Advanced experimental approaches and applications

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Major nanolithography

		Process	Wave length	Resolution	Throughput
UV		Parallel	~ 400 nm	2 μm	Excellent
Deep UV		Parallel	248 nm	0.5 μm	Excellent
Extreme UV		Parallel	13.4 nm	50 nm (30nm)	Excellent
E-beam lithography		Serial	< 1 nm	10 nm	Fair
SPM	STM	Serial	N/A	0.1 nm	Fair
	Dip-pen	Serial	N/A	50~100 nm	Fair
Soft litho	μ-contact printing	Parallel	N/A	300 nm	Very good
	NIL	Parallel	N/A	100(10 nm)	Very good
X-ray		Parallel	< 1 nm	100 (20 nm)	Very good
?		**High resolution, high throughput lithography is required.**			

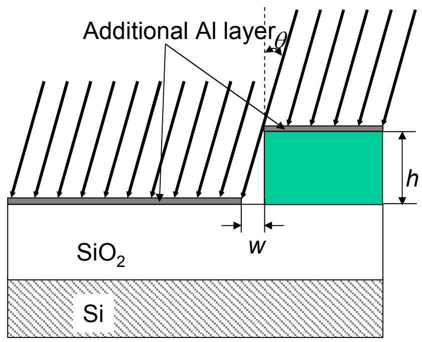
Low cost, high throughput nanomanufacturing is essential for biochips.

Shadow Effect

Electron beam evaporator
Washington technology center

- "line-of-sight" deposition in high-vacuum evaporation.
- When the deposition angle is α and the thickness the pre-patterned layer is h, the nanogap width is

$$w = h \tan \alpha$$



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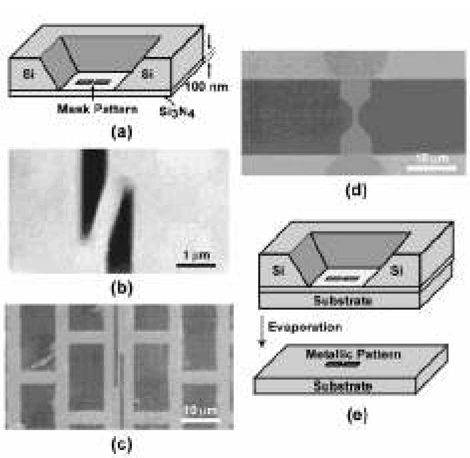
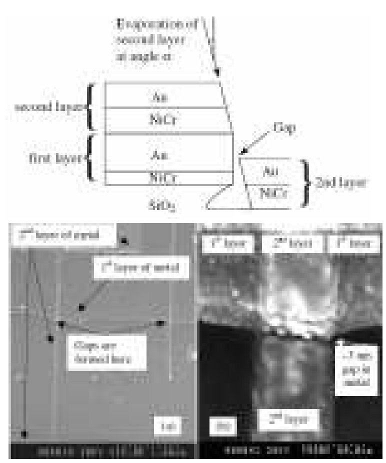
Shadow effect for nanopatterning



Patterning using nanoscale stencil

Zhou YX, et al., Nano Letters, 2003



Nanogap creation

Sun LF, et al, Nanotechn., 2005

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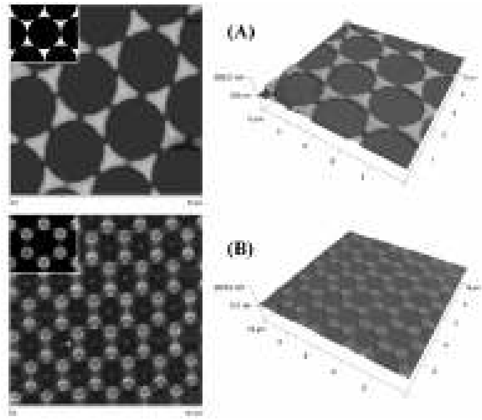
Shadow effect for nanopatterning (cont'd)

