Comparison of actinic and non-actinic inspection of programmed defect masks

Funded by SEMATECH

Kenneth Goldberg, Anton Barty

Hakseung Han*, Stefan Wurm*,
Patrick Kearney, Phil Seidel

Obert Wood*, Bruno LaFontaine

Ted Liang

Christian Holfeld

Rainer Fettig

Yoshihiro Tezuka, Tsuneo Terasawa

additional support

**current and former project managers*

Fundamental questions remain for EUV reticles

Isolated Defects

- Can we detect all printable defects?
- Are there "**actinic-only" defects?**

Pattern/Proximity Defects

- Can we use **aerial image data** to improve modeling?

Inspection tools

- **How well** do they perform?
- Does inspection cause **damage?**

Printing

Modeling

AFM, SEM

Non-Actinic Inspection
λ = 266, 488 nm

Actinic (EUV) Inspection
scanning & imaging
bright-field, dark-field

cross-comparison is the path to greater knowledge

KAGoldberg@lbl.gov

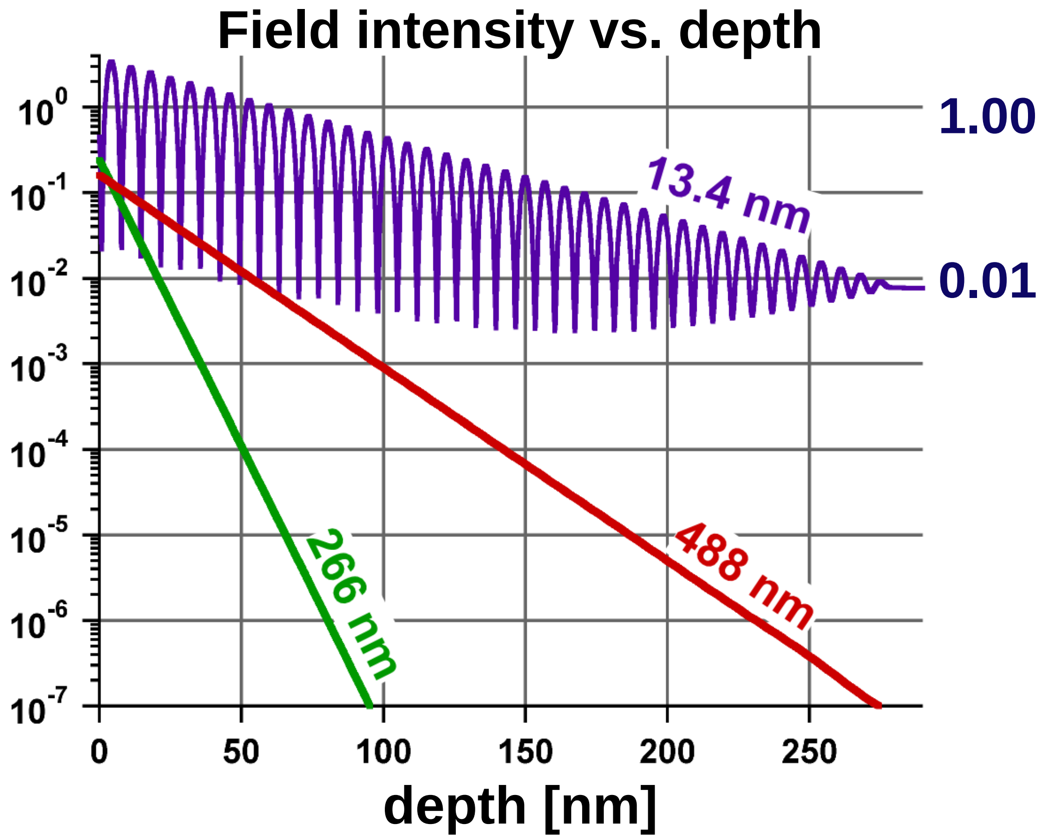
Different wavelengths see different ML structures

- **EUV light penetrates deeply** into the resonant ML structure
- **488-nm** and **266-nm** light barely reaches below the surface

Field Penetration for three λs

λ	"1%" depth	bi-layers
13.4 nm	215 nm	31
488 nm	53.6 nm	8
266 nm	20.6 nm	3

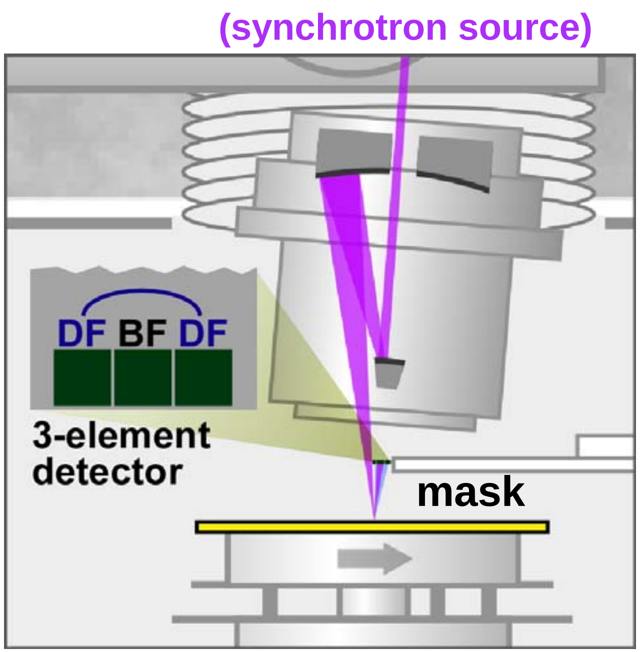
At-wavelength testing *probes the actual multilayer response.*

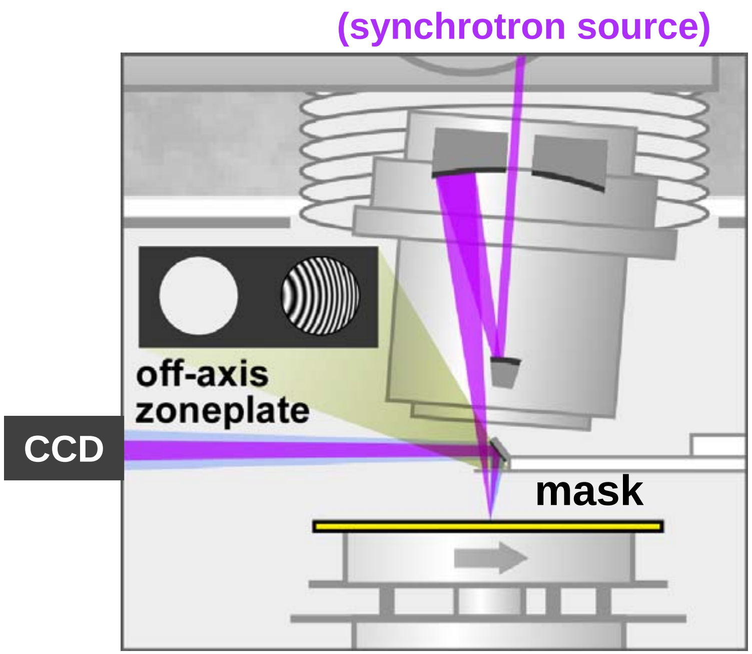


KAGoldberg@lbl.gov

The SEMATECH Berkeley Actinic Mask Inspection Tool

Worldwide, this is the only EUV mask inspection tool offering **imaging** *and* **scanning** in **dark-field** *and* **bright-field** modes.





Scanning reveals open-field defects, measures subtle mirror reflectivity changes not seen without EUV light.

Imaging uses a zoneplate lens to measure the aerial image directly, testing defect printability models without printing.

KAGoldberg@lbl.gov

SEMATECH Actinic Mask Inspection tool is fully operational

Scanning & Imaging in routine daily operation

Scanning

Bright-field *Reflectivity testing*
→ ≥1 μm spot
→ *R* measurements to ±0.1%

Dark-field *Scattering*
→ Finds printable defects not seen by non-actinic tools.

Region-of-Interest identification
→ Used to locate regions of interest for imaging.

