Advancing the Ion Beam Thin Film Planarization Process to Mitigate EUVL Mask Substrate *Pit* Defects

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Third International EUVL Symposium
Nov. 3, 2004

This work supported under the auspices of the U.S. DOE by the Univ. of Calif. Lawrence Livermore Laboratory (under contract W-7405-Eng-48) and Lawrence Berkeley National Laboratory.
Funding was provided by Intel Corporation through a work-for-others agreement.

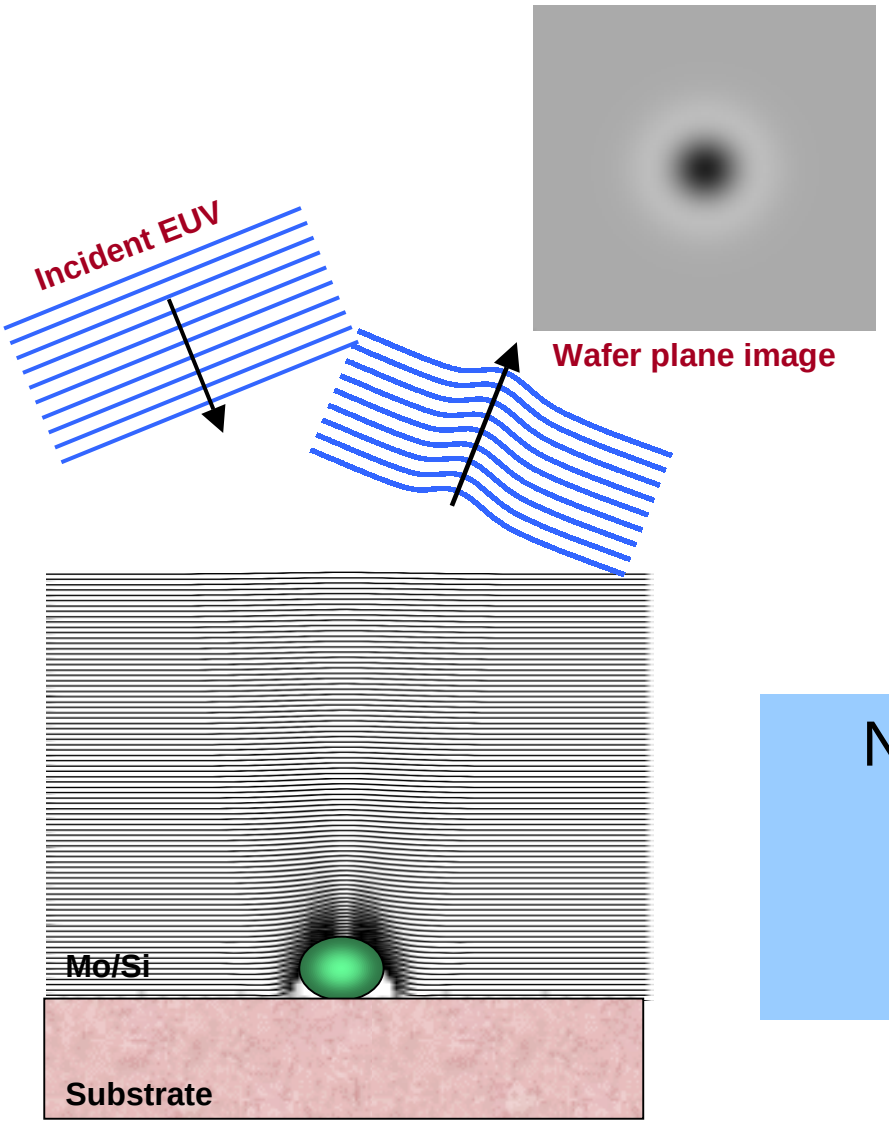
Strategy for combating EUVL mask blank defects

EUVL mask blank defects

- Defects nucleated at the substrate
  - **Smoothing**
  - Substrate cleaning
  - ~~Phase defect repair~~ (e-beam technique)
- Defects nucleated in the bottom layers
  - Low defect deposition
  - ~~Phase defect repair~~ (e-beam technique)
  - **Smoothing**
- Defects nucleated in the top layers
  - Low defect deposition
  - Amplitude defect repair (milling technique)

Due to issues with phase defect repair in the past year, it is likely that more will be expected from smoothing (as well as substrate cleaning, and low defect deposition).

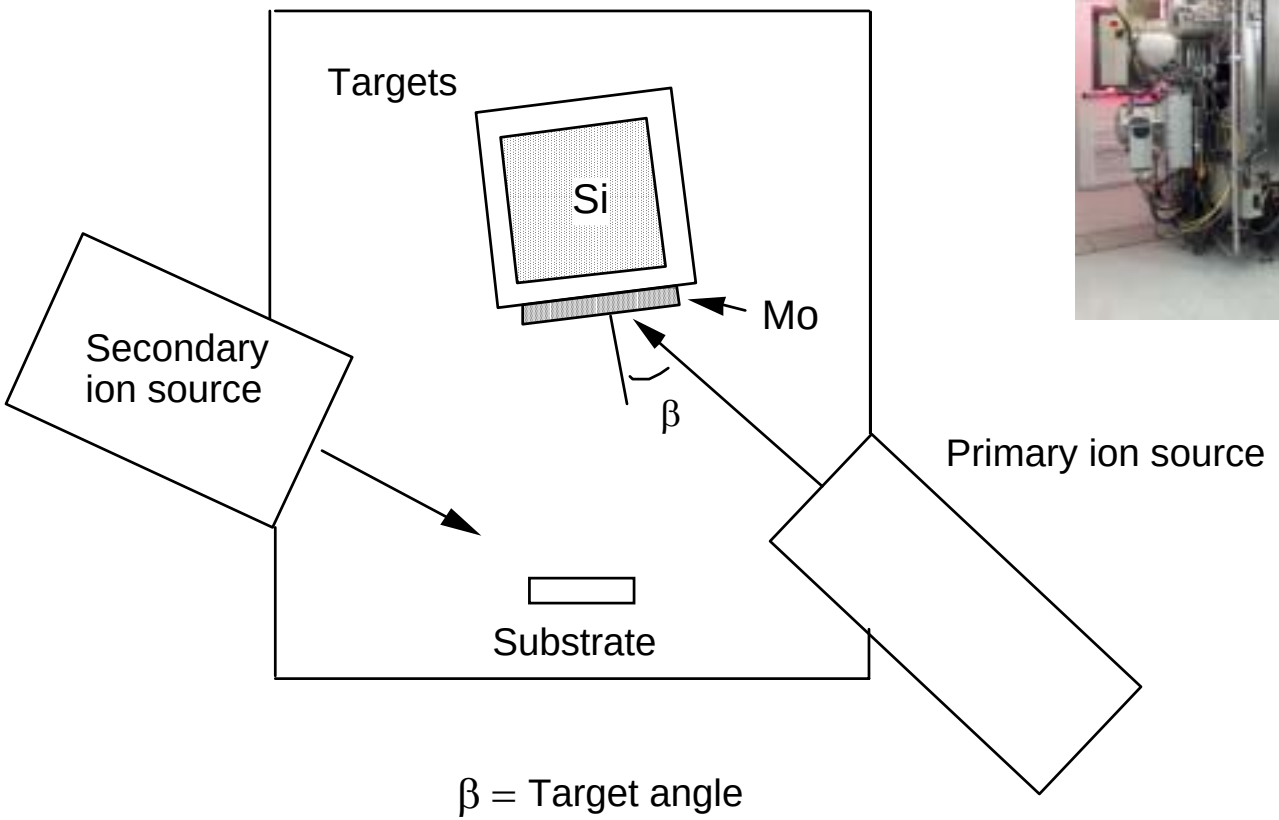
Example of printable phase defects in EUVL mask blanks



