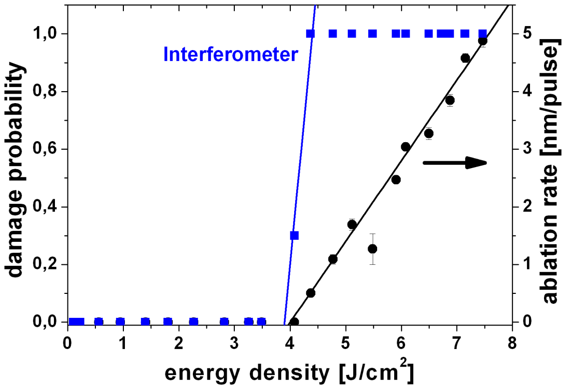
Fused silica

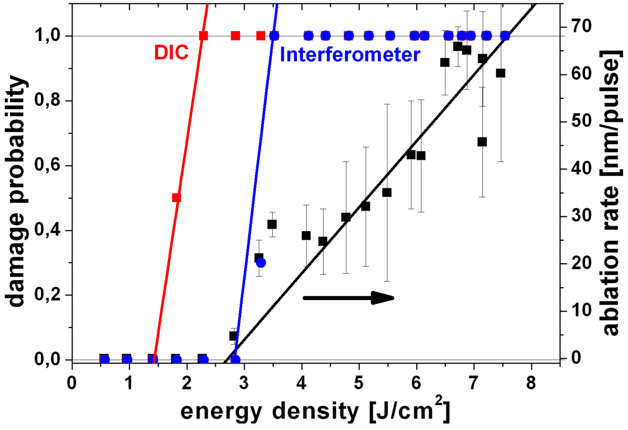
- Ablation threshold 4 J/cm^2
  - Smooth profiles
  - Rates up to 5 nm/pulse
- Damage threshold = ablation threshold

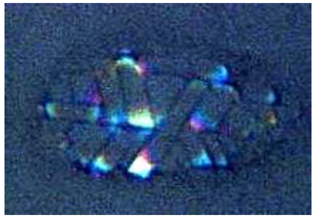
P.R.Herman (1999)
Ablation with 157nm



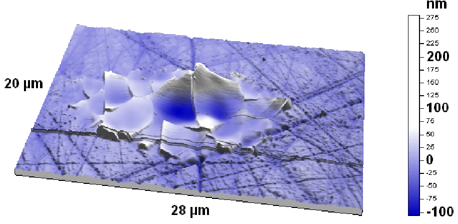








VIS-micrograph; 25m x 20 µm,
1 pulse, highest fluence



Calciumfluoride (CaF$_2$)

- Damage threshold 1.3 J/cm^2
  - bulk damage (DIC)
  - Colour center generation?
- Ablation threshold 2.8 J/cm^2
  - Surface damage
  - Recrystallization

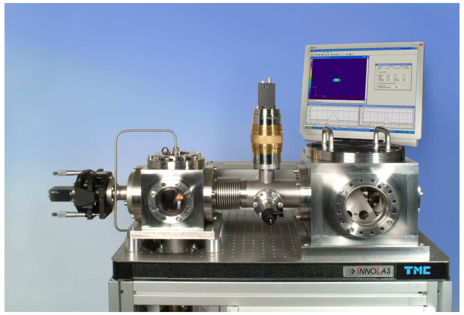
Outline

Laser-
Laboratorium
Göttingen e.V.

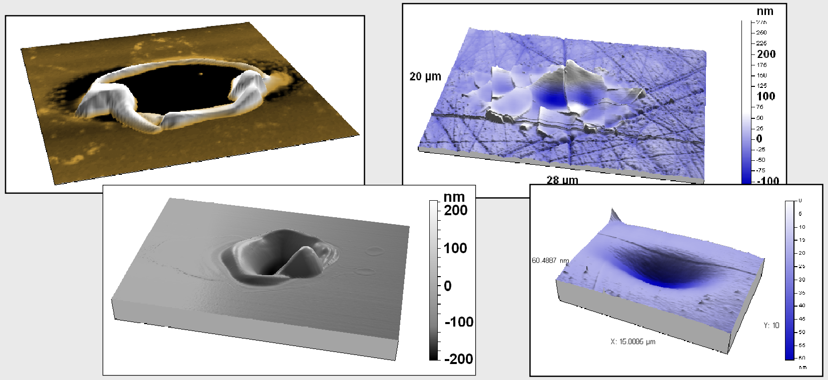
- Laser driven EUV/XUV Plasma-Source
- Overview: EUV Material Interaction Studies
- Damage to EUV sensors and optics
  - Photo-diodes
  - Grazing incidence mirrors (gold layers)
  - Multilayer mirrors (Mo/Si)
  - Mirror substrates (silicon, fused silica / CaF_2)
- Summary