*We find **actinic-only defects**, in dark-field and bright-field.*

Imaging

Exposure Time
→ **0.3–1.5 s** alignment & navigation
→ **20–35 s** for highest resolution

Resolution
→ **~100 nm**, Mask
~25 nm, 4× Wafer equivalent

Magnification
→ **~700x**, *direct to EUV CCD*

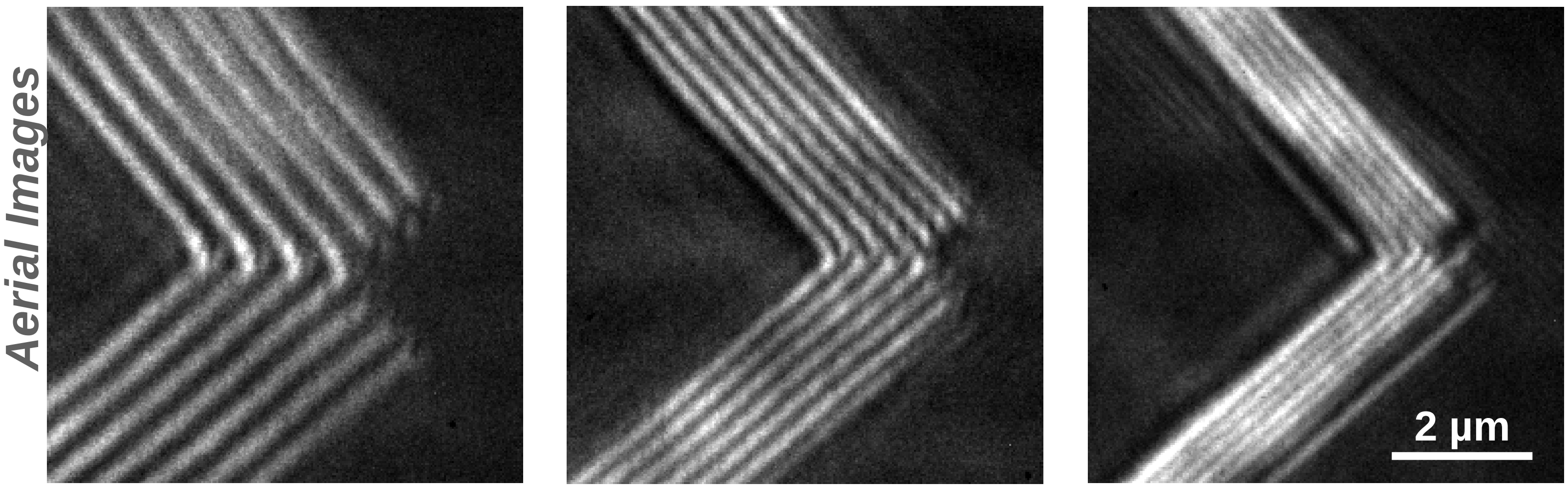
***NA* = 0.0625** (0.25 NA, 4x stepper)

***Higher resolutions** and custom pupil shapes are possible.*

KAGoldberg@lbl.gov

Early tests resolved elbow images down to 100-nm (mask), 25-nm (4x wafer equivalent)

- **System Resolution** is currently designed to match a 4×, 0.25-NA stepper.
- **Illumination:** 6° incidence. Partial coherence: $\sigma_x > 1.0$, $\sigma_y = 0.7$



half-pitch: 250 nm	**150 nm**	**100 nm** (mask)
62.5 nm	**37.5 nm**	**25 nm** (4x wafer equiv.)

Imaging is performed with **EUV light, directly**

- There is **no scintillator**, **no conversion** to visible light, and **no microscope** objective.
- Consequently the measurements are **linear**.

In collaboration with
T. Liang, *Intel*

We have evaluated programmed defects and defect-repair sites on member company masks

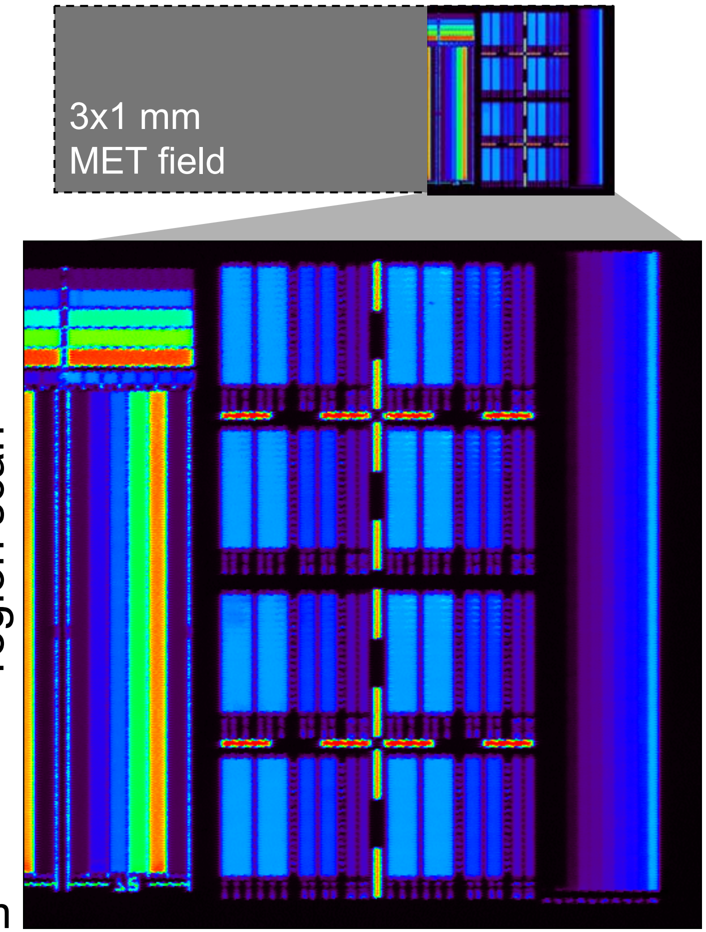
In **imaging mode**, we have studied **programmed-defects** and **programmed-defect repair** sites on an AMTC MET mask.

Measurements conducted include:

300-nm half pitch (75-nm 4x wafer equiv.)
- *dark defects,* size variation
- *bright defects*, size variation
- specific defects through focus

150-nm half pitch (37.5-nm 4x wafer equiv.)
- *dark defects*, size variation
- *bright defects*, size variation

450-nm half pitch (112.5-nm 4x wafer equiv)
- many specific repair cases

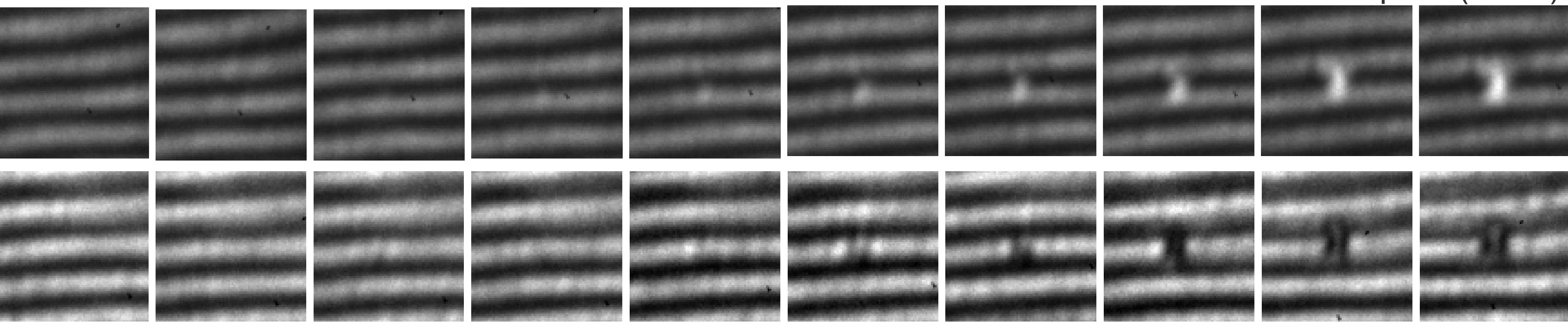


KAGoldberg@lbl.gov
In collaboration with
C. Holfeld *AMTC*, B. LaFontaine *AMD*

Measuring the aerial image: size series, through focus, and repair sites

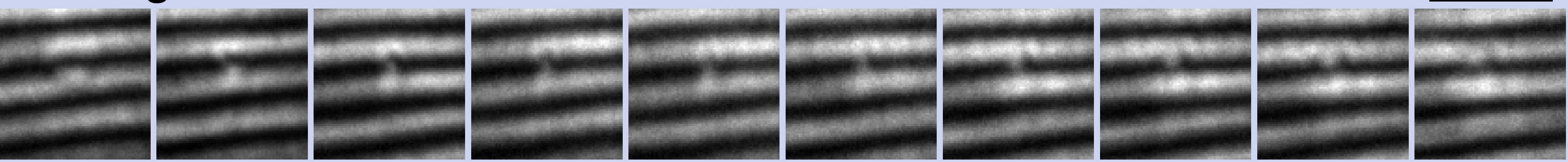
Size series: bright and dark defects

300 nm half-pitch (mask)
75 nm half-pitch (wafer)