Note: Printable multilayer phase defects can also be nucleated by substrate pits

Our ion beam sputter deposition tool has a secondary ion source for ion-assisted deposition

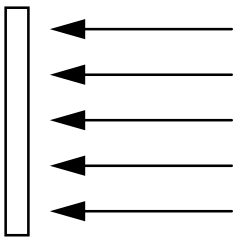
Our Ion Beam sputter Deposition (IBD) system



The ion beam thin film planarization process utilizes a Mo/Si-based coating and etching technique to smooth substrate particles

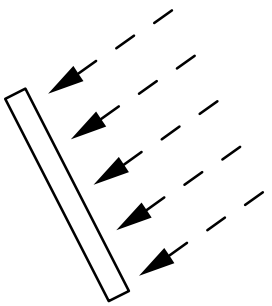
- ***Deposit extra Si when depositing the Si layers***

Deposit at near-normal incidence



Deposit

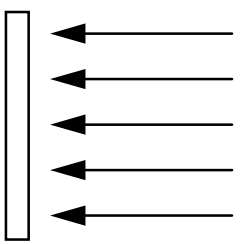
- ***Etch the extra Si away***



Etch

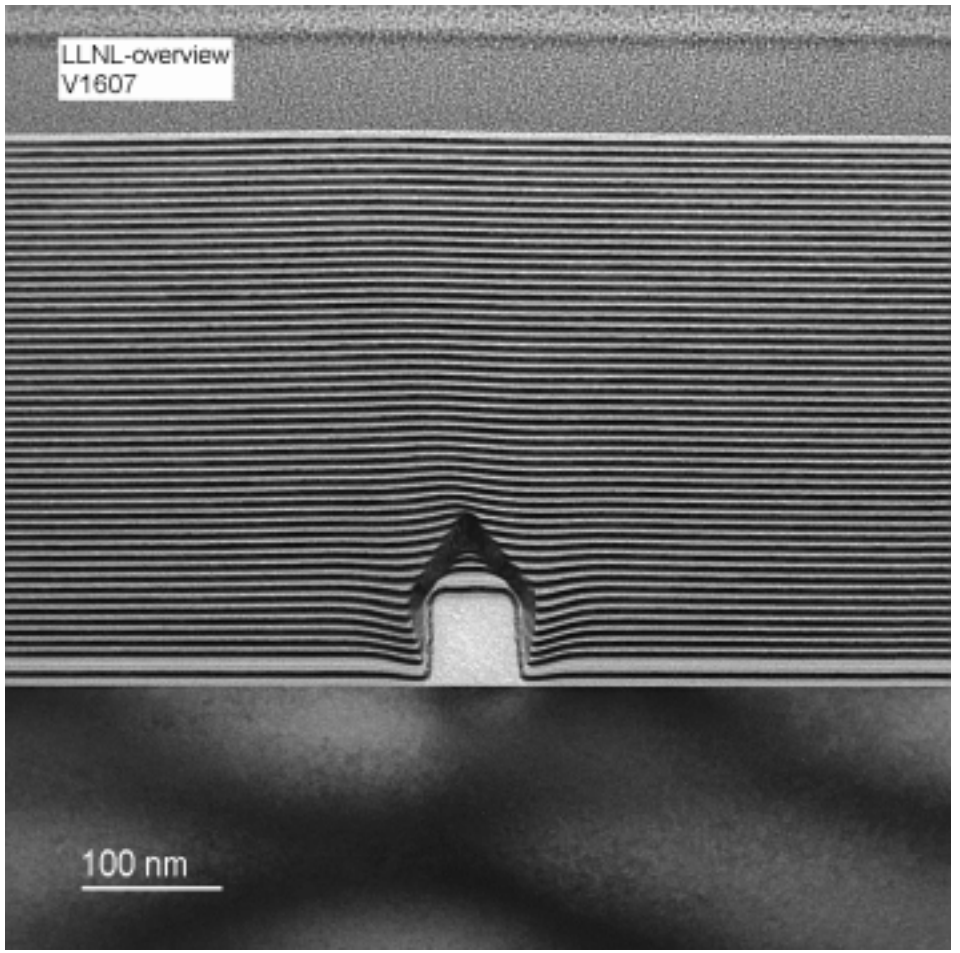
- ***Design process so that Mo/Si bilayer period thickness is approximately 7 nm***

