EUV mask reflectivity measurements with micron-scale spatial resolution

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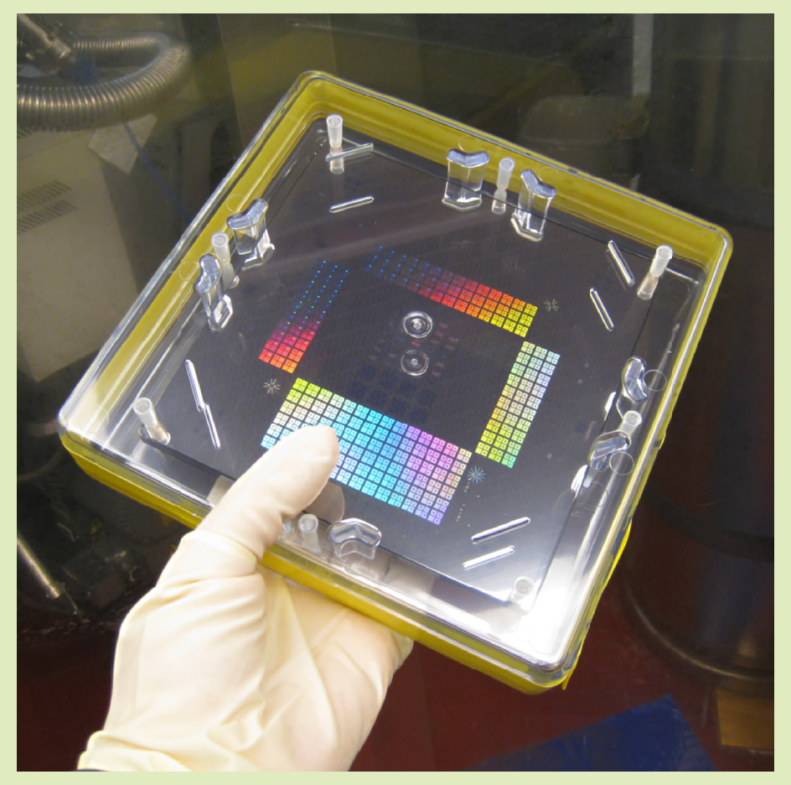
The *SEMATECH Berkeley Actinic Inspection Tool* (AIT) is a dual-mode scaning and imaging EUV microscope dedicated to photomask research



A 6” EUV Reticle
ready for actinic (EUV) inspection

EUV reticles are complex, wavelength-sensitive optical systems. Resonant-reflective multilayer coatings provide high EUV reflectivity below protective layers and patterned absorber structures.

Ultraviolet inspection wavelengths are 20–36x longer than EUV wavelengths; they cannot penetrate below the top few surface layers.

ABSTRACT

The effort to produce defect-free mask blanks for EUV lithography relies on increasing the detection sensitivity of advanced mask inspection tools, operating at several wavelengths. We describe the unique measurement capabilities of a prototype actinic (EUV wavelength) microscope that is capable of detecting small defects and reflectivity changes that occur on the scale of microns to nanometers.