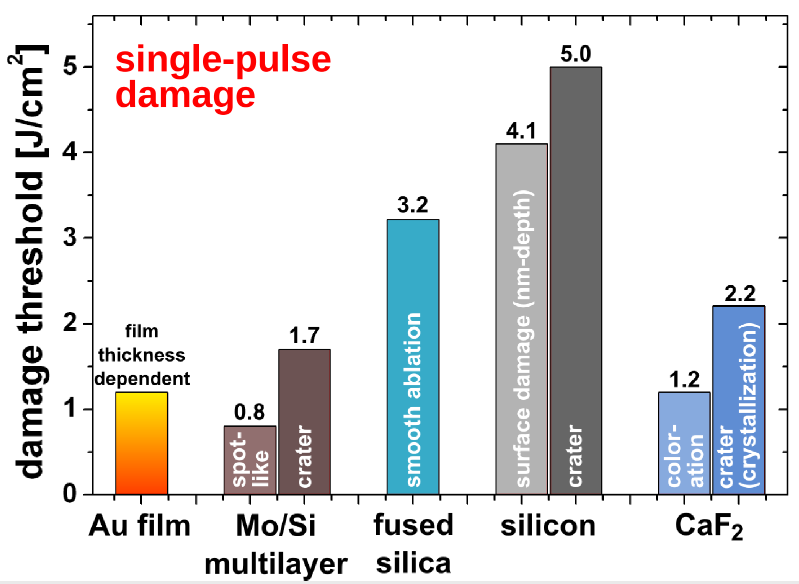
Summary

- Laser driven EUV/XUV plasma source setup
  - 1.2 J/cm^2 (@ 13,5 nm, 2 % bandwidth)
  - 7.4 J/cm^2 (filtered by 2 Mo/Si mirrors)



- Damage thresholds of mirrors / substrates

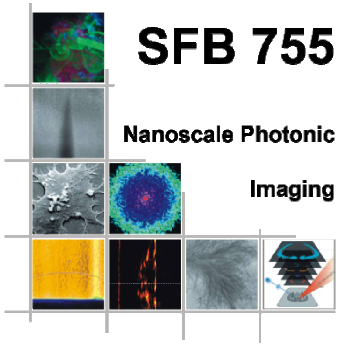




Thank You for your attention.

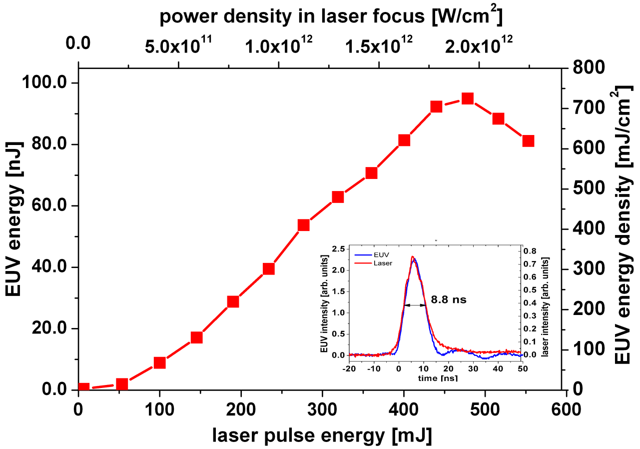
Acknowledgement

- SFB 755: “Nanoscale Photonic Imaging”

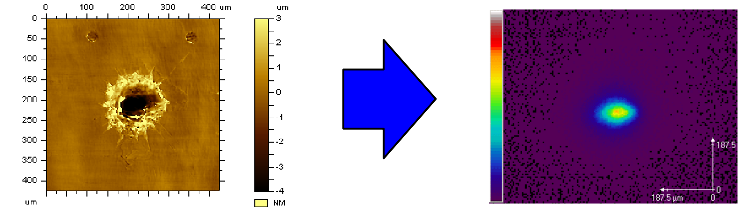


Energy density in focus

Target	Spot Size	EUV fluence
Xenon (gaseous)	~ 30 µm	**0.05 J/cm²**
Gold (solid)	~ 4 µm	**0.72 J/cm²**
Gold (solid, beam shaping)	~ 2 µm x 5 µm	**1.2 J/cm²**



