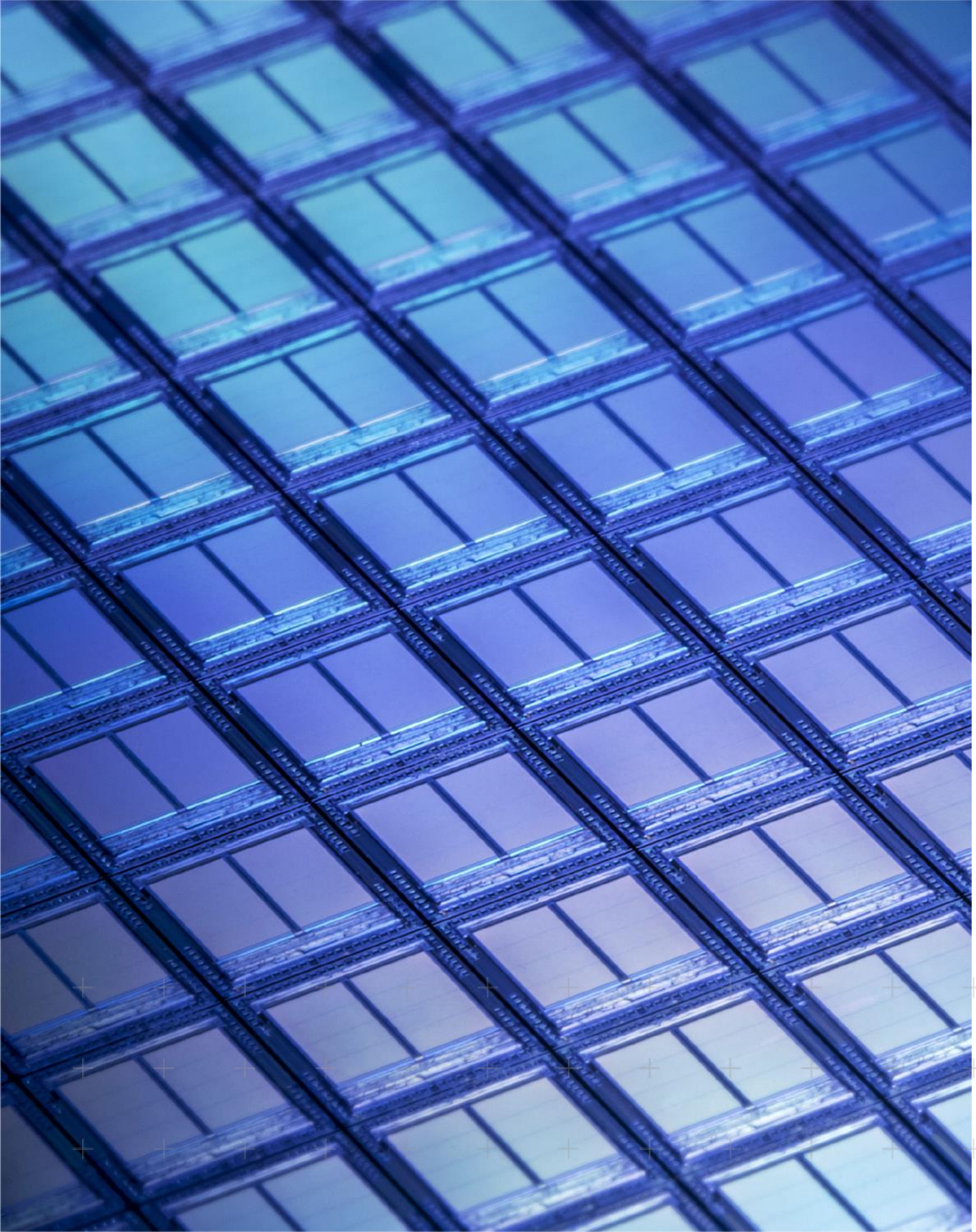


# Source performance metrics for EUV mask inspection

Larissa Juschkin, Dan Wack, and James Westphal

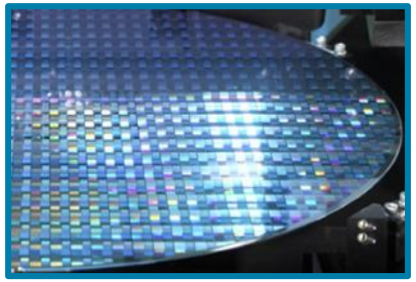
11/04/2020

# Outline

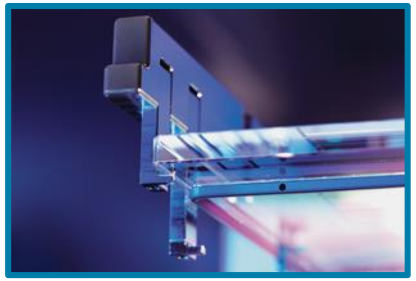
- Introduction of the task of EUV patterned mask defect inspection
  - Differences/similarities to scanner
  - Mask scan and image capture by TDI
- Brightness requirements as a function of sensitivity index, optical contrast, system transmission and throughput
- Source power estimate depending on throughput and photon count per pixel
- Limitations on source brightness set by mask damage threshold
- System and source cleanliness requirements
- Importance of the source availability and life-time

# KLA Markets Served

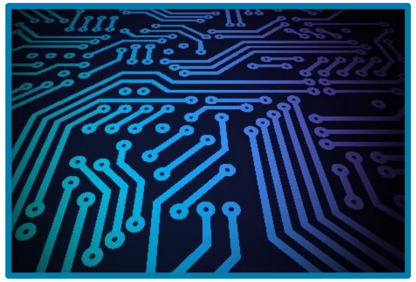
## Semiconductor Manufacturing


IC Manufacturing


Wafer Manufacturing


Reticle Manufacturing


IC Packaging

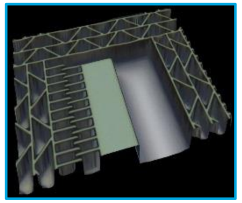

Printed Circuit Board

## Related Electronics Industries


Compound Semiconductor

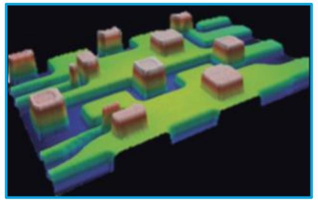

Power Device


LED


MEMS


Data Storage / Media Head


Flat Panel Display


General Purpose / Labs

# Inspection of lithography masks

- Chiphistory.org: KLARIS$^{TM}$ – **KLA** 200 Series Reticle Inspection Systems, time period: **1980’s**
  - **The problem: How can you identify and eliminate killer defects before these are repeated?**
  - “…The inability to compare a photomask pattern to its database can result in a fatal defect being repeated... However, installing a database comparison method ensures that the geometry is correct and that errors are located in a timely manner to avoid...”
- Semiengineering.com, **2020**: “...Defects are unwanted deviations in chips, which can impact yield and performance… Fortunately, several companies are developing new mask inspection systems that can find defects in EUV-based photomasks…”

## We inspected 100% of this mask and increased potential yield in less than 5 minutes.*

### Introducing the KLA-100 automatic photomask inspection system.

**The new KLA-100 inspects photomasks for defects as small as 50 microinches, at a rate of 2 square inches per minute – automatically.**

Using advanced electro-optical pattern recognition techniques, coupled with a microprocessor-based computer system, the KLA-100 virtually eliminates the need for tedious visual inspection by trained operators. Within minutes, the job is done – the number of defects and their locations are recorded – all automatically.

**100% inspection of all photomasks is economically feasible and will increase your yields!**

Whether you're operating a photomask shop, QA, or wafer fabrication area, you'll know for sure the yield characteristics of the photomask before either releasing it to your customer or for production. No longer do you have to rely on random sampling or discarding after a set number of prints. With the new KLA-100, and 100% mask inspection, you'll find the average number of prints per mask will increase and the cost per good die will drop. You'll be able to recognize and react to process control problems faster, too.

---

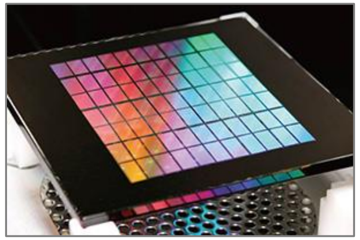
**5 minutes' inspection time, based on a rate of 2 square inches per minute for a 3 inch mask.*

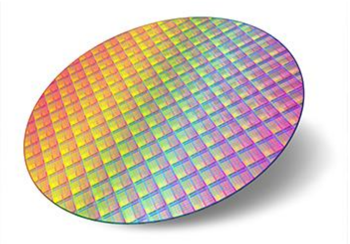
KLA Instruments Corporation
2900 Corvin Drive
Santa Clara, CA 95051
(408) 738-1441

