Public

EUV optics lifetime
Radiation damage, contamination, and oxidation

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ASML Research

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Preamble

- ASML builds lithography scanners
  - High-resolution ‘photocopiers’
  - Copies mask pattern into resist layer into a silicon wafer

mask

wafer

scanner

patterned wafer

Preamble

- Smaller features require shorter wavelength radiation

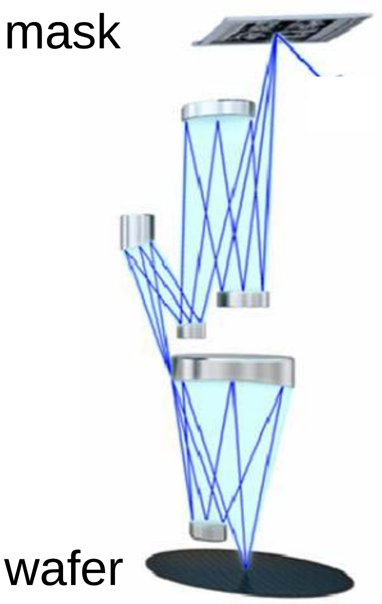
Hg lamp	KrF laser	ArF laser	Laser-produced plasma
365 nm	248 nm	193 nm	13.5 nm / EUV

Resolution:	>1µm	> 500 nm	> 400 to 90 nm	> 100 to 38 nm	> 32 to 20 nm
Overlay:	250 nm	100 nm	100 to 12 nm	20 to 4 nm	2 nm

Preamble

- EUV radiation is strongly absorbed
  - 10 µm air (STP) absorbs ~50%
  - 10 nm carbon absorbs ~5%
  - 1 nm tin absorbs ~10%

- Impact
  - Vacuum
  - Mirrors, no lenses
  - Sensitive to (sub-)nm contaminant layers
    - Lithography tool contains ~10 mirrors
    - 1% loss per mirror: 10% loss in tool productivity
    - 1% loss per mirror: 5 atomic layers C or 0.2 atomic layers Sn



Outline

EUV optics lifetime

- Radiation damage

- Carbon growth

- Oxidation

- Mitigation

Radiation damage

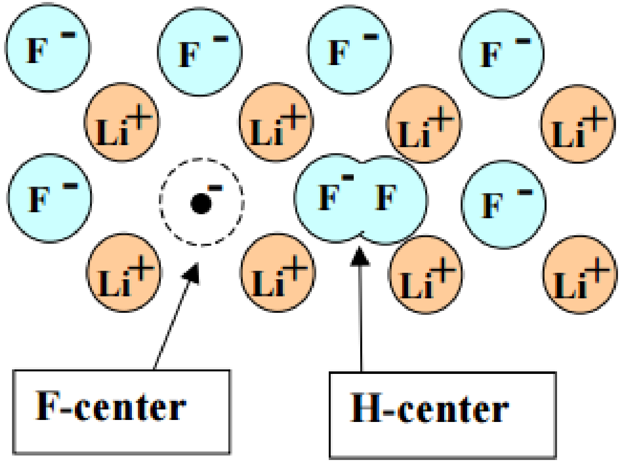
- Many compounds can be damaged by (EUV) radiation
  - Polymers
  - Ionic compounds (salts)
  - Glasses
  - Oxides
  - …

- Impact
  - Optical lithography works (photo-resist)
  - Contamination / oxidation of EUV mirrors
  - Changes in optical and mechanical properties
  - Photo-induced desorption (outgassing, material removal)

Radiation damage

Example: LiF (salt)

(1)



Farbe-center
color-center

(2)

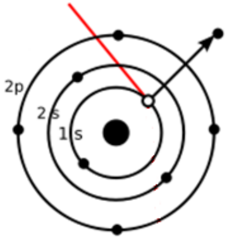
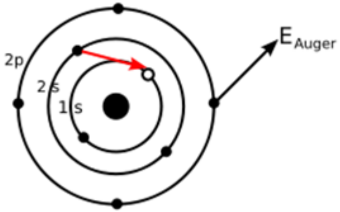
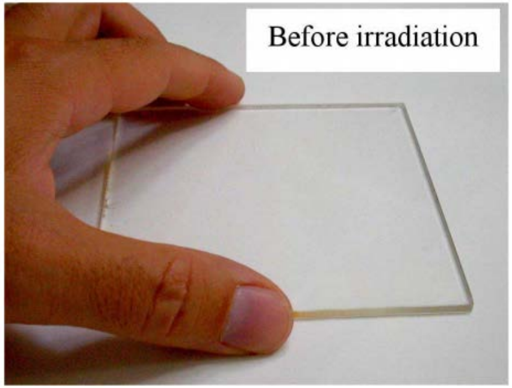
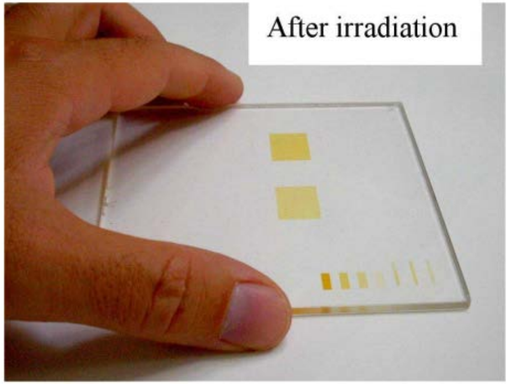


