Scratching by Pad Asperities in Chemical-Mechanical Polishing

ERC TeleSeminar

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Outline

- Introduction
- Theory of Scratching by Pad Asperities
- Scratching Experiments using Polymer Pins
- Scratching Experiments using CMP pads
- Conclusions

Schematic of Scratching by Hard, Agglomerated Abrasives and by Soft Pad Asperities in CMP

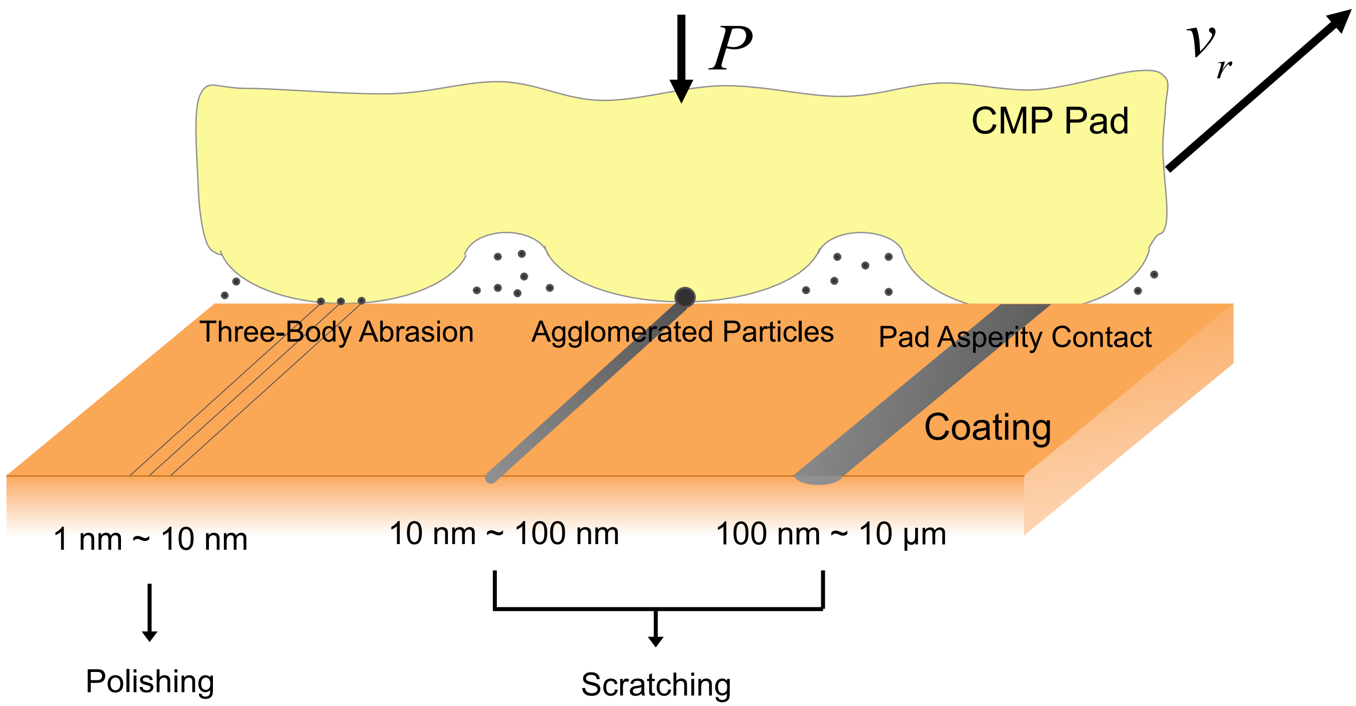


Figure. Schematic of three different modes of contact and scratching in CMP.

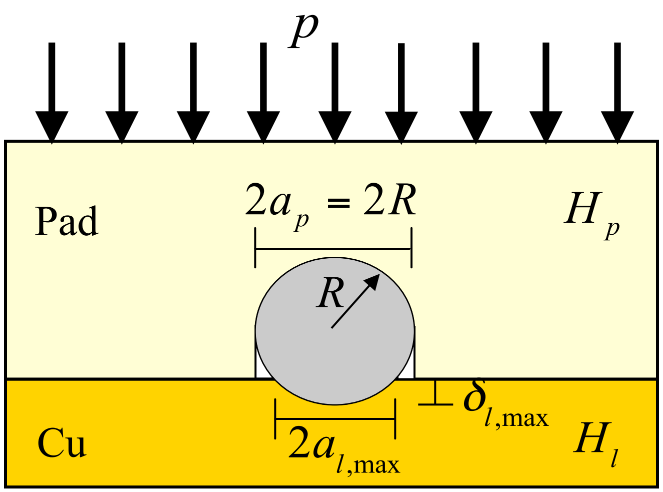
Maximum Scratch Width and Depth

- Maximum Scratch Semi-Width

$$a_{l,\max} = \sqrt{\frac{H_{p,\max}}{H_l} R_{\max}}$$

- Maximum Scratch Depth

$$\delta_{l,\max} = \frac{H_{p,\max}}{H_l} R_{\max}$$



Particle Scratching Experiments

Parameter	Value
Tool	Alpsitec E460
Wafer Diameter	200 mm
Cu thickness	1 µm
Pad	Rohm & Haas IC1000
Conditioner	Diamond (3M)
Rotational Speed of Wafer	65 rpm
Rotational Speed of Pad	40 rpm
Normal Pressure	27.5 kPa (4 psi)
Slurry Flow Rate	200 ml/min
Slurry Size	45 nm
Slurry Chemistry	5% solids, 0.3% H_2O_2
Polishing Time	60 sec

Experiments performed by Dr. Silvia Armini

Alpsitec E460 CMP polisher

Experimental Results

- Maximum measured scratch: $a_{l,\max} = 292 \ \text{nm}, \ \delta_{l,\max} = 7 \ \text{nm}$

Experimental Results

- Maximum measured scratch: $a_{l,\max} = 292 \text{ nm}, \ \delta_{l,\max} = 7 \text{ nm}$
- Material properties: $H_{p,\max} = 0.31 \text{ GPa}, \ H_l = 1.2 \text{ GPa}$

$$a_{l,\max} = \sqrt{\frac{H_{p,\max}}{H_l} R_{\max}} \qquad \delta_{l,\max} = \frac{H_{p,\max}}{H_l} R_{\max}$$