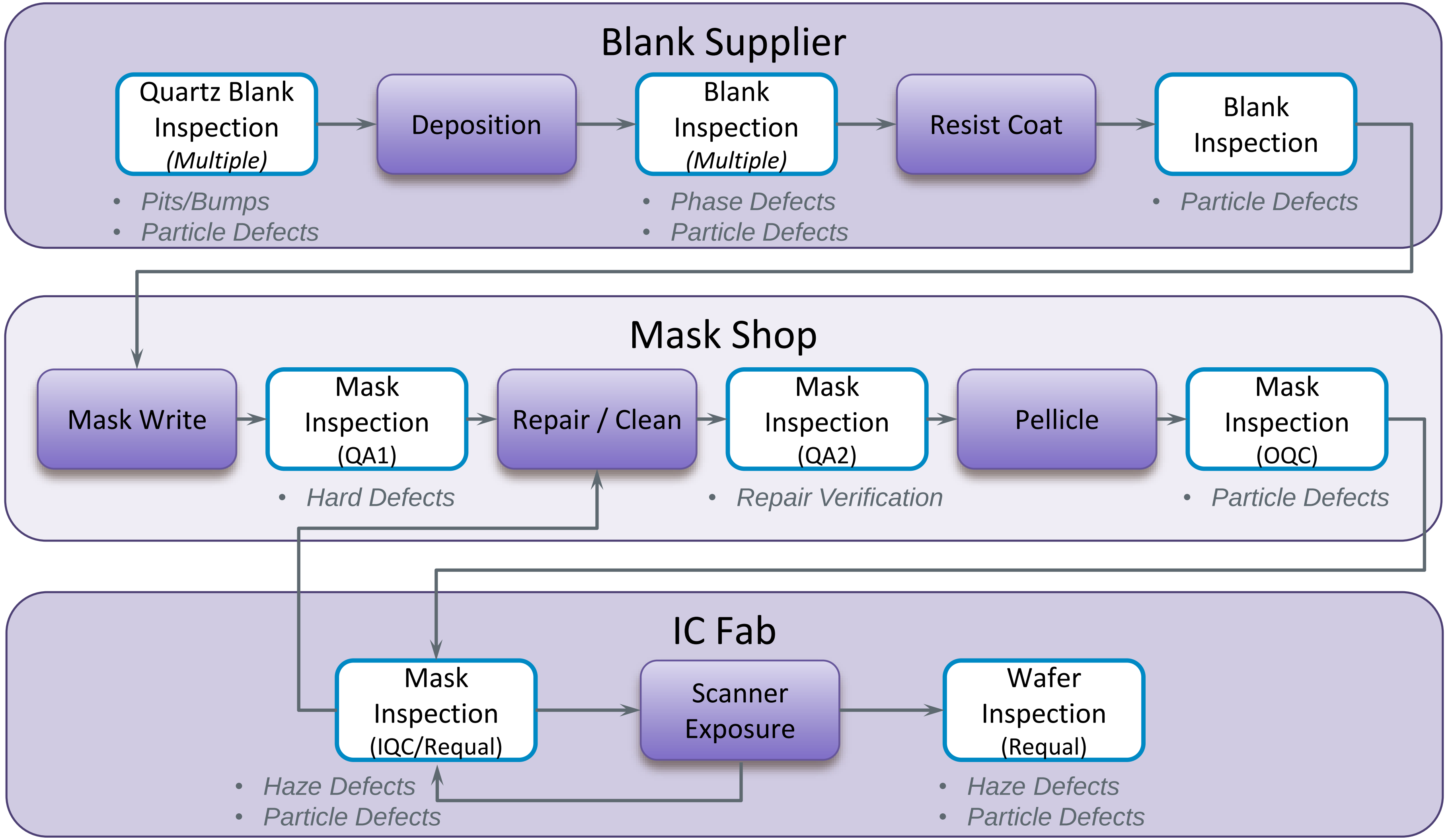
KLA 100
1978

# EUV mask inspection flow

## Inspection critical from blank supply through wafer fabrication







### Blank Supplier

Quartz Blank Inspection *(Multiple)*
- *Pits/Bumps*
- *Particle Defects*

Deposition

Blank Inspection *(Multiple)*
- *Phase Defects*
- *Particle Defects*

Resist Coat

Blank Inspection
- *Particle Defects*

### Mask Shop

Mask Write

Mask Inspection (QA1)
- *Hard Defects*

Repair / Clean

Mask Inspection (QA2)
- *Repair Verification*

Pellicle

Mask Inspection (OQC)
- *Particle Defects*

### IC Fab

Mask Inspection (IQC/Requal)
- *Haze Defects*
- *Particle Defects*

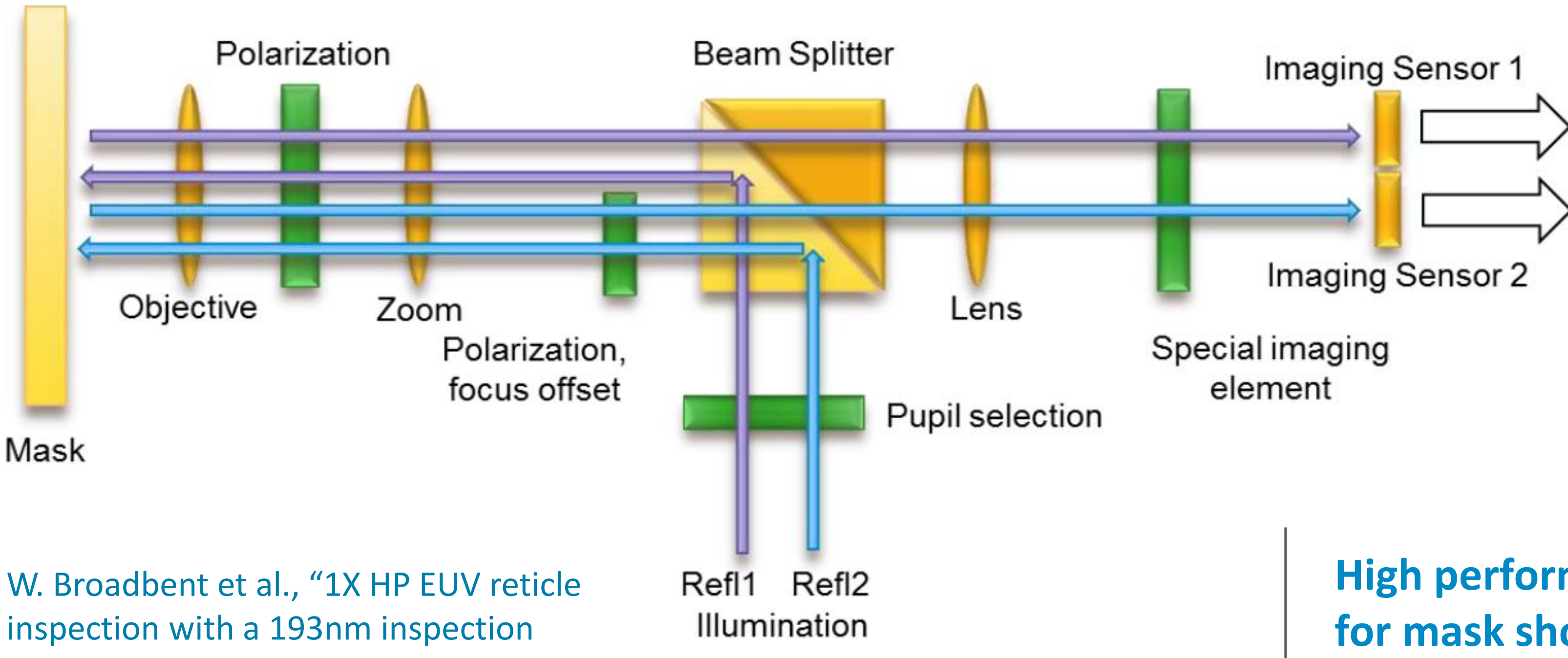
Scanner Exposure

Wafer Inspection (Requal)
- *Haze Defects*
- *Particle Defects*

# Teron™ 647e

## Defect Inspection for EUV and 193 Mask Manufacturing

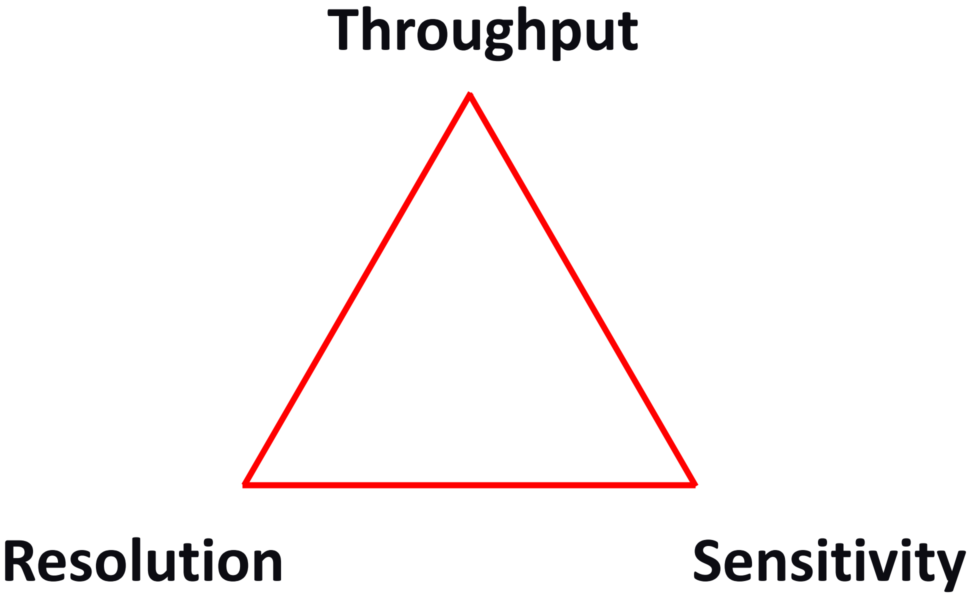
- Mask quality and technical ability to qualify masks are key issues for EUVL.
- Optical inspection systems offer inspection options that are suitable for the development and production of masks down to below 20 nm wafer HP.
  - Innovative optics modes for defect enhancement
  - Advanced database modeling and defect detectors



W. Broadbent et al., “1X HP EUV reticle inspection with a 193nm inspection system”, Proc. SPIE **10451**, 104510M (2017)

**High performance defect quality control for mask shops at 7nm and beyond**

# Inevitable compromises in defect inspection



**Throughput**

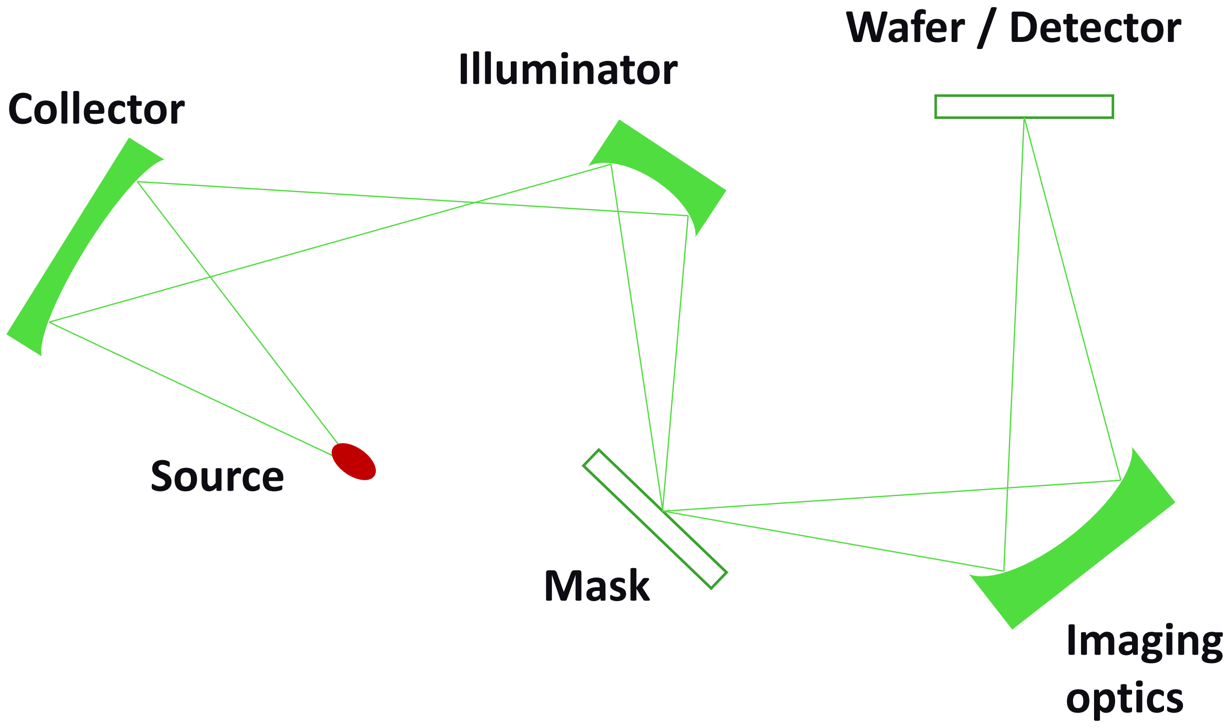
**Resolution**

**Sensitivity**

**⇒ Implications on source requirements for an actinic EUV mask inspector**

# Scanner vs. mask inspector

| Parameter | Scanner | Inspector |
|---|---|---|
| Source | High power | High brightness |
| Illuminator | Large etendue | Small etendue |
| Mask | Moving | Moving |
| Imaging optics | De-magnifying<br>(×1/4)<br>Large FOV | Magnifying<br>(×500-1000)<br>Small FOV |
| Wafer/Detector | Moving | Static, charge transfer |
| Dose control | Pulse count modulation | Reference correction |



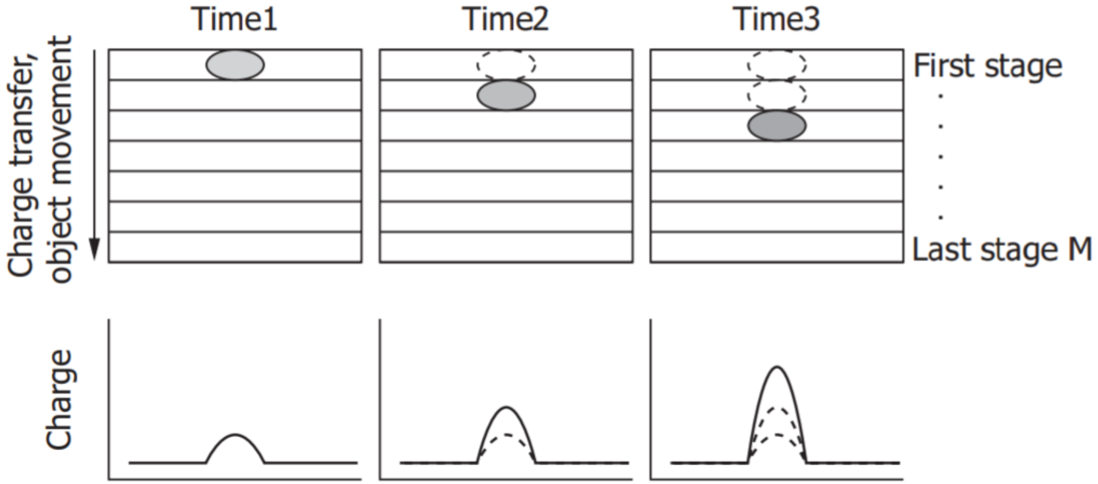
**Mask inspector – typical mask scan and image capture:**

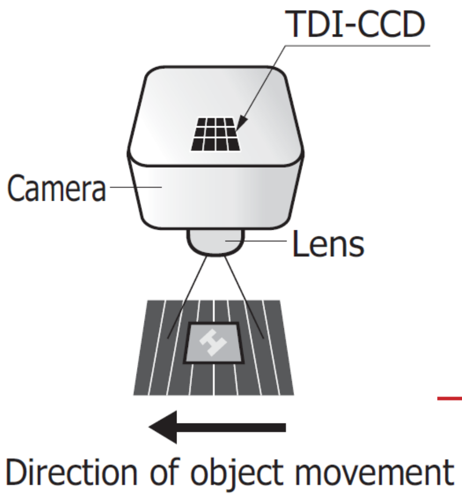
Mask is moved across field of view (FOV) during the image capture: photo-induced charge is shifted to the adjacent pixel columns synchronously with the motion of the image across the array of element.