Photo-emission



Auger emission





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[1] Lithium fluoride thin-film detectors for soft X-ray imaging at high spatial resolution, R.M. Montreali *et al.*, Nucl. Instr. and Meth. in Phys. Research Section A **623**, 758–762

[2] https://en.wikipedia.org/wiki/Auger_effect

Radiation damage

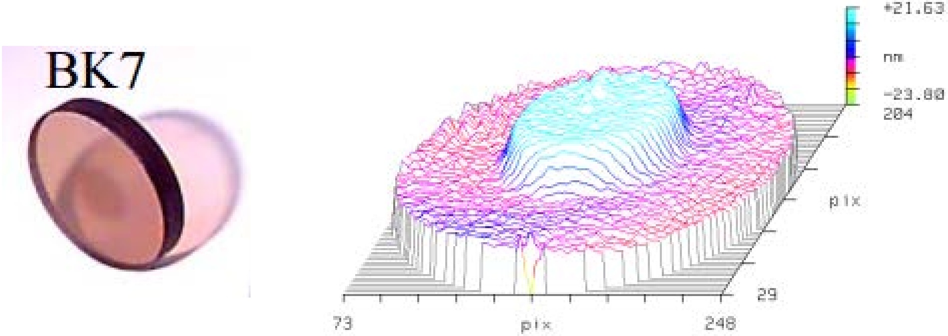
Glasses / mirror substrates

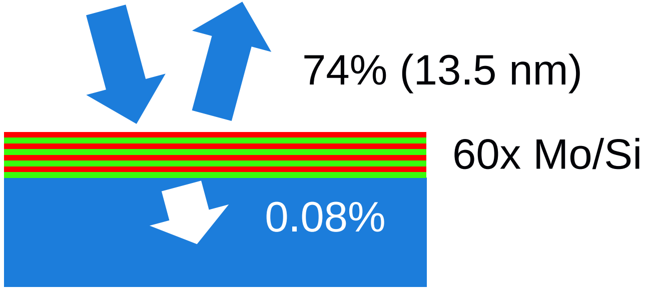
- Similar effects occur in glasses / glass-ceramics
  - BK7
  - UltraLowExpansion (ULE) glass
  - Zerodur

→ typical mirror substrates

- Irradiation also leads to *compaction* or *expansion*
  - Glass mirror substrates should be protected from EUV irradiation
  - Mo/Si stack transparent, especially for out-of-band radiation

(1)





74% (13.5 nm)

60x Mo/Si

0.08%

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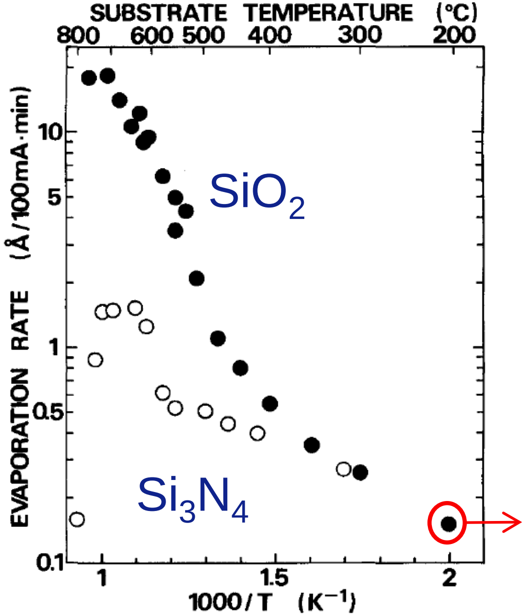
[1] D. Doyle, Radiation Hardness of Optical Materials, sci.esa.int/science-e/www/object/doc.cfm?fobjectid=46396