Through-focus series

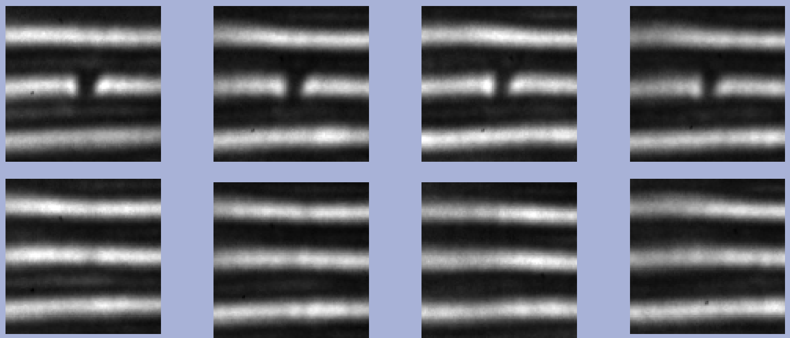
2 µm



Defect repair studies

2 µm

half-pitch: 450 nm (mask)
112.5 nm (wafer)



Complete series with ≥ 17 images were collected in **30-40 minutes.**

KAGoldberg@lbl.gov

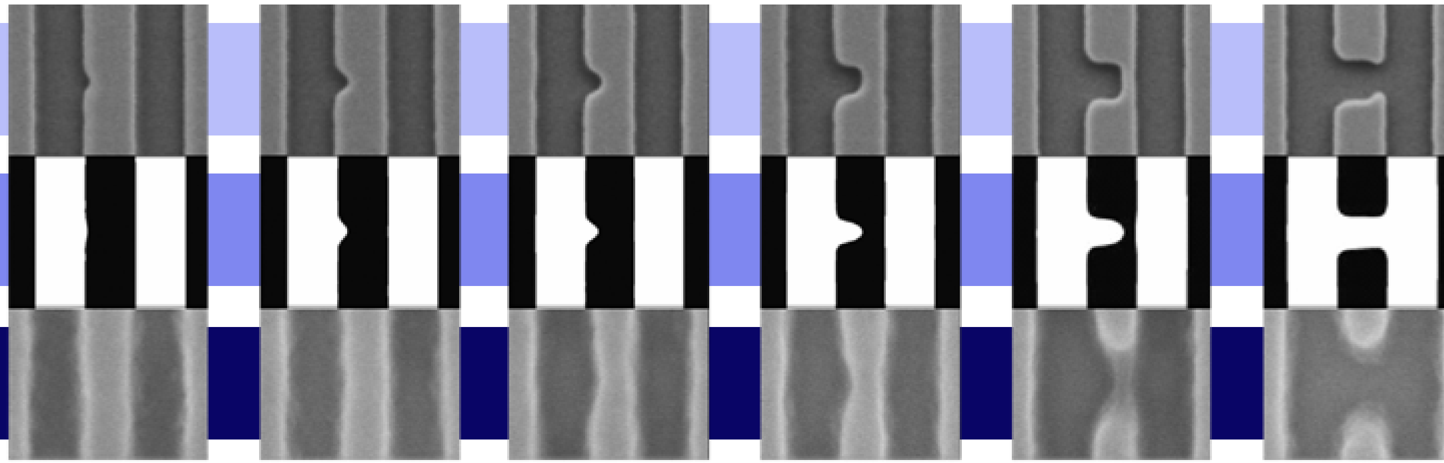
In collaboration with
C. Holfeld *AMTC*, B. LaFontaine *AMD*

ADVANCED MASK TECHNOLOGY CENTER

Comparing Printing, Simulation

Programmed *bright* absorber defects.

300 nm half-pitch (mask)
50-nm (5x wafer equiv.)



MET exposures showed:

Defect printability was ***limited by resist resolution***

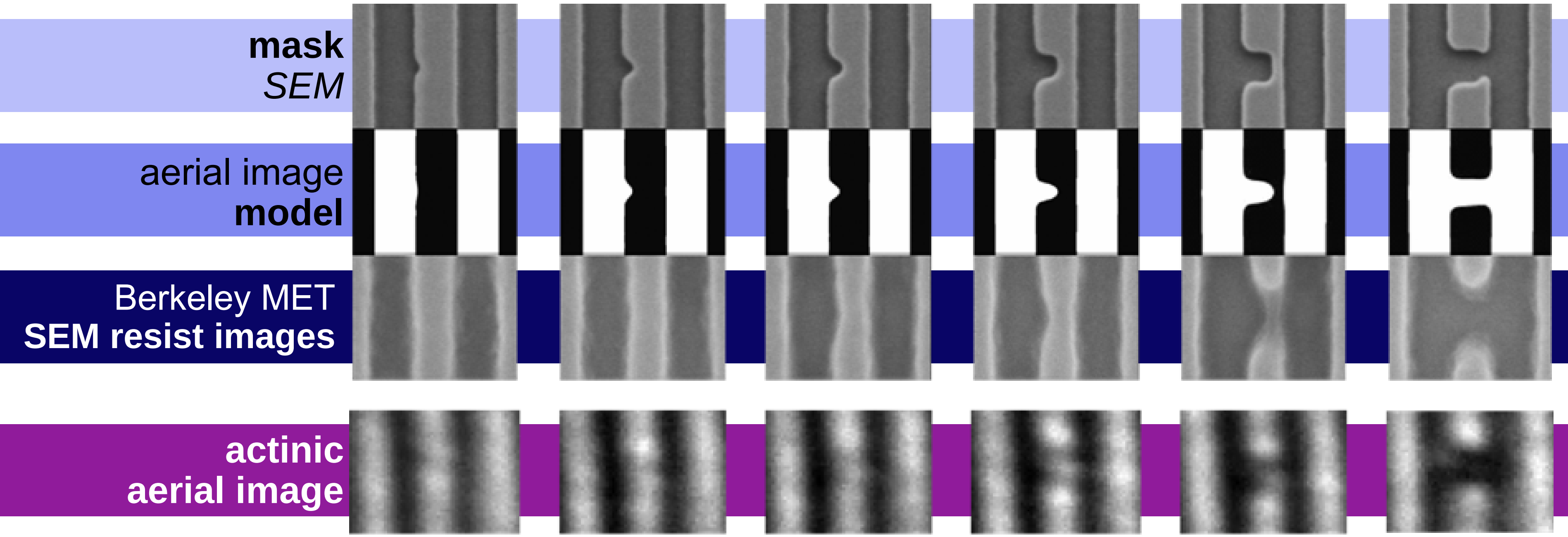
Christian Holfeld, Bubke, Lehmann, LaFontaine, Pawloski, Schwarzl, Kamm, Graf, and Erdmann
SPIE **6151**, **61510U** (2006)

In collaboration with
C. Holfeld *AMTC*, B. LaFontaine *AMD*

Comparing Printing, Simulation, *and Actinic Imaging*

Programmed *bright* absorber defects.

300 nm half-pitch (mask)
50-nm (5x wafer equiv.)