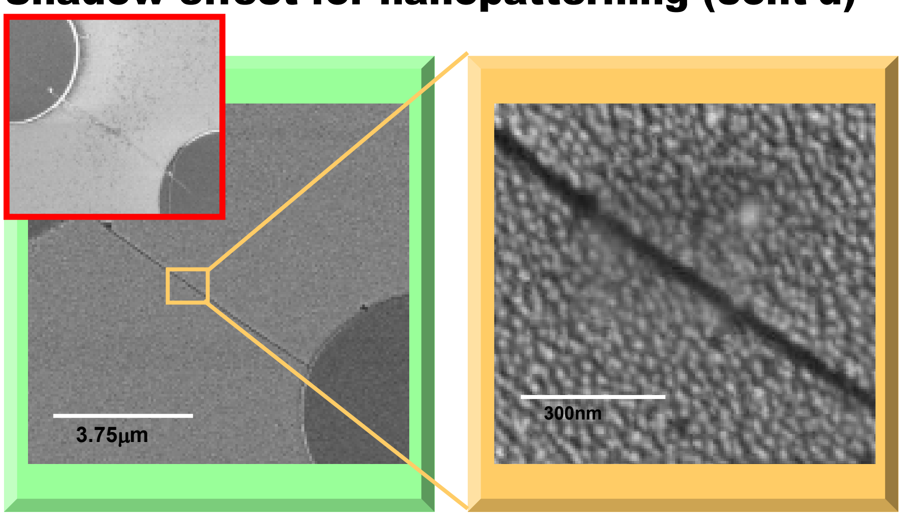


Simulation and experiment

Shadow nanosphere lithography

Kosiorek A, et al., NANO LETTERS, 2004.

Shadow effect for nanopatterning (cont'd)



Nanotube assembly-> pattern reversal-> nanogap

Chung J et al., Nano Letters, 2003

Lithography using the Shadow Effect?

Pros

- It is demonstrated that a few nanometer scale is working (High resolution).
- Evaporation is performed for a whole wafer (High throughput).
- Simulation matches experiment quite well.
- Depending on angle and perpatterned shapes, various patterns can be conceivable.

Cons

- Theoretical model is not established.
- Wafer scale fabrication is yet to be shown.
- Geometrical variation across a wafer was not considered.
- The prepatterned layers or particles have defects.

PROPOSE Shadow edge lithography

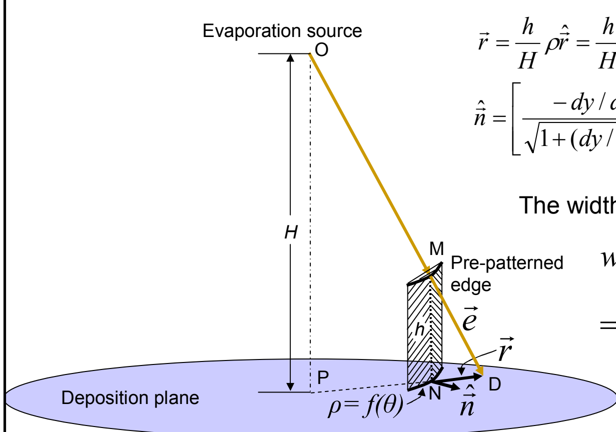
- Prepatterned Al layer will be used to create nanoscale patterns.

Shadow width; Point Source

A shadow edge on the deposition plane with an arbitrary shape can be expressed by:

$\rho = f(\theta)$ In the corresponding Cartesian coordinates:

$$x = f(\theta)\cos\theta$$
$$y = f(\theta)\sin\theta$$



$$\vec{r} = \frac{h}{H}\rho\hat{\vec{r}} = \frac{h}{H} f(\theta)(\cos\theta, \sin\theta)$$

