Smoothing EUVL mask substrate defects with an emphasis on real-world pits

Paul B. Mirkarimi, Eberhard Spiller, Sherry L. Baker,
and Jeffrey C. Robinson,
Lawrence Livermore National Laboratory, Livermore, CA. 94550

F. Salmassi and E.H. Anderson
Lawrence Berkeley National Laboratory, Berkeley, CA. 94720

EUVL Symposium, Barcelona, Spain.
October 16, 2006

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).

Funding was provided by Intel Corporation through a work-for-others agreement.

Outline

I. Introduction.

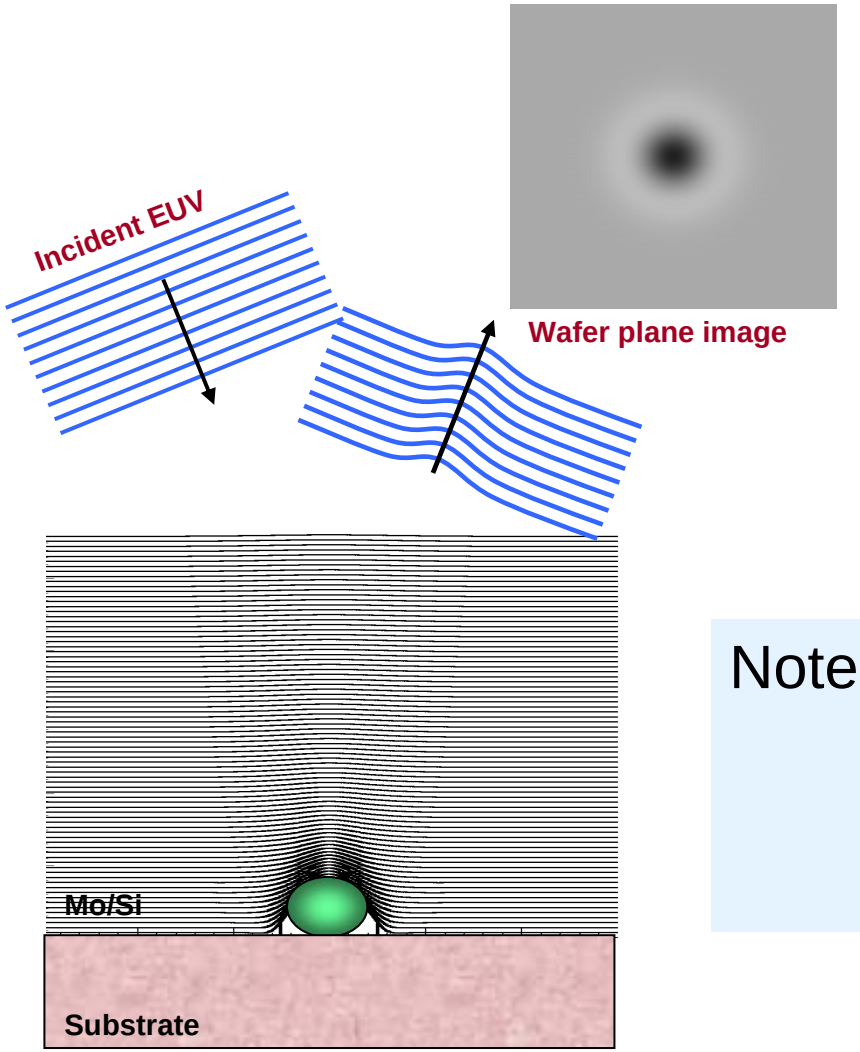
II. Smoothing lower aspect ratio pits.
- With etching
- Without etching