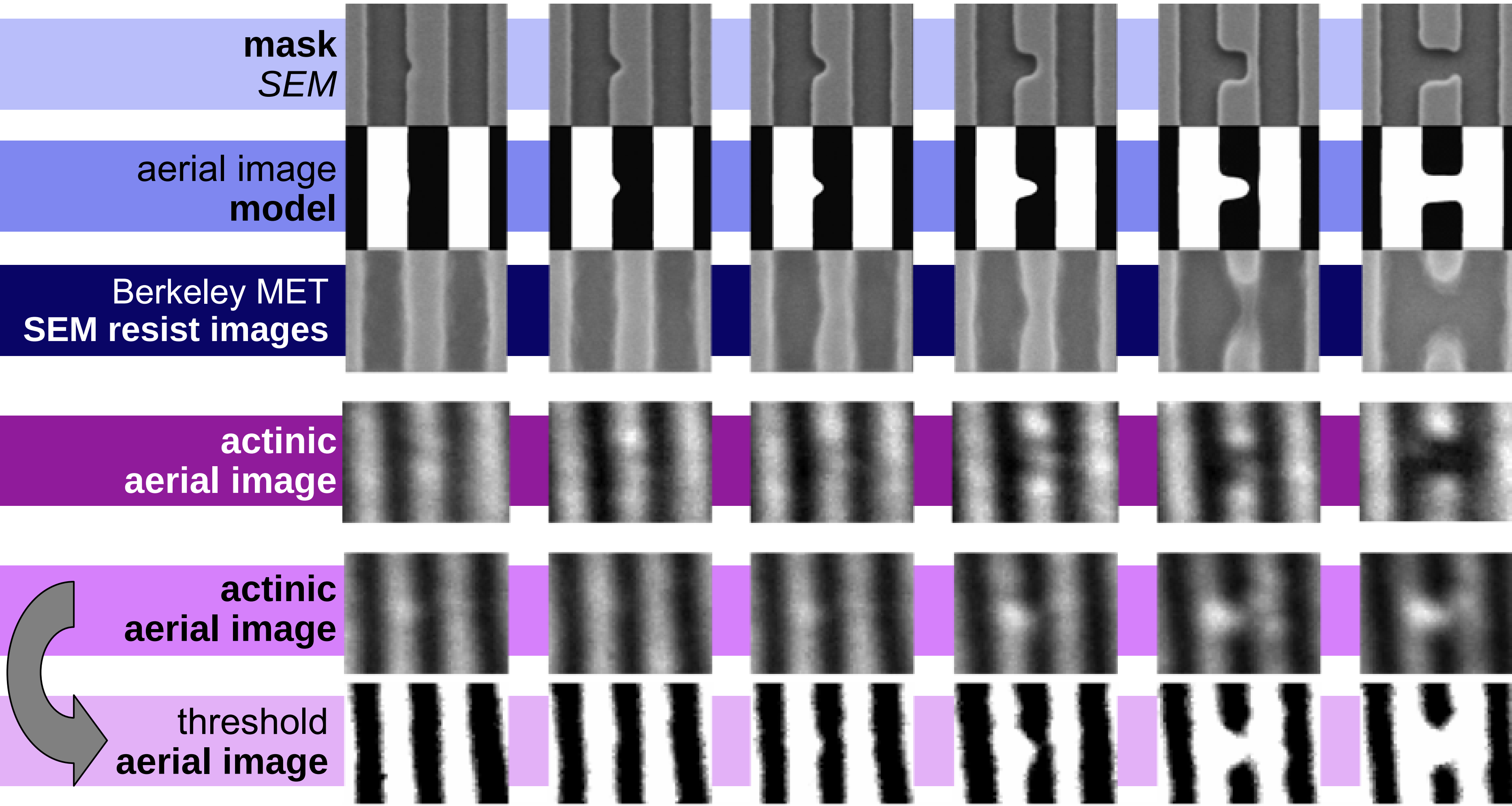


In collaboration with
C. Holfeld *AMTC*, B. LaFontaine *AMD*

Comparing Printing, Simulation, *and Actinic Imaging*

Programmed *bright* absorber defects.

300 nm half-pitch (mask)
50-nm (5x wafer equiv.)



2006 EUVL Symposium
KAGoldberg@lbl.gov

In collaboration with
C. Holfeld *AMTC*, B. LaFontaine *AMD*

Actinic scanning-mode: a 1-μm reflectometer

Our **focused beam** probes the **surface reflectivity** and **scattering** *micron-by-micron*.

ALS Beamline 6.3.2 **Reflectometer** (absolute *R*)	≥ 10 x 300 μm
Berkeley Actinic Mask Inspection scanning **Focal Spot** (relative *R*)	5 x 5 μm 3 x 3 μm 1 x 1 μm

In 2006 we studied:

- The **sensitivity** of actinic & non-actinic inspection tools vs. printing
- The EUV response of open-field **defect-repair sites**
- **Damage** caused by mask inspection

KAGoldberg@lbl.gov

Using a buried substrate-bump mask, we compared the sensitivity of 4 inspection tools

Many defects are seen **only with EUV** inspection

MIRAI (EUV)

- high DF solid-angle
- normal incidence illum.
- low-res DF images

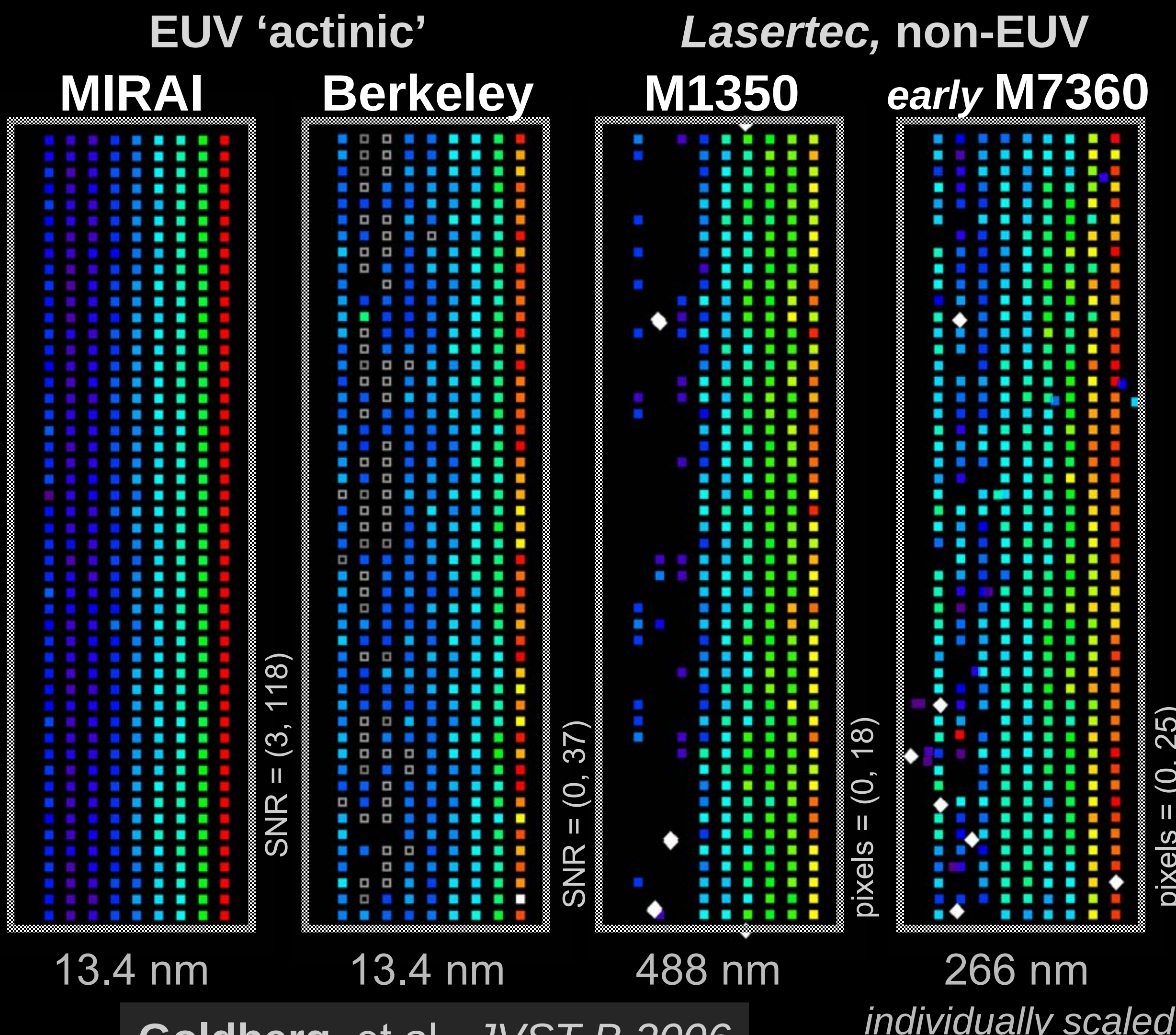
Berkeley (EUV)

- BF & DF scanning
- 6° illumination

Lasertec tools

- **M1350** (λ = 488 nm)
- **M7360** (λ = 266 nm)