Radiation damage

Etching

- Radiation can etch materials
  - E.g. SiO_2 observed to etch in EUV

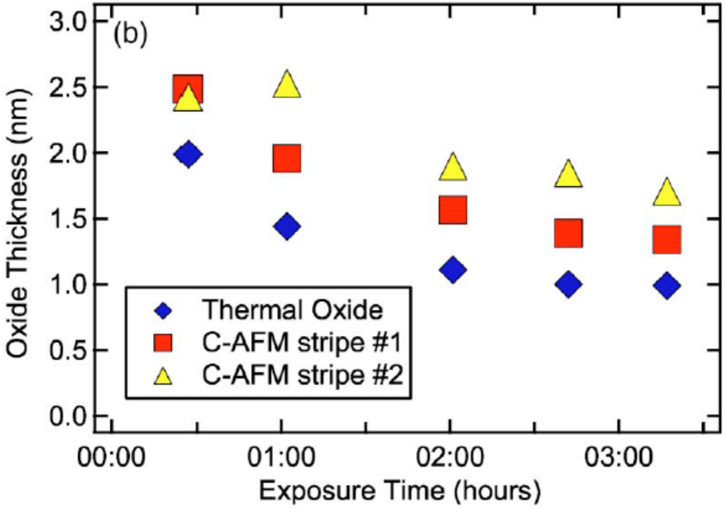
(1)



0.7 nm/hr
~50 mW/mm^2
λ=‘1-100 nm’
200 °C

(2)

~0.3 nm/hr, ~20 mW/mm^2, 142 eV, RT



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[1] H. Akazawa *et al.*, Photostimulated evaporation of SiO_2 and Si_3N_4 films by synchrotron radiation…, J. Vac. Sci. Technol. A **9**, 2653 (1991)
[2] S. Heun *et al.*, Behavior of SiO_2 nanostructures under intense extreme ultraviolet illumination, J. Appl. Phys. **97**, 104333 (2005)

Radiation damage

Wrap-up

- EUV irradiation can directly damage mirrors
  - Change glass-like substrate properties (e.g. compaction)
  - Etch and/or alter compounds

- EUV irradiation also damages contaminants on a mirror
  - Hydrocarbons: carbon growth
  - Water or oxygen: oxidation by oxygen radicals
  - Next topics

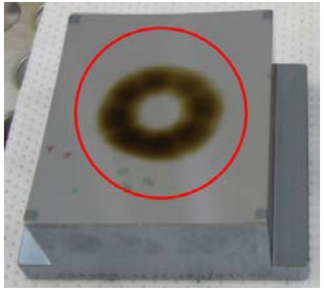
Carbon contamination

- ‘Vacuum’ contains residual (hydrocarbon) contaminants

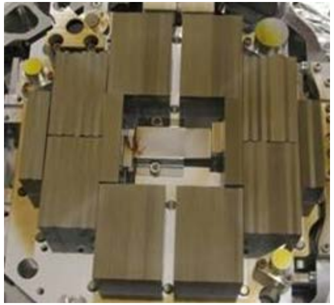
- Hydrocarbons adsorb on (mirror) surfaces

- EUV photons and secondary electrons cause
  - Transformation of C_xH_y chains to aC:H
  - Reduction of H-content with irradiation dose
  - Radiation-induced outgassing of fragments

- EUV lifetime issue
  - How fast does carbon grow under actual tool conditions?



SEMATECH MET, 2007



ADT mirror, 2007

Carbon growth model

- Carbon growth rate d*C*/d*t* [m/s] given by[1]:

$$\frac{\mathrm{d}C(t)}{\mathrm{d}t} = \sigma \cdot I(t) \cdot N(t) \cdot V_C$$

σ	Cross-section [m^2]
$I(t)$	EUV photon flux [$1/(m^2 \cdot s)$]
$N(t)$	Contaminant surface coverage[$1/m^2$]
V_c	Deposited carbon volume per molecule [m^3]

- Carbon growth rate is linear in intensity and contaminant coverage
  - But contaminant coverage is a complex term