III. Smoothing lower aspect ratio pits and particles simultaneously.

IV. Brief smoothing retrospective

V. Conclusions.

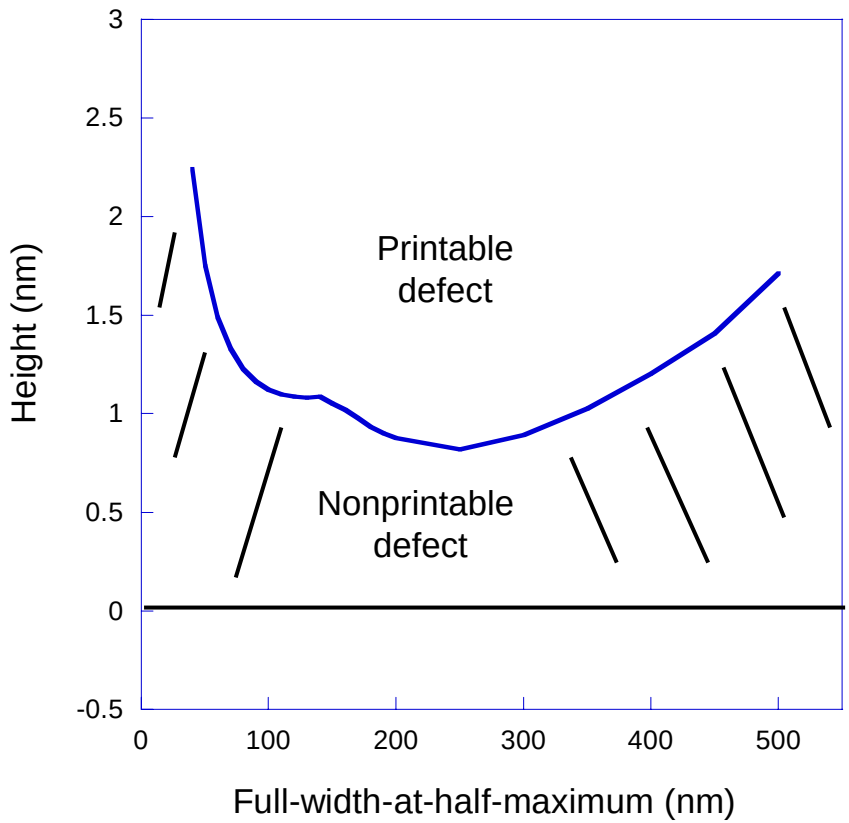
Critical <u>phase defects</u> can be nucleated by substrate particles (or particles appearing early in the multilayer depo process)



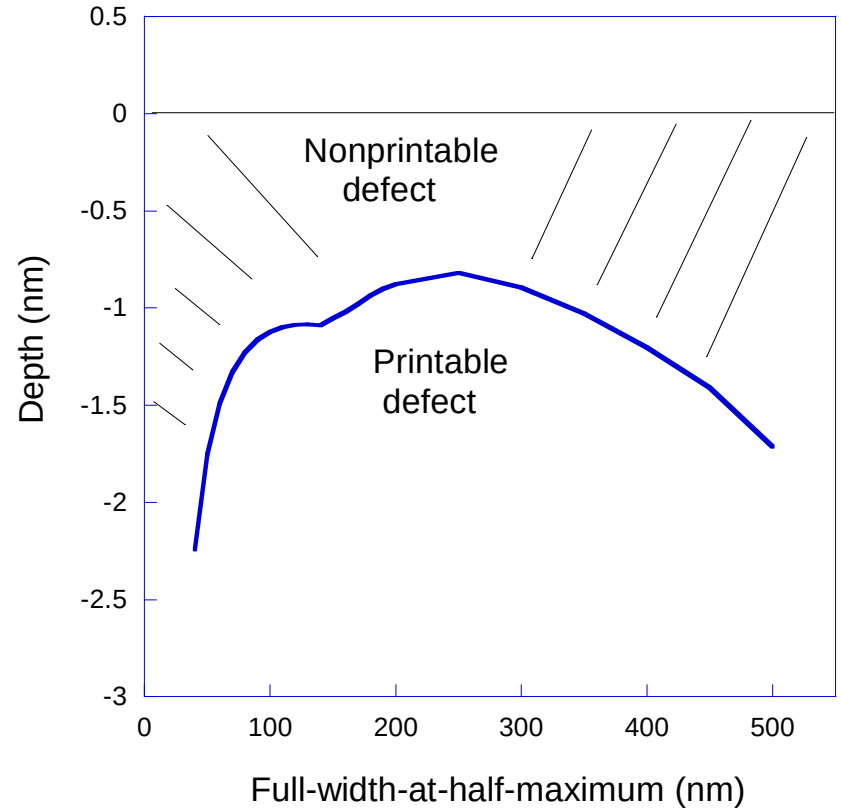
Note: Critical multilayer phase defects can also be nucleated by substrate pits.

Theoretical EUVL printability curve suggests that our goal is to smooth the defects to an approximate height or depth ≤ 1 nm.