Significant improvement from M1350 to M7360



Goldberg, et al., *JVST B 2006*

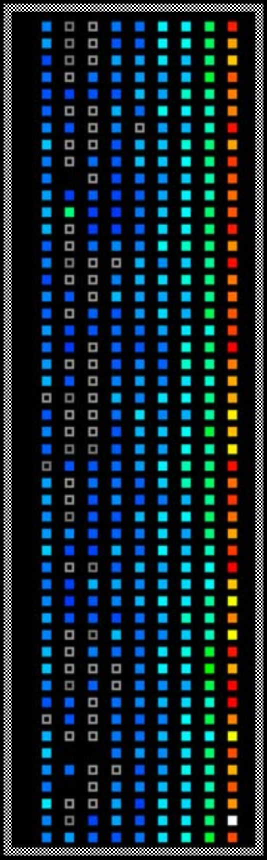
In collaboration with ***Lasertec***,
Y. Tezuka, T. Terasawa, P. Kearney

Bright-field scan reveals details not observable in dark-field

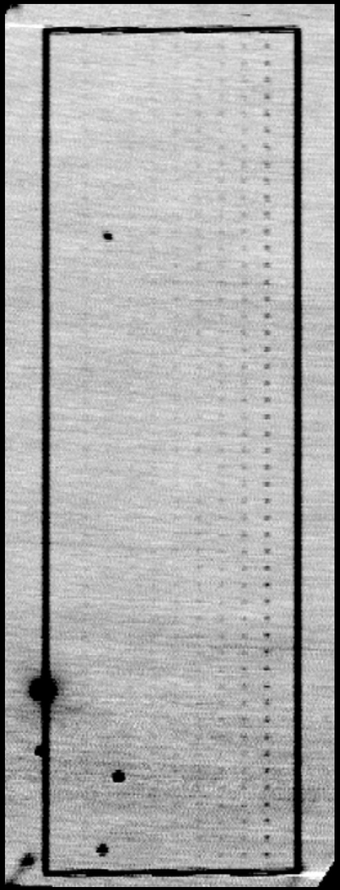
EUV Bright-field inspection clearly reveals absorptive native defects added *after* the first MIRAI measurement (in Japan).

- These surface defects **do not scatter** well.
- In some cases the large surface defects **were not seen** with dark-field detection.

Berkeley *dark-field*



Berkeley *bright-field*



Scanning versus Imaging:

- SEMATECH Berkeley tool uses BF/DF scanning: *no collection optics*, only detectors.
- In an *imaging* tool with bright-field detection, **flare would severely limit resolution**, but would have little impact on dark-field.

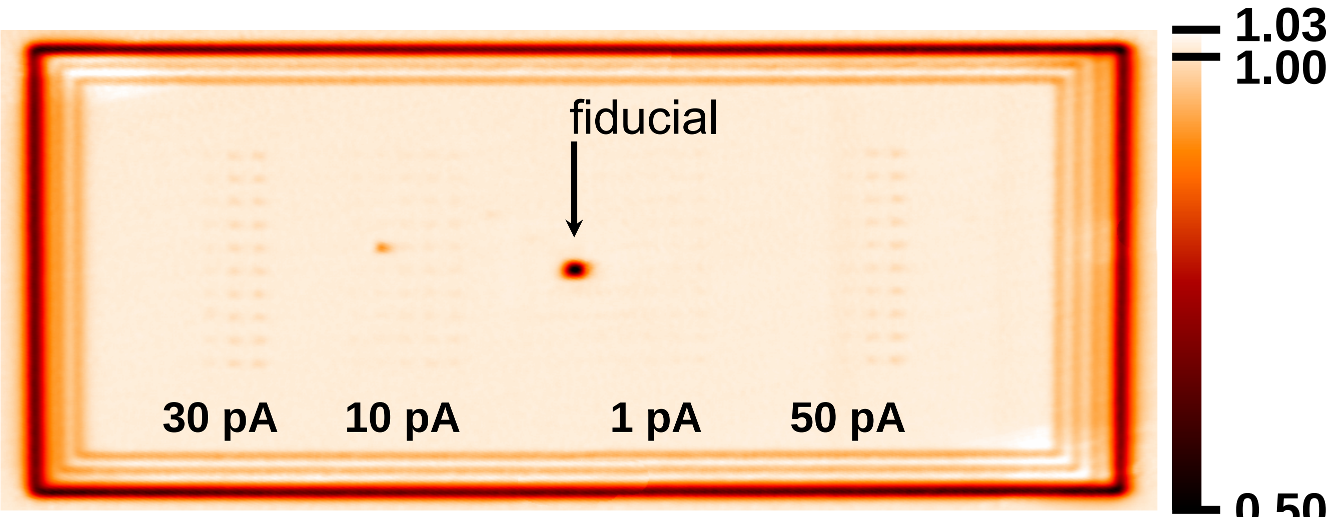
KAGoldberg@lbl.gov

In collaboration with ***Lasertec,***
Y. Tezuka, T. Terasawa, P. Kearney

Cross-comparison measurements of buried-pit defects

Barty, SPIE Photomask 2006

- **Pits are milled** in a first ML coating **using FIB**.
- A **second ML** coating buries the pits.



bright-field scan
scaled 50% to 103% relative reflectivity

Again, in bright-field, actinic inspection finds **native defects** and features possibly related to damage produced during **non-actinic inspection**.

KAGoldberg@lbl.gov

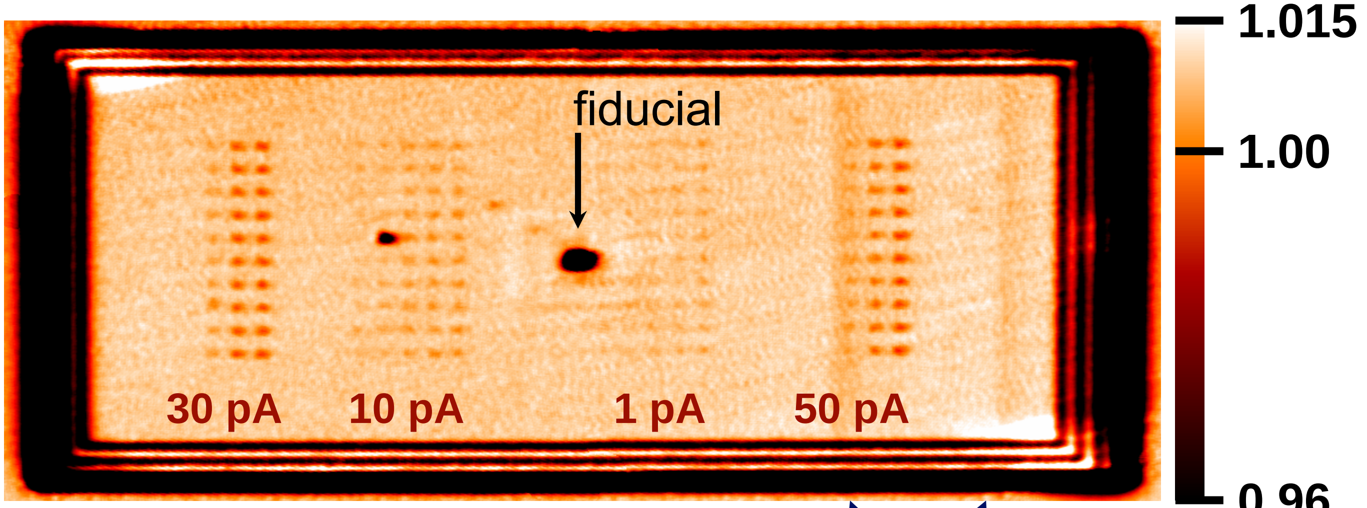
In collaboration with
B. LaFontaine, P. Kearney

AMD SEMATECH BERKELEY LAB

Cross-comparison measurements of buried-pit defects

Barty, SPIE Photomask 2006

- **Pits are milled** in a first ML coating **using FIB**.
- A **second ML** coating buries the pits.



bright-field scan
scaled 96% to 101.5% relative reflectivity

Again, in bright-field, actinic inspection finds **native defects** and features possibly related to damage produced during **non-actinic inspection**.

Unexplained vertical line features. Other edge features surround the central fiducial region.