Rotate back and deposit



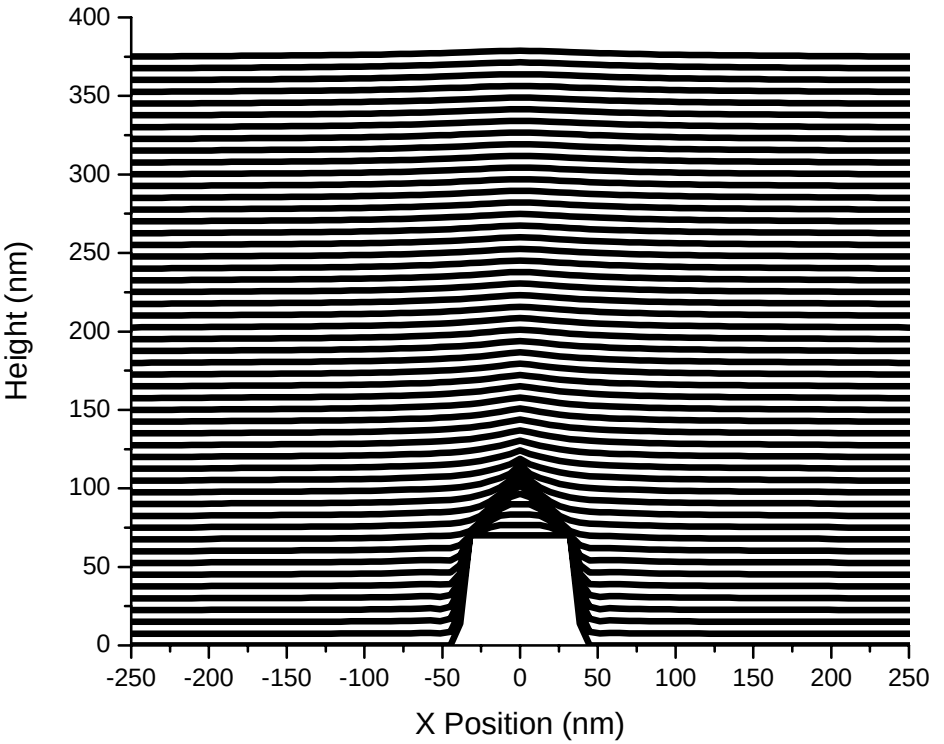
Deposit

Particle-smoothing results from the Mo/Si-based coat and etch process



XTEM image of a smoothed ~70 nm high x 70 nm wide substrate line defect

Smoothed to a mean height of ~ 0.5 nm

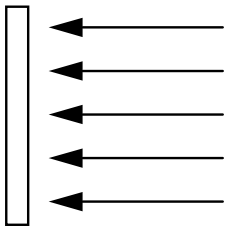


Simulations using the ML growth model (note that it predicts the dark, hat-shaped regions above the defect)

The ion beam thin film planarization process has been recently advanced to use ***Si-only*** coating and etching for smoothing

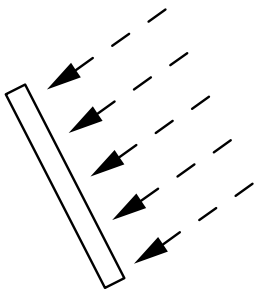
Deposit at near-normal incidence

- ***Deposit a Si layer***



Deposit

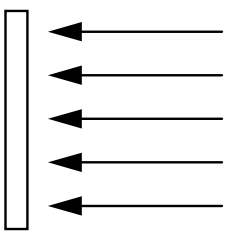
- ***Etch most of the Si away***



Etch

Rotate back and deposit

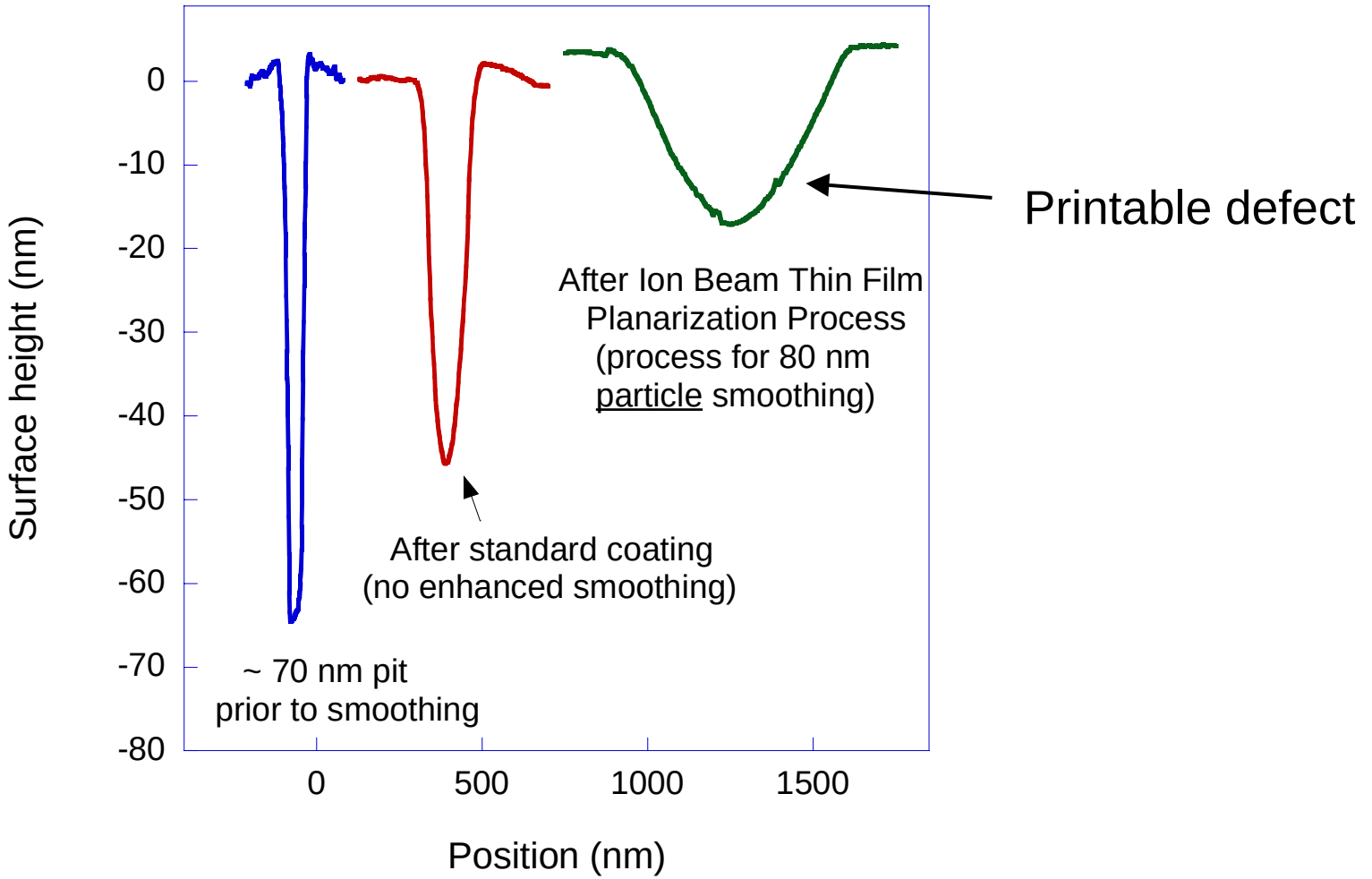
- ***Leave a thin residual Si film at the end (no Mo depo steps needed)***