Types of Defects

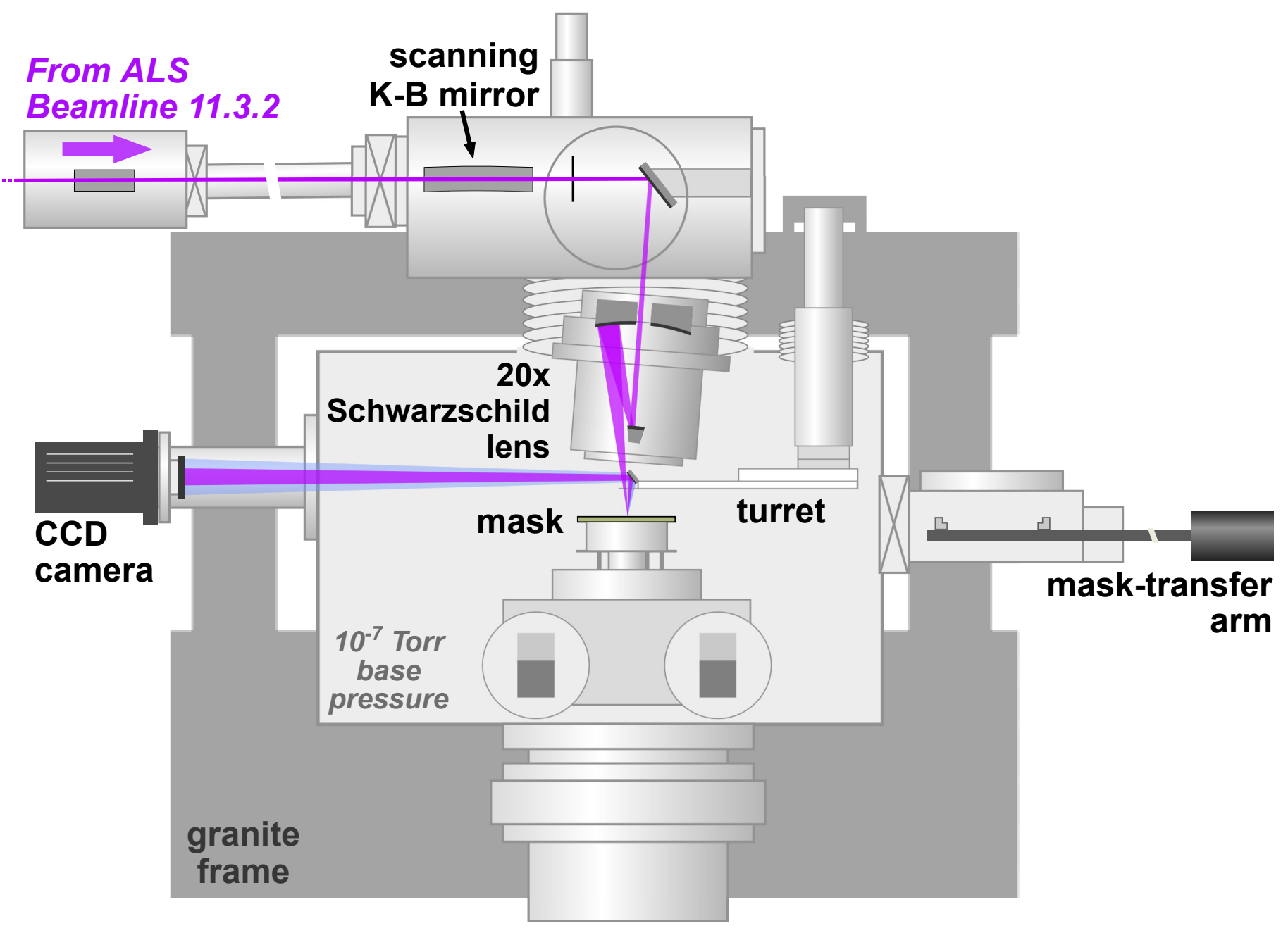
- **Buried Substrate Defects: particles & pits** causes amplitude and/or phase variations
- **Surface Contamination** reduces reflectivity and (possibly) contrast
- **Damage from Inspection and Use** reduces the reflectivity of the multilayer coating.

Scanning Actinic Inspection

This paper presents an overview of several topics where scanning actinic inspection makes a unique contribution to EUVL research. We describe the role of actinic scanning inspection in four cases:

- **Defect Repair** studies
- Observations of **Laser Damage**
- After **Scanning Electron Microscopy**
- **Native and Programmed Defects**