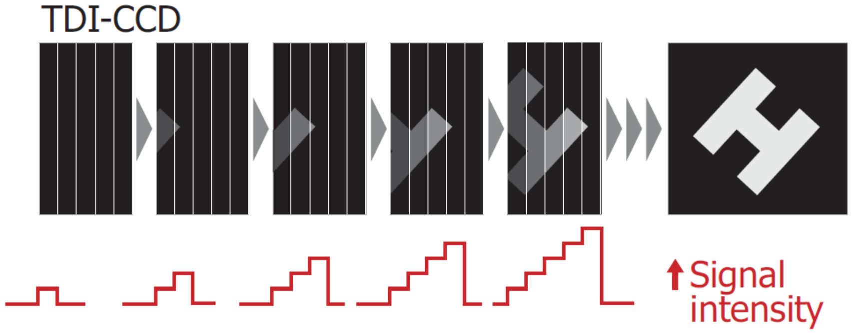
# Time Delay Integration

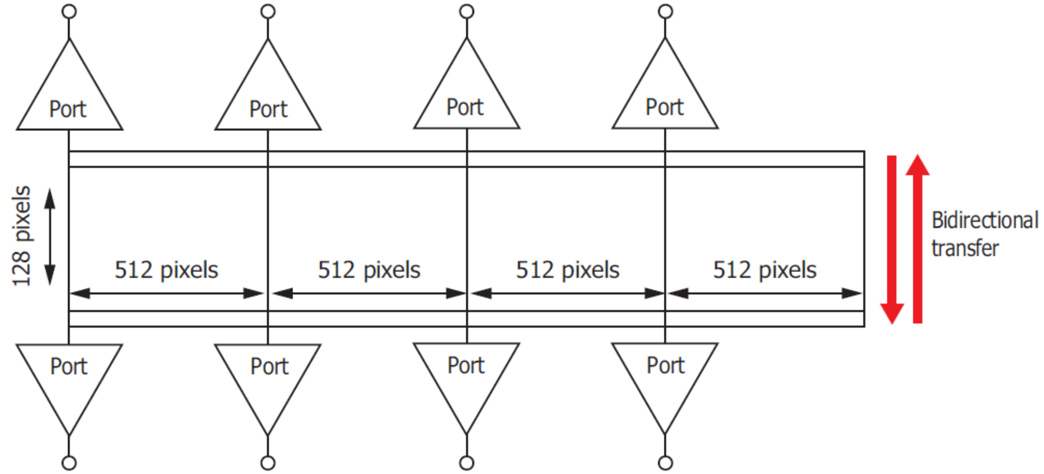
- Detecting low-light-level and/or imaging moving objects
- Image moves on CCD at speed $v$; CCD vertical transfer is synchronized with transfer frequency $f \Rightarrow v = f \cdot p_d$ ↙ ***detector pixel size***
- Signal charge on each row is sequentially output from the horizontal shift register. High speed line-rate using multiple ports (multiple amplifiers arrangement and parallel readout) => Continuous imaging of high-speed moving objects
- Improved sensitivity variations compared to 2d mode

Schematic of integrated exposure in TDI operation









https://www.hamamatsu.com/resources/pdf/ssd/fft_ccd_kmpd9002e.pdf
https://www.hamamatsu.com/resources/pdf/ssd/tdi-ccd_kmpd9004e.pdf

# Pixel size, field of view and throughput

- Signal integration by TDI operation - Integrating exposure of a moving object

*image capture time*

$$t_{image} = t \cdot \frac{\#pix_{det}}{\#pix_{mask}} = t \cdot \frac{N^2 \cdot p^2}{A_{mask}},$$ $N$ – linear detector size in pixels

$t$ – **net** inspection time without overhead (for retrace etc.)

$p = p_d / M$ – pixel size at mask, $M$ – magnification

- Nyquist sampling: at least 2 pixel per resolution
- **Critical sampling**:

*point spread function*

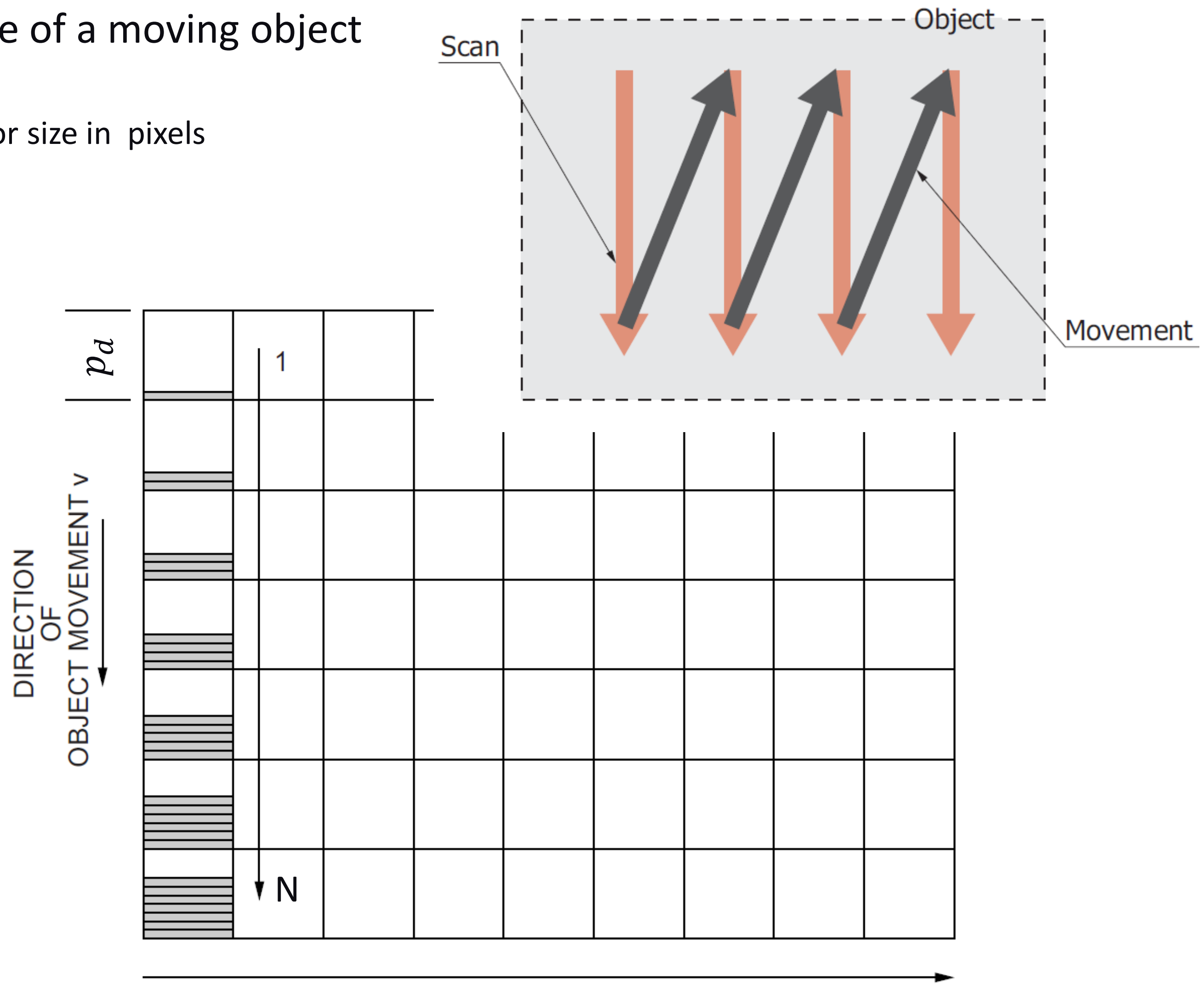
$$p = \frac{\lambda}{4 \cdot NA_{im}}, \ a_{PSF} = \frac{1.22 \cdot \lambda}{NA_{im}}, \ \frac{a_{PSF}}{p} = 4.88$$

- Mask speed:

$$v_{mask} = \frac{p \cdot N}{t_{image}} = \frac{A_{mask}}{t \cdot p \cdot N} = \frac{v}{M}$$

- Line readout rate:

$$f = \frac{v}{p_d} = \frac{v_{mask}}{p}$$



# Requirements on source radiance

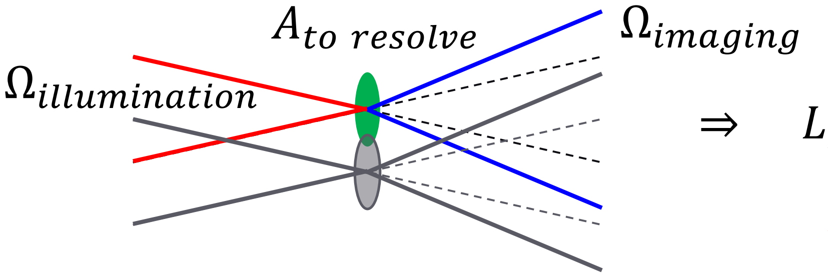
not increasing

not increasing

$$\boxed{\text{Radiance}} = \frac{\text{photon flux}}{\text{etendue}}$$

← not decreasing

**At sample:** $n_{ph}$, $t_{image}$, $\Omega_{illumination}$, $A_{to\ resolve}$



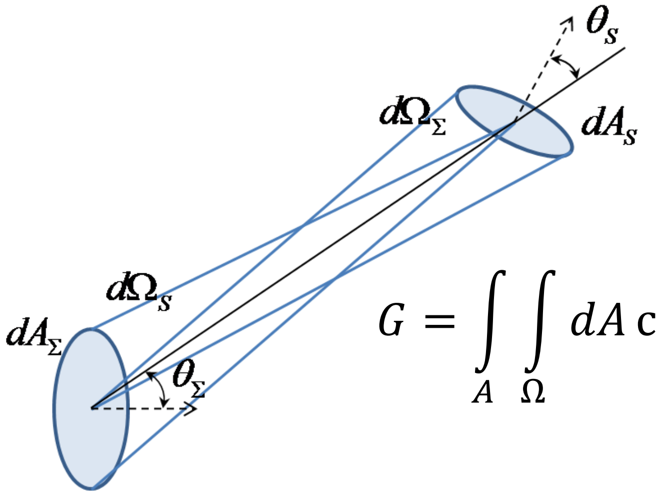
$$\Rightarrow \quad L_{sample} = \frac{n_{ph} \cdot E_{ph}/t_{image}}{\Omega_{illumination} \cdot A_{to\ resolve}}$$