Deposit

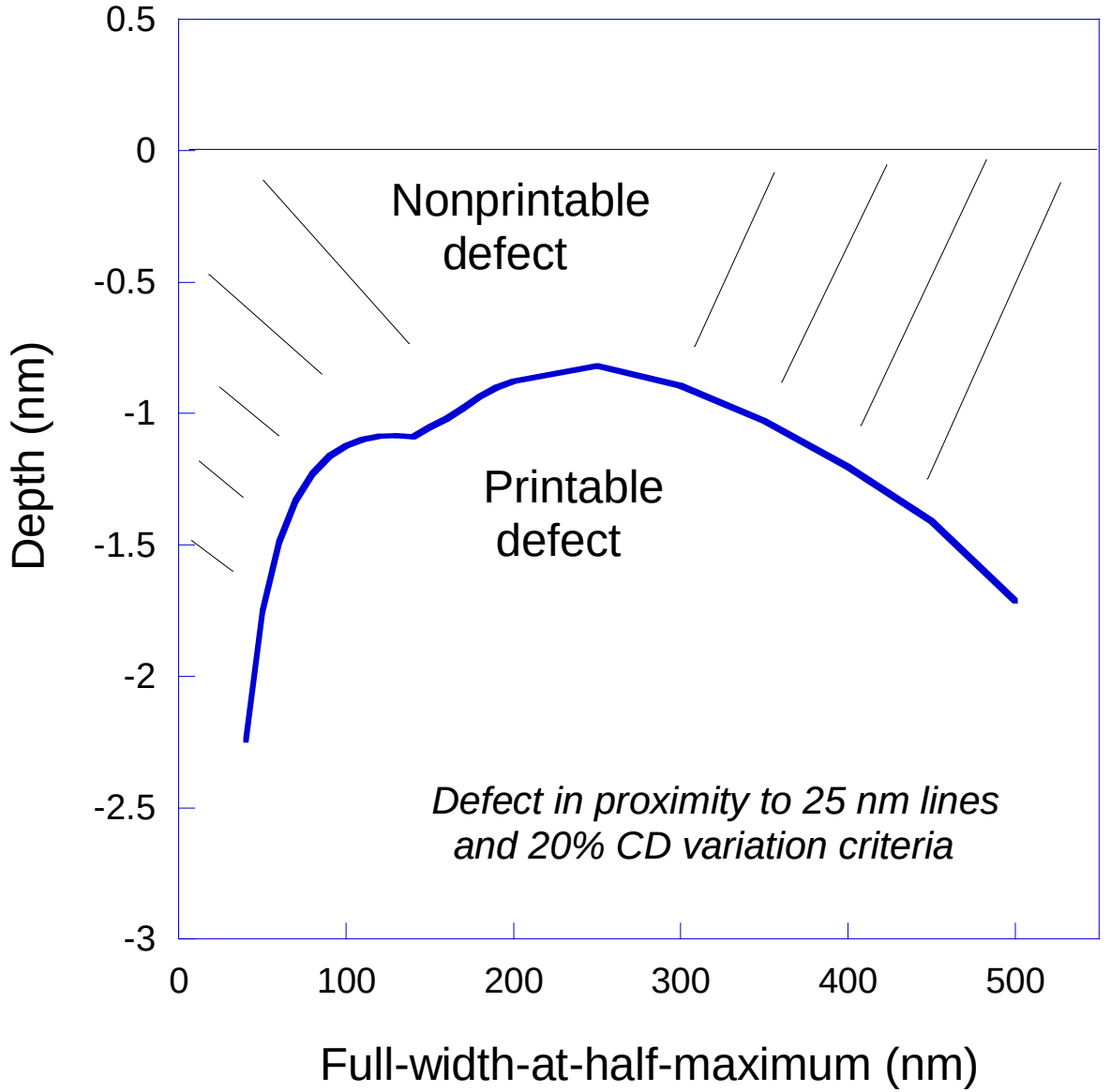
Smoothing results shown later in this presentation will be based on this process

A viewgraph taken from last year's symposium . . .



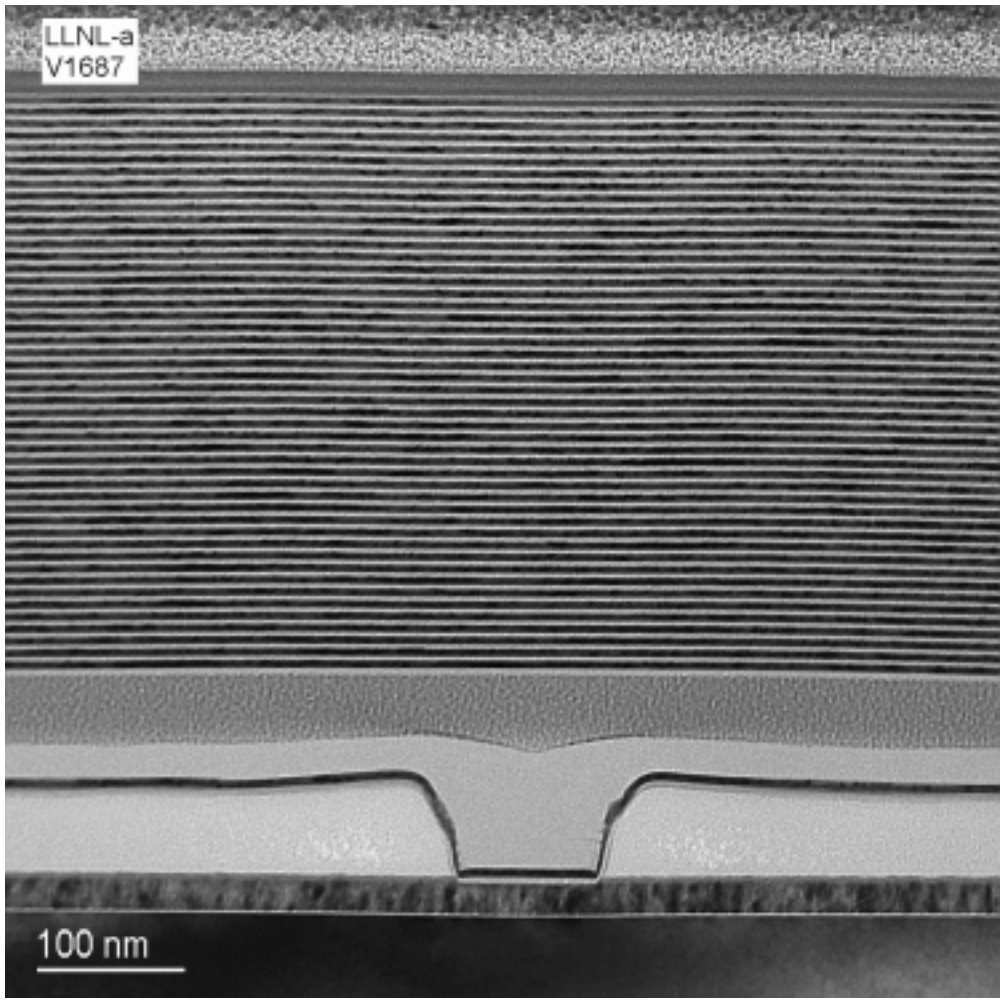
This is definitely a challenge but we believe that we can make good progress in this (new) area by next year's symposium