SYSTEM DESIGN



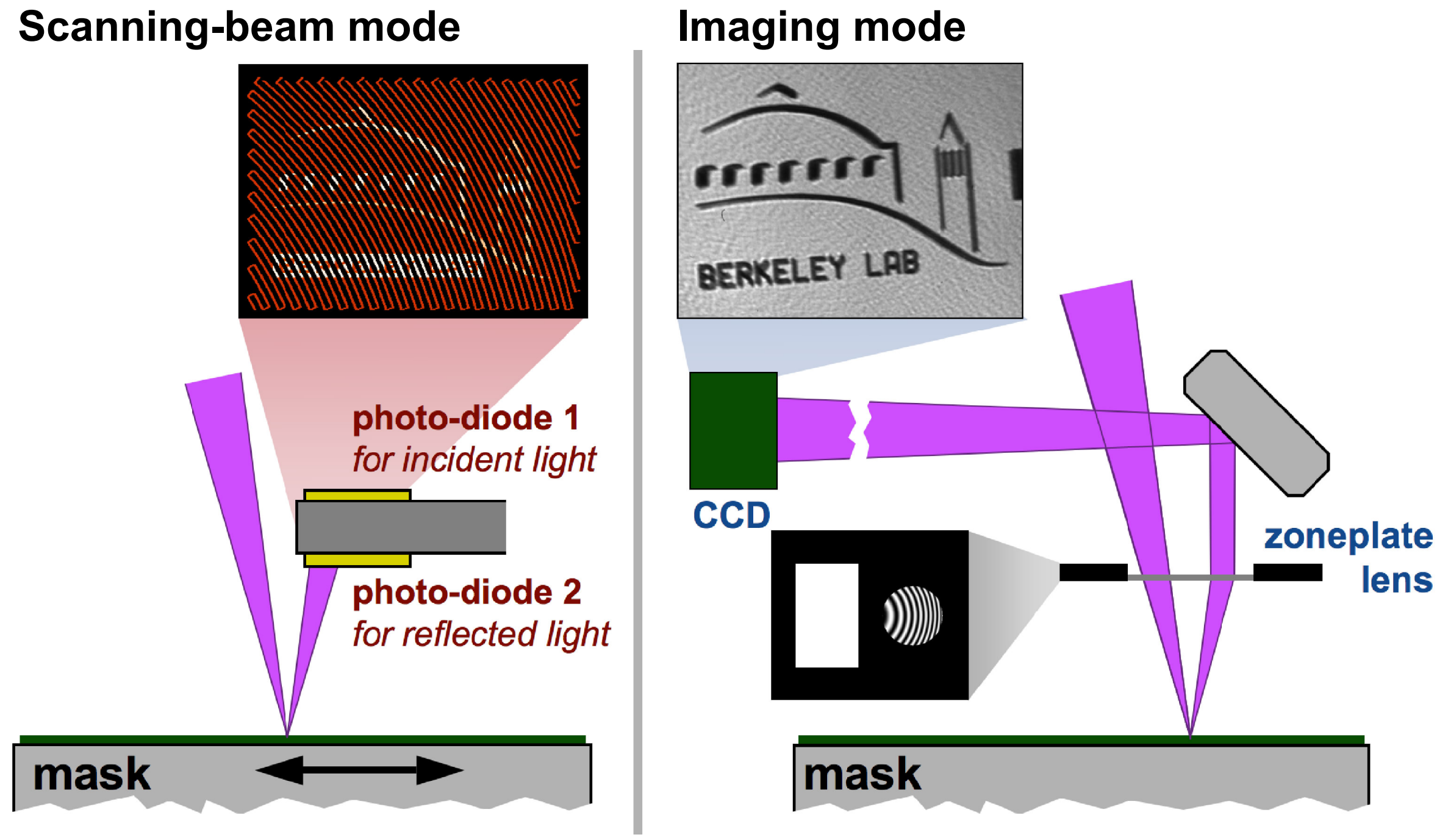
The SEMATECH Berkeley Actinic Inspection Tool (AIT)

At *Lawrence Berkeley National Laboratory’s Advanced Light Source* (synchrotron).

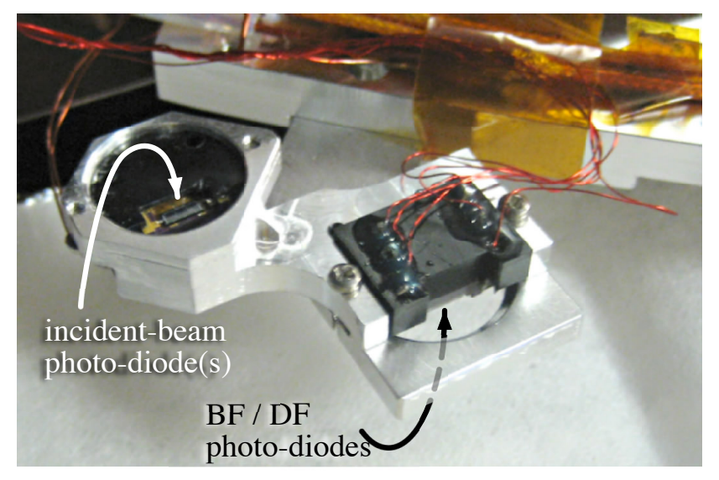
- **Two microscope modes**
  1. **Scanning-beam mode:** The mask moves under the focused beam, while the reflected light is measured.
  2. **Imaging mode”** A tiny Fresnel zoneplate lens projects an image of the mask surface onto an EUV CCD camera.

Two Microscope Modes: Scanning-beam & Imaging

Scanning-beam mode / **Imaging mode**



System Specs in scanning mode



- Monochromatic EUV light ($\lambda = 13.4$ nm)
- 6° incidence angle
- 1–5 μm beam spot
- 1 mm square (IRD) photo-diodes (3x1), 2–5 mm above the mask.
- Bright-field (BF) measures the full specular beam
- Dark-field (DF) measures scattered and re-directed light, outside of the specular beam’s solid angle.
- 1–10 nA, typical BF photo-current
- 10–100 pA, typical DF photo-current
  These low current values require slow-speed scanning

Issues Addressed with Scanning-mode Inspection

In four topics studied below, we review the unique contribution actinic scanning-beam inspection makes to EUV reticle research. We believe that this is an underutilized research capability given the insights developed in previous and new experiments.

MAIN CONCLUSIONS

Dark-field (DF) scanning
- Sensitive to small defects that scatter light. *However,*
- DF is much less sensitive to absorbing surface defects and can only detect them by the *absence* of background scattering.