**At source:**

$$\boxed{L_{source} = \frac{n_{ph} \cdot hc/\lambda}{T_{sys} \cdot t_{image} \cdot \Omega_{illumination} \cdot A_{to\ resolve}}}$$

**Resolution matched imaging:** $A_{to\ resolve} = \left(\frac{\lambda}{NA_{im} + NA_{ill}}\right)^2$

$\sigma = NA_{ill}/NA_{im}$ $\quad\quad$ $\Omega_{illumination} = \pi \cdot NA_{ill}^2 = \pi \cdot \sigma^2 \cdot NA_{im}^2$



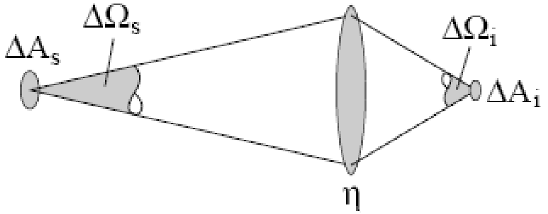
**Etendue:**

$$G = \int_A \int_\Omega dA \cos\theta \cdot d\Omega = \pi \cdot NA^2 \cdot A$$

*NA* – numerical aperture
*A* – area (in field of view)

→ **constant in optical system (at best)**

$\Delta A_s \cdot \Delta\Omega_s = \Delta A_i \cdot \Delta\Omega_i$ ; $\eta = 100\%$



$T_{sys} = T_{ill} \cdot T_{mask} \cdot T_{im} \cdot QE$ – system transmission

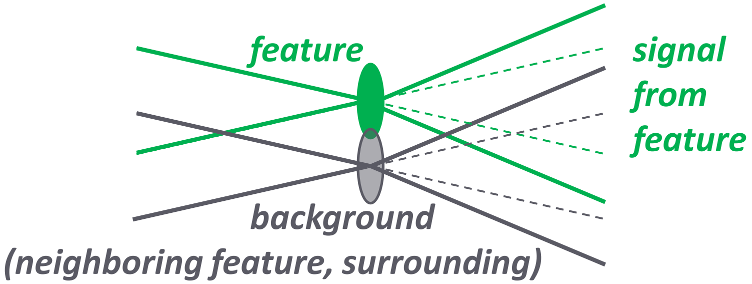
?

$\approx 4/\sigma$ for $\sigma > 0.3$

$$\Rightarrow L_{source} = \frac{hc}{\pi\lambda^3} \cdot \frac{n_{ph} \cdot A_{mask}}{T_{sys} \cdot t \cdot N^2 \cdot p^2} \cdot \frac{(1+\sigma)^2}{\sigma^2}$$

L. Juschkin, “Source radiance requirements for high-resolution imaging and interference techniques”, Source Workshop 2014

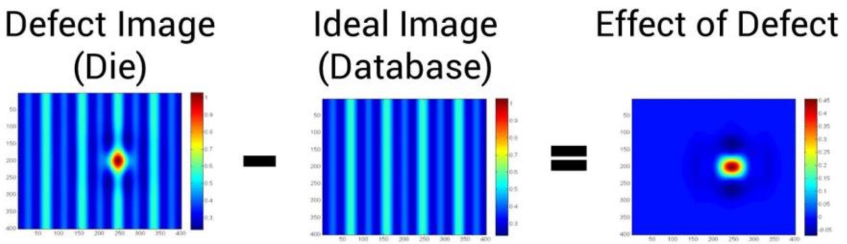
# Photon detections: contrast-defined flux



**Contrast:** $$C = \frac{n_{ph\_f} - n_{ph\_b}}{n_{ph\_f} + n_{ph\_b}} \approx \frac{\text{signal difference}}{\text{signal max}}$$

**Noise:** $$\delta_{ph} = \sqrt{n_{ph\_f} + n_{ph\_b}} \approx \sqrt{\text{signal max}}$$

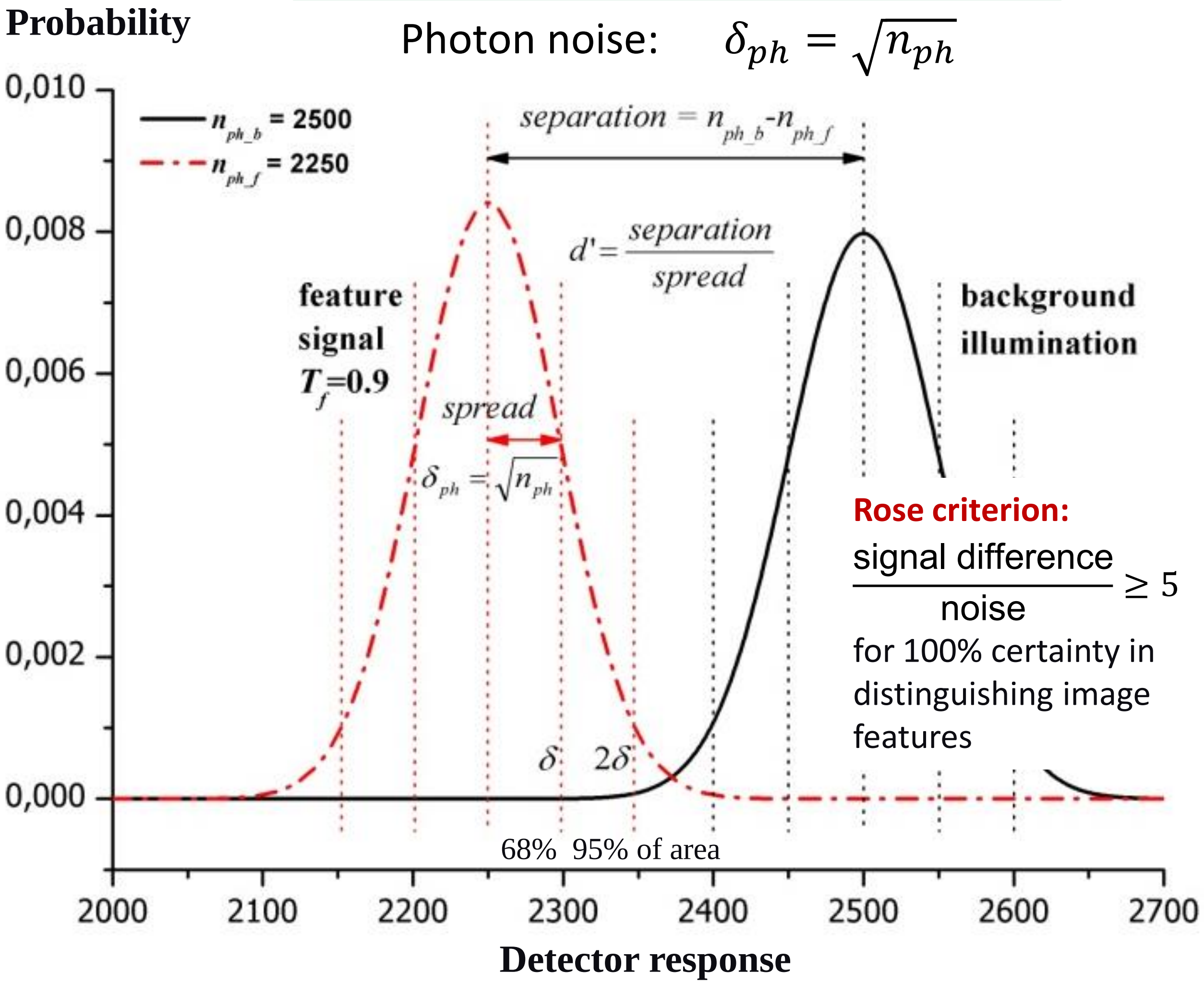
**Contrast in mask inspection:** $$C = \frac{n_{with\ defect} - n_{without\ defect}}{n_{blank\ multilayer}} = \frac{\Delta n}{n}$$



Y.-G. Wang, “Key challenges in EUV mask technology: Actinic mask inspection and mask 3D effects”, PhD thesis UC Berkeley, 2017

photon detections → Poisson statistics

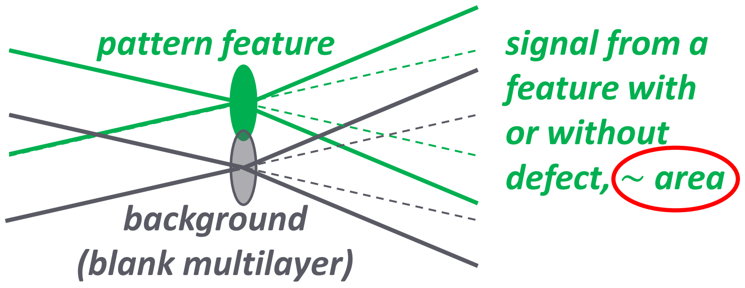
Photon noise: $\delta_{ph} = \sqrt{n_{ph}}$

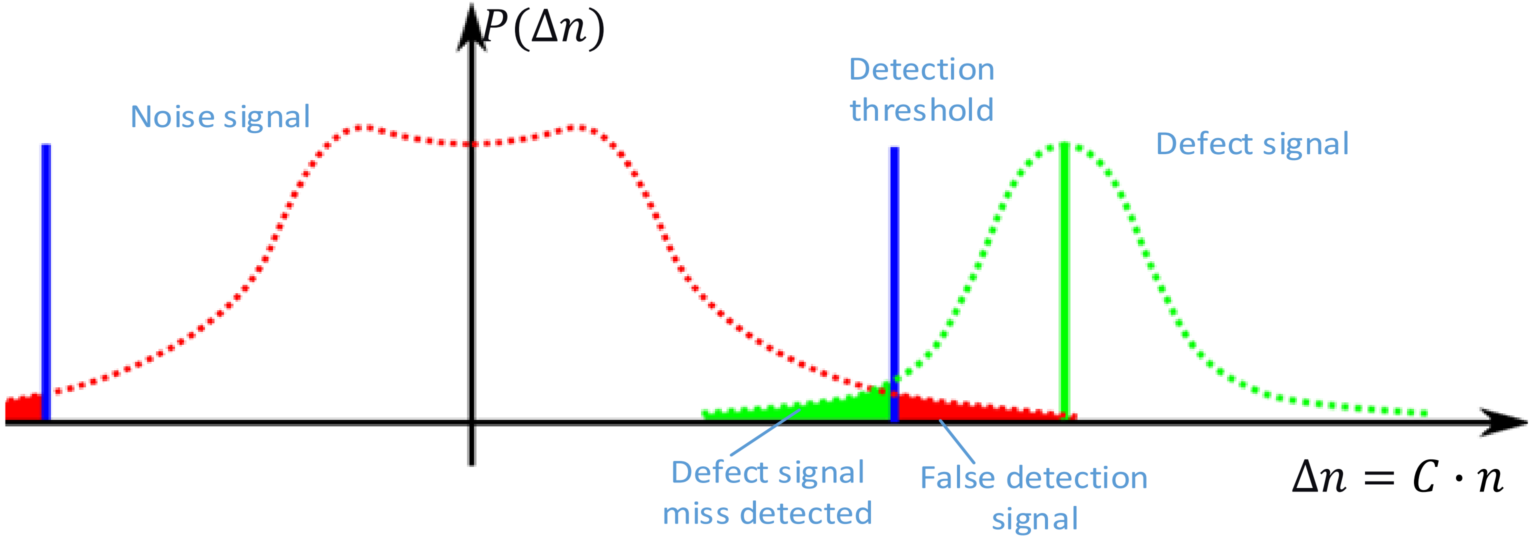


**Rose criterion:**
$$\frac{\text{signal difference}}{\text{noise}} \geq 5$$
for 100% certainty in distinguishing image features

L. Juschkin, “Source radiance requirements for high-resolution imaging and interference techniques”, Source Workshop 2014

# Sensitivity index





***How many photons $n$ need to be detected from a blank multilayer pixel to ensure targeted defect capture rate?***

**Sensitivity index:** $d' = \frac{\text{separation}}{\text{spread}} \geq TNR$

"Signal Detection Theory" or A. Rose, "Television pickup tubes and the problem of vision", Advances in Electronics **1**, 131-166 (1948)

$$d' = \frac{\Delta n}{\delta} = \frac{C \cdot n}{(1+\varepsilon)\cdot\sqrt{n}} \geq TNR$$