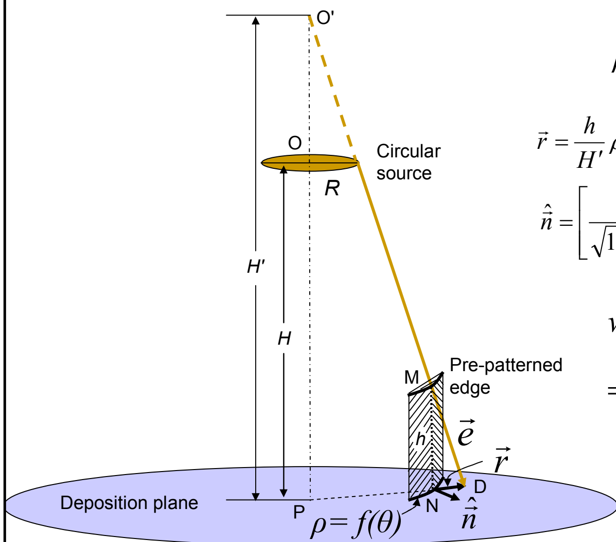
$$\hat{\vec{n}} = \left[\frac{-dy/dx}{\sqrt{1+(dy/dx)^2}}, \frac{1}{\sqrt{1+(dy/dx)^2}}\right]$$

The width of nanogap is defined by:

$$w = \vec{e}\cdot\hat{\vec{n}} = \vec{r}\cdot\hat{\vec{n}}$$

$$= \frac{h}{H}\frac{f(\theta)}{\sqrt{1+[f'(\theta)/f(\theta)]^2}}$$

Shadow width; Parallel, Circular Source



$$\rho = f(\theta) \qquad x = f(\theta)\cos\theta, \quad y = f(\theta)\sin\theta$$

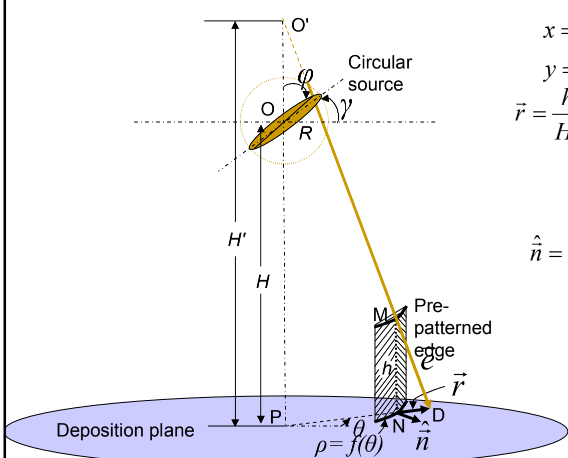
$$\vec{r} = \frac{h}{H'}\rho\hat{\vec{r}} = \frac{h}{H}(\rho - R)(\cos\theta, \sin\theta)$$

$$\hat{\vec{n}} = \left[\frac{-dy/dx}{\sqrt{1+(dy/dx)^2}}, \frac{1}{\sqrt{1+(dy/dx)^2}}\right]$$

$$w = \vec{e}\cdot\hat{\vec{n}} = \vec{r}\cdot\hat{\vec{n}}$$

$$= \frac{h}{H}\frac{f(\theta) - R}{\sqrt{1+[f'(\theta)f(\theta)]^2}}$$

Shadow width, Non-Parallel, Circular Source



$$x = f(\theta)\cos\theta, \quad y = f(\theta)\sin\theta \qquad \rho = f(\theta)$$

$$\vec{r} = \frac{h}{H'}\rho\hat{\vec{r}} \cong \frac{\rho - R\sin\varphi}{H + R\cos\varphi}h(\cos\theta, \sin\theta)$$

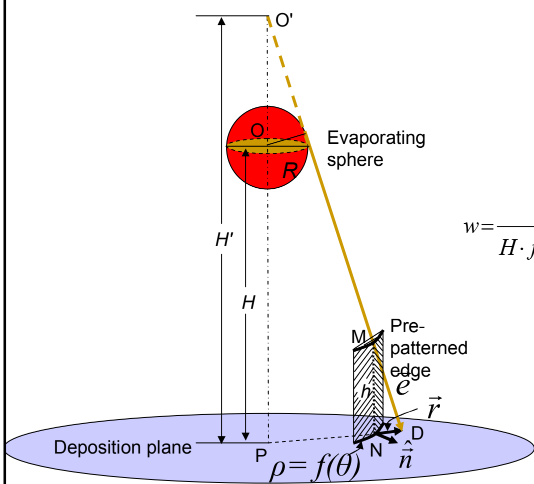
where $\tan\varphi = \dfrac{\cot\gamma}{\cos\theta}$