Bright-field (BF) scanning
- Detects reflectivity changes on μm length scales.
- Much less sensitive to tiny defects than DF, unless focusing is improved.
- Probes damage that can be caused by inspection.
- Can be used to set inspection power levels below the damage threshold.

SEM Inspection
- SEM inspection resulted in carbon staining on a patterned mask.
- In a quick, limited test, we did not detect EUV reflectivity changes.
- Therefore, SEM may not be a very high risk for EUV reflectivity, but more detailed, careful experiments should be performed.

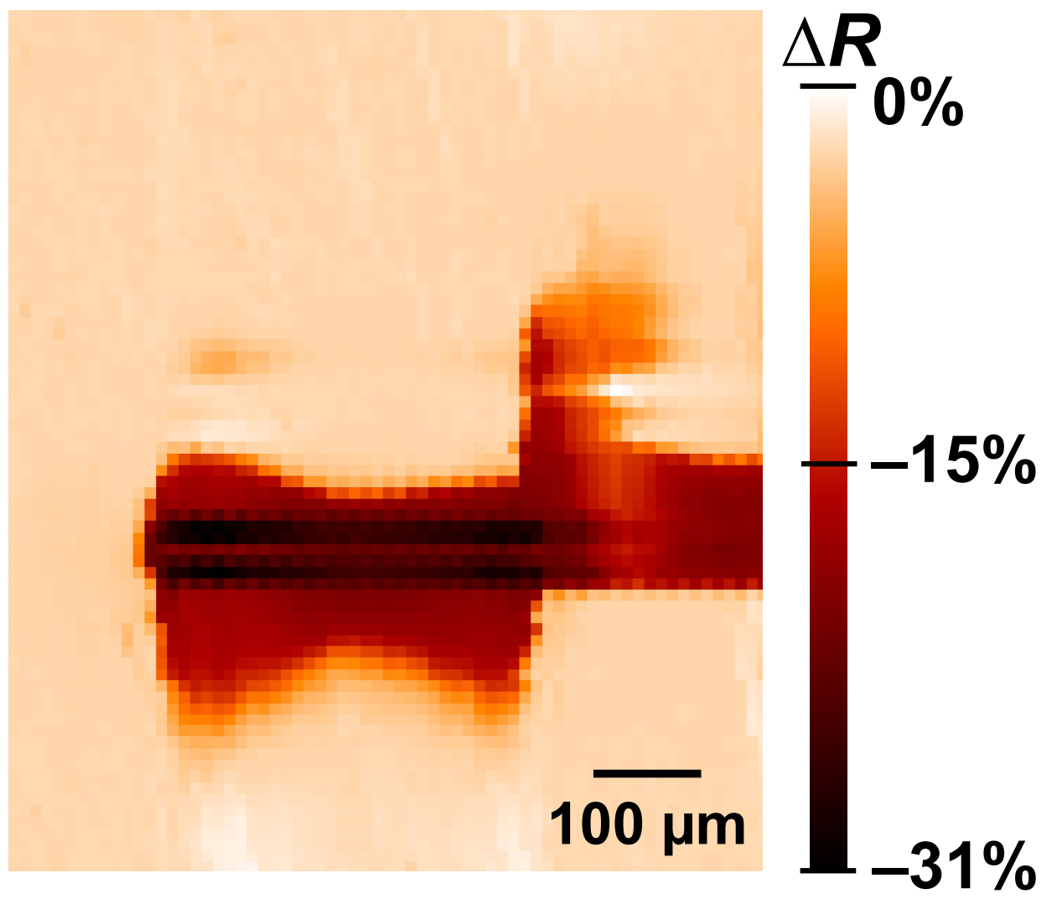
Laser Damage
- High powered lasers can damage EUV reflectivity in ways that may not be detectable with ultraviolet (non EUV) light.

Challenges
- The most difficult challenge facing high-accuracy scanning-beam mask inspection in the AIT is beam stability. Intensity fluctuations can only be accurately normalized in ‘simple’ inspection regions. A combination of hardware current monitoring and software is required for improvement.

Four experiments conducted with scanning actinic inspection

1. LASER DAMAGE

High Powered UV Lasers are used in commercial mask blank inspection. With high power, there is a potential for *inspection damage* that lowers EUV reflectivity on 1–100-μm length scales. *Damage may only be apparent at EUV wavelengths.* We used actinic scanning (BF) inspection to measure reflectivity changes and to help set power levels below the damage threshold.