- $R_{\max} = 45 \text{ nm}$

$$a_{l,\max} = 25 \text{ nm}$$

$$\delta_{l,\max} = 13 \text{ nm}$$

100 particles agglomerate →

- $R_{\max} = 230 \text{ nm}$

$$a_{l,\max} = 117 \text{ nm}$$

$$\delta_{l,\max} = 60 \text{ nm}$$

Schematic of Scratching by Hard, Agglomerated Abrasives and by Soft Pad Asperities in CMP

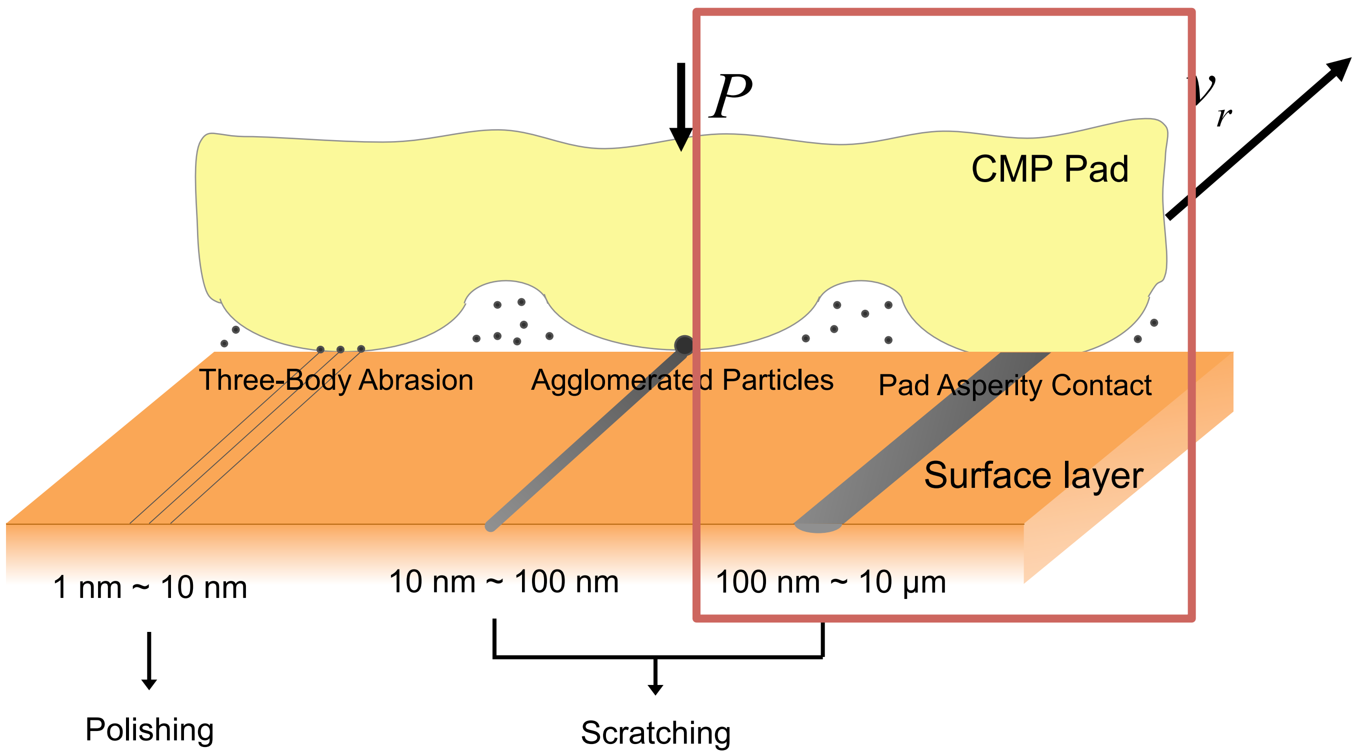
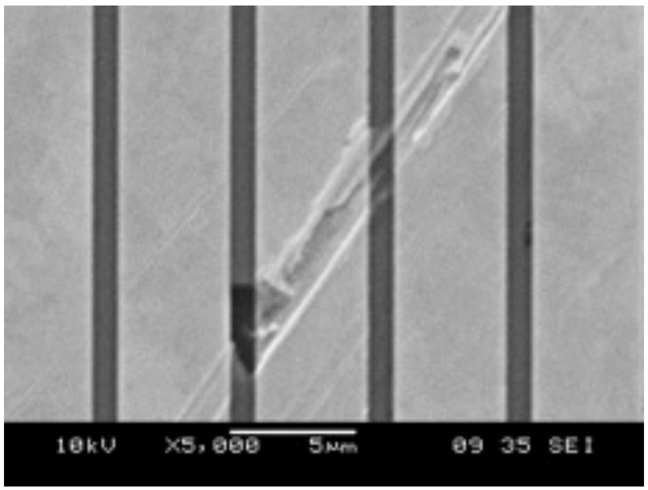
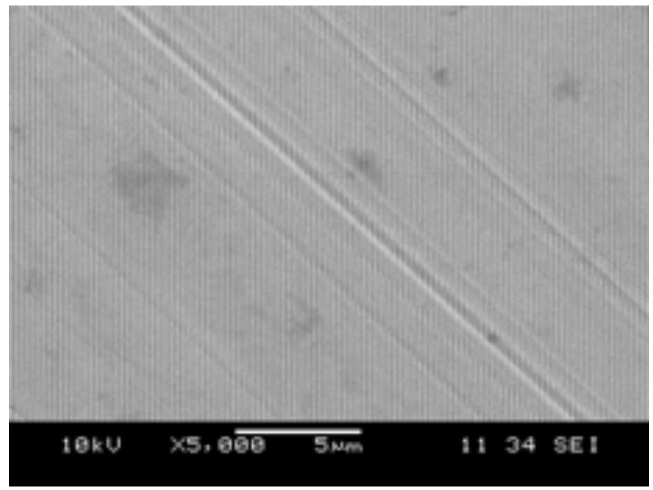


Figure. Schematic of three different modes of contact and scratching in CMP.