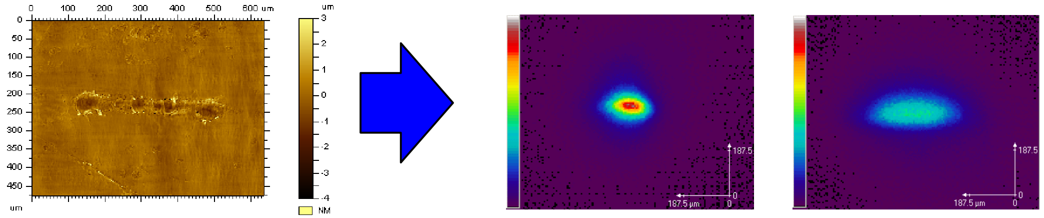
- Limit: Overheating of plasma with spherical focus
- Solution: stretching of plasma in one direction
  - line focus of Nd:YAG laser on target
  - Plasma transparent vor EUV light



Laser profile on Au target

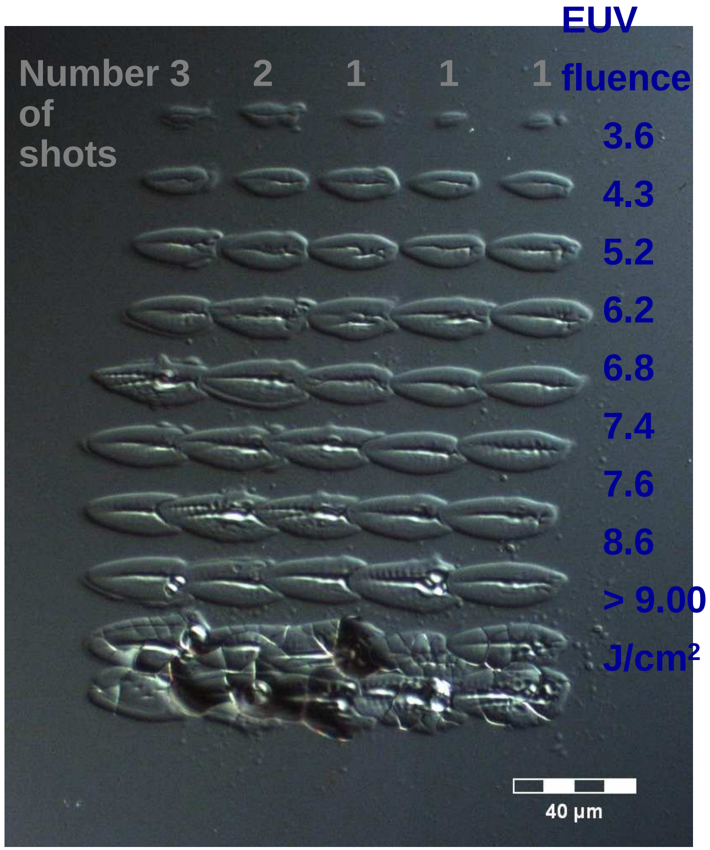
Front view (objective)