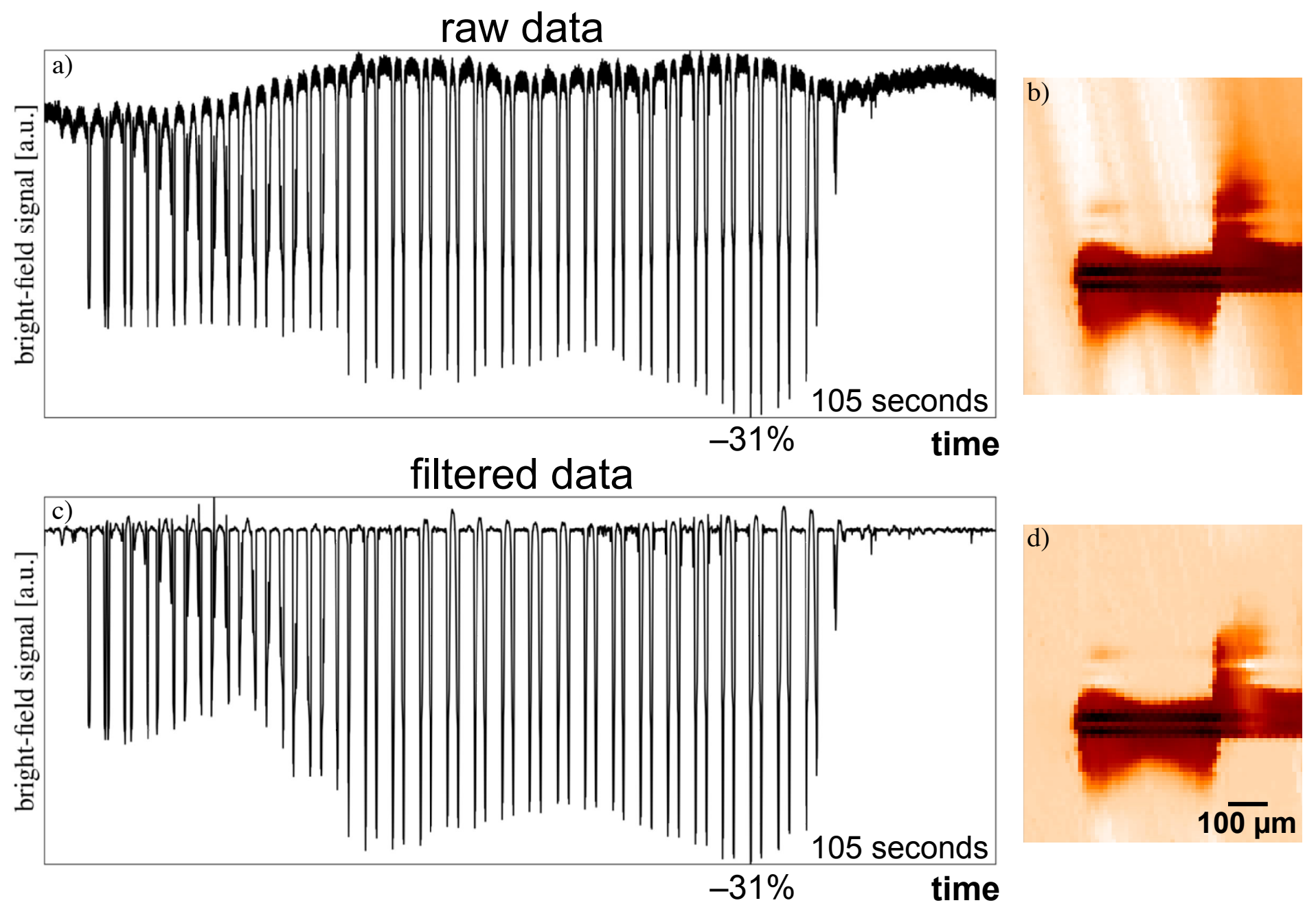


Coarse Actinic (bright-field) Reflectivity Scan with 10-μm scan steps. We measured intentional damage caused by high-powered, focused UV lasers. Reflectivity changes up to 31% were observed in this scan.

Scanning-data normalization

Signal normalization is the biggest challenge for scanning actinic inspection on the AIT. Illumination instability creates slow changes in the flux level. The figures below show raw scanning data, and the improvement that comes from normalization. Software normalization is most reliable in *open-field* areas. We are working to develop current-monitoring hardware for improved, automatic normalization.

Raw and filtered data reconstructions. Without filtering (a, b), fluctuations in the illumination flux level can appear as large-scale changes in the apparent reflectivity that follow the direction of the scanning path (slightly inclined from vertical.) Intensity-level filtering (c, d) is most effective for features surrounded by open (blank) mask areas.



Acknowledgement: Erdem Ultanir (formerly Intel) supported this work.