$$\hat{\vec{n}} = \left[\frac{-dy/dx}{\sqrt{1+(dy/dx)^2}}, \frac{1}{\sqrt{1+(dy/dx)^2}}\right]$$

$$w = \vec{e}\cdot\hat{\vec{n}} = \vec{r}\cdot\hat{\vec{n}}$$

$$= \frac{f(\theta) - R\sin\varphi}{H + R\cos\varphi}\frac{h}{\sqrt{1+[f'(\theta)f(\theta)]^2}}$$

Shadow width; Spherical Source



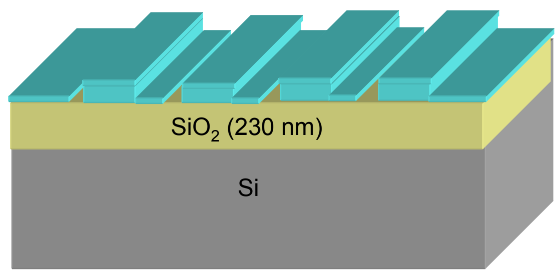
$$w = \frac{h}{H \cdot f(\theta) + R\sqrt{H^2 - R^2 + f^2(\theta)}} \frac{f^2(\theta) - R^2}{\sqrt{1 + [f'(\theta)/f(\theta)]^2}}$$

Summary of Shadow width

The shadow width of the pre-patterned edges with different shapes on a deposition plane

Evaporation sources (with a radius R and a deposition height H)	Shapes of shadow edge (with a uniform height h)		
	Arbitrary shape: $\rho = f(\theta)$	Straight line: $\rho = \frac{\rho_0}{\cos\theta}$	Center circle: $\rho = \rho_0$
Spherical source	$w = \frac{h}{H \cdot f(\theta) + R\sqrt{H^2 - R^2 + f^2(\theta)}} \frac{f^2(\theta) - R^2}{\sqrt{1 + [f'(\theta)/f(\theta)]^2}}$	$w = \frac{\rho_0^2 - R^2\cos^2\theta}{H \cdot \rho_0 + R\sqrt{(H^2 - R^2)\cos^2\theta + \rho_0^2}} h$	$w = \frac{\rho_0^2 - R^2}{H \cdot \rho_0 + R\sqrt{H^2 - R^2 + \rho_0^2}} h$
Circular source (*tilted case*)	$w = \frac{h}{H + R\cos\varphi} \frac{f(\theta) - R\sin\varphi}{\sqrt{1 + [f'(\theta)/f(\theta)]^2}}$ (where $\tan\varphi = \cot\gamma / \cos\theta$)	$w = \frac{\rho_0 - R\sin\varphi\cos\theta}{H + R\cos\varphi} h$	$w = \frac{\rho_0 - R\sin\varphi}{H + R\cos\varphi} h$
Circular source (*parallel case*)	$w = \frac{h}{H} \frac{f(\theta) - R}{\sqrt{1 + [f'(\theta)/f(\theta)]^2}}$	$w = \frac{\rho_0 - R\cos\theta}{H} h$	$w = \frac{\rho_0 - R}{H} h$
Point source (R = 0)	$w = \frac{h}{H} \frac{f(\theta)}{\sqrt{1 + [f'(\theta)/f(\theta)]^2}}$	$w = \frac{\rho_0}{H} h$	$w = \frac{\rho_0}{H} h$

Nanogap fabrication steps



Si wafer- Oxidation- Al conformal evaporation-Lithography –Al non conformal evaporation- **Shadow gap**

Why Al? Good for evaporation and etching
Good for masking layer to reactive ion etching
Easy height variation
Easy selective etching- pattern reversal is enabled

Experimental—2nd Al deposition

1st Al deposition:

Conformal deposition: uniform Al height.