side view



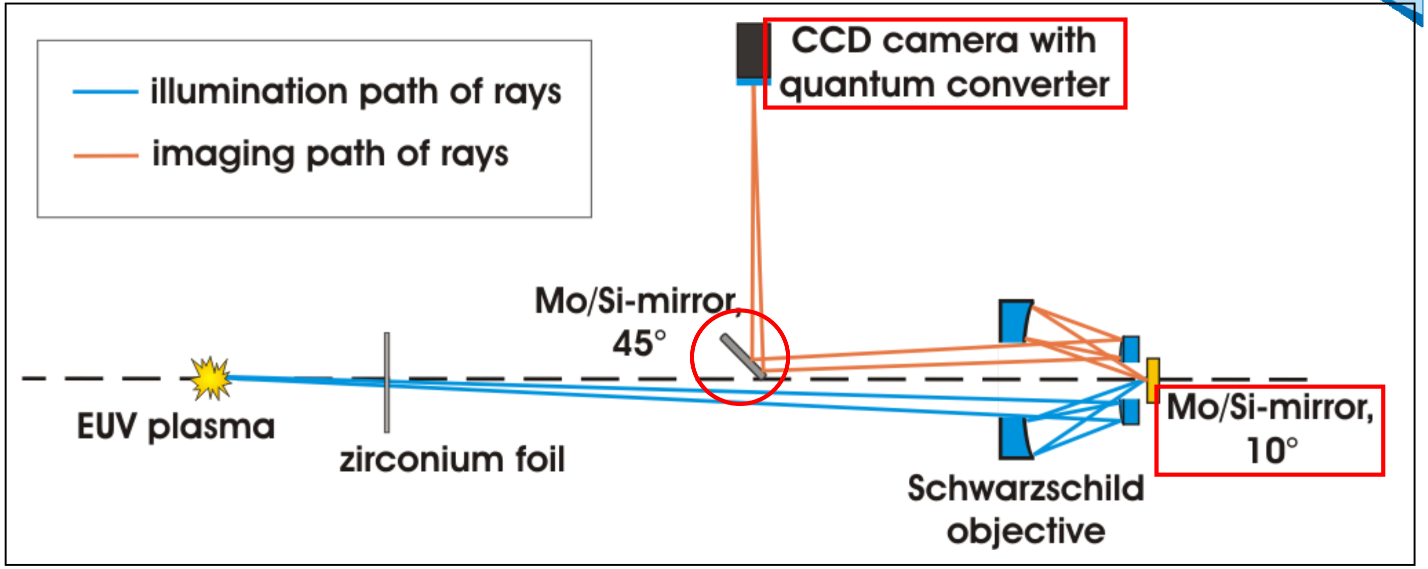
Visible Damage of 20° Mo/Si mirror

- Mo/Si mirror, 20° @ 13.5 nm
- Silicon-substrate / $[\mathrm{Mo/Si}]^{60}$



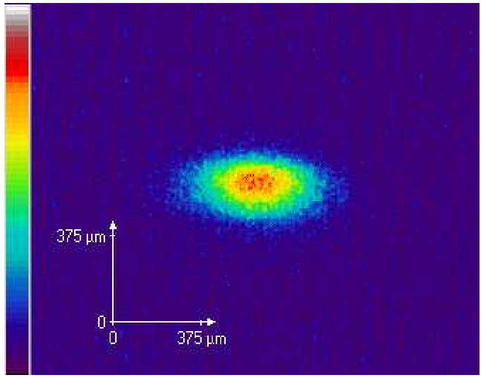
- Nomarski / DIC contrast
  - AFM-images of damaged areas
  - Craters with bulge in middle
  - Crater depth ~ 40 nm (multilayer: ~440 nm)
  - Comparable to fs-pulse damage

Modified Setup:
⇒ Inline EUV Microscope



plasma image

on Mo/Si mirror:



→Applications:

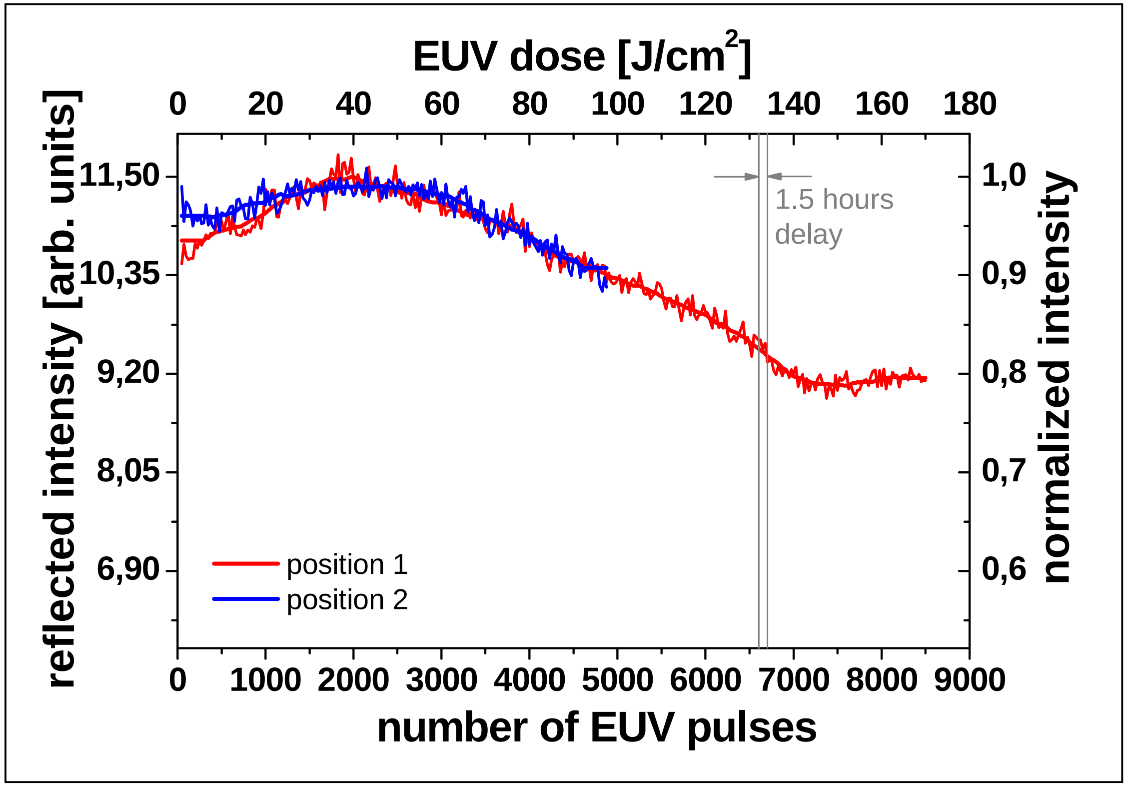
- ➢ Actinic inspection of mirrors
- ➢ **In-situ monitoring of reflectivity changes**