***TNR***: threshold-to-noise ratio, $\gtrsim 7$ for mask inspection depending on targeted defect capture rate

$$\boxed{\Rightarrow n \geq \left(\frac{(1+\varepsilon)\cdot TNR}{C}\right)^2 \approx \frac{TNR^2}{C^2}}$$

**Noise:** $\delta = (1+\varepsilon)\cdot\delta_{ph}$

$\delta_{ph} = \sqrt{\text{signal max}} \approx \sqrt{n}$

$\varepsilon$: noise overhead

**Quasi-ideal detector:** $\varepsilon \ll 1$

(signal noise dominating)

***How to estimate signal $\Delta n$, i.e. contrast $C$?***

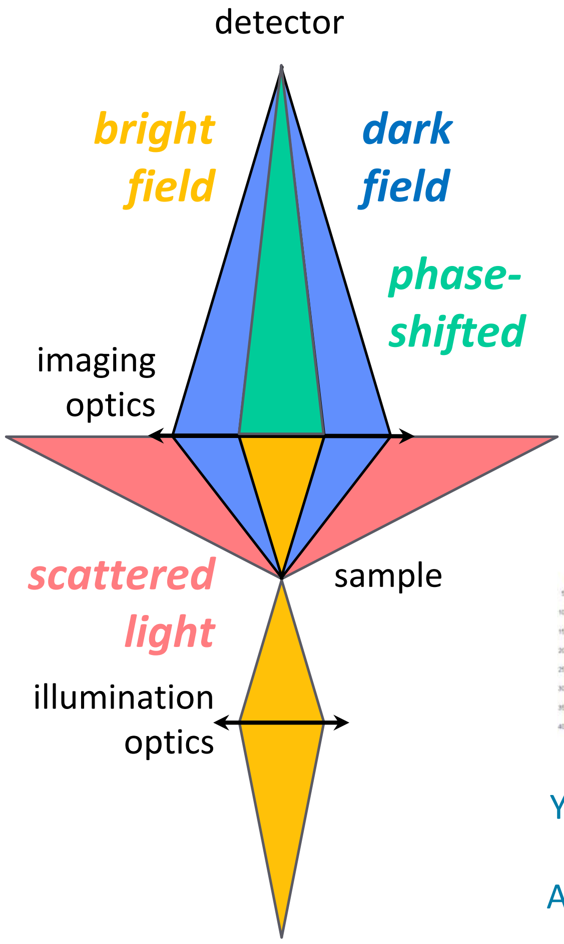
Absorbing defect within pattern area $A$: $C \cong \frac{(T_{defect} - T_{pattern})\cdot A_{defect}}{T_{mask\ blank}\cdot A} \approx \frac{-A_{defect}}{A_{to\ resolve}}$

**Sub-resolution detection:**

$A_{defect} \leq A_{to\ resolve}$

***small absorber on multilayer***

# Impact of illumination conditions, material properties, defect and pixel sizes on defect sensitivity and its peak signal



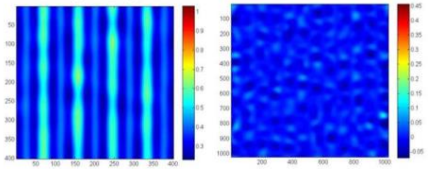
defect scatter pattern scatter

$$C = \frac{SC_d - SC_p}{SC_{ml}}, \qquad SC = \int_{\Omega_{im}} DSC \, \mathrm{d}\Omega$$

surface scatter

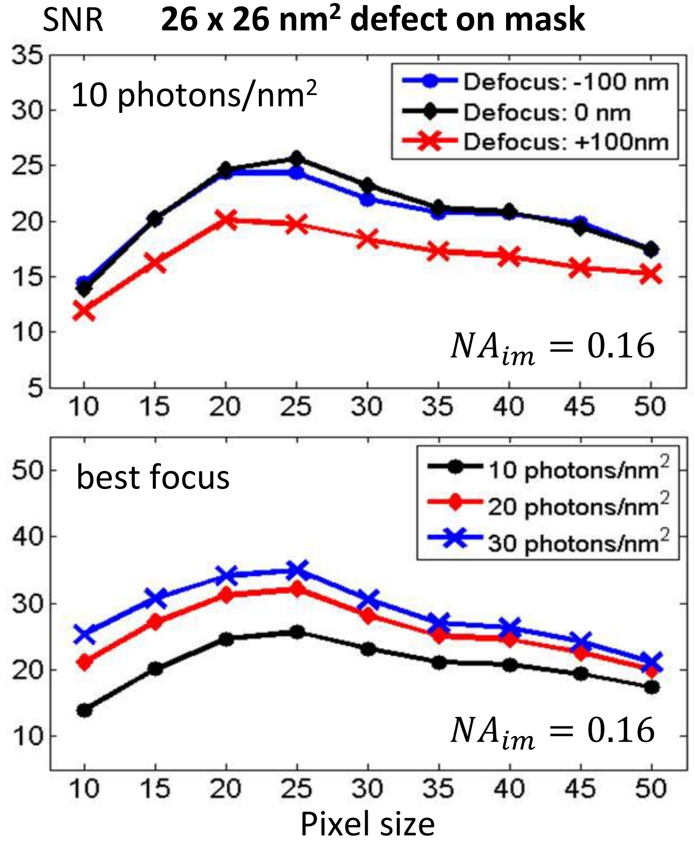
DSC: differential scattering cross-section
SC: scattering cross-section – probability of finding a scattered particle within a given solid angle,
~ defect area × scattering efficiency into objective NA

Effect of roughness

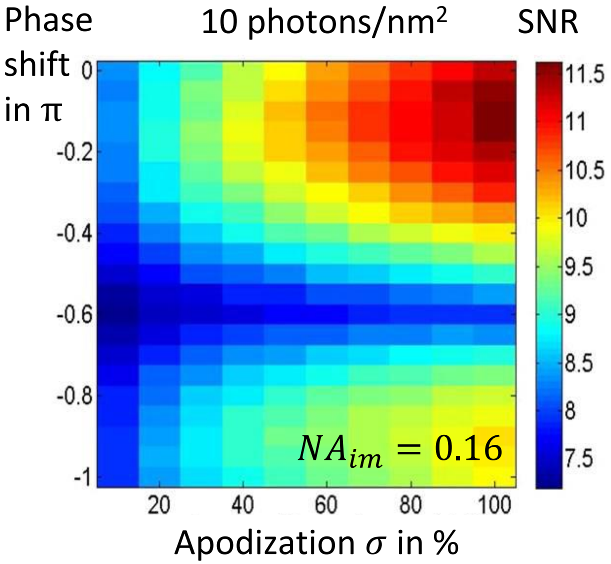


Y.-G. Wang, "Key challenges in EUV mask technology: Actinic mask inspection and mask 3D effects", PhD thesis UC Berkeley, 2017

26 x 26 nm² defect on mask



**Sensitivity index at best focus for an intrusion defect with a size of 26 x 26 nm² on mask, 10 nm pixel size at mask**



# Defect impact – contrast vs. ΔCD/CD on wafer

- **Defect printability in scanner**: defect impact is measured by the CD change
- Specification on min photon flux is governed by most challenging defects.
  => Kamo et al. reported strongest impact for protrusion defects.

$$\frac{\Delta CD}{CD} \approx \frac{A_{defect}[\text{nm}^2]}{4000} \cong \left(\frac{a[nm]}{\underbrace{4\cdot 16}}\right)^2$$

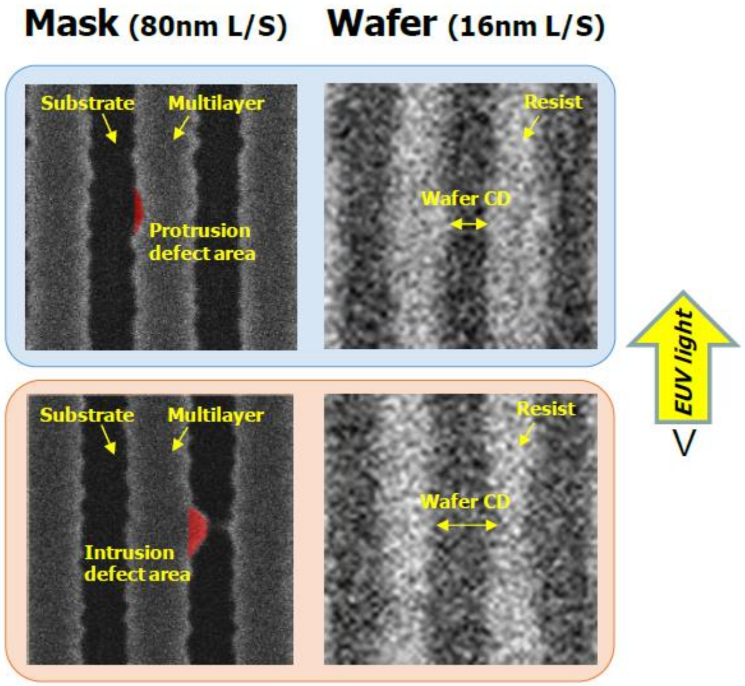
$a = \sqrt{A_{defect}}$ – defect size ~ ***hp*** *(mask half-pitch)*

**Protrusion defect: small absorber on multilayer**

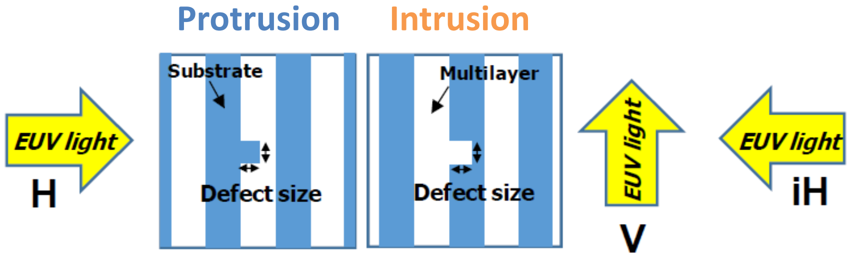
$$|C| \approx \frac{A_{defect}}{A_{to\,resolve}} \approx \left(\frac{a}{hp}\right)^2 \cong \frac{\Delta CD}{CD}$$

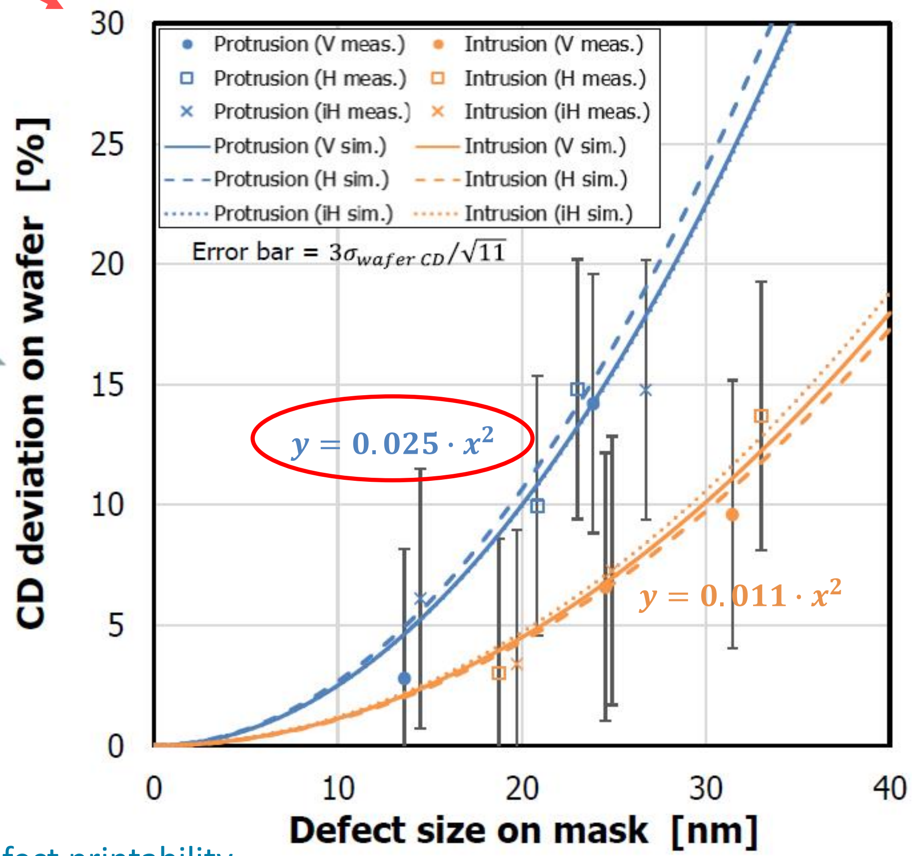
*assuming resolving pattern*

⇒ For $\Delta CD/CD$=0.1, $TNR$=7, $\varepsilon$=0.1, ~6000 detectable photons needed within *hp*-defined area