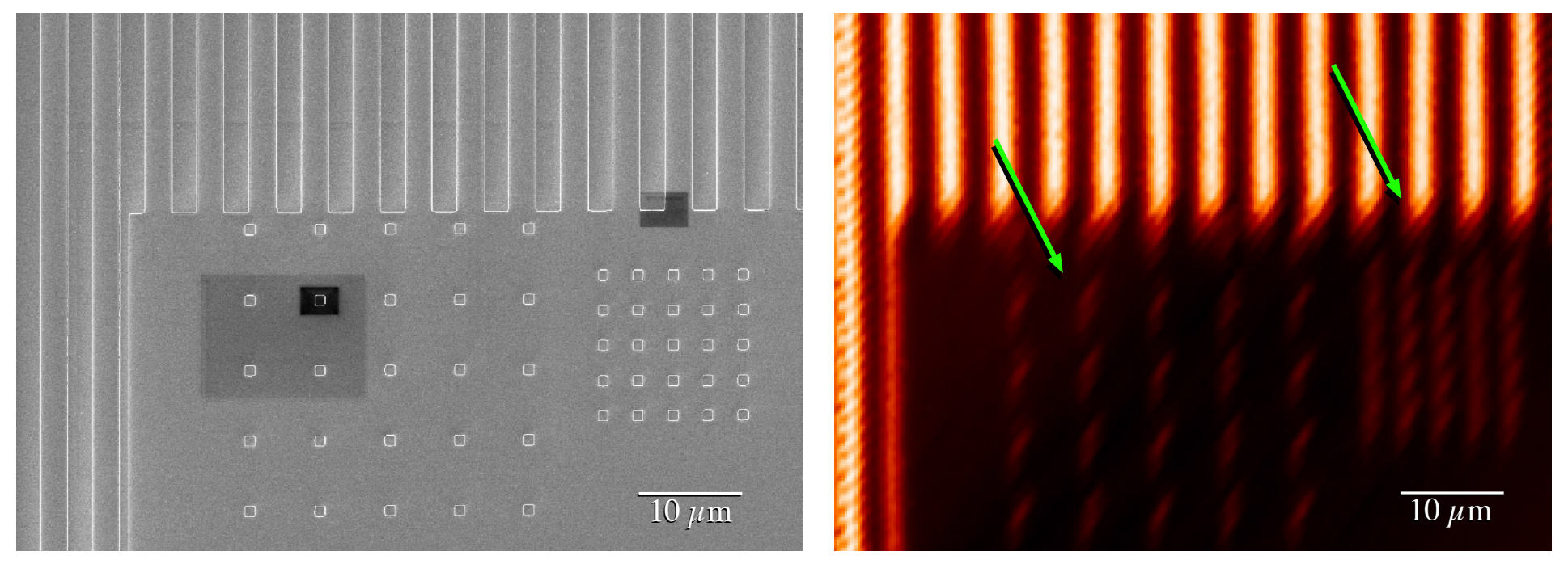
2. SEM INSPECTION

SEM inspection can induce carbon deposition onto surfaces. Regions studied at high resolution appear noticeably darker, stained by a thin carbon layer. How does SEM inspection affect EUV reflectivity?

We performed a simple test, inspecting a patterned reticle with an SEM and then with actinic scanning inspection. Although the regions we scanned were very dark in the SEM, we could not detect a drop in EUV reflectivity, within our measurement uncertainty.

Carbon is very transparent to EUV light. A 1-nm layer on the surface attenuates λ=13.4-nm light by approximately 1.26% (optical path length is 2 nm).

This test was too limited to draw firm conclusions, but it indicates that moderate, high-resolution SEM imaging may not be a severe threat to EUV reflectivity.