Theoretical EUVL printability curve suggests that our goal is to smooth the pits to a depth < 1 nm.



Plot provided courtesy of Eric Gullikson, LBNL

We have made excellent progress in substrate pit defect smoothing since last year's symposium



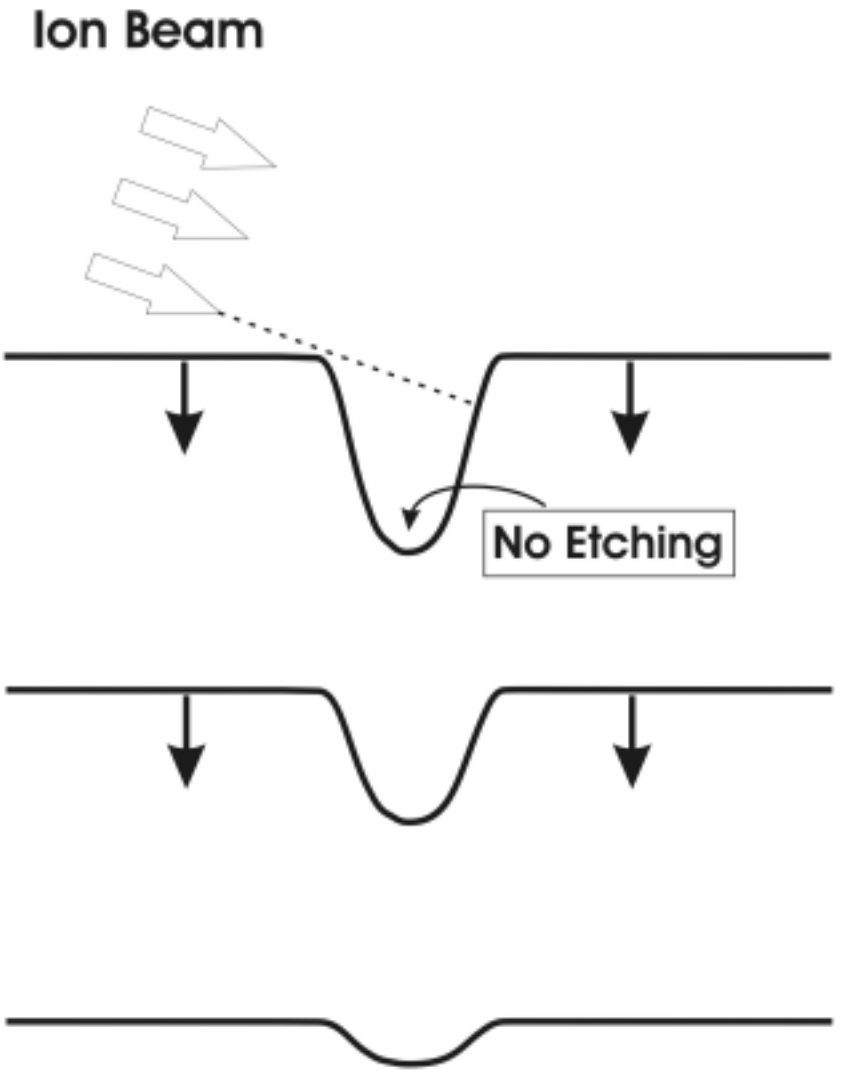
~70 nm deep x ~70 nm wide nm pit smoothed until they were undetectable*

*Given the higher roughness of our pit defect substrates (~0.7 nm rms) and the fact that this process slightly adds to the roughness, we estimate the detectability threshold for pit depths is ~ 1 nm after coating.

XTEM of a smoothed ~70 nm x ~70 nm trench

Note: Dark layer over pit is thin Mo deposited to enhance image contract. Also, trenches provide clearer images of layering (and are easier to locate in FIB) than pits.