Multilayer defects nucleated by particles

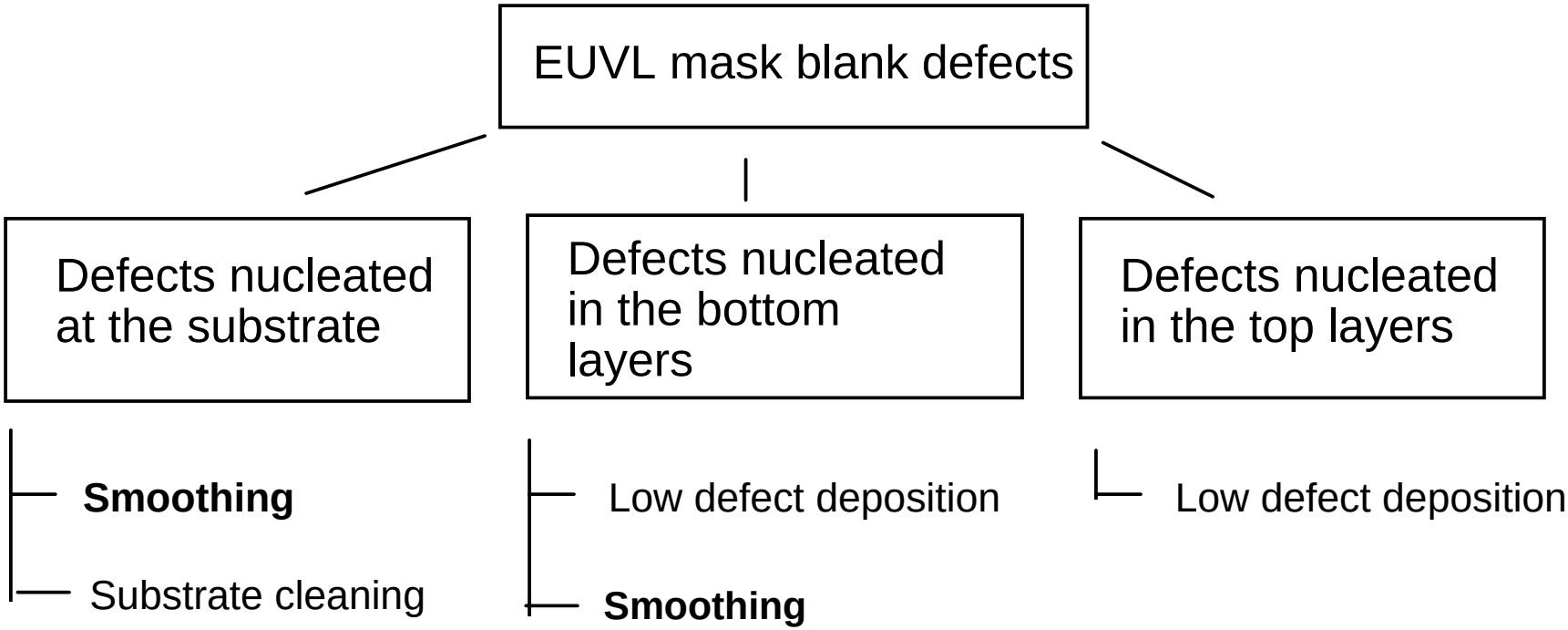


Multilayer defects nucleated by pits



- *Defect in proximity to 25 nm lines and 20% CD variation criteria*
- *From the Gullikson model for EUVL printability [E.M. Gullikson et al., JVST B 20, 81 (2001)].*

Strategy for combating EUVL mask blank defects

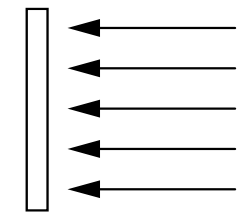


With *smoothing* we plan to enhance the smoothing properties of the coating to minimize the disturbance of the layers in the multilayer (and render a printable defect nonprintable).

<u>Note</u>: Only smoothing can mitigate substrate pits

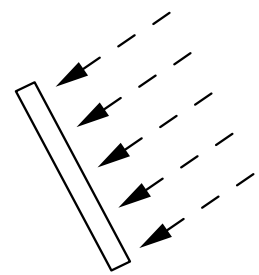
We use an ion beam sputtered, Si coat-and-etch process for smoothing substrate defects

- ***Deposit a Si layer***



Deposit

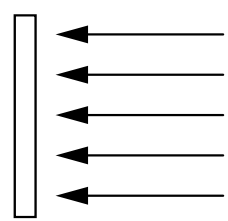
- ***Rotate and then etch most of the Si away***