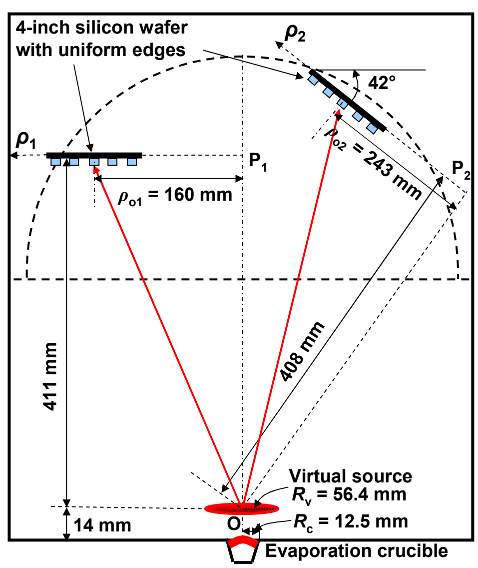
2nd Al deposition:

Nonconformal deposition at fixed angles.

<u>85, 120, and –t, -p</u>

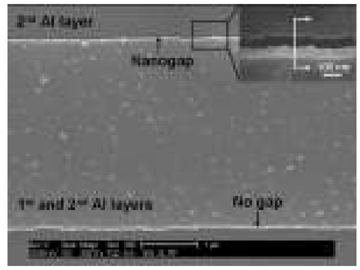
85, 120, 180- thickness (nm)

t: tilted, p: parallel

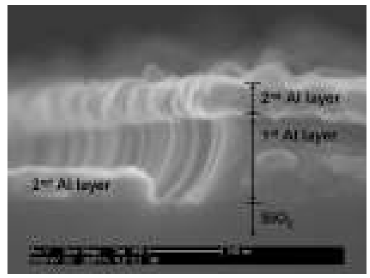


Shadow gap shape

Various Al patterns for shadow edges

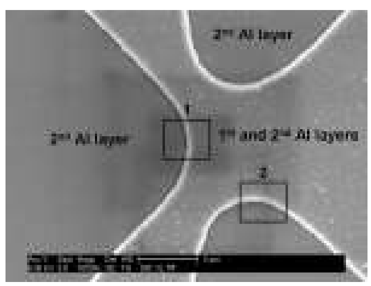


Nanogap on a straight Al sripe

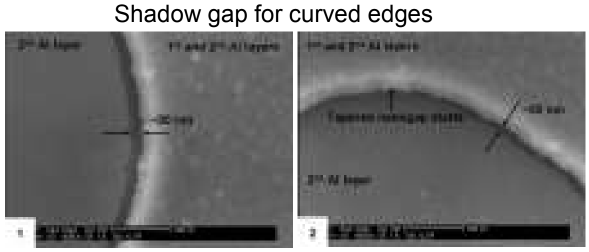


Cross-section of a nanogap

Shadow gap shape (cont'd)