Examples of Scratches Generated by Pad Asperities



Cu linewidth : 4.5 μm
Low-*k* linewidth : 1.0 μm

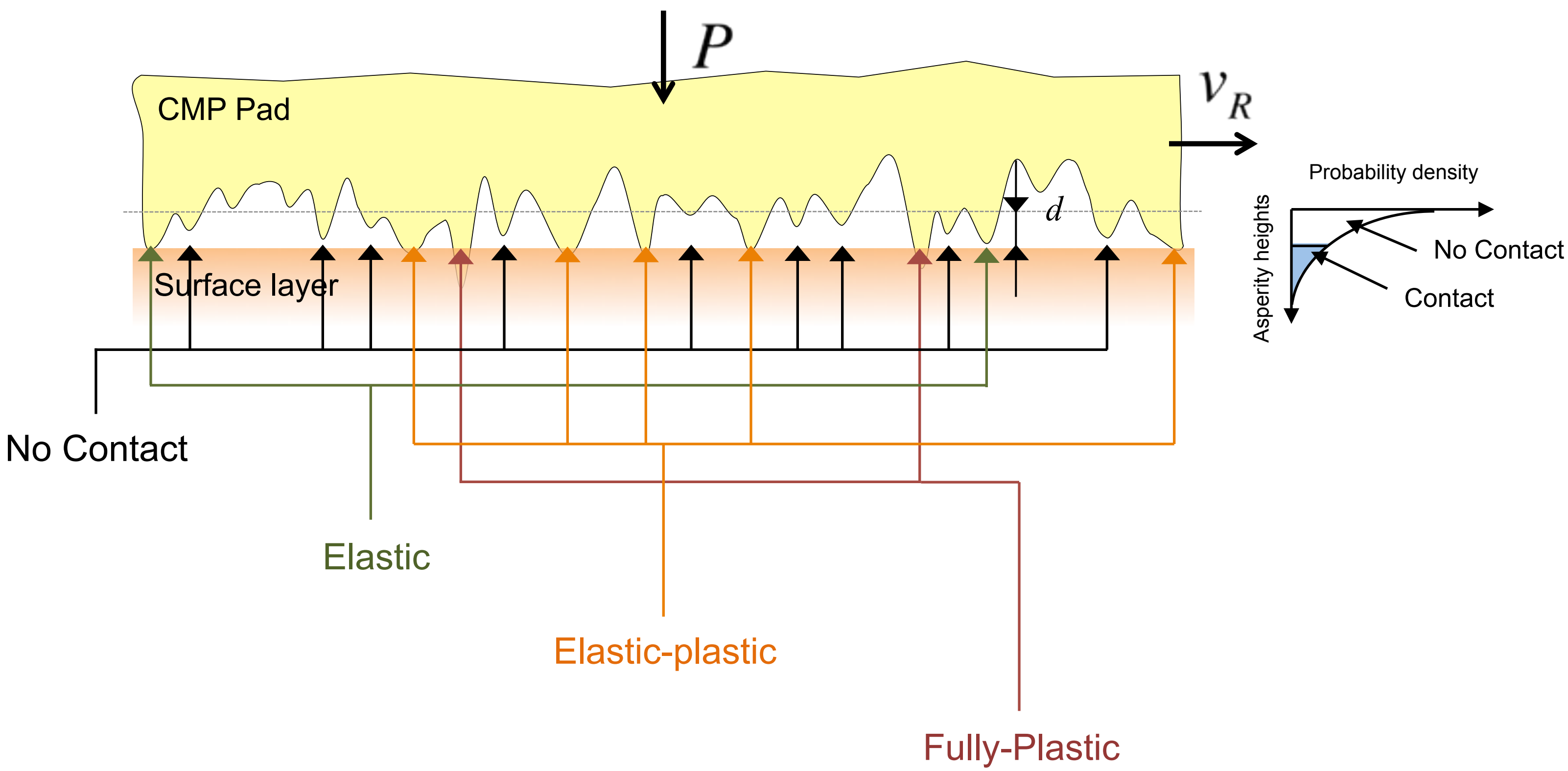


Cu linewidth : 0.05 μm
Low-*k* linewidth : 0.05 μm

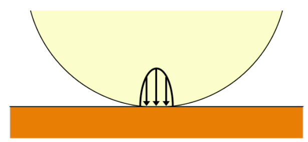
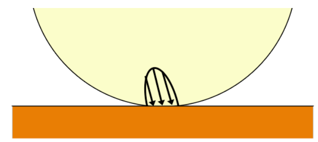
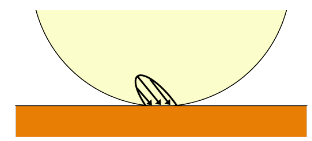
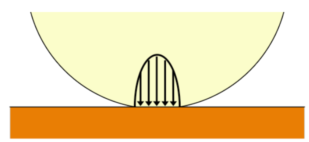
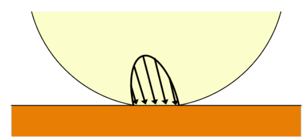
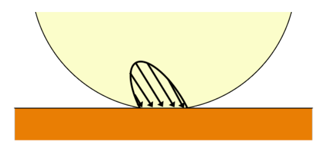
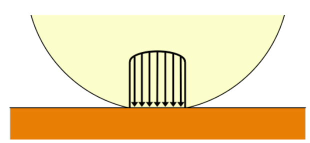
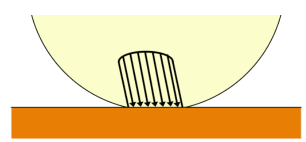
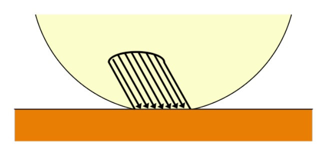
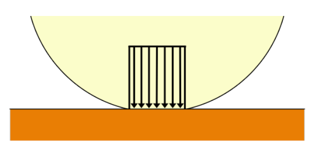
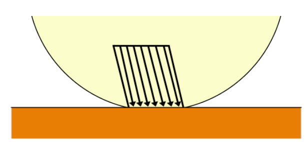
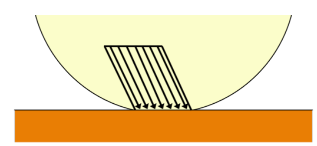
Figure. SEM images of scratches produced by a IC1000 pad on patterned Cu/low-*k* layers. Deionized water was used as a "lubricant".