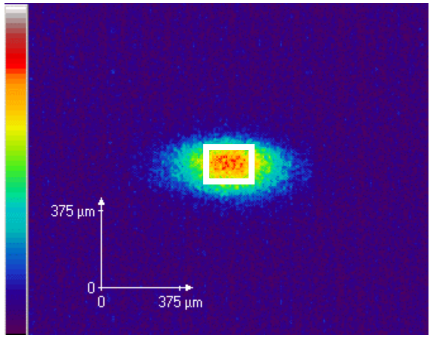
EUV induced degradation of Mo/Si Mirror

Laser-Laboratorium Göttingen e.V.

Sample:
Multilayer mirror @ 13nm / 15°

EUV fluence:	**~ 20mJ/cm²**
# of pulses:	8500
total EUV dose:	170J/cm²



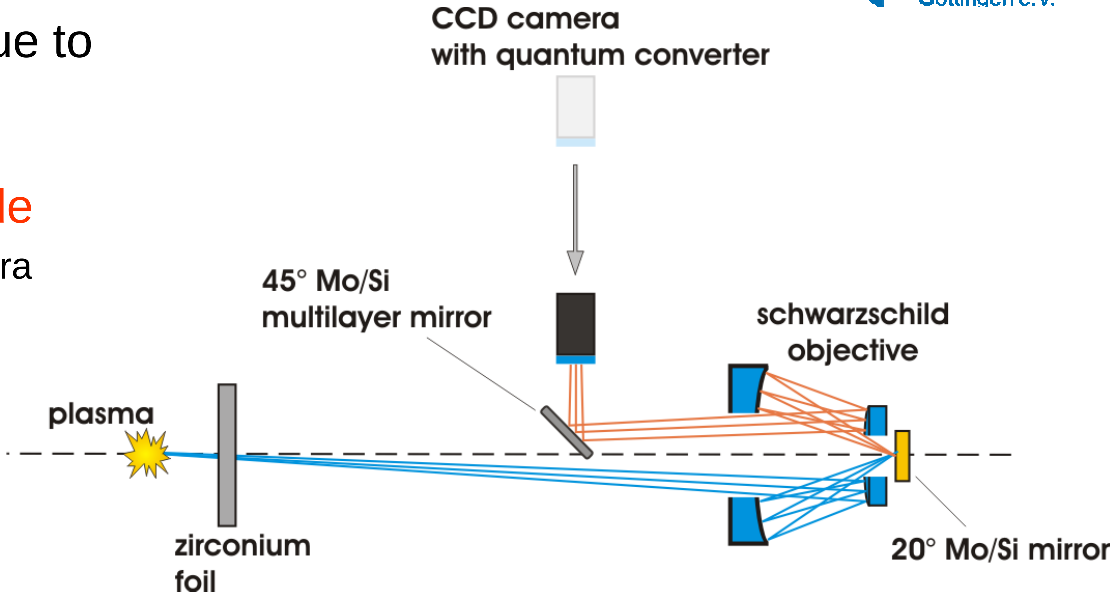


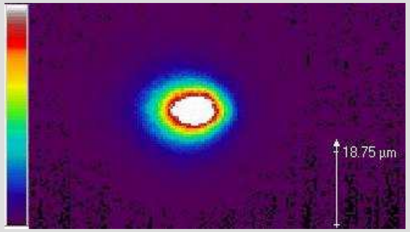
- conditioning / surface cleaning
- oxidation (?)