This was achieved by using off-normal incidence etching



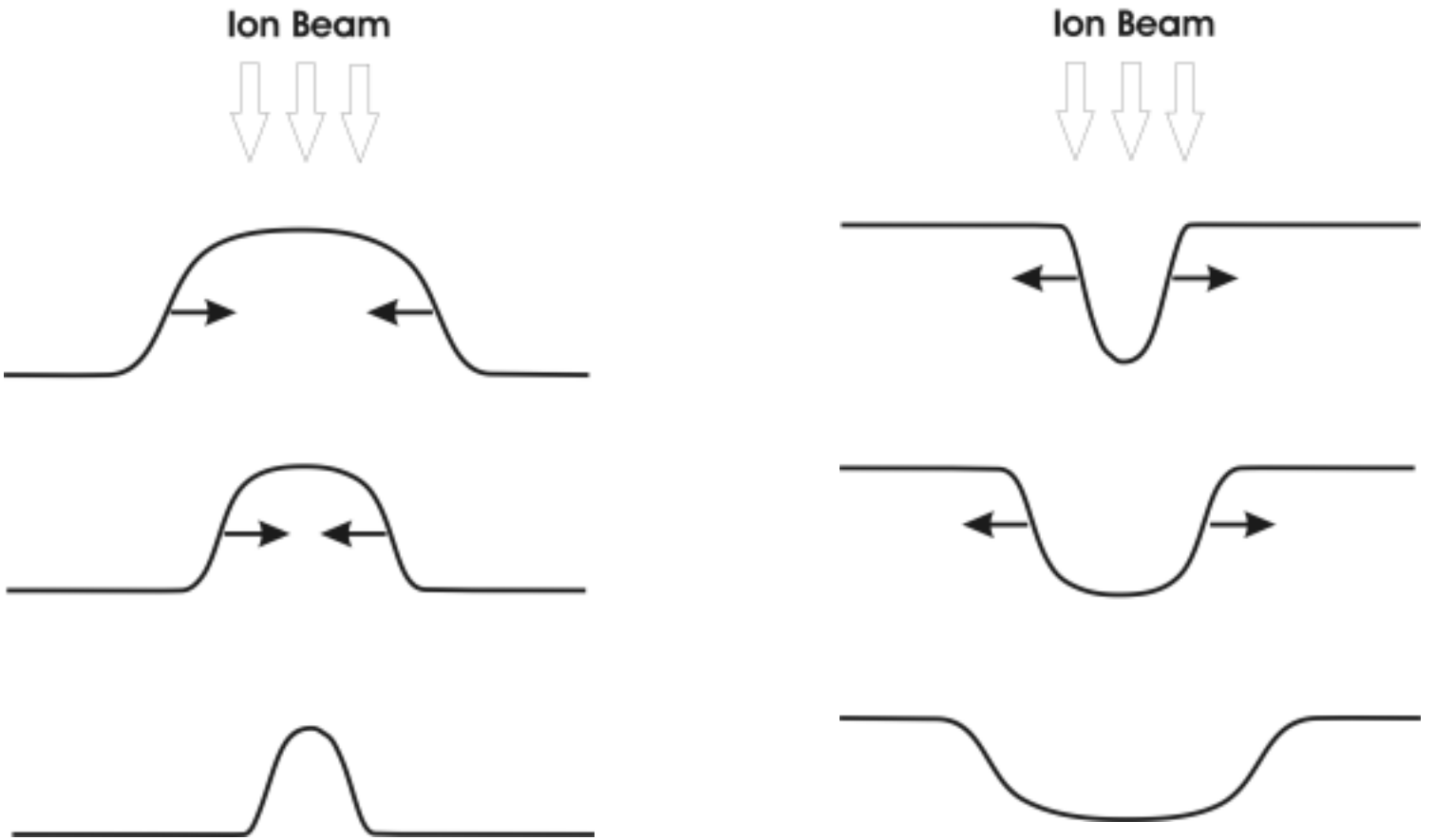
However the pit smoothing process causes the defects nucleated by substrate particles to get larger

Example: Deposition run V1651 (substrates with particles and pits being smoothed with an identical process, the one designed for pit smoothing)

- ~70 nm substrate pits were smoothed to an undetectable depth (~1 nm)

- ~80 nm substrate particles were smoothed to a height of 76 nm and a width (FWHM) of **~222 nm**, i.e., *the defect height was little changed and the width got much larger*.

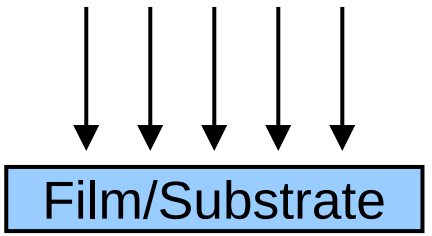
The mechanism which causes particle-defects to shrink could cause pit-defects to enlargen



Assumes primary mechanism relies upon higher etch rate at incident angles approaching 45 degrees

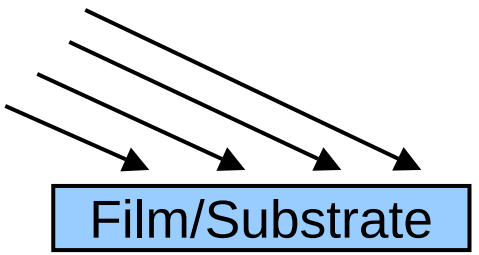
Etching at normal incidence vs. off-normal incidence: benefits and drawbacks

Ion etching at normal incidence



- Excellent for particle smoothing
- Does a fair/mediocre job on pit smoothing
- Also, greatly reduces high-spatial frequency roughness