Theory of Scratching by Pad Asperities

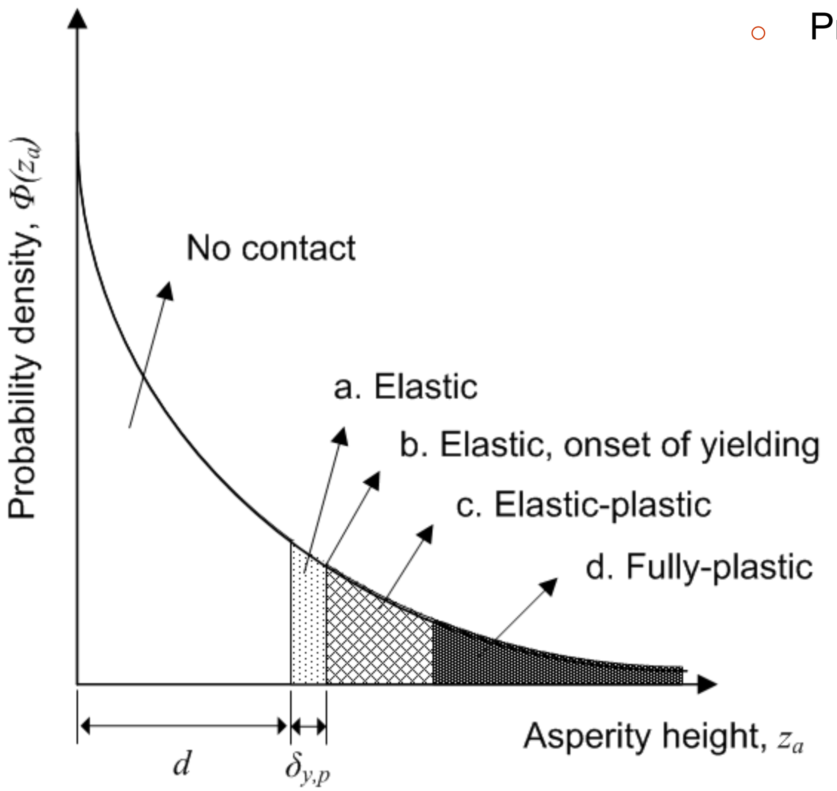
Contact between a Rough Pad and a Smooth, Flat Surface Layer



Types of Traction Distribution in a Frictional Contact

Mode of pad deformation	Frictionless contact	Low frictional contact	High frictional contact
a. Elastic			
b. Elastic, Onset of yielding			
c. Elastic-Plastic			
d. Fully-Plastic			

Proportion of Plastically Deforming Pad Asperities



d : distance between centerline and coating surface.
$\delta_{y,p}$: displacement of asperity at the onset of yielding.

- Proportion of plastically deforming pad asperities:

$$\frac{N_p}{N_c} = \exp\left\{ -\frac{\pi^2}{16}\left(\frac{H_p}{E_p}\right)^2 \frac{R_a}{\sigma_z} \right\}$$

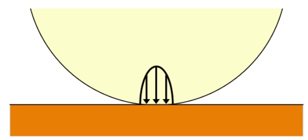
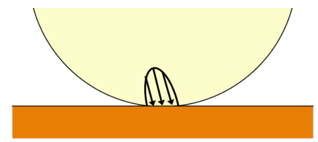
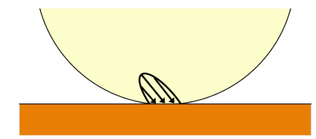
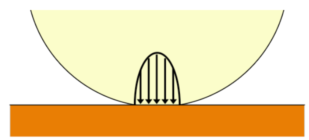
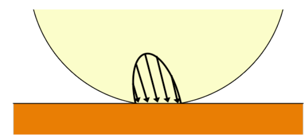
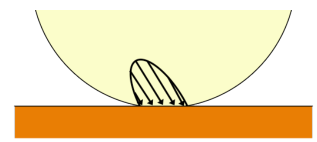
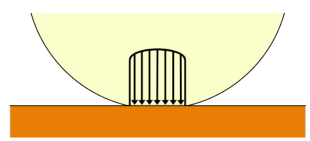
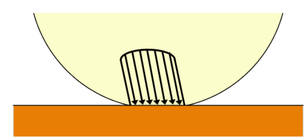
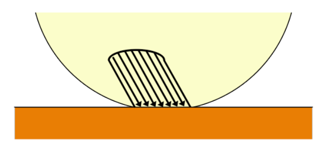
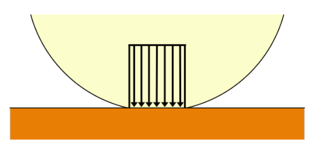
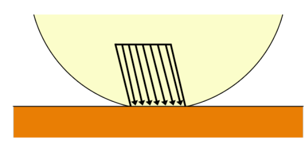
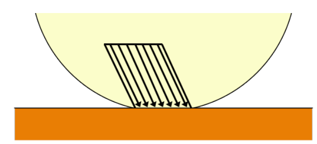
where N_p : Number of plastically deforming asperities.
N_c : Number of asperities in contact.
H_p : Hardness of pad asperity.
E_p : Young's modulus of pad asperity.
R_a : Asperity radius of curvature.
σ_s : Standard deviation of asperity heights.

CMP Pad	N_p / N_c
Pad A	0.92
Pad B	0.76
Pad C	0.79
Pad D	0.86
Pad E	0.83
Pad F	0.84

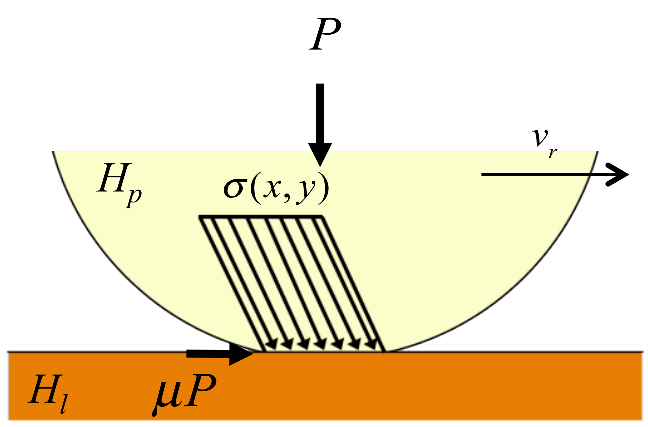
* Pad A - F : Commercial pads used in industry.