KAGoldberg@lbl.gov

In collaboration with
B. LaFontaine, P. Kearney

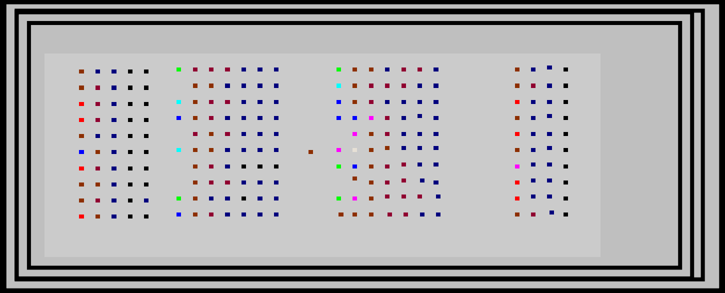
Comparing: Actinic ↔ Non-Actinic ↔ MET printing

We found that **each pit type** has a **different** characteristic . . .

- MET printability • M1350 detectability
- Actinic BF and DF detection strength

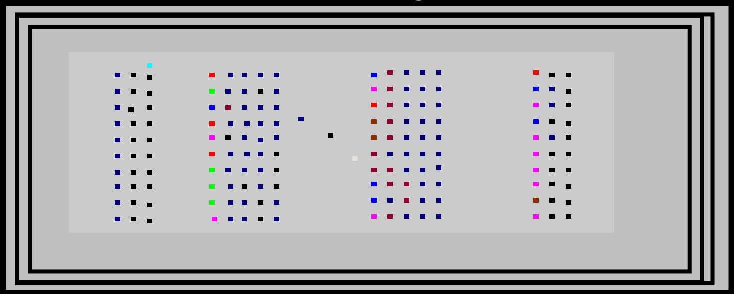
Lasertec M1350 before the 2nd coating

before



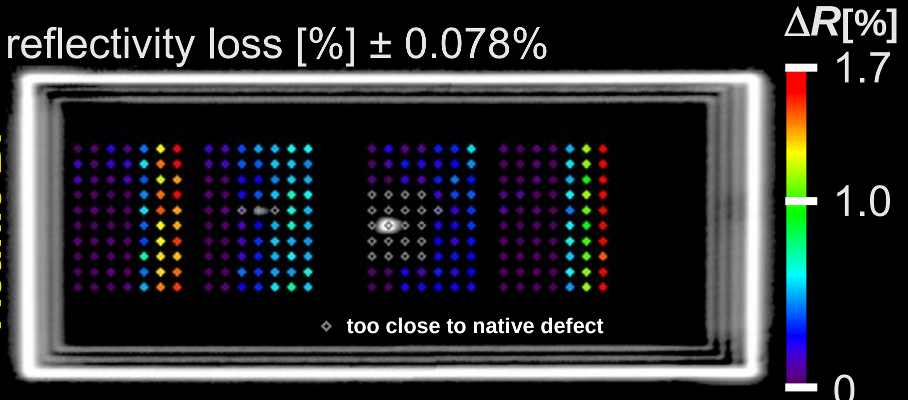
. . . after 2nd coating

after



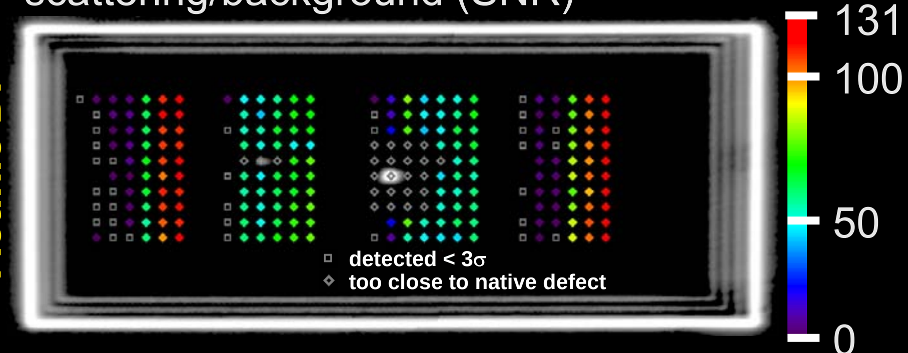
reflectivity loss [%] ± 0.078%

Actinic BF

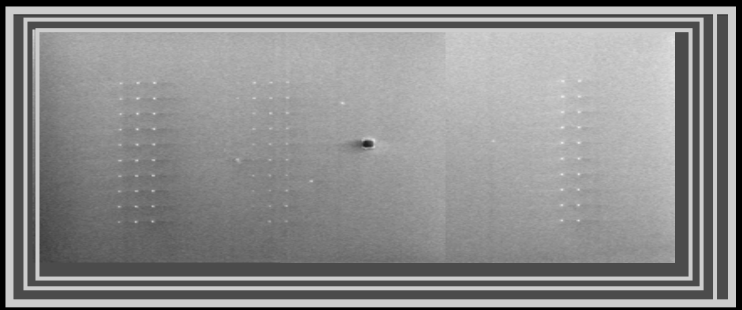


scattering/background (SNR)