Visit from Germany´s cancellor Angela Merkel

Spectral Responsivity near threshold fluence

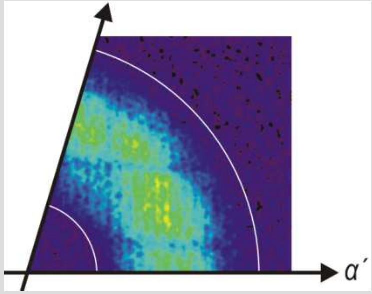
- change in spectral response due to multilayer damage
- Imaging mode → Spectral mode
  - 50 mm displacement of CCD camera
- Angular resolved reflectivity
  - 13.5 nm wavelength
  - Angular spectrum 10°- 25°





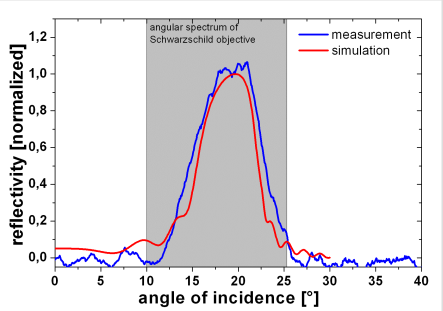
Focus image (reflected light by 20°Mo/Si mirror)

Camera shift



Angular resolved reflectivity

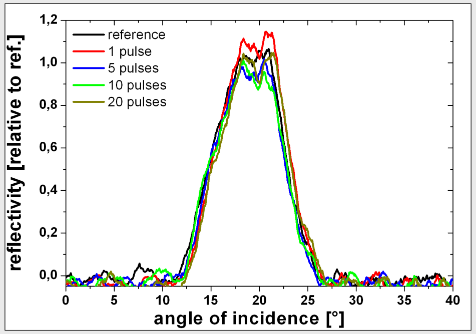
Image processing



Comparison to simulated reflectivity (CXRO, Berkeley)

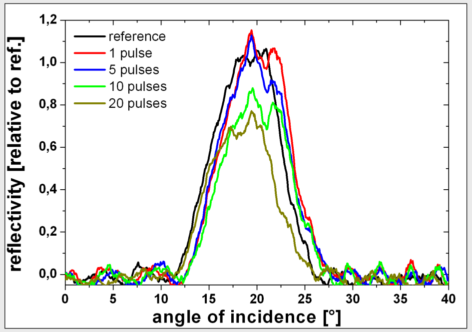
Spectral reflectivity change

- Spectral shift depending on number of high-energy EUV pulses
  - Probing with fluence below threshold (0.5 J/cm^2)



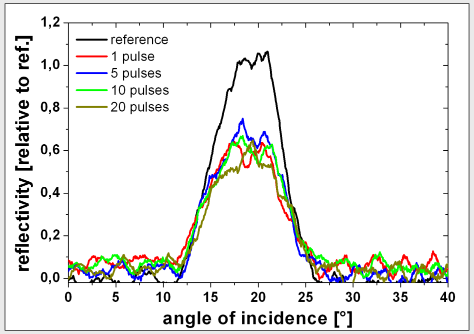
Spot-like damage

(1.64 J/cm$^{2)}$



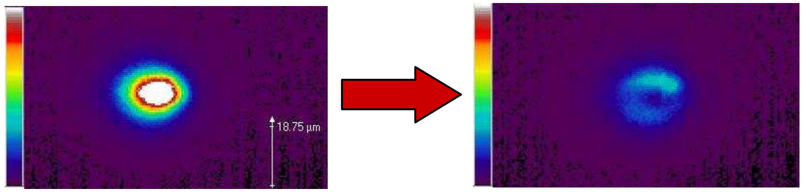
Intermediate regime

(2.4 J/cm^2)



One-crater damage

(3.1 J/cm^2)



→ doughnut profile

⇒ Drop of reflectivity

- no reflectivity on damaged area
- Damaged crater area increases with fluence

⇒ No spectral shift detectable ⇒ no layer compaction