Defect size: $\sqrt{defect\ area}$





T. Kamo et al., "Mask 3D effect reduction and defect printability of etched multilayer EUV mask", Proc. SPIE **10957**, 109571C (2019)

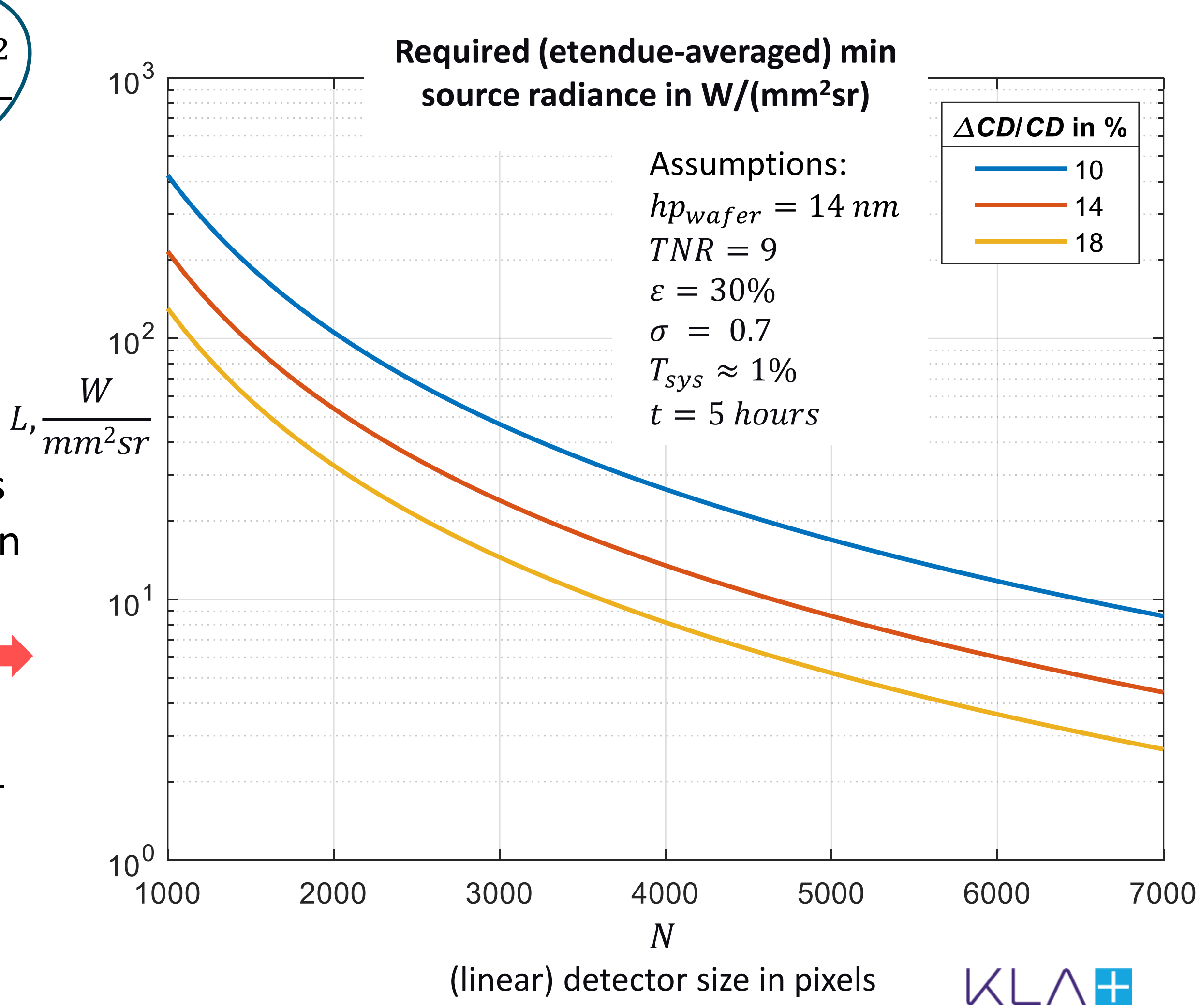
# Scaling laws of required source brightness

- Combining previous findings results in the following scaling of the required source brightness for actinic patterned mask inspection application (with $C$ optical contrast of critical defect and $p$ mask pixel size of an inspection tool):

$$L_{source} = \underbrace{\frac{hc}{\pi\lambda^3}}_{\text{photon energy \& resolution}} \cdot \underbrace{\left(\frac{(1+\varepsilon)\cdot TNR}{C}\right)^2}_{\text{Sensitivity (photon count to ensure targeted defect capture rate)}} \frac{A_{mask}}{\underbrace{T_{sys}\cdot t\cdot N^2}_{\text{throughput}}\cdot p^2} \cdot \underbrace{\frac{(1+\sigma)^2}{\sigma^2}}_{\text{optical part (impacts contrast and resolution)}}$$

- **Practical estimate** using targeted defect sensitivity in terms of $\Delta CD/CD$ and half-pitch at wafer (**assuming** an inspection tool resolving mask half-pitch and having **optical contrast comparable to that of scanner for printable defects**):

$$L_{source} = \frac{hc}{\pi\lambda^3} \cdot \left(\frac{(1+\varepsilon)\cdot TNR}{\Delta CD/CD}\right)^2 \frac{A_{mask}}{T_{sys}\cdot t\cdot N^2\cdot hp_{wafer}^2\cdot \sigma^2}$$



**Required (etendue-averaged) min source radiance in W/(mm²sr)**

# Source power estimate

$$P_{source} = L_{source} \cdot \frac{N^2 \cdot G_{pix}}{ff} = \frac{hc}{16\lambda} \cdot \left(\frac{(1+\varepsilon)\cdot TNR}{C}\right)^2 \frac{A_{mask}\cdot(1+\sigma)^2}{ff \cdot T_{sys} \cdot t \cdot p^2}$$

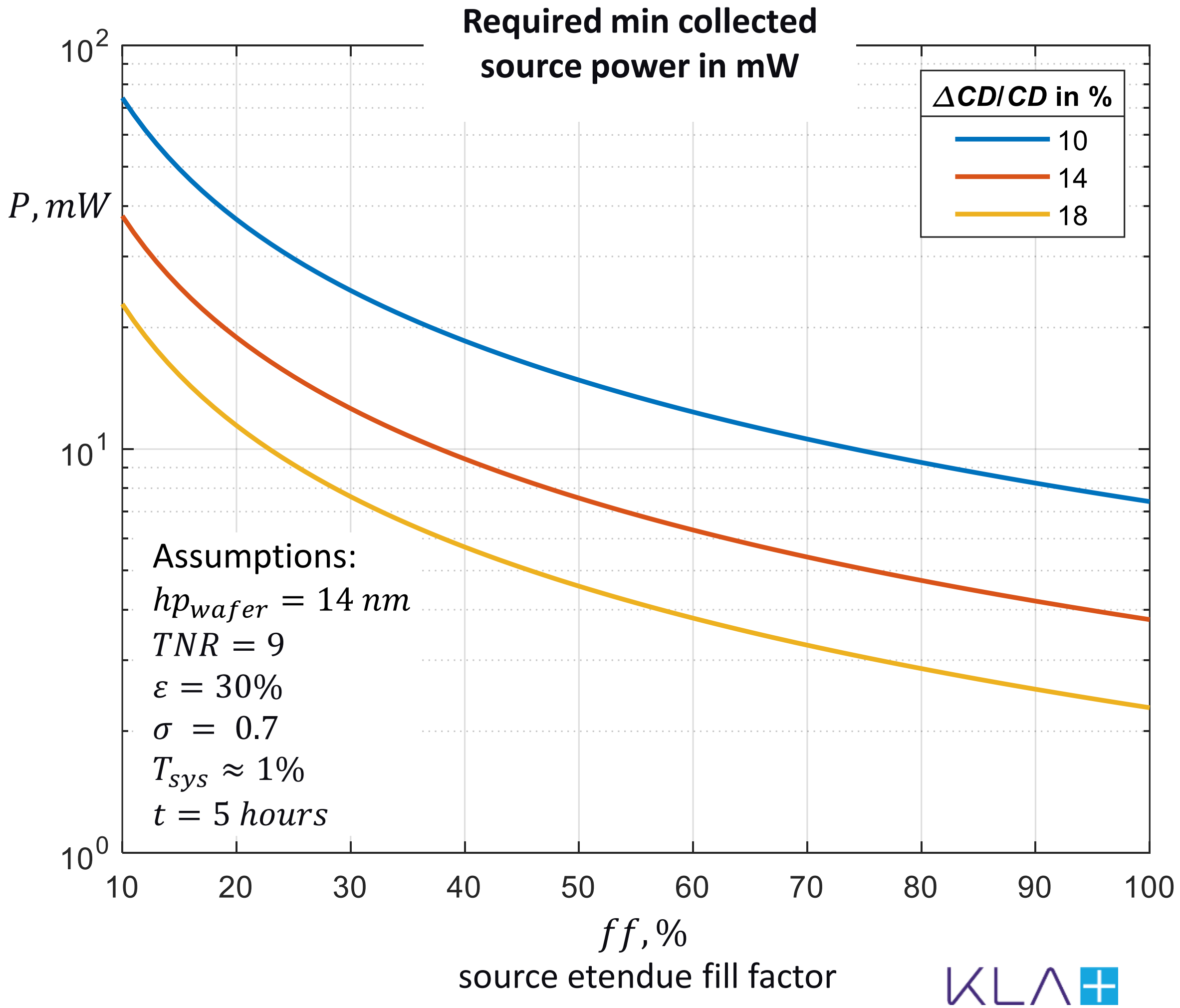
$$\text{Photon flux} = \text{radiance} \cdot \text{etendue}$$

$ff$ – etendue fill factor (ratio of usable power to collected power)

- Estimate using $\Delta CD\ /\ CD$ and half-pitch at wafer:

$$P_{source} = \frac{hc}{16\lambda} \cdot \left(\frac{(1+\varepsilon)\cdot TNR}{\Delta CD/CD}\right)^2 \frac{A_{mask}}{ff \cdot T_{sys} \cdot t \cdot hp_{wafer}^2}$$

- Required source power is determined by photon count per pixel, mask size, pixel size at mask and throughput (and is independent of detector pixel number).
- $\gtrsim 20-30$ terapixels need to be inspected at mask with $> 1000$ detected photons per pixel within a few hours.
- HHG sources can't be used for inspection due to insufficient power (about 1 – 100 mW are needed from source which is by far above of what is technically feasible with HHG).