SEM micrograph / **actinic bright-field scan**

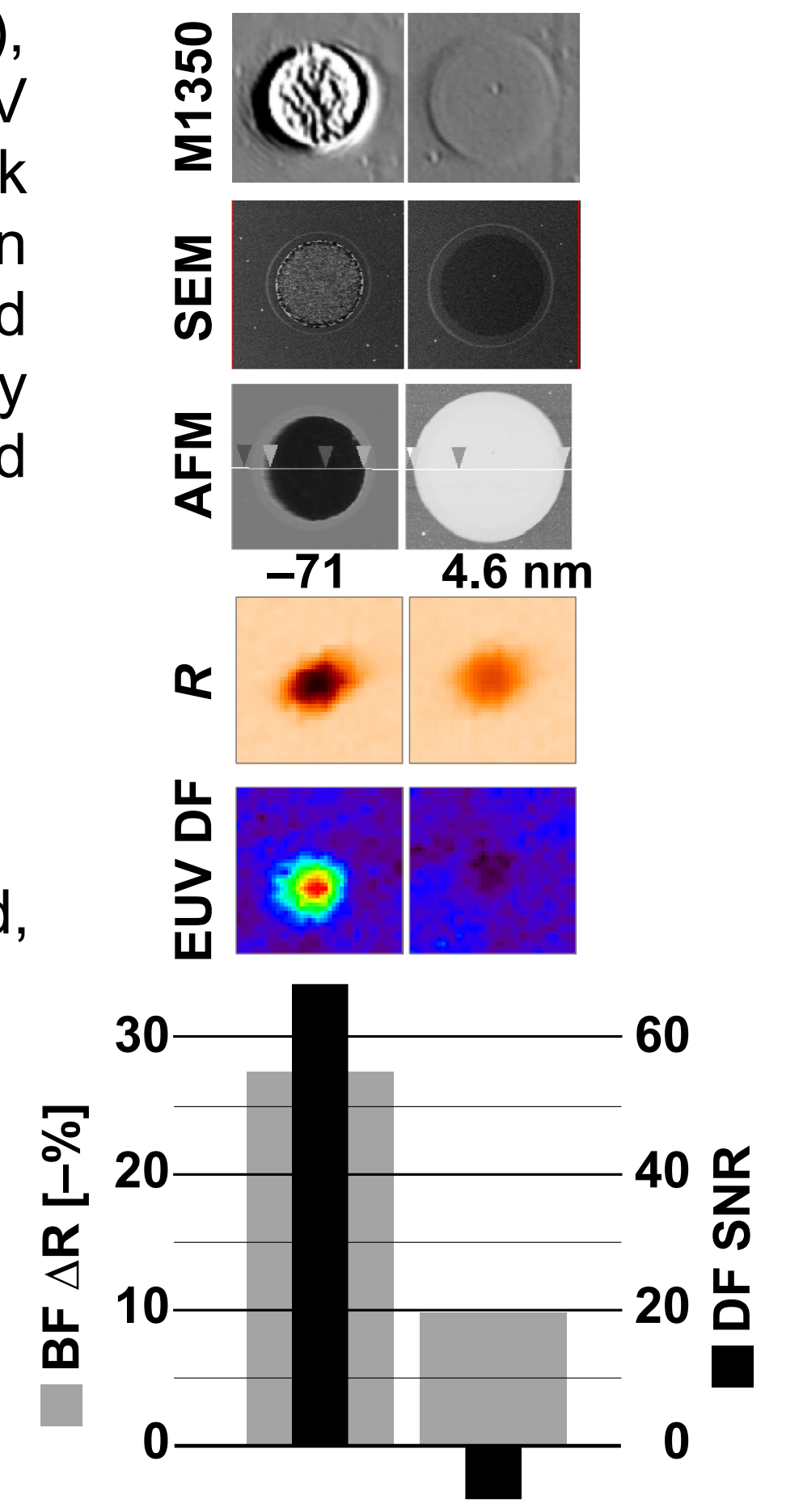
Simple Tests (performed in limited time)
- High-resolution SEM images collected in patterned region of a mask: 1-μm contacts, 2.5-μm line end.
- Actinic BF scans were performed with 2.5-μm beam. (Elliptical beam footprint is probably due to astigmatism in the illuminator.)
- Measurement within the patterned region makes intensity normalization difficult.

Acknowledgement: The patterned mask was provided by Ted Liang, Intel.

3. OPEN-FIELD MASK BLANK REPAIR

As reported in 2007 (Goldberg, *et al. SPIE* **6517**), the AIT has been used to probe the EUV response of prototype, open-field, mask blank defect repair strategies. Working in collaboration with researchers from Carl Zeiss, AMD, and SEMATECH, we found that the EUV reflectivity and scattering response to the repair sites could be markedly different, and uncorrelated.

Experiment overview
- ML-coated EUV mask blank
- Array of defects & repair sites (two are shown)
- Etched pits with 2-4° sidewall angles
- Repair: e-beam activated, chemically-induced, local etching, developed by Carl Zeiss SMS
- These early experiments did not identify a successful repair recipe.



Actinic Measurements
- **DF:** 5-μm beam diameter for improved SNR
- **BF:** 1-μm beam diameter for spatial resolution