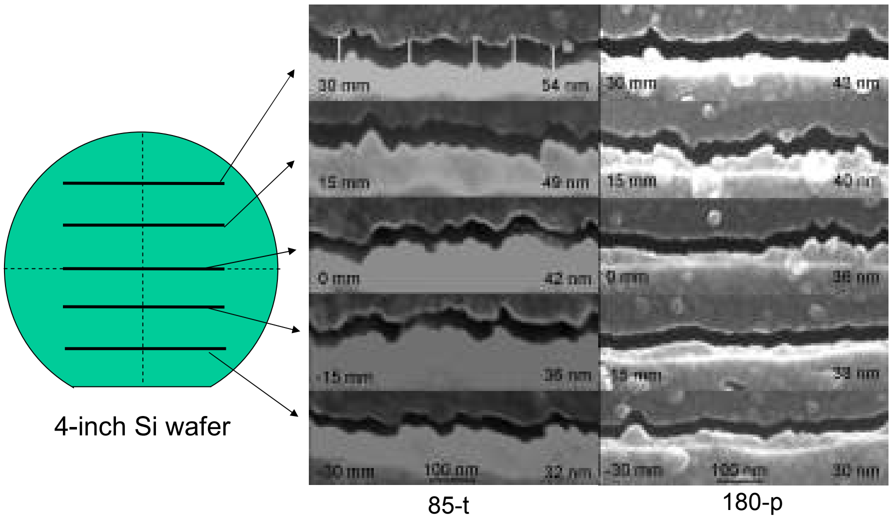


Shadow gap for curved edges

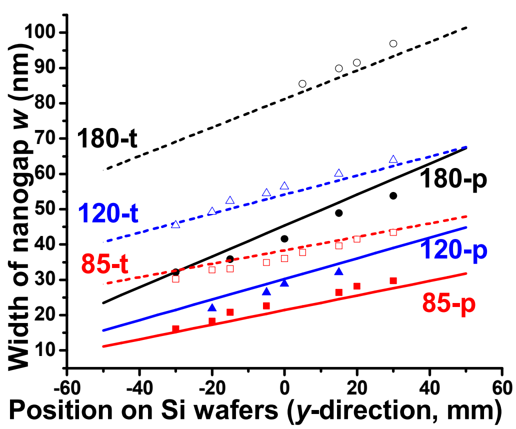


Crescent nanogaps; gradual variation of nanogaps due to the Al edge patterns

Experimental Results —without Compensation

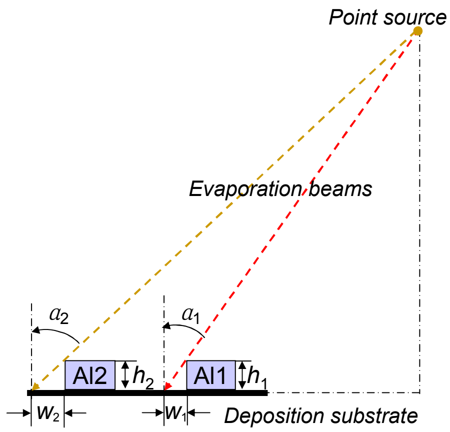


Shadow gap variation on 4-in wafer



Nanogap width variation along the *y*-direction of the 4-inch Si wafers
<u>Approximately ±10 nm variation in 60mm.</u>

Compensation for uniform gap width



- When the deposition angle is α and the thickness the pre-patterned Al layer is h, the nanogap width is

$$w = h \tan \alpha$$

- Gap width is varying due to the angle (α) change across wafer.
- The angle variation can be compensated by the height variation of the prepatterned Al.

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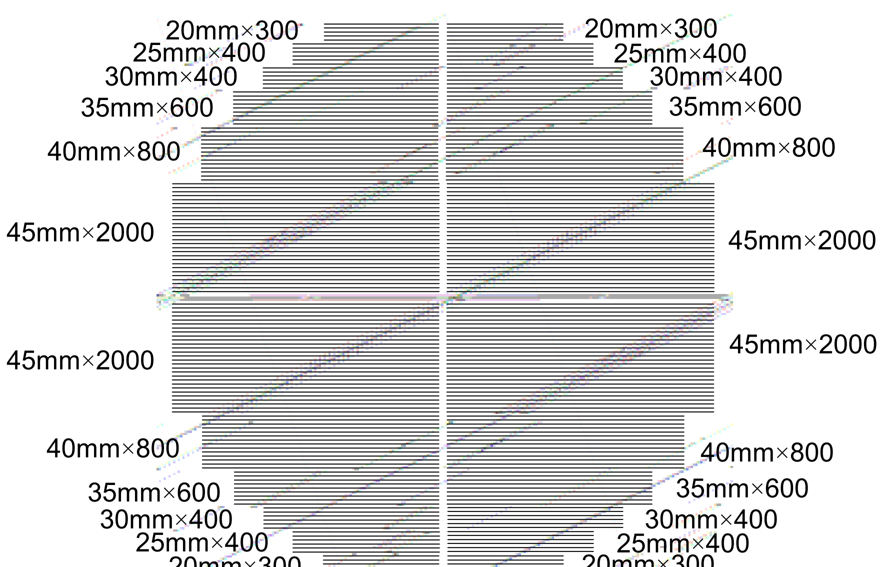
Mask pattern for compensation experiment