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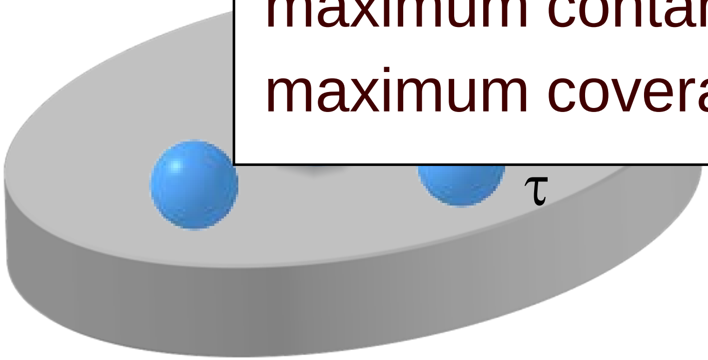
[1] J. Hollenshead and L. Klebanoff, Modeling radiation-induced carbon contamination of extreme ultraviolet optics, J. of Vac. Sc. & Tech. B **24**, 64 (2006)

Carbon growth model: *N(t)*

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = \left[N_{\max} - N(t)\right]\cdot s\Gamma - \frac{1}{\tau}N(t) - \frac{1}{f}\frac{\mathrm{d}C(t)}{\mathrm{d}t}$$

- Ingredients Langmuir isotherm

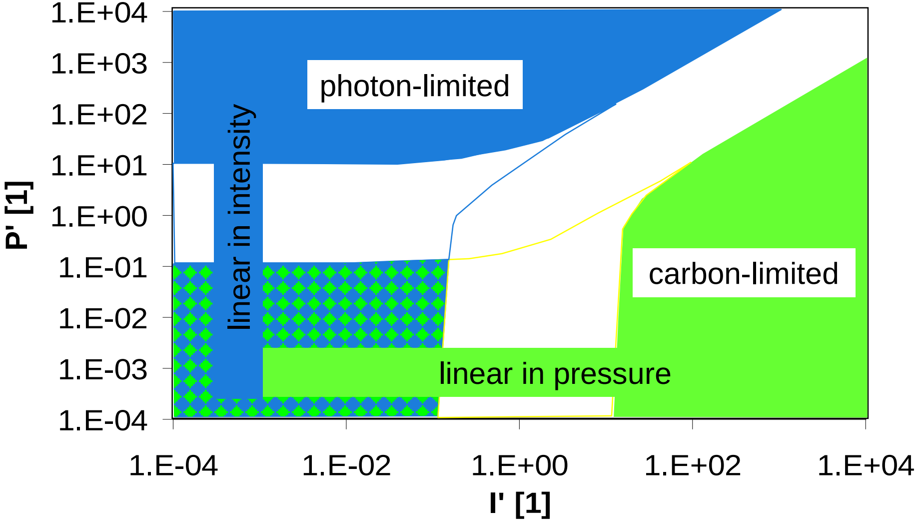
Γ	Contaminant flux to mirror (linear in contaminant partial pressure)
N_{max}	Maximum coverage
$\tau_{residence}$	Contaminant residence time
$\mathrm{d}C/\mathrm{d}t$	Loss by carbon growth



maximum contaminant flux Γ $\propto$ *pressure*
maximum coverage N_{max}

Carbon growth model

- Two limiting regimes can be identified
  1. **Carbon-limited**: high intensity, low contaminant pressure $\propto$ p, independent of I
  2. **Photon-limited**: low intensity, high contaminant pressure $\propto$ I, independent of p



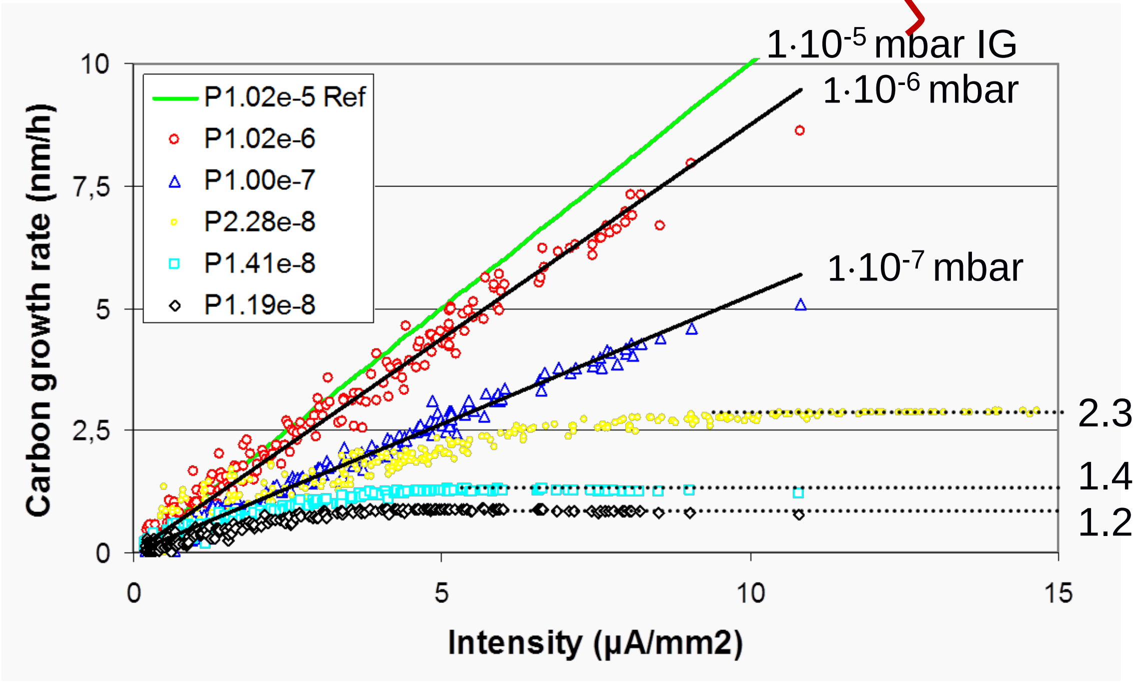
$$P' = \frac{s\Gamma \cdot \tau}{N_{\max}}$$