Etch

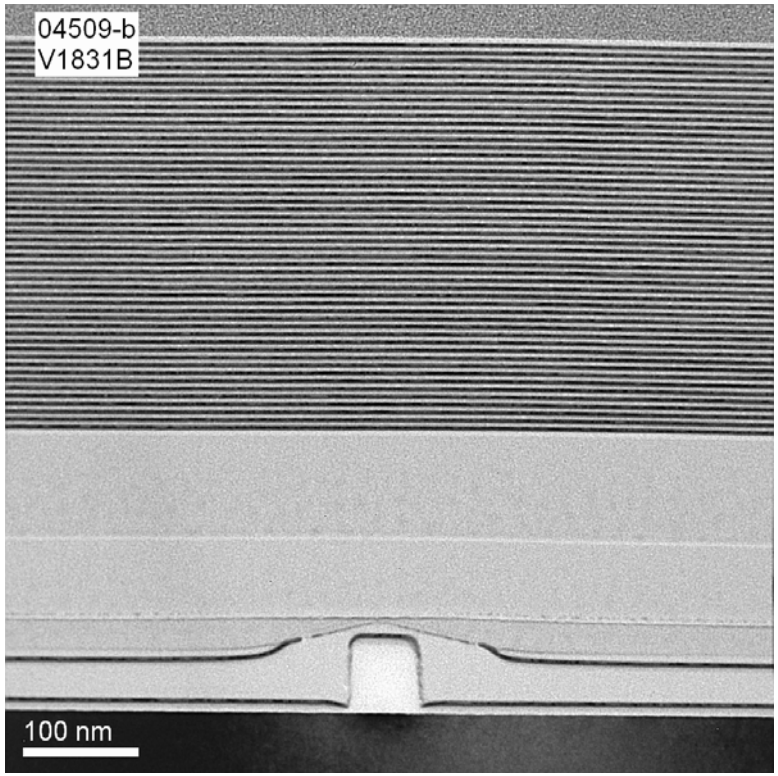
- ***Rotate back and deposit Si again***

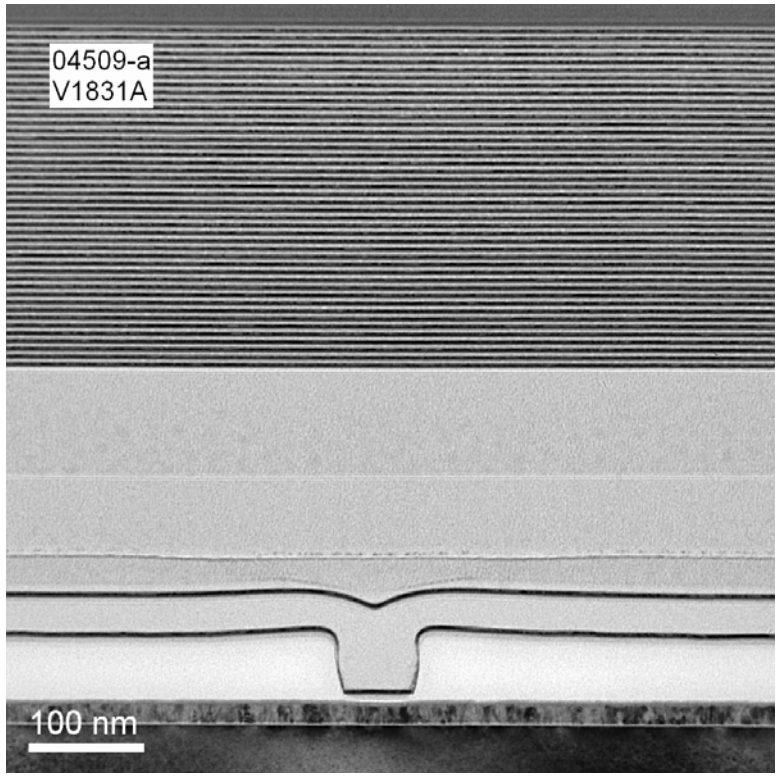
- ***Leave a thin residual Si film at the end (no Mo depo steps needed)***



Deposit

Previously we demonstrated a Si-based, coat-and-etch process that successfully smooths ~70 nm mask substrates particles and pits *simultaneously*





XTEM image of a smoothed 70 nm substrate line and trench

[Note that it's more straightforward to make XTEM samples from lines/trenches than particles/pits]

From P.B. Mirkarimi et al., J. Nanosci. and Nanotech. 6, 28 (2006).

The focus of this presentation is lower aspect ratio substrate pit defects (like real-world pits)

- Pit defects dominate the defect distribution of state-of-the-art mask substrates (can't clean pit defects). *See presentation by Randive et al. tomorrow for information on this topic.*

- These real-world pit defects tend to be shallower and wider than those smoothed previously (such as in last year's presentation).