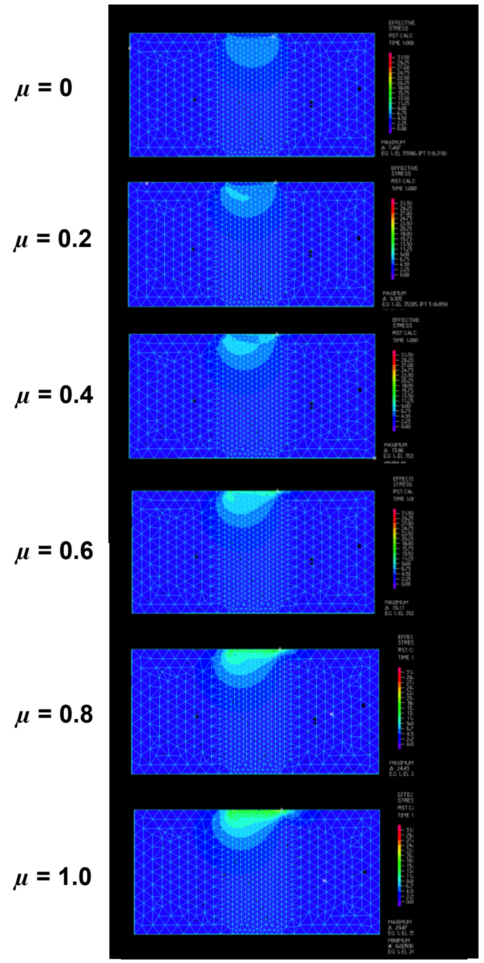
- ✓ Typically, 75 – 90 percent of pad asperities in contact deform plastically.
- ✓ It may be assumed that several asperities in contact will deform fully-plastically.

Types of Traction Distribution in a Frictional Contact

Mode of pad deformation	Frictionless contact	Low frictional contact	High frictional contact
a. Elastic			
b. Elastic, Onset of yielding			
c. Elastic-Plastic			
d. Fully-Plastic			

Criteria for Scratch Generation by Fully-Plastically Deformed Asperities[1-2]





- Scratching criteria based on Finite Element Analysis (FEA) :

$$\frac{H_p}{H_l} > 0.34 \quad , \quad (0 \le \mu \le 0.1)$$

$$\frac{H_p}{H_l} > \frac{1}{4}\left[7.8\mu^2 + 0.8\mu + 0.4\right]^{-1/2} \quad , \quad (\mu \ge 0.1)$$

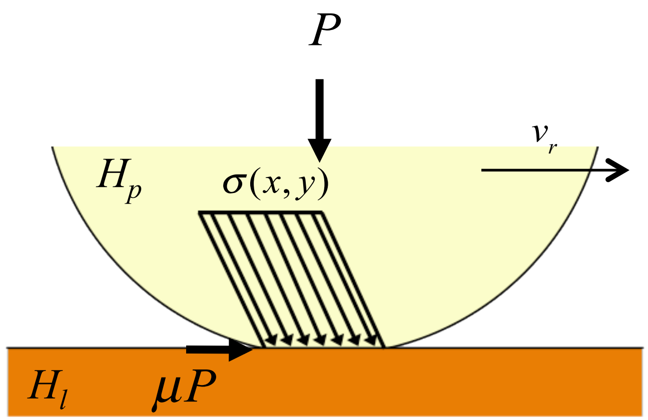
where H_p : hardness of pad asperities
H_l : hardness of the surface layer
μ : coefficient of friction between the pad asperity and the surface layer

[1] T. Eusner, 2010, "Multi-Scale Scratching in Chemical-Mechanical Polishing," Ph.D Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA.

[2] N. Saka et al., 2010, "Scratching by Pad Asperities in Chemical-Mechanical Polishing," *Annals of the CIRP*, vol. 59/1, pp.329-332.

Criteria for Scratch Generation by Fully-Plastically Deformed Pad Asperities

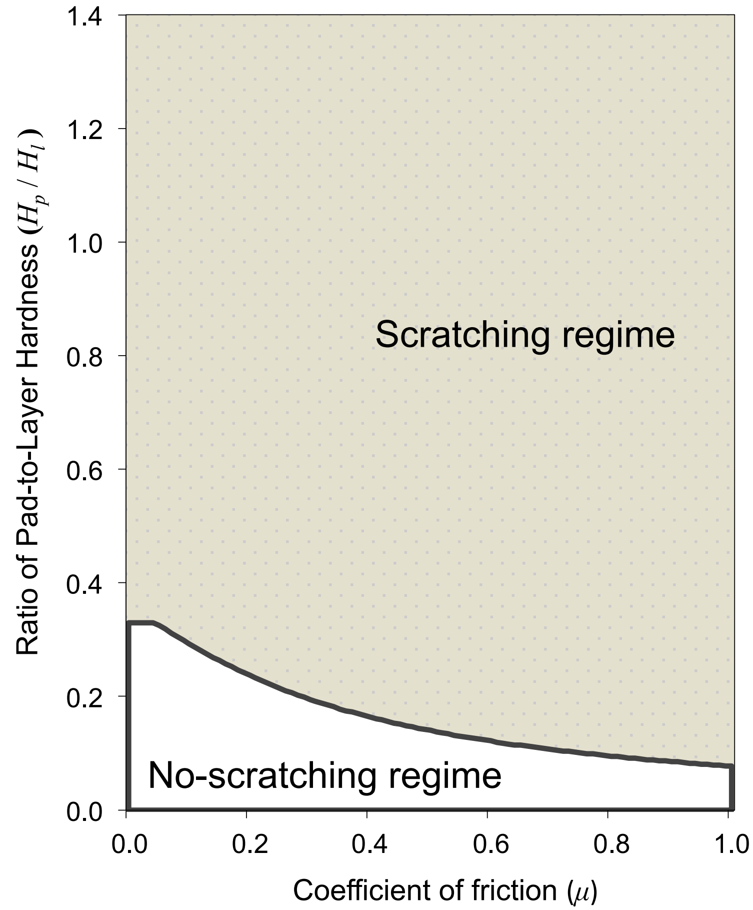
Case I. Monolithic Layers



- A monolithic layer will be scratched if:

$$\frac{H_p}{H_l} > 0.34 \quad , \quad (0 \le \mu \le 0.1)$$

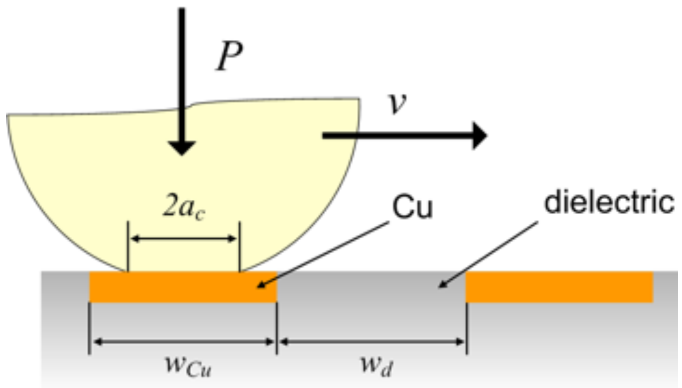
$$\frac{H_p}{H_l} > \frac{1}{4}\left[7.8\mu^2 + 0.8\mu + 0.4\right]^{-1/2} \quad , \quad (\mu \ge 0.1)$$