$$I' = \frac{IY \cdot \tau}{f}$$

Carbon growth - experimental

- N-dodecane ($C_{12}H_{26}$) growth rate versus pressure and intensity
  - Electron irradiation

photon-limited



$1{\cdot}10^{-5}$ mbar IG

$1{\cdot}10^{-6}$ mbar

$1{\cdot}10^{-7}$ mbar

$2.3{\cdot}10^{-8}$ mbar

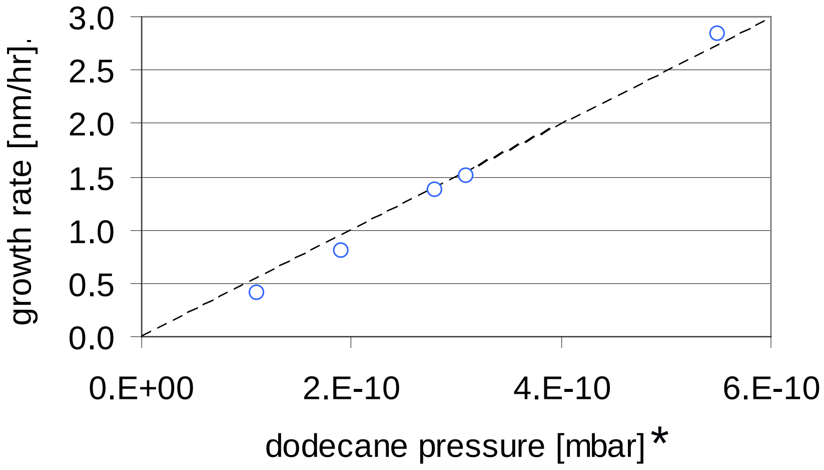
$1.4{\cdot}10^{-8}$ mbar

$1.2{\cdot}10^{-8}$ mbar

flux-limited

Carbon growth - experimental

- Flux-limited carbon growth rate ∝ contaminant pressure
  - Large fraction (>10%) of incident flux is ‘carbonized’
    - Worst-case obviously 100%
  - Flux-limit depends on few (known) parameters



* Pressure calibration not absolute

Carbon growth – litho tools

- Specify a maximum C_xH_y partial pressure in the tool
    - To be achieved by e.g.
        - Cleanliness (handling, cleaning, material selection, …)
        - Pumping

- Maximum C_xH_y pressure yields maximum contamination rate
    - E.g. $p_{max} = 10^{-12}$ mbar gives ~0.01 nm/day ($C_{10}H_{22}$)
    - Still some mitigation needed to achieve years of lifetime

Oxidation

- ‘Vacuum’ contains residual H_2O
  - Litho-tool vacuum compartment cannot be baked!