Actinic DF



Berkeley MET

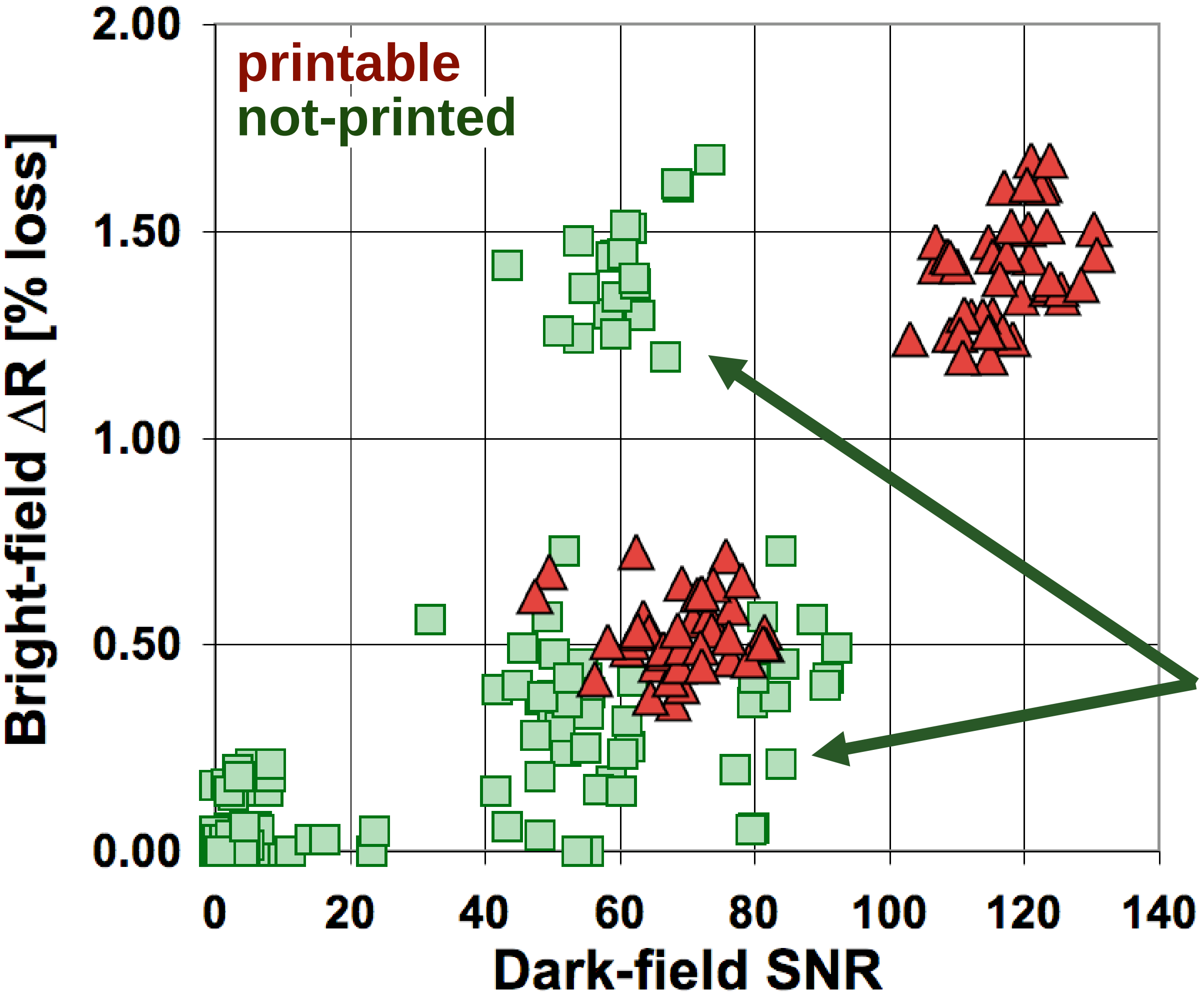


2006 EUVL Symposium
KAGoldberg@lbl.gov

In collaboration with
B. LaFontaine, P. Kearney

Actinic inspection found all MET-printable defects

Arrays of buried substrate pits



Early results

We detected many defects that were below the MET printing threshold

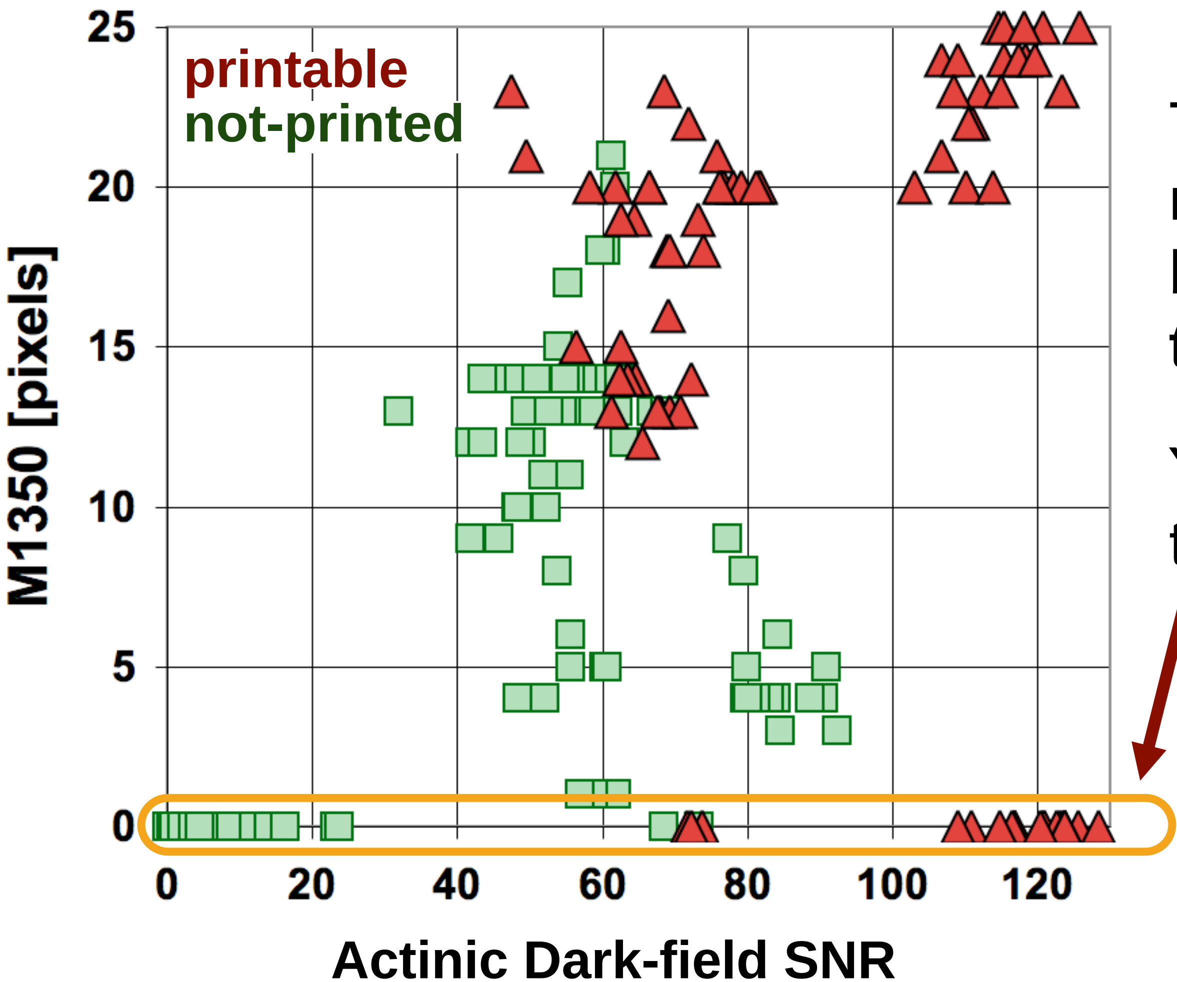
These strong defects did not print

*BF measured with a 2.5 μm beam spot

In collaboration with
B. LaFontaine, P. Kearney

The correlation between actinic dark-field and M1350 showed some inconsistencies

Arrays of buried substrate pits



The M1350 detected many defects that were **below the MET-printing threshold.**

Yet, the M1350 missed these **printable defects**

We need more data like this, and also cross-correlation with the M7360.

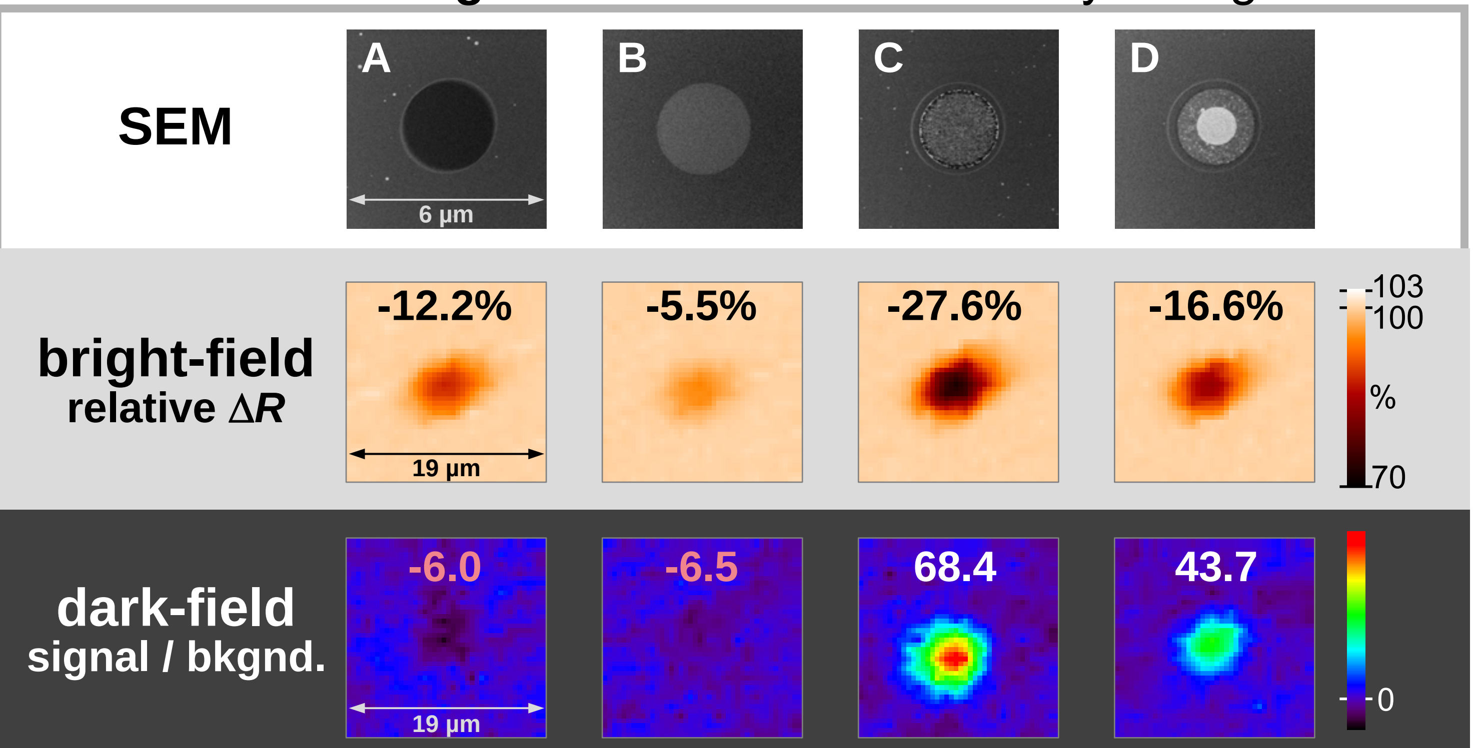
KAGoldberg@lbl.gov

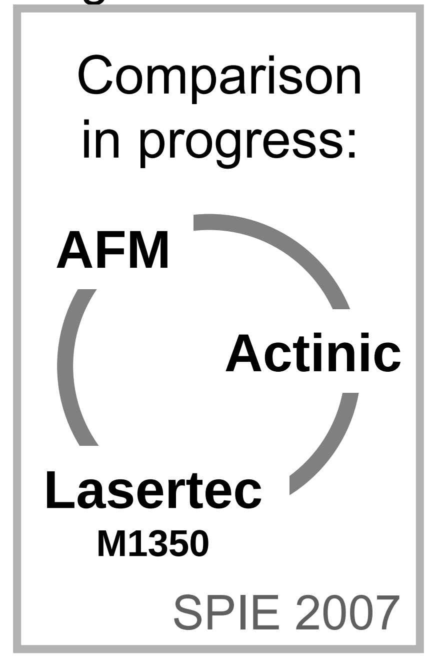
In collaboration with
B. LaFontaine, P. Kearney