- There is a need to alter the smoothing process to planarize these lower aspect ratio pit defects (along with particles). This is the primary thrust of this presentation.

- To develop the process it is useful for the substrate size/shape to be constant (i.e., so it's not a variable). Thus we used lithographically fabricated programmed pit defects.

II. Smoothing lower aspect ratio pits

a) With etching

- We've looked at 52 degree, 60 degree, 65, and 70 degree etch angles. To date the 65 degree and 70 degree etch angles perform the best for pit-only smoothing.

Table 1. Smoothing of an 18 nm deep by 100 nm wide pit with a **70 degree etch angle**. 500 eV etch source energy and 800 eV primary ion source energy. Each cycle has ~ 9.3 nm deposited and ~ 8 nm etched away.

Sample	# of cycles	Etch angle (degrees)	Pit depth (nm)	Pit FWHM (nm)	Process time* (min)
V2159	10	70	-14.1	47.4	14.5
V2160	4	70	-9.9	37.7	5.8
V2161	9	70	-4.6	44.2	13.1
V2162	15	70	-2.8	63.0	21.9
V2163	15	70	-	-	21.9
"	25	0 (to remove roughness)	**-0.4**	~115	36.4 **(total = 1.9 hours)**

* Does not include mechanical motion

Table 2. Smoothing summary for the V2159-V2163 process sequence as described in Table 1 **(70 degree etch angle).**

Description	Final depth (nm)	FWHM (nm)	Comments
18 nm deep by 100 nm wide pit	**-0.4**	~115	Noncritical.
18 nm deep by 140 nm wide pit	**-0.6**	-	Noncritical.
18 nm deep by 100 nm wide scratch	**-0.6**	~180	Noncritical. **(first time ever observed for a reasonably large scratch).**
18 nm deep by 140 nm scratch	**-1.5**	~195	Almost noncritical.

The (high spatial frequency) roughness for this sample was 1.4 Å rms.

Note that the 65 degree etch angle is slightly better than the 70 degree etch angle for pit-only smoothing; for example, it smooths to about the same level in 1.4 hours and leaves a 1.0 Å rms roughness. However, it does not smooth particles as well as the 70 degree etch so we won't discuss it further here.

b) Pit smoothing <u>without</u> etching

- Etching presents a risk in that the process may add particles to the coating as it's smoothing away substrate particles (see Randive et al.'s talk tomorrow).

- What if one were able to clean all of the particles? Then a no-etch pit smoothing process could be very valuable.

- We conducted a brief investigation to ascertain how easy it might be to smooth pits without etching. Previously we had investigated particle smoothing without etching *[see Mirkarimi et al., Appl. Phys. Lett. 77, 2243 (2000)]* but not pit smoothing.

Only minor pit smoothing was observed without etching

Table 3. Smoothing of **9 nm deep pits** with deposition but **without** etching.
The primary variable was the deposition angle.

Sample	**Deposition angle (degrees)**	Starting Width (nm)	**Pit depth after smoothing (nm)**	FWHM after smoothing (nm)	Comments
V2135	**0**	50	**-5.7**	37.8	Pure Si; ~ 104 nm thick. Roughness = 0.19 nm rms.
"	"	100	**-8.5**	83.4	"
V2137	**45**	50	**-5.0**	37.8	Pure Si; ~ 83 nm thick; Roughness = 0.20 nm rms.
"	"	100	**-7.5**	84.0	"
V2122	**79**	100	**-18**	-	Pure Si; ~ 80 nm thick; Roughness = 1.75 nm (very rough – not practical).
V2145 + V2148	**0**	50	**-4.5**	41	Mo/Si with enhanced silicide; ~ 185 nm thick. Roughness = 0.20 nm rms.
"	**0**	100	**-6.4**	92	"

- Need etching to smooth significant substrate pits.