Scratch-regime map

Criteria for Scratch Generation by Fully-Plastically Deformed Pad Asperities

Case II. Patterned Layers with wide Cu and dielectric lines (w_{Cu} and $w_d > 2a_c$)



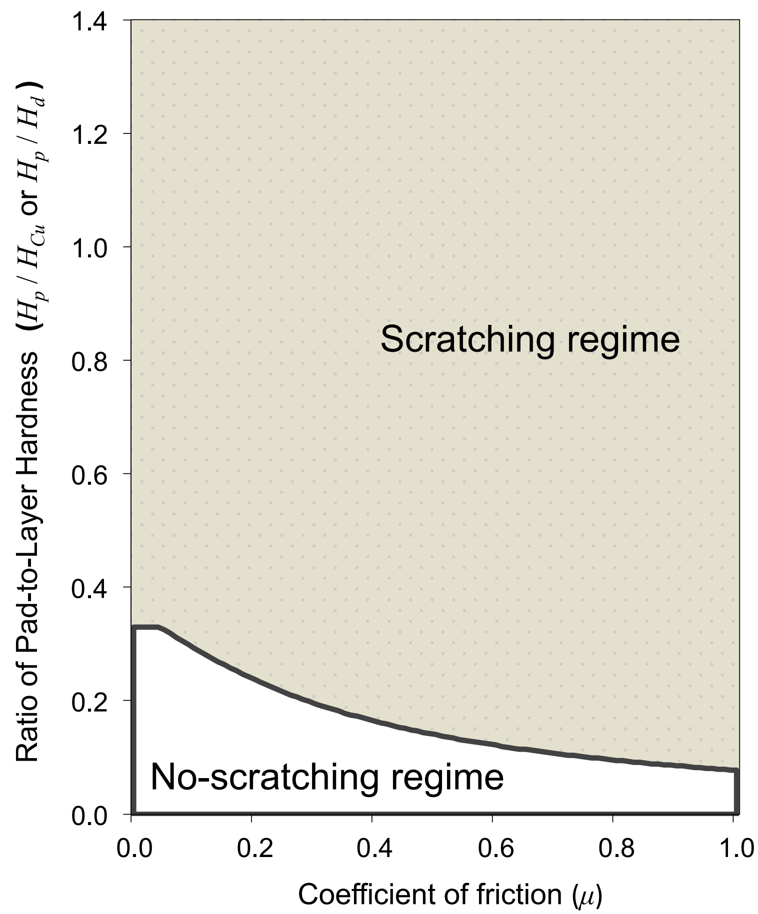
Pad asperities slide over Cu and dielectric lines sequentially.

- Cu lines will be scratched if :

$$\frac{H_p}{H_{Cu}} > \frac{1}{4}\left[7.8\mu^2 + 0.8\mu + 0.4\right]^{-1/2} \quad , \quad (\mu \geq 0.1)$$

- Dielectric lines will be scratched if :

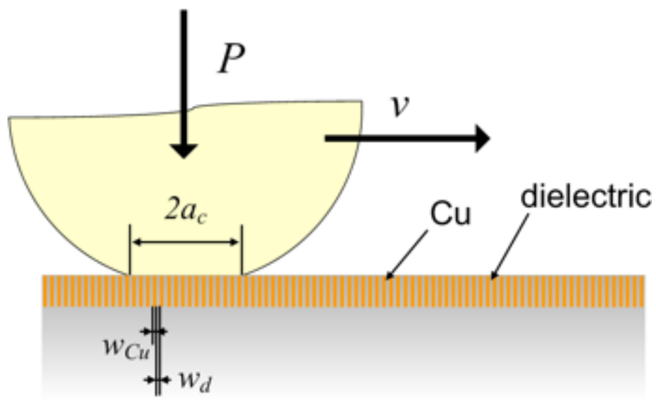
$$\frac{H_p}{H_d} > \frac{1}{4}\left[7.8\mu^2 + 0.8\mu + 0.4\right]^{-1/2} \quad , \quad (\mu \geq 0.1)$$



Scratch-regime map

Criteria for Scratch Generation by Fully-Plastically Deformed Pad Asperities

Case III. Patterned Layers with narrow Cu and dielectric lines (w_{Cu} and $w_d << 2a_c$)

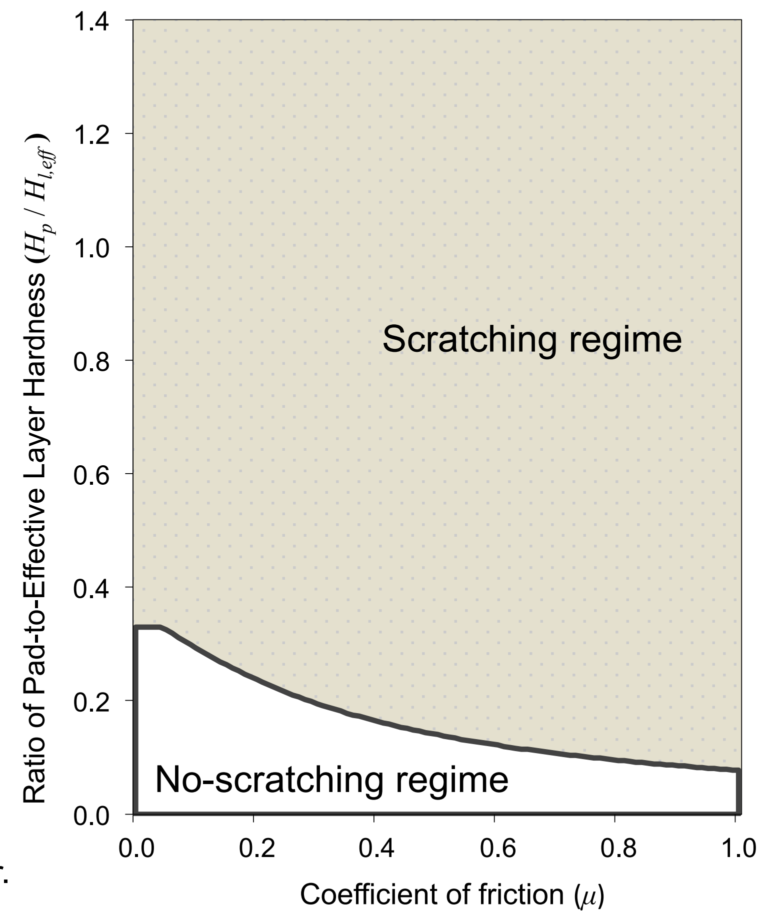


Pad asperities slide over Cu and dielectric lines concurrently.