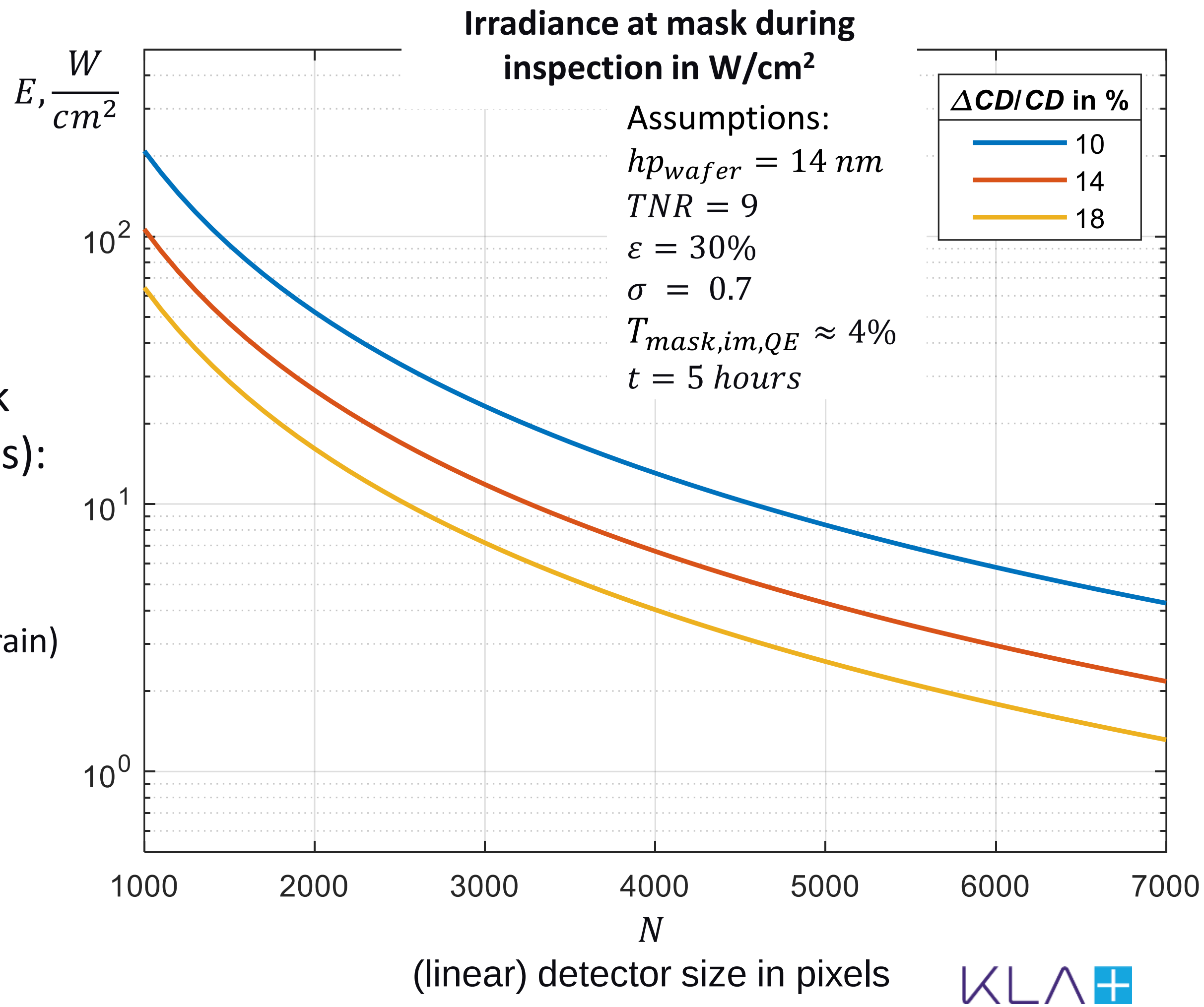
Assumptions:
$hp_{wafer} = 14\ nm$
$TNR = 9$
$\varepsilon = 30\%$
$\sigma = 0.7$
$T_{sys} \approx 1\%$
$t = 5\ hours$

# Limitations on source brightness set by mask damage threshold

- **Irradiance at mask:** $E_{mask} = L_{mask} \cdot \Omega_{ill} = \frac{hc}{16\lambda} \cdot \left(\frac{(1+\varepsilon) \cdot TNR}{C}\right)^2 \frac{A_{mask} \cdot (1+\sigma)^2}{T_{mask} \cdot T_{im} \cdot QE \cdot t \cdot N^2 \cdot p^4}$
- Estimate using $\Delta CD\ /\ CD$ and half-pitch at wafer:

$$E_{mask} = \frac{hc}{16\lambda} \cdot \left(\frac{(1+\varepsilon) \cdot TNR}{\Delta CD/CD}\right)^2 \frac{A_{mask}}{T_{mask,im,QE} \cdot t \cdot N^2 \cdot hp_{wafer}^4 \cdot (1+\sigma)^2}$$

- **Fluence per pulse**: $H_{pulse} = E_{mask}/f_{source}$
- **Damage** mechanisms begin at 10 mJ/cm² for patterned mask (mainly thermally activated and thermomechanical processes):
  - Due to diffusion, $MoSi_2$ is formed at the interfaces between Mo and Si
  - Reduction in period and reflection (compaction due to denser phase)
  - Surface roughening (accumulation of plastic strain due to cyclic thermal strain)
  - At 325°C, the $MoSi_2$ layer crystallizes, followed by complete intermixing
- **Requirement:** $\Delta R/R < 0.1\%$ for 25 inspections
  - ⇒ Lattice constant changes < 5 pm



**Irradiance at mask during inspection in W/cm²**

Assumptions:
$hp_{wafer} = 14\ nm$
$TNR = 9$
$\varepsilon = 30\%$
$\sigma = 0.7$
$T_{mask,im,QE} \approx 4\%$
$t = 5\ hours$

# Limitations on source brightness set by mask damage threshold

- M. Müller et al., “EUV damage threshold measurements of Mo/Si multilayer mirrors”, Appl. Phys. A **108**, 263 (2012)
- S. Bruijn et al., “Thermal stability and lifetime scaling of multilayer EUVL optics” (2009), and references therein
- S. P. Hau-Riege, D. G. Stearns, “Correction of figure errors on optical surfaces by laser-induced contraction of Mo/Si multilayers”, Opt. Lett. **28**, 456 (2003)
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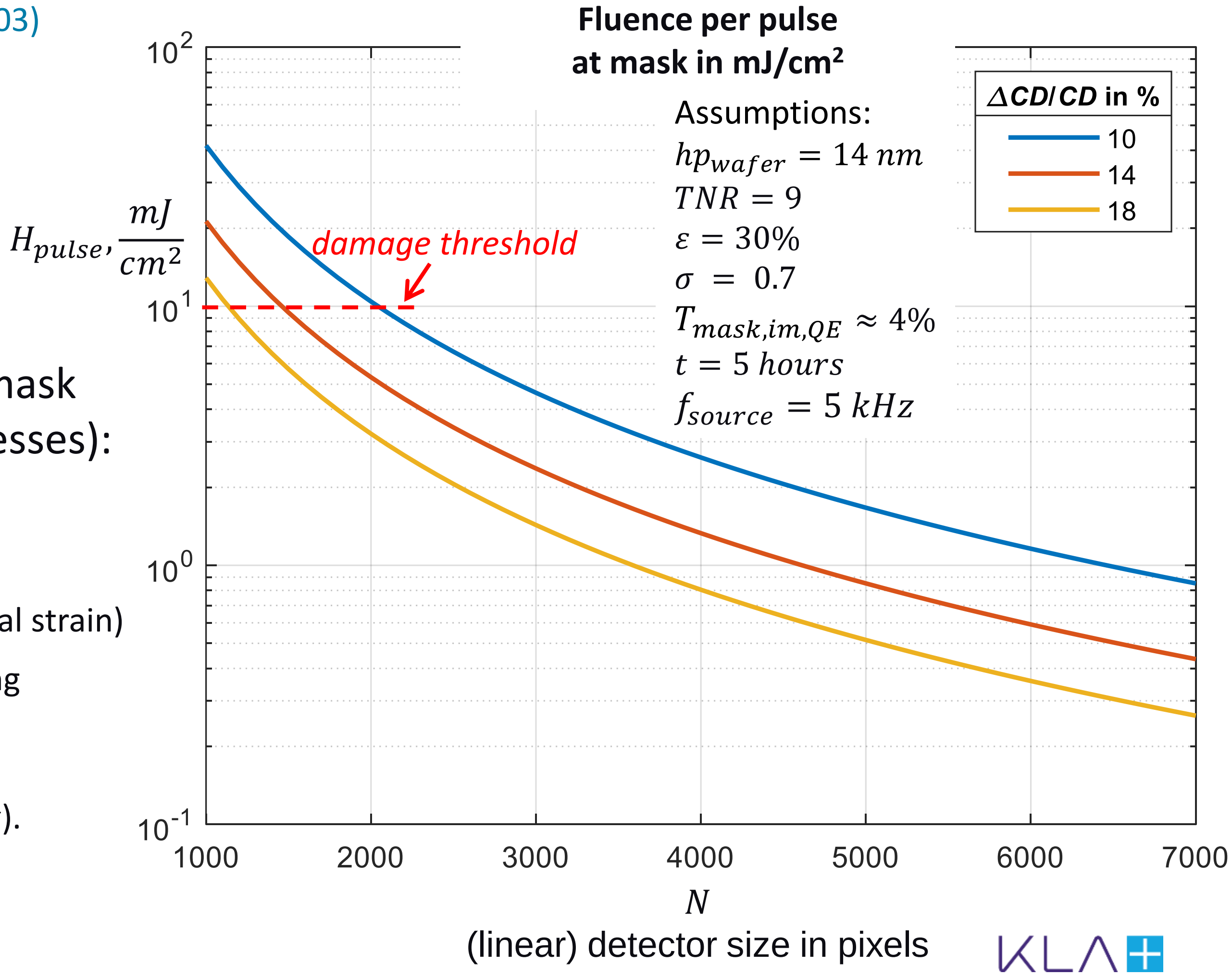
  - At 325°C, the $MoSi_2$ layer crystallizes, followed by complete intermixing
- **Mask damage threshold sets ultimate limit on source brightness** (repetition rate dependent, $\sim 100 \frac{W}{mm^2 sr}$ @ $5\ kHz$).



**Fluence per pulse at mask in mJ/cm²**

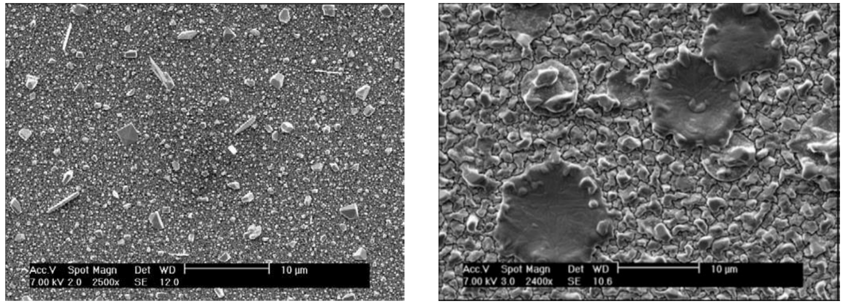
# System and source cleanliness requirements

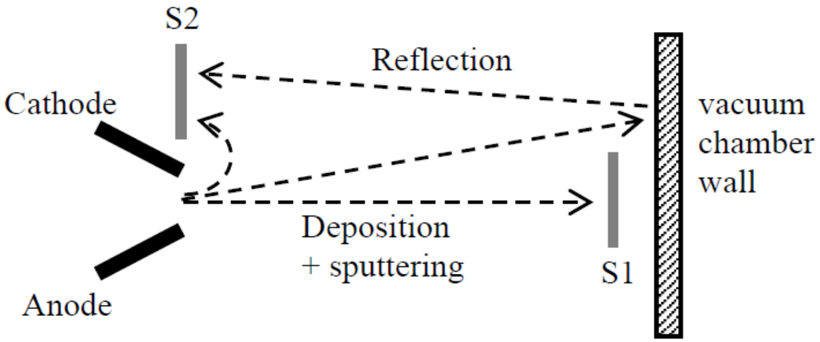
- EUV mask inspection, specifically final one at mask shop, must find defects but **not contaminate**!