- H_2O adsorbs on (mirror) surfaces

- EUV photons and secondary electrons cause dissociation[1]
  - Formation of OH and O

- EUV lifetime issue
  - Reflectivity loss by cap- and ‘deep’ oxidation of multilayer mirror

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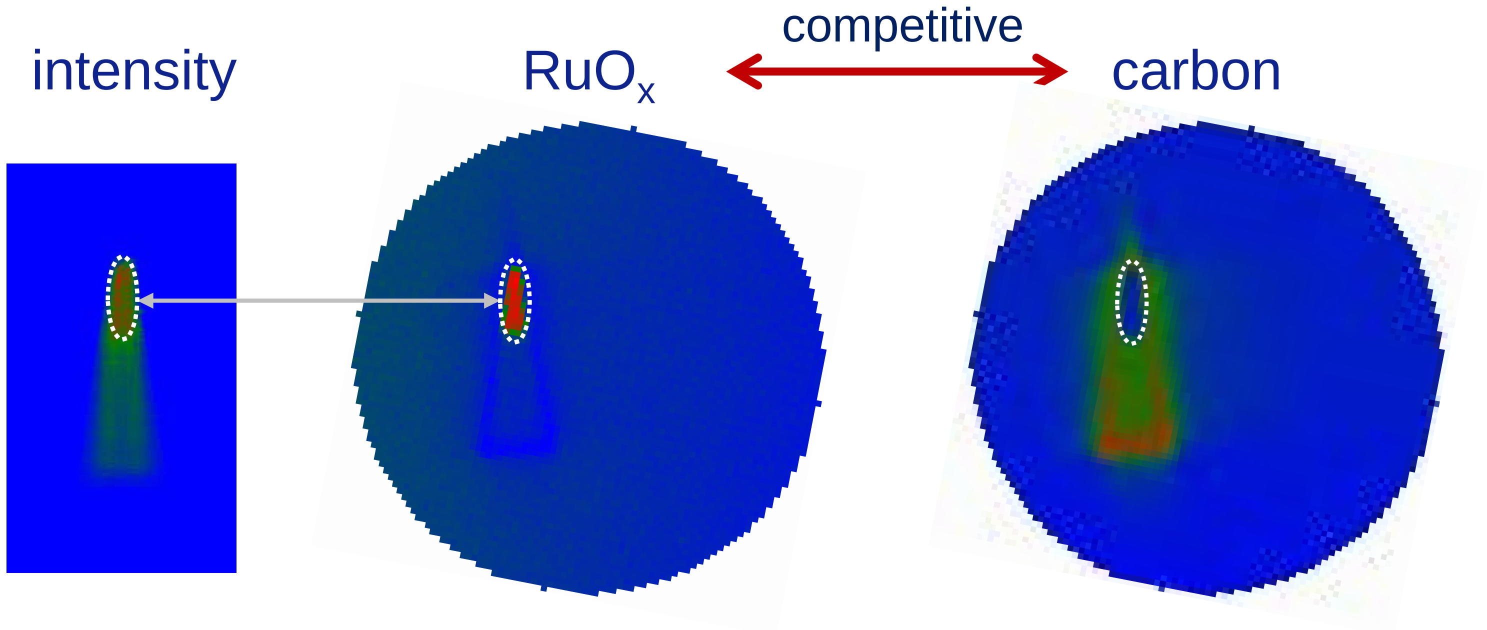
[1] F. Liu *et al.*, Extreme UV induced dissociation of amorphous solid water and crystalline water bilayers on Ru(0001), Surface Science **646**, 101 (2016)

Oxidation - experimental

Ru-capped MLM

- Synchrotron exposure of a Ru-capped MLM
  - 10^{-6} mbar H_2O
  - 30 mW/mm^2 peak intensity