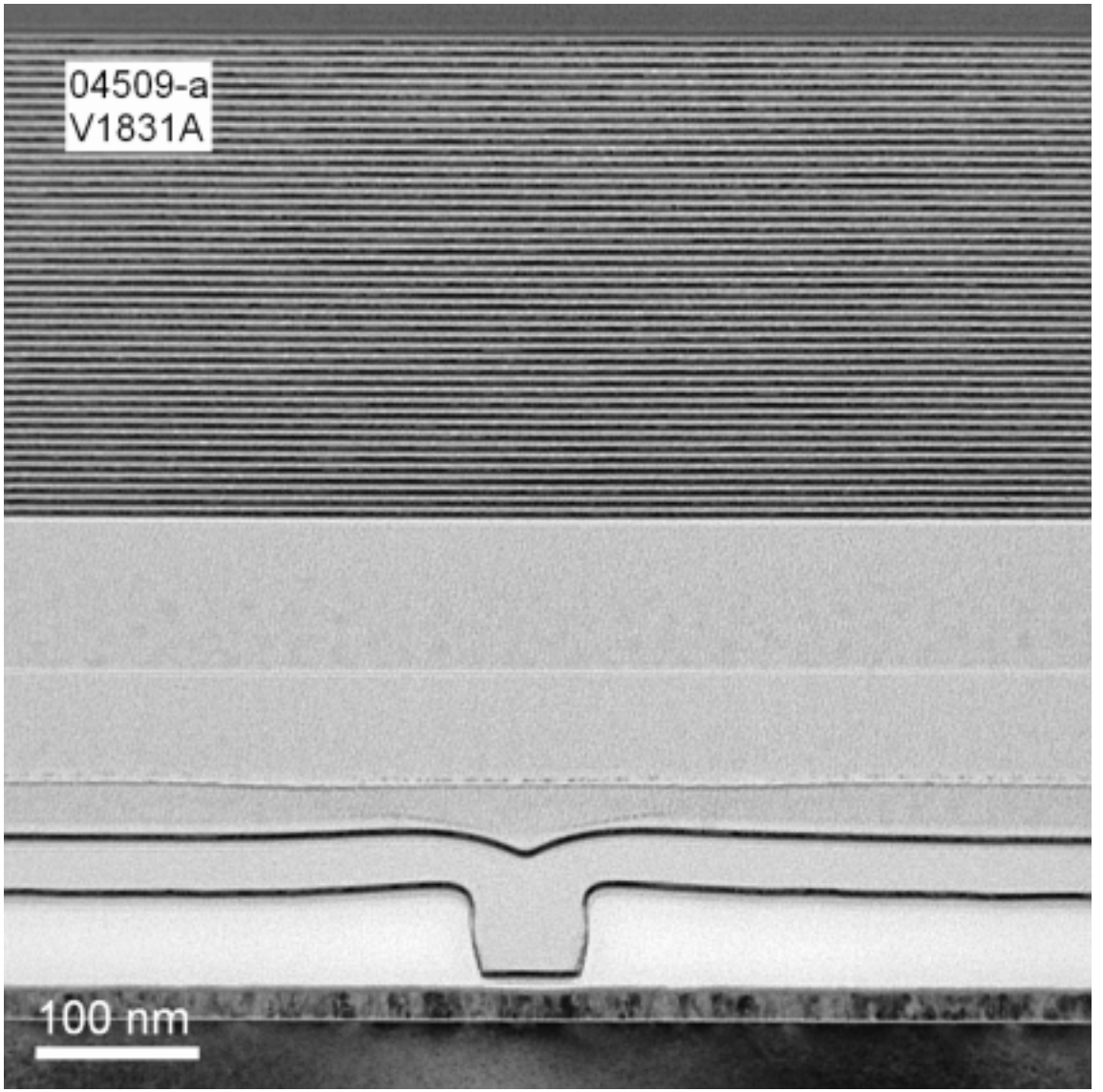
Ion etching at off-normal incidence



- Excellent for pit smoothing
- Does a poor job for particle smoothing
- Also, slightly increases high-spatial frequency roughness

A practical process will need to have components from each process to smooth pit and particles simultaneously

We have developed a process that successfully smooths ~70 nm substrate pits and particles simultaneously: *pit smoothing*

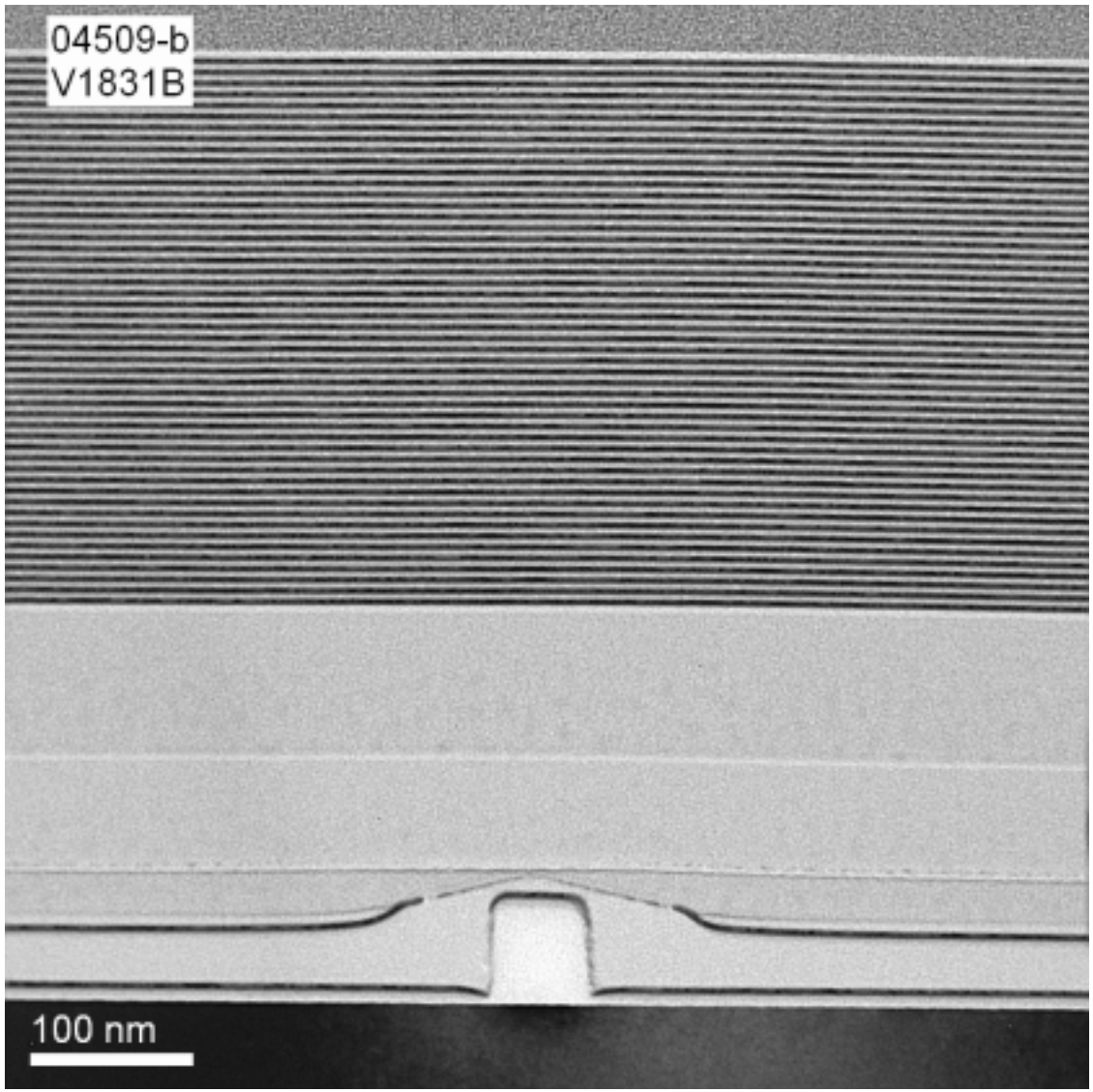


XTEM image of a smoothed 70 nm substrate trench

Depo run V1831

~70 nm pits smoothed to an undetectable depth (< 1 nm)

We have developed a process that successfully smooths ~70 nm substrate pits and particles simultaneously: *particle smoothing*