III. Smoothing lower aspect ratio pits and particles simultaneously

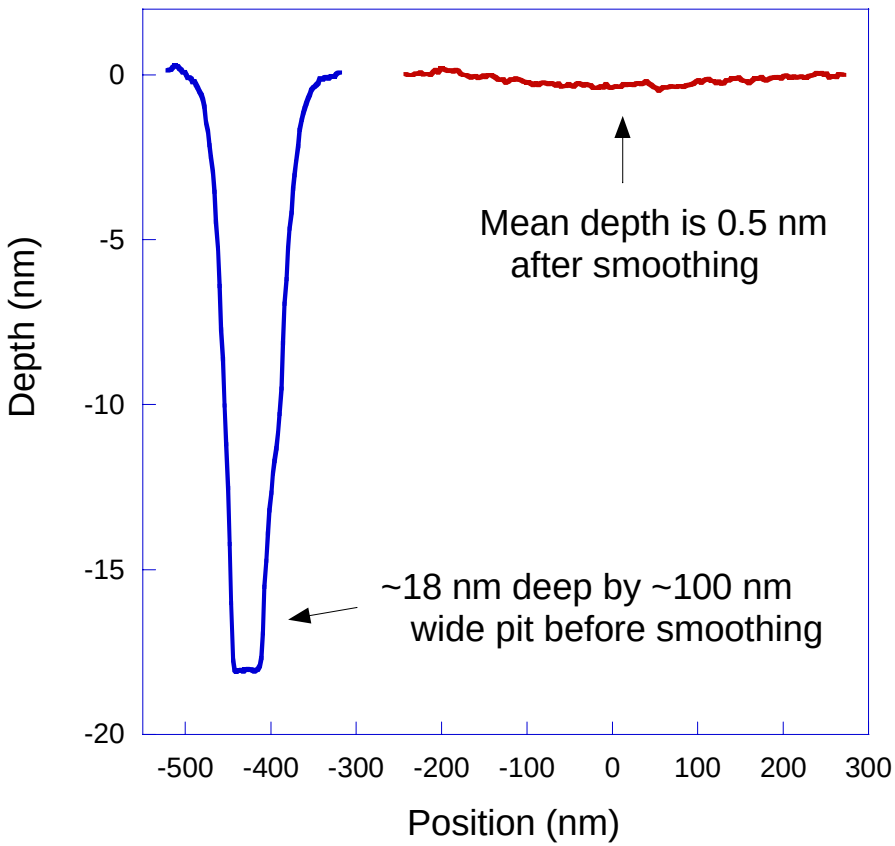
Table 4. *Simultaneous* smoothing of an 18 nm deep by 100 nm wide pit and a 40 nm by 40 nm particle. 500 eV etch source energy and 800 eV primary ion source energy. Each cycle has ~ 9.3 nm deposited.

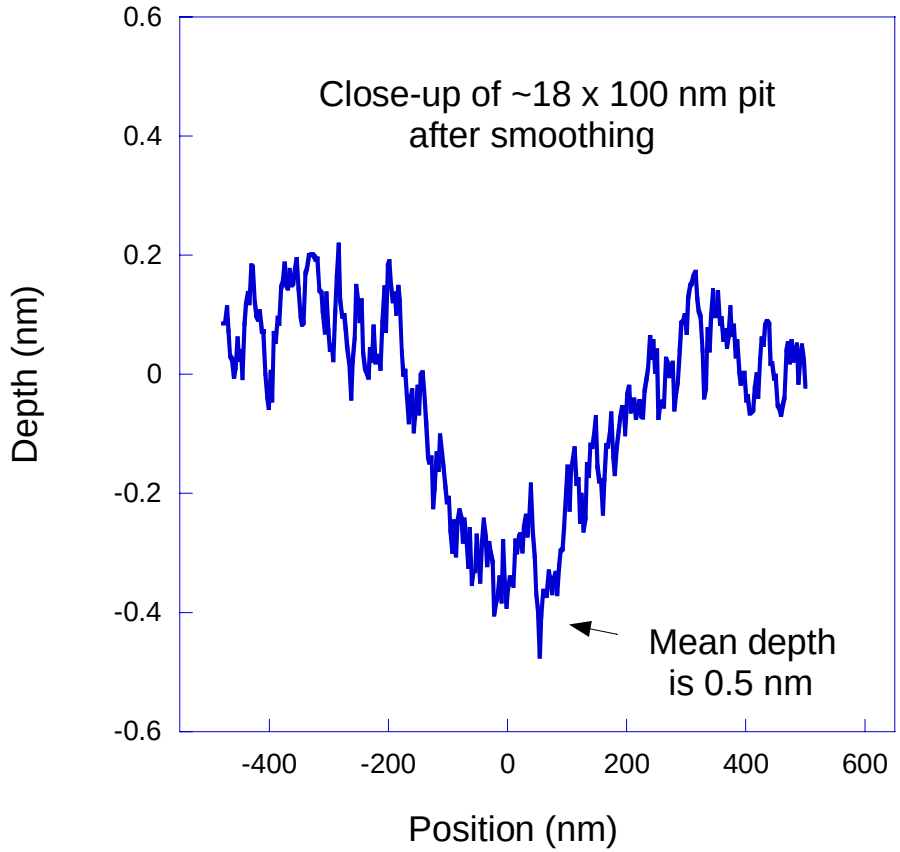
Sample	# of cycles	Etch angle	Amount etched per cycle (nm)	**Pit depth (nm)**	Pit FWHM (nm)	Particle height (nm)	Particle FWHM (nm)	Process time* (min)
V2171	10	70°	8.2	-3.3	54	-	-	23.3
V2173	2	0°	8.2	-1.0	164	2.3	172	36.5
V2174	5 40	0° 0°	9.9 8.2	**-0.5**	188	**0.9**	231	7.6 58.1 (total =125.5, or **2.1 hours**)