- A composite layer will be scratched if :

$$\frac{H_p}{H_{l,eff}} > \frac{1}{4}\left[7.8\mu^2 + 0.8\mu + 0.4\right]^{-1/2} \quad , \quad (\mu \geq 0.1)$$

where $H_{l,eff}$: effective hardness of the composite layer.



Scratch-regime map

Effective Modulus and Hardness of Cu/Dielectric Composite Layers

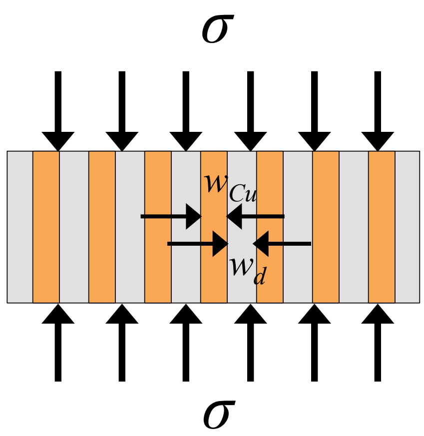
- Rule of Mixture (ROM) :

  Iso-strain model

$$E_{l,eff} = \frac{w_{Cu}}{\lambda} E_{Cu} + \frac{w_d}{\lambda} E_d$$

$$H_{l,eff} = \frac{w_{Cu}}{\lambda} H_{Cu} + \frac{w_d}{\lambda} H_d$$

where $\lambda = w_{Cu} + w_d$



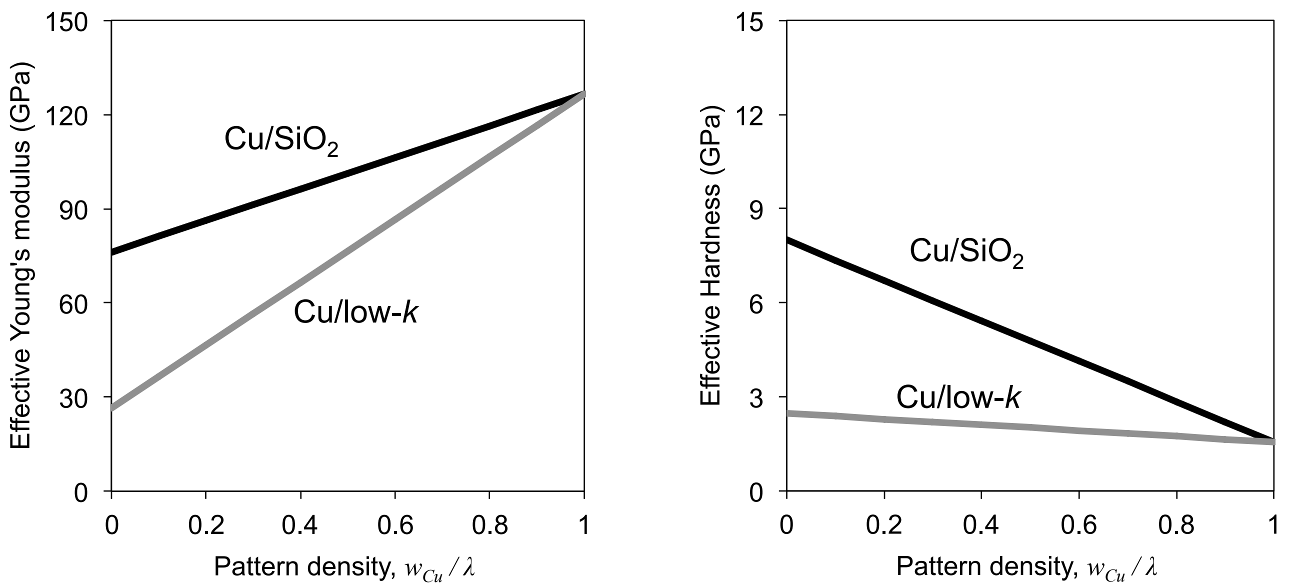
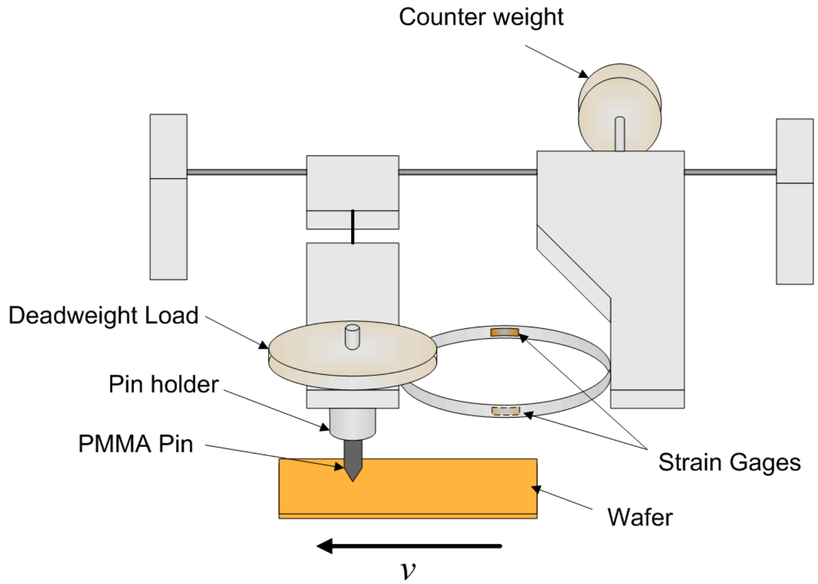


Figure. Effective Young's modulus and hardness of Cu/dielectric composite layers.