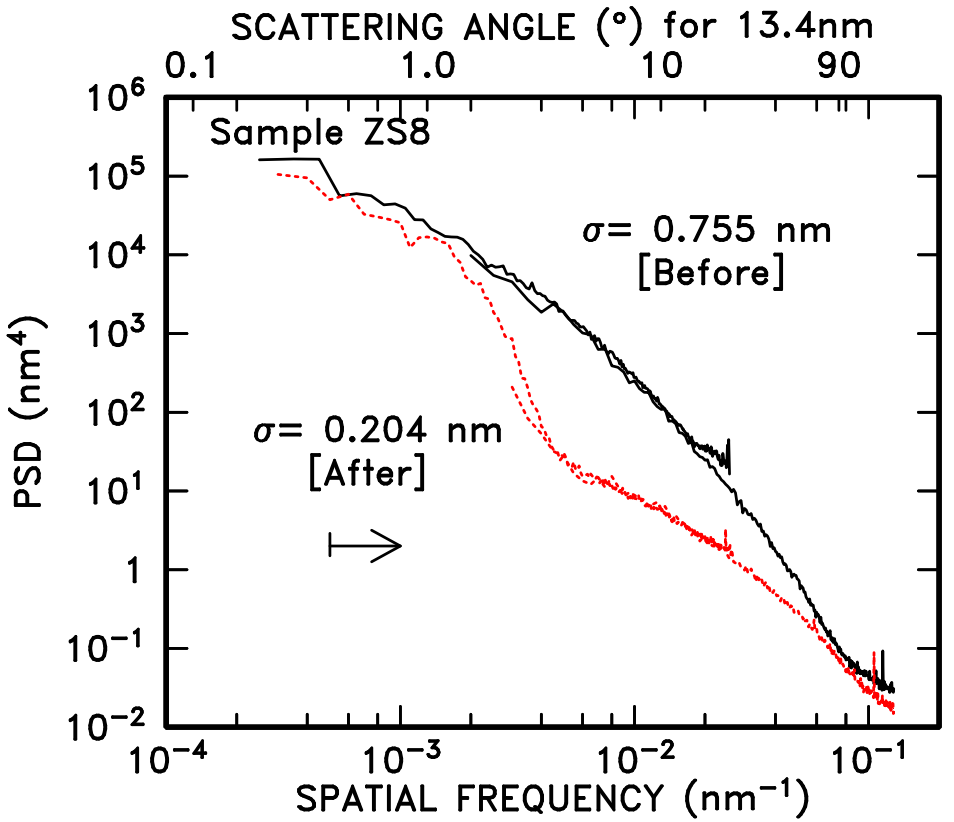


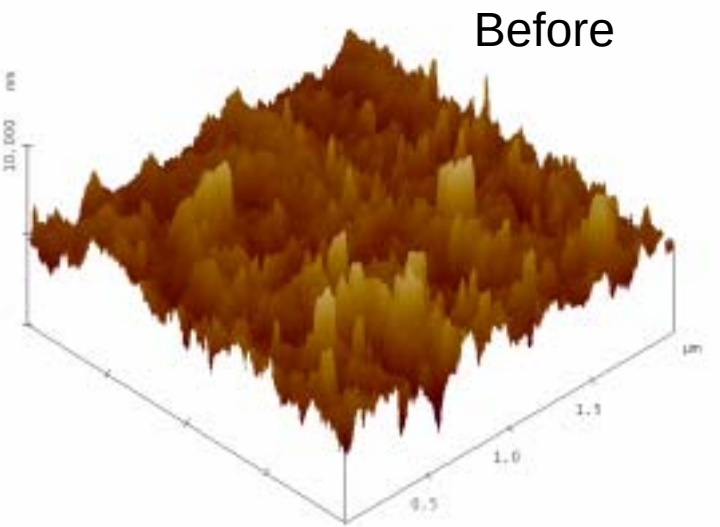
XTEM image of a smoothed 70 nm substrate line

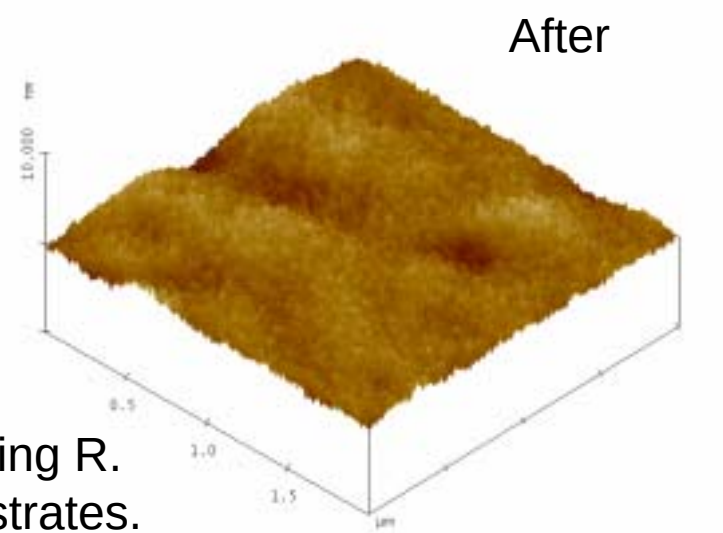
The same depo run V1831

~70 nm particles smoothed to a mean depth of 1.0 nm

Note that the process also works very well for reducing high spatial frequency roughness







- Relaxes HSF roughness spec for mask substrates.
- Since etching occurs before multilayer deposition, no concern about Ar incorporation (or other effects) decreasing R.
- Could have a major (positive) impact on EUVL optic substrates.

Future Work

- Reduce process time (this effort is now underway)
  - Current process time to smooth 70 nm pits and particles is ~ 8 hours (roughly half of this time is to smooth the particles by the last ~1 nm). This needs to be reduced; there are a number of underutilized parameters which should make a positive impact here (higher etch energies, etc).
- Combine the above process with a coating process yielding excellent EUV reflectance uniformity and reflectivity (based on past experience this should be straightforward).
- Combine the above process with an ultralow defect density coating process.
- And possibly . . . EUVL printing tests . . . Smooth irregularly shaped pits and particles . . .Smooth optic substrates . . .

Summary

- The ion beam thin film planarization process has been modified to employ a Si-only coat and etch process.
- By employing off-normal etch angles ~70 nm deep by ~70 nm wide substrate pits can be smoothed below the printability threshold; however, such a process causes particle-nucleated defects to widen significantly.
- A process has been developed and demonstrated which can smooth ~70 nm pits and particles *simultaneously*; the drawback is a larger process time but we are confident that significant progress can be made in this area.
- The above process can smooth the HSFR of a 0.75 nm rms surface to 0.20 nm rms.