* Does not include mechanical motion

Roughness was ~ 0.8 Å rms at the end

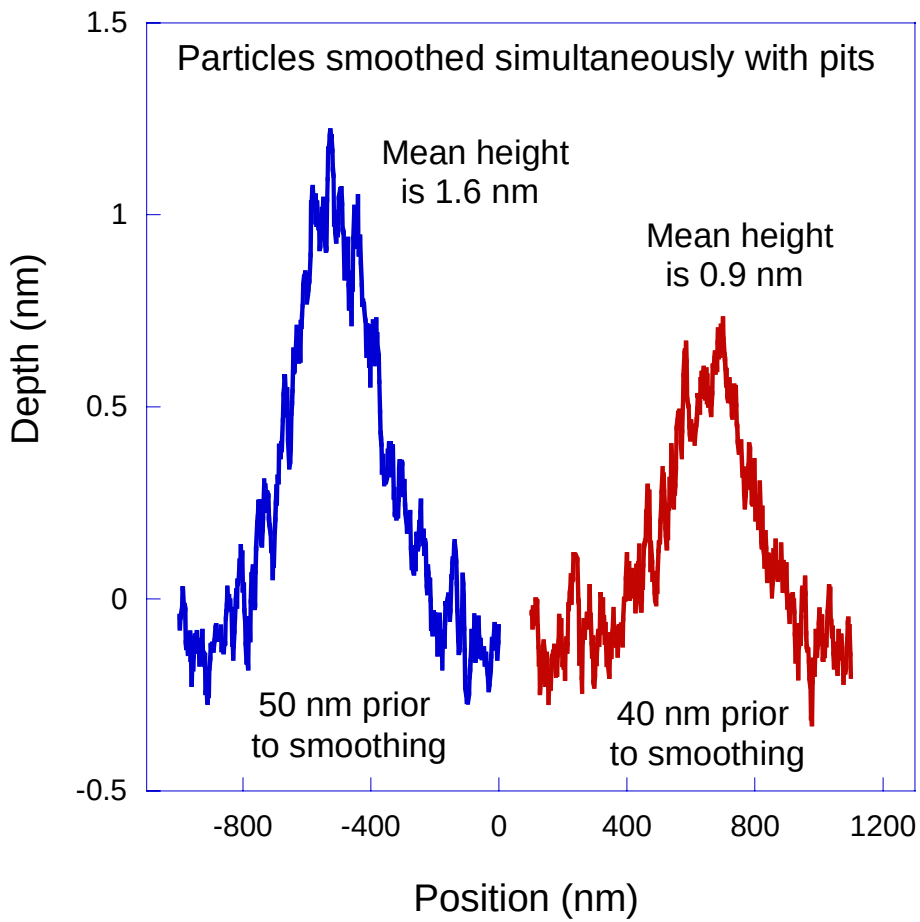
AFM cross-section of smoothed pits





- 18 nm deep by 100 nm wide pits rendered noncritical

AFM cross-section of smoothed particles



- 40 nm particles rendered noncritcal <u>at the same time</u> as the pits shown on the previous viewgraph. With a little more process tuning we're confident that the 50 nm particles could be rendered noncritical.

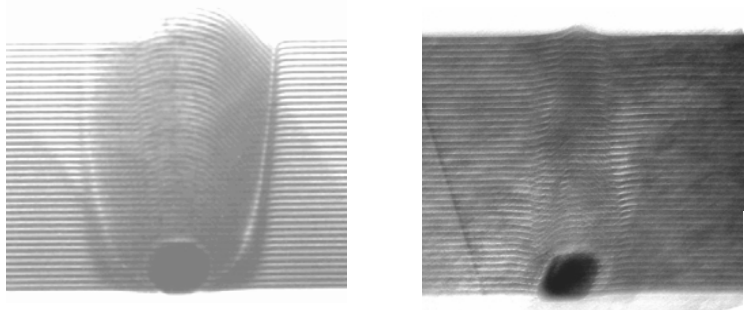
IV. Brief smoothing retrospective

- We have given presentations on the topic of defect smoothing at this symposium every year since it began; this probably will be the last one since the focus in 2007 will be on making the process sufficiently clean rather than making it more powerful (work to be done elsewhere).