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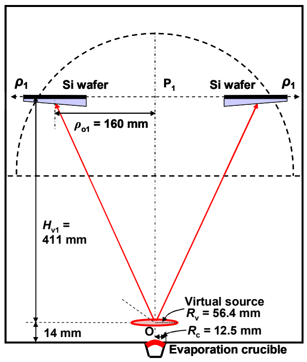
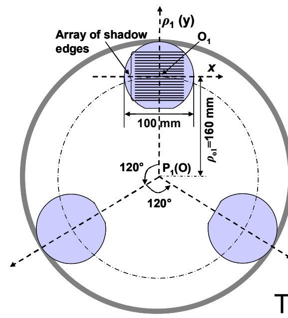
Experimental—with Compensation During 1st Al Deposition



Side view

Assuming cosine distribution law for a planar area source:

$$h = A\cos\phi\cos\alpha / r^2$$



Top view

Al thickness distribution:

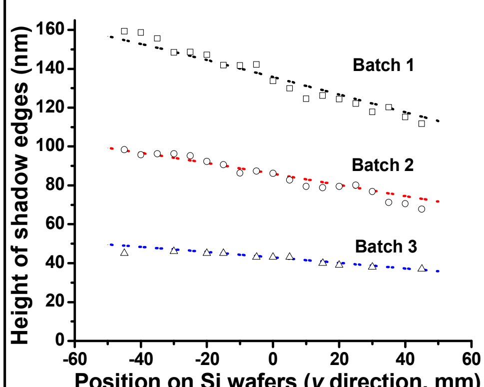
In ρ_1(y) direction for the central line (x=0):

$$h(\rho_1) = h_0 / \left[1 + (\rho_1 / H_{v1})^2\right]^2$$

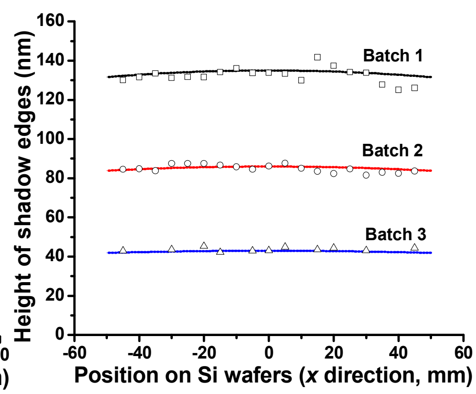
In x direction for the central line (y=0):

$$\frac{h(x)}{h(0)} = \frac{\left(H_{v1}^2 + \rho_{o1}^2\right)^2}{\left(H_{v1}^2 + \rho_{o1}^2 + x^2\right)^2} = \frac{\left(411^2 + 160^2\right)^2}{\left(411^2 + 160^2 + x^2\right)^2}$$