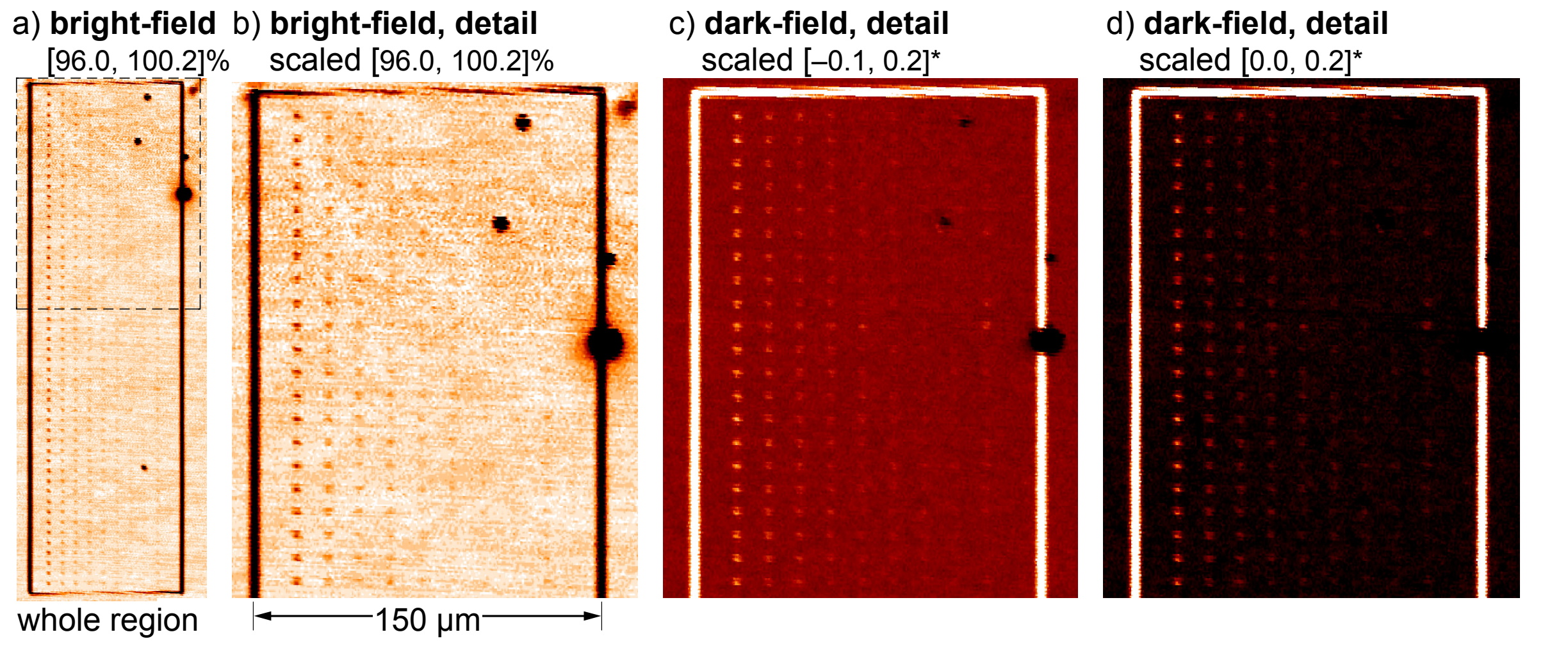
(Figure) Two very different sites
- **Left: etched pit with no protection**
  Large BF reflectivity loss and strong scattering DF signal
- **Right: etched pit with 5-nm SiO_2 protection layer**
  Strong absorption caused a decrease in DF in addition to R loss.
- **UV Inspection:** Both sites were easily detected in the *Lasertec M1350,* λ = 488-nm. ‘Defect review’ images are shown.

Acknowledgement: Mask was provided by Rainer Fettig, Carl Zeiss. M1350 and AFM inspection were performed by Patrick Kearney and his team at *SEMATECH, North.* Phil Seidel also supported this work.

4. PHASE AND AMPLITUDE DEFECTS

We measured an EUV reticle with a programmed defect array developed by *HOYA* for *MIRAI*. We have previously described the four-tool cross-comparison (Goldberg, *et al.*, *JVST B* **24,** 2006) that led to significant new insights about actinic inspection. The mask had ‘buried’ substrate phase-defects and a few native defects on the surface.

Experiment specs
- 150 x 500 μm programmed defect field, defects in columns
- 7-nm-thick CrN ‘pads’ on the substrate prior to ML coating
- AFM of surface: profiles from 70–420-nm wide x 3.5–7-nm high
- No absorber pattern on the mask
- Accidental contamination added several particulate defects.
- Actinic scanning BF and DF inspection were performed.


a) **bright-field** [96.0, 100.2]% b) **bright-field, detail** scaled [96.0, 100.2]% c) **dark-field, detail** scaled [–0.1, 0.2]* d) **dark-field, detail** scaled [0.0, 0.2]*

Results
- **Surface Defects:**
  BF: significant reflectivity drop at the surface defect locations.
  ΔR = –90% in the largest defect; ΔR ~ 50% in nearby defects.
  DF: surface defects do not scatter strongly.
  However, surface defects should be easily detectable by UV inspection.
- **Buried phase defects**
  BF ΔR < 2% (typically it was much smaller.)
  Note: peak ΔR is difficult to characterize—depends on beam size.

Acknowledgement: Yoshihiro Tezuka and Tsuneo Terasawa collaborated on this work as part of the MIRAI project; we appreciate HOYA’s work in creating the mask.