- Hence it's appropriate to present a brief retrospective with some key points to remember . . .

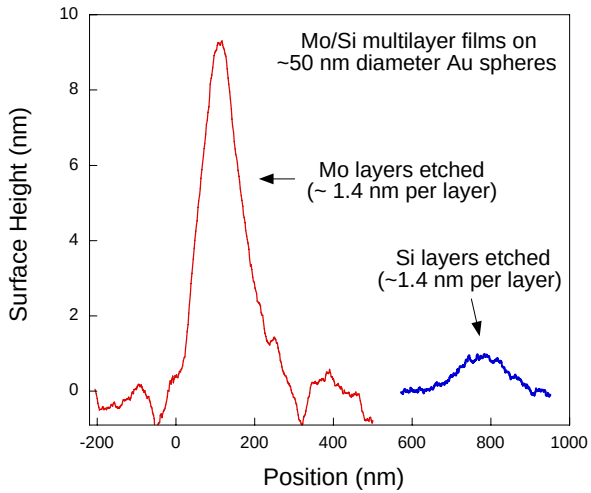
➢ For Mo/Si with *no etch*, particle smoothing properties depend critically on depo angle.

48 deg off-normal dep *9 deg off-normal dep*



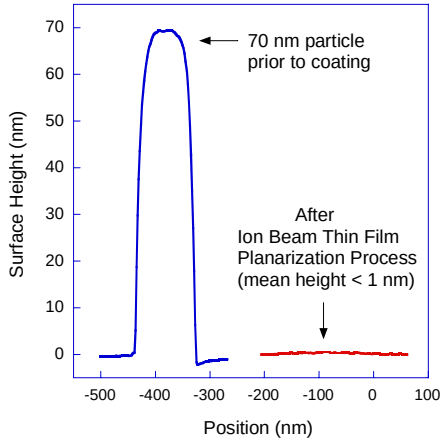
➢ Etching of the silicon layers in Mo/Si multilayers greatly enhances particle smoothing.

This discovery generated an R&D 100 award



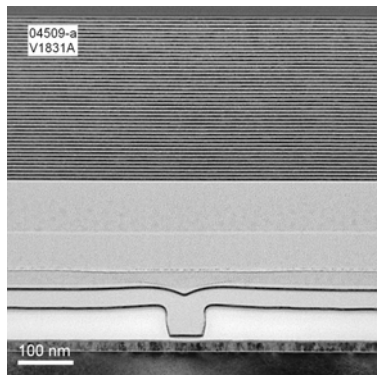
Smoothing retrospective (continued)

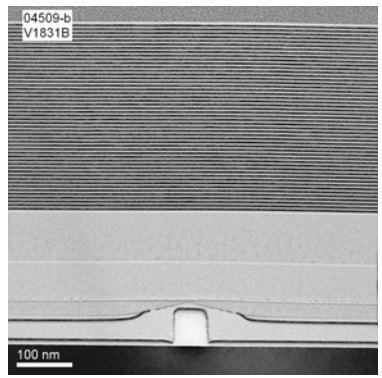
- Can use pure Si instead of Mo/Si to smooth substrate defects. This enables one turn up the power of the smoothing process since no concern of multilayer damage.



- Pits can be smoothed by using more glancing angles for etch flux.

- Particles and pits can be smoothed by a multi-step process which utilizes two different etch angles (first focus on pits, then on particles, since optimal etch angles are different).





- Process is agile. We have adjusted the process to smooth particles, pits, to smooth them simultaneously, to smooth them faster, and to smooth low aspect ratio pits. Now it needs to be rendered clean enough for manufacturing (see Randive et al. presentation tomorrow).

V. Conclusions

- Have demonstrated that low aspect ratio pits (up to 18 nm deep by 100 nm wide) and scratches (18 nm deep by 100 nm wide) can be smoothed to a noncritical size in ~1.4 - 1.9 hours.

- Have smoothed the above pits along with 40 nm particles to a noncritical size in ~2.1 hours. Expect that 50 nm particles can also be rendered noncritical with some further process tuning.

- We were not able to smooth substrate pit defects to a noncritical size without etching (as expected).

- The smoothing process has shown itself to be powerful and agile. The next step is to make the process clean enough for manufacturing.