intensity

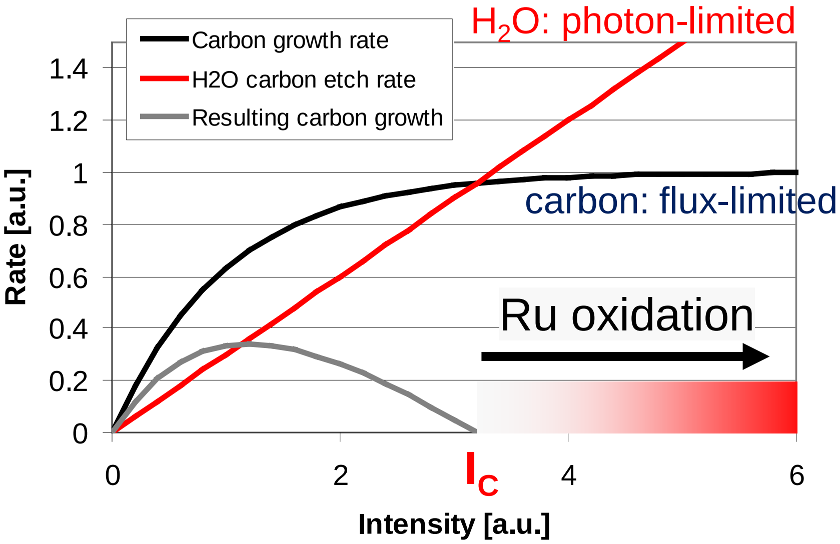
RuO_x

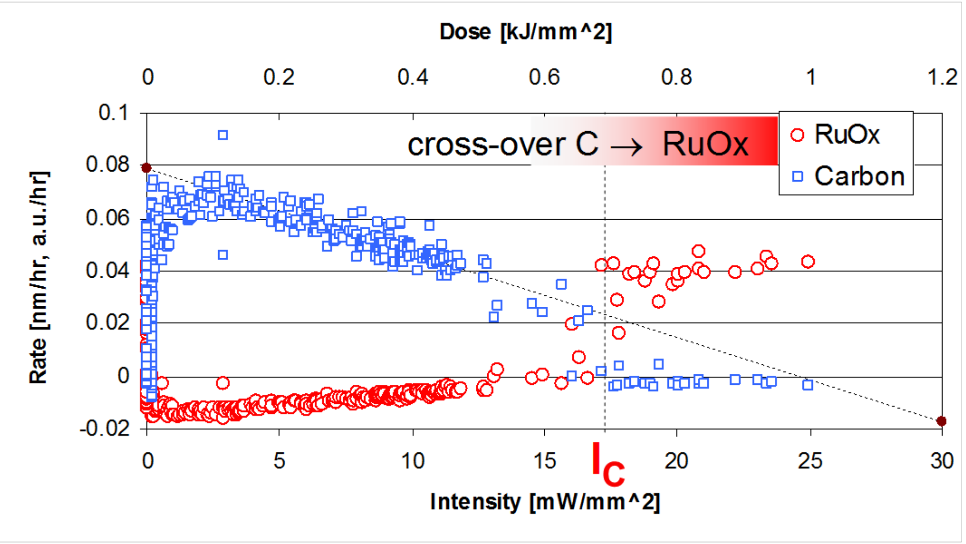
competitive

carbon

Oxidation – carbon growth competition

- Conceptual model
  - Carbon growth saturates with intensity (flux-limited)
  - Oxidation (Ru *and* C) linear in intensity (photon-limited)
  - Cross-over at intensity I_c





Impact

- Carbon growth can be slowed by reducing p_{CxHy}
  - E.g. $p_{max} = 10^{-12}$ mbar gives ~0.01 nm/day ($C_{10}H_{22}$)
  - Still some mitigation needed to achieve years of lifetime

- But: oxidation occurs above certain EUV intensity

— Either ‘bitten’ by carbon growth or oxidation —

Mitigation options

- Better vacuum
  - $p_{CxHy}\downarrow$, $p_{H2O}\downarrow$, $p_{O2}\downarrow$

practically infeasible

- Controlled C_xH_y contamination
  - Balancing oxidation & carbon growth

intensity dependence

- Carbon growth & (periodic) cleaning

down time, control

- Oxidizing environment
  - O_2, O_3, O^+, …
  - $C + O_2 \rightarrow CO_2$

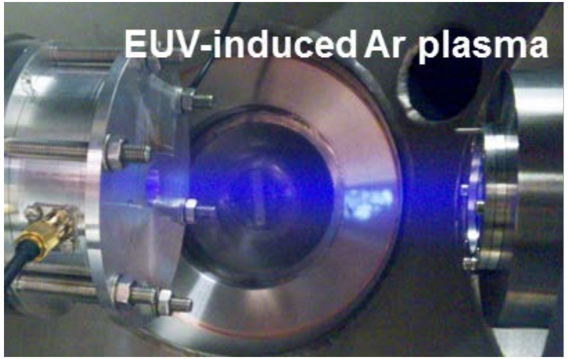
no oxidation-stopping cap?

- Reducing environment

Reducing environment

- **Operate tool with H_2 background gas**

- Generation of an EUV-induced plasma
  - $H_2 + \nu \rightarrow H_2^+ + e^-$ [$H + H^+ + e^-$ / $H^+ + H^+ + 2e^-$]



- Mitigates oxidation by oxide reduction
  - $MO_x + 2x\,H \rightarrow M + x\,H_2O$