Actinic inspection of mask-blank defect-repair sites shows significantly different bright-field and dark-field responses

Actinic **bright-field** and **dark-field scanning** shows the effectiveness of mask-blank defect repair strategies.

- **Some sites scatter strongly**, others **absorb light.** EUV tools relying on **dark-field only** will likely fail to observe some sites with incomplete repair. Non-actinic tools may mischaracterize repair.
- **No other existing tool** can resolve reflectivity changes on this length scale.





KAGoldberg@lbl.gov

In collaboration with
Rainer Fettig, Phil Seidel, Pat Kearney

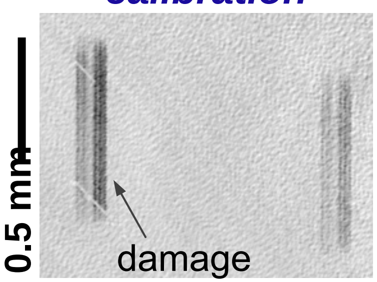
We measured reflectivity losses caused by *inspection damage*

High power inspection can damage masks

- A mask was prepared to **assess the damage threshold** of the Lasertec M7360, during qualification.
- **Actinic bright-field scanning** observed narrow damage regions (reflectivity loss up to –6%) outside of the die area, at high power.
  - Some of the regions are ***undetectable*** in the Lasertec tool itself.

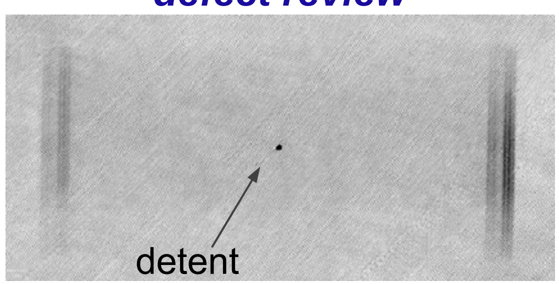
Actinic BF scans of Lasertec inspection regions intentionally damaged with different operating modes and power levels.

calibration



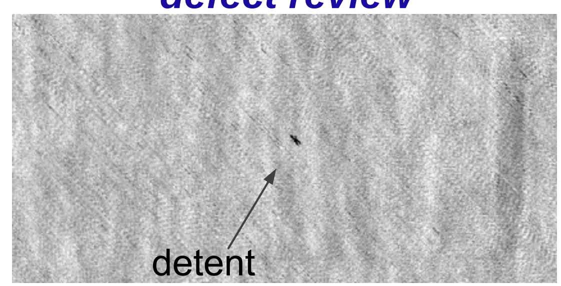
5 @ full power
ΔR_{max} = –5.4%

defect review



20 @ full power
ΔR_{max} = –2.1%

defect review



1 @ lower power
ΔR_{max} = –0.8%

scanning region edge, out of die area

20 @ full power
ΔR_{max} = –3.5%

KAGoldberg@lbl.gov

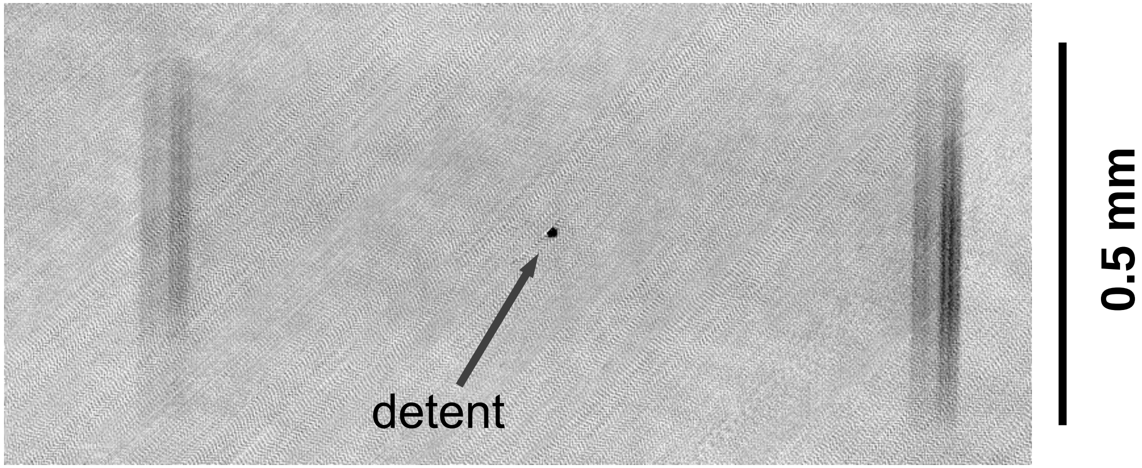
In collaboration with
***Lasertec*, P. Kearney, H. Kusunose**

We used actinic inspection to help set safe power levels

Areas of concern:

- Damaged areas may be **too small** for conventional reflectometry to see.
- **Damage could be problematic** if it can only be seen with EUV light. However, we can **use actinic inspection to help set safe power levels**.
- **The SEMI P38 standard** ($|\Delta R_{max}| < 0.5\%$) is poorly defined regarding the spatial scale of *R* variations—abrupt *R* changes may cause problems.

an intentionally damaged **defect review** test region



power level & dose: **20 @ full power**

peak reflectivity drop: $\Delta R_{max} = -2.1\%$

In collaboration with *Lasertec*, **P. Kearney, H. Kusunose**

Actinic Mask Inspection Tool: *routine daily operation*

A unique tool, aiding the development of EUV reticles

Thank you

Scanning: Probes reflectivity & scattering µm-by-µm

- **Relative *R* ±0.1%** at 1–5 µm spatial resolution
- Actinic vs. non-actinic **cross-comparisons**

Imaging: Emulates stepper optics

- 100–200 **high-resolution images** per shift
- In September/October: **Five masks** in **five weeks**
- **Quantitative analysis** & comparison with MET imaging is in progress (*programmed **absorber** and **phase defects***)
- Studying **defect-repair site** aerial images
- **Upgrades**
  - multiple lenses with emulated **NA > 0.25**
  - arbitrary **pupil shapes**
  - better **through-focus control**
  - illumination **uniformity**
  - **distortion** control / correction

KAGoldberg@lbl.gov
Funded by SEMATECH

Results and conclusions

EUV inspection probes *resonant* multilayer properties:
penetrates 4× deeper than 488-nm, 10× deeper than 266-nm

BF and DF

Both **EUV bright-field (BF) and dark-field (DF)** are important
– **DF** alone does not detect all absorbing **surface defects**
– **BF** defect sensitivity relies on **high flux and a small beam**

Pit Defect Cross-Comparison

We detected all MET-printable pit defects, and many below threshold
– **More data is required** (M7360, AFM, modeling, etc.)

Defect Repair Feedback

Actinic inspection provides **feedback for defect repair strategies**
– **mask-blank defects** and **pattern defects**

Inspection Damage

Inspection tools **can lower EUV reflectivity** on short length scales
– Some damage may only be seen at-wavelength
– **EUV inspection can help** set power levels below damage threshold

Thank you

ADVANCED MASK TECHNOLOGY CENTER
AMD
HOYA
intel
Lasertec
MIRAI
NEDO
ZEISS

KAGoldberg@lbl.gov

Funded by SEMATECH

BERKELEY LAB
SEMATECH