  ⇒ These inspectors are the cleanest machines among all tools used in a fab / mask shop.
- Example Teron 640e: less than **0.1 PRP** (particles per reticle pass). ***Requirement will tighten for future nodes!***
- Plasma based sources are the dirtiest parts in EUV tools. In inspectors, the problem of isolating the mask from source debris is more severe than in scanners.
  - Scanner best values: 1 adder per 10k wafers, 140 wafers/hr => ~70 hours (status 2016: 120 adders).

  ⇒ Assuming 5 hrs per mask inspection, it corresponds to at least 1 adder per ~15 inspections! (2016-equivalent: ~10 adders per 1 inspection).
  - Based on scanner research, tin may reach the mask due to secondary effects of bounced/released micro-particles, liquid tin splashing, and accumulation (and sputtering) of deposited tin at the walls.

I. V. Fomenkov, "EUV sources for high-volume manufacturing", from *EUV Lithography*, ed. V. Bakshi (2018)





K. Gielissen, "The nature and characteristics of particles produced by EUV sources: exploration, prevention and mitigation", PhD thesis TU Eindhoven, 2009

# Production systems need high availability and long life-time

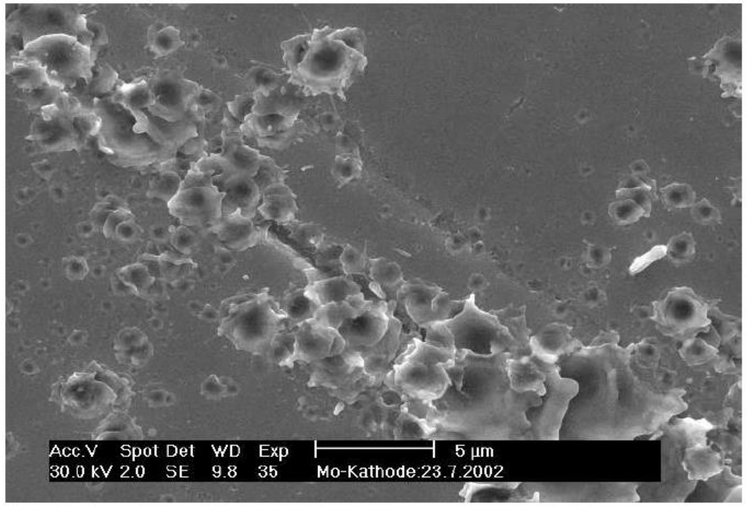
- Every % of tool availability is critical for mask shops that run 24/7. Anything less than 85% is not acceptable.

⇒ In APMI, **the source has to be highly reliable to avoid impact to overall system availability.**

- Plasmas are efficient EUV sources, but to produce one the matter must be ablated > 5000 times per second. The problem of target recovery and life-time is the biggest challenge. This includes life-time of any component facing plasma and/or being in close proximity to it.

- Example of electrode erosion in discharges:
  H. Verbraak et al., J. Appl. Phys. 108, 093304 (2010)
  J. Pankert et al., Proc. SPIE 6151, 61510Q (2006)
  - Electrode mass loss is about 1 g per Mshot (corresponds to 5 kg per 10 days).
  - Electrode life-time of 2 billion shots is reported for LDP concept (corresponds to ~5 days @ 5 kHz).

- For an inspection tool, replacement of components (e.g. electrodes) every week is not an option. Maintenance time of 5-10% represents a serious problem for the entire tool availability.



Electrode surface after one shot in a HCT discharge showing cathode spots

L. Juschkin, G. Derra, and K. Bergmann, “EUV light sources”, from *Low temperature plasmas*, ed. R. Hippler et al. (2008)

# Summary and conclusions

- Mask quality and technical ability to find and eliminate killer defects before they are printed over 100 times/wafer are key issues for EUV lithography.
- The guidelines to determine requirements on source brightness are provided. These are tool dependent and cover large parameter space. Minimum required source radiance of $\sim 10 - 50 \frac{\mathrm{W}}{\mathrm{mm^2 sr}}$ scales quadratically with the targeted defect sensitivity and inversely with throughput and detector pixel number.
- Required source power of ~1 – 100 mW is determined by photon count per pixel, mask size, pixel size at mask and throughput and is independent of detector pixel number.
- Mask damage threshold sets upper limit on source brightness, and lower limit on repetition rate, e.g. $\sim 100 \frac{W}{mm^2 sr}$ @ $5\ kHz$. Higher repetition rates are favorable.
- These inspectors are the cleanest machines among all tools used in a fab / mask shop. Contamination and particle control are extremely critical.
- The source has to have high reliability to not impact the overall system availability. Every 1% availability loss is critical for mask shops that run 24/7. Weekly maintenance is not an option.

# Thank you for attention!

# Scaling laws of brightness requirement

- Combining previous findings results in the following scaling of the required source brightness for actinic patterned mask inspection application (with $C$ optical contrast of critical defect and $p$ mask pixel size of an inspection tool):

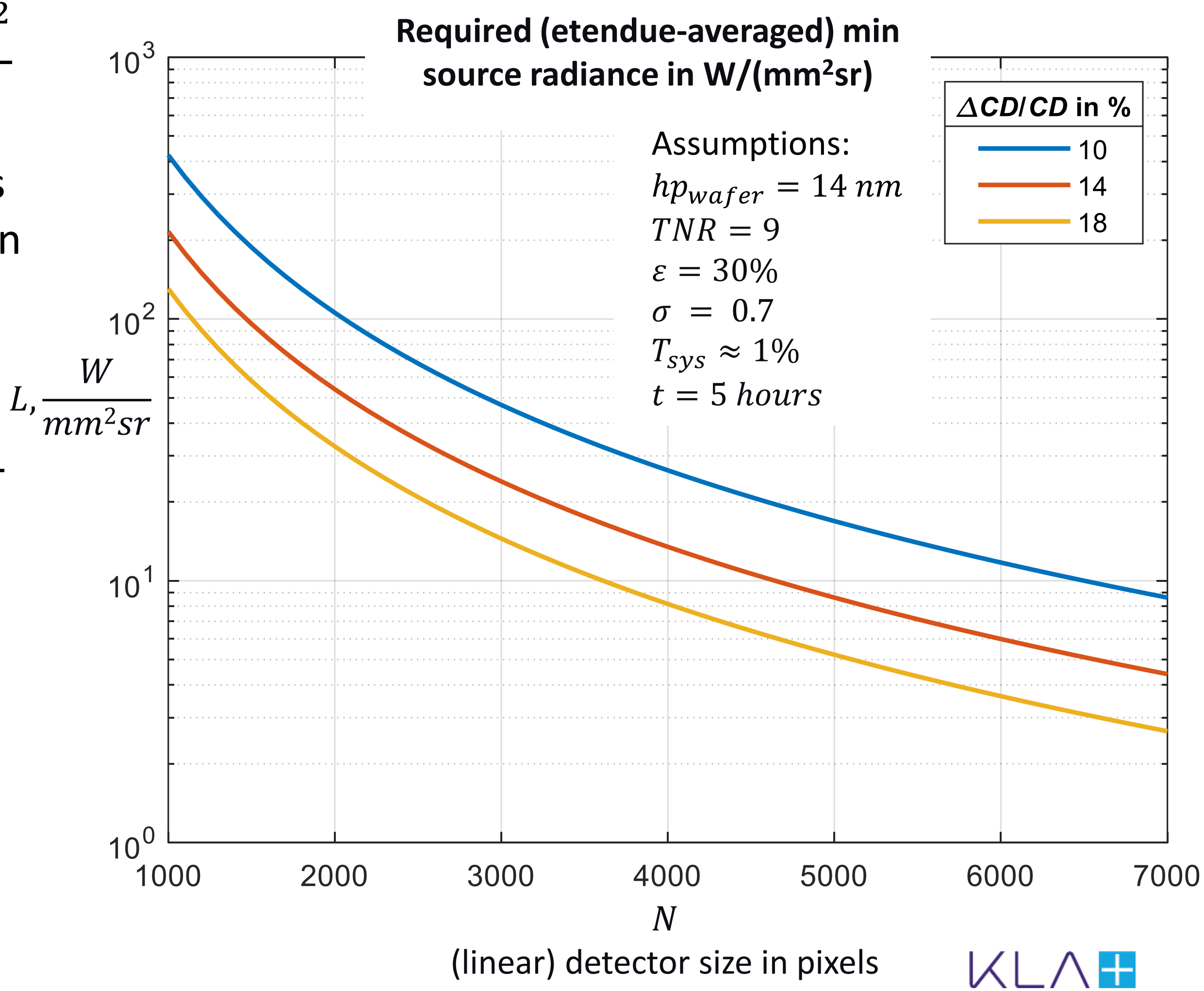
$$L_{source} = \frac{hc}{\pi\lambda^3} \cdot \left(\frac{(1+\varepsilon)\cdot TNR}{C}\right)^2 \frac{A_{mask}}{T_{sys}\cdot t\cdot N^2\cdot p^2} \cdot \frac{(1+\sigma)^2}{\sigma^2}$$

- **Practical estimate** using targeted defect sensitivity in terms of $\Delta CD/CD$ and half-pitch at wafer (**assuming** an inspection tool resolving mask half-pitch and having **optical contrast comparable to that of scanner for printable defects**): ➡

$$L_{source} = \frac{hc}{\pi\lambda^3} \cdot \left(\frac{(1+\varepsilon)\cdot TNR}{\Delta CD/CD}\right)^2 \frac{A_{mask}}{T_{sys}\cdot t\cdot N^2\cdot hp_{wafer}^2\cdot \sigma^2}$$

- Practical estimate using wafer half-pitch and defect area at mask of a critical low-scattering absorption defect of protrusion type (assuming resolving mask half-pitch):

$$L_{source} = \frac{256hc}{\pi\lambda^3} \cdot \frac{(1+\varepsilon)^2\cdot TNR^2\cdot A_{mask}\cdot hp_{wafer}^2}{T_{sys}\cdot t\cdot N^2\cdot \sigma^2\cdot A_{defect}^2}$$



# Total dose at mask

- M. Müller et al., “EUV damage threshold measurements of Mo/Si multilayer mirrors”, Appl. Phys. A **108**, 263 (2012)
- S. Bruijn et al., “Thermal stability and lifetime scaling of multilayer EUVL optics” (2009), and references therein http://euvlsymposium.lbl.gov/pdf/2009/poster/P012_Bruijn_FOMInstitute.pdf
- S. P. Hau-Riege, D. G. Stearns, “Correction of figure errors on optical surfaces by laser-induced contraction of Mo/Si multilayers”, Opt. Lett. **28**, 456 (2003)
- J. Blanchard, “Roughening mechanisms for heated surfaces” (2002) http://homepages.cae.wisc.edu/~blanchar/res/BlanchardRoughening.pdf
- C.-H. Ban et al., “Pattern dependent distortion and temperature variation in EUV mask”, Proc. SPIE **11147**, 111471R (2019)

- **Fluence per pulse:** $H_{pulse} = E_{mask}/f_{source}$

- Dose at mask (total pixel fluence):

$$H_m = E_{mask} \cdot t_{exposure} = E_{mask} \cdot t \cdot N^2 \cdot p^2 / A_{mask} / f_{ff}$$

$f_{ff}$ – field fill factor at mask (ratio of detector field-of-view to illuminated area)

$$H_m = \frac{hc}{16\lambda} \cdot \left(\frac{(1+\varepsilon) \cdot TNR}{\Delta CD/CD}\right)^2 \frac{1}{f_{ff} \cdot T_{mask} \cdot T_{im} \cdot hp_{wafer}^2}$$

- Total dose at mask is determined by photon count per pixel and depends only on targeted defect sensitivity, pixel size and tool efficiency. For actinic inspection, it may become $\gtrsim 1\, J/cm^2$.