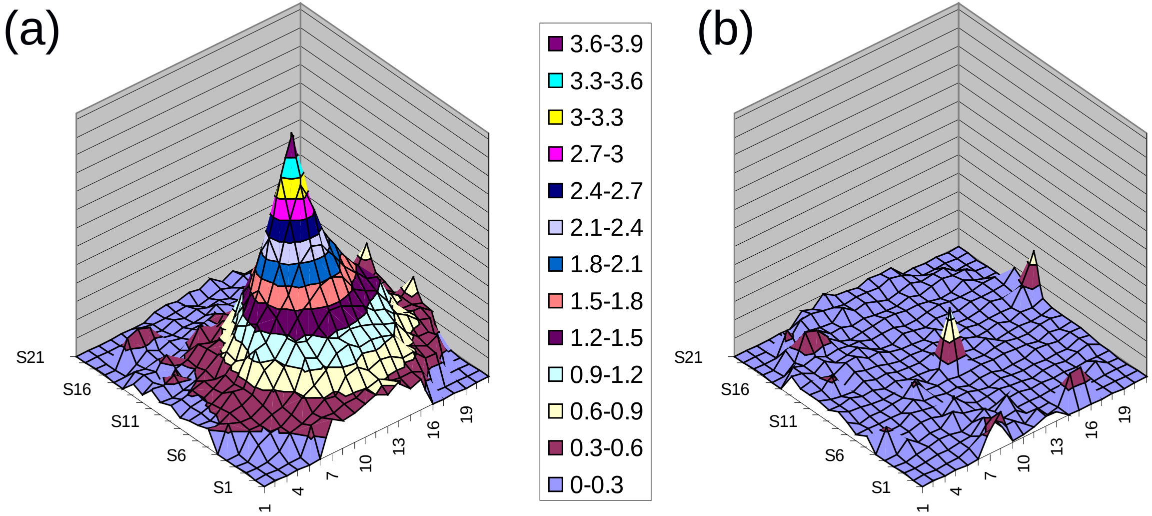
- Mitigates carbon growth by ion- and radical-induced etching
  - $C + 4H \rightarrow CH_{4\,(gas)}$

Reducing environment

Carbon etching / ‘plasma cleaning’

(a) ~4 nm thick carbon spot grown by EUV + dodecane

(b) after EUV + H_2 exposure

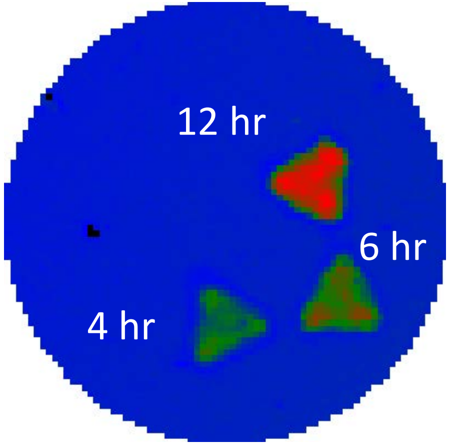


Reducing environment

Oxide reduction

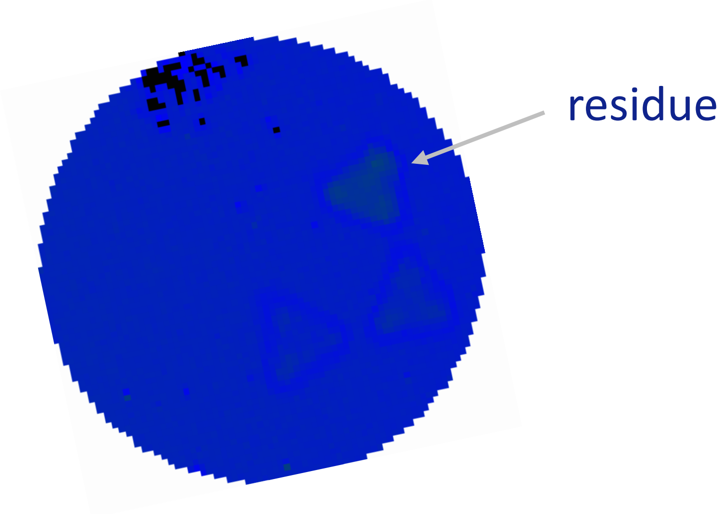
- Oxidized Ru caps can be completely reduced
  - Some residues after ‘deep’ oxidation using atomic H
- **No** EUV-induced oxidation in $H_2/H_2O/O_2$ environments
  - For sufficiently large H_2 fraction

Oxidized (e-gun)



10^{-7} mbar H_2O
1 keV electrons

Cleaned (filament-generated H)



Conclusions

- Direct EUV radiation damage is important
    - Substrates, caps, …

- Carbon growth and oxidation are competitive degradation mechanisms
    - One process will bite you

- Mitigation is possible using e.g. a H_2 ambient

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