Experimental Results—with Compensation During 1st Al Deposition

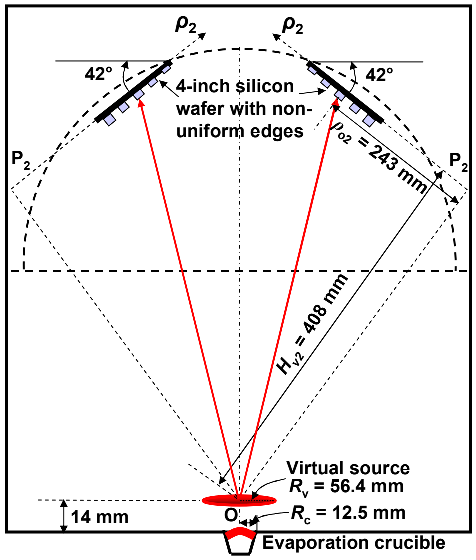


Al thickness along y direction on Si wafer

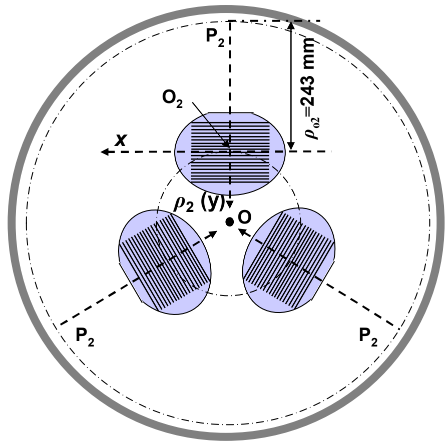


Al thickness along x direction on Si wafer

Experimental—with Compensation During 2nd Al Deposition

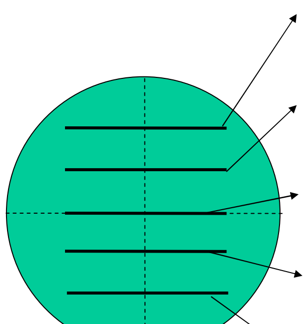


Side view

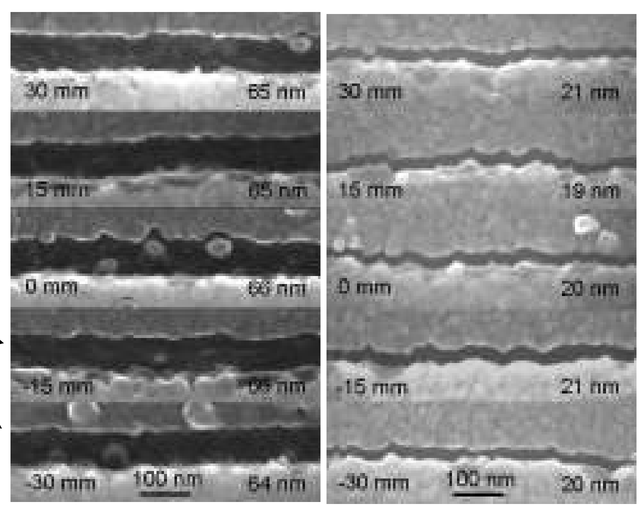


Top view

Experimental Results with Compensation

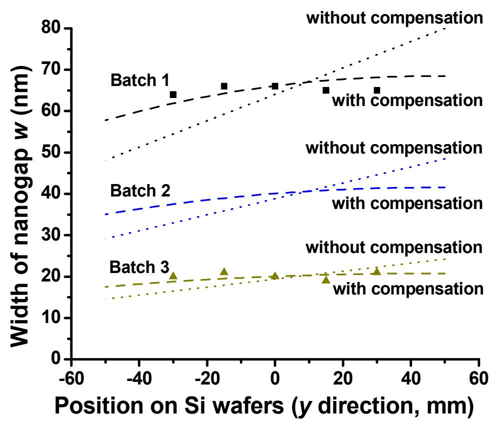


4-inch Si wafer



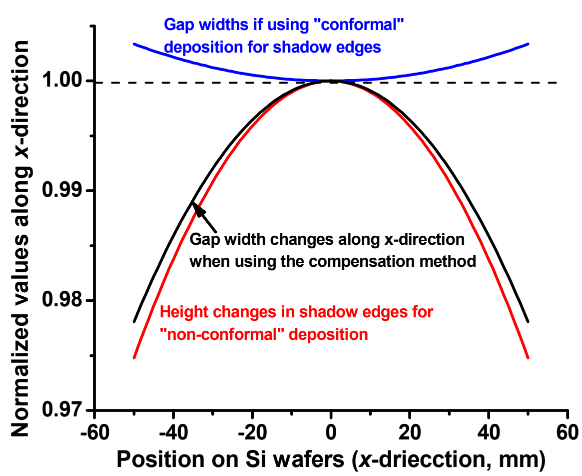
Batch 1 Batch 3

Experimental Results —with Compensation



Nanogap width distribution along the *y*-direction of the 4-inch Si wafers
<u>±1nm variation across 4in wafers.</u>

Nanogap Width along X Direction with Compensation



Normalized distribution along the *x*-direction of the 4-inch Si wafers
<u>Approximately 2% variation is expected,</u> which is not measurable.

Extension of Shadow Edge Lithography

Acknowledgement

Supported by
NSF
NSF summer institute on Nano Mechanics and Materials
Office of Naval research (ONR)
Technology gap innovation fund (TGIF)
University of Washington

Experimented by
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WoonHong Yeo

Reference

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