Scratching Experiments using Polymer Pins

Sliding Friction Apparatus and Experimental Conditions



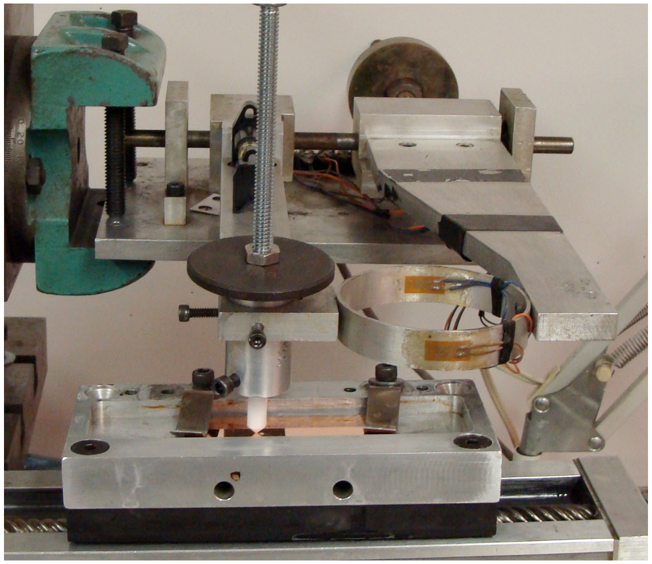


Figure. Sliding friction apparatus.

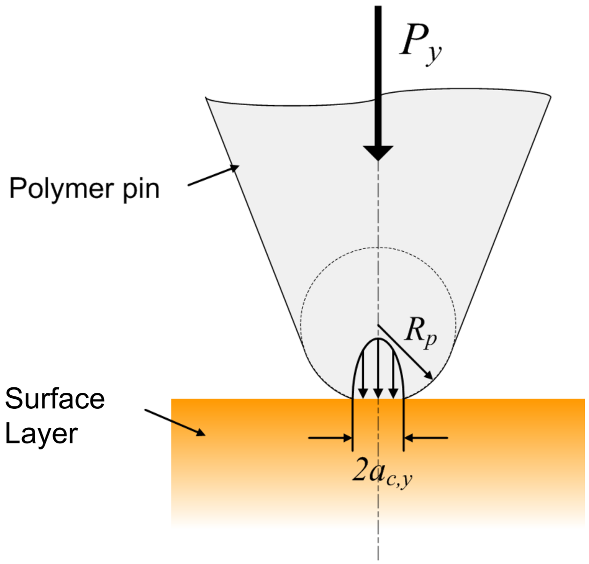
Table. Experimental conditions.

Parameter	Value
Radius of pin tip	~ 50 μm
Normal load	1 N
Velocity	7 mm/s

* Deionized water was used as a "lubricant".

Pressure Distribution and Contact Radius at the Pin/Layer Interface

Elastic contact
(at the onset of yielding)

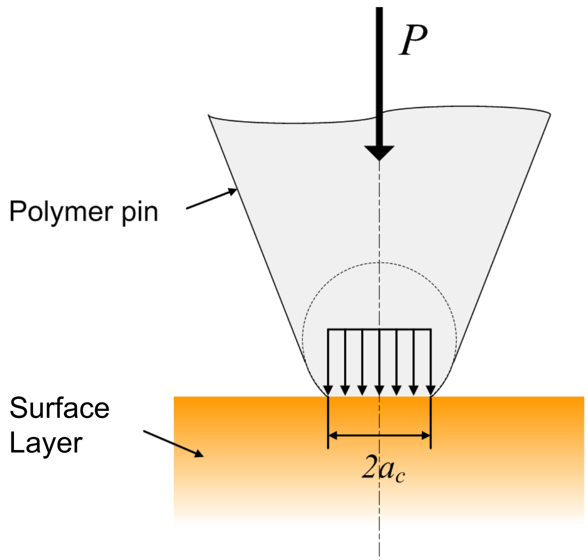


$$P_y = (0.79)\frac{H_p^3}{E_p^2}R_p^2$$

$$p(x,y) = \frac{1}{2}H_p\left[1-\left(\frac{x^2}{a_{c,y}^2}+\frac{y^2}{a_{c,y}^2}\right)\right]^{1/2}$$

$$a_{c,y} = \left[\frac{3}{4}\frac{P_y R_p}{E_p}\right]^{1/3}$$

Plastic contact
(fully-plastic)



$$P >> P_y$$

$$p(x,y) = H_p$$

$$a_c = \sqrt{\frac{P}{\pi H_p}}$$

a_c : contact radius

$a_{c,,y}$: contact radius at the onset of yielding

E_p : Young's modulus of pin

H_p : hardness of pin

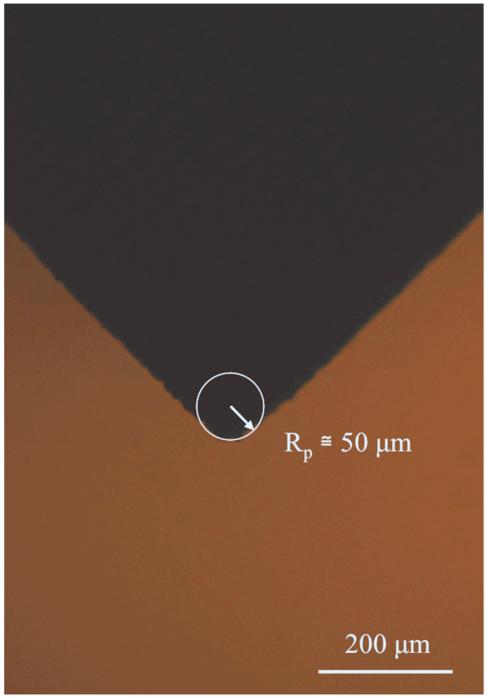
P : applied normal load

P_y : normal load at the onset of yielding

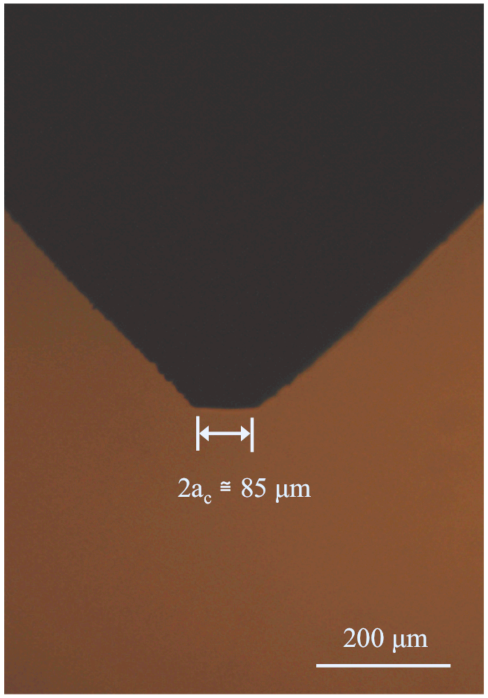
$p(x,y)$: pressure distribution

R_p : radius of pin tip

PMMA Pin Tip before and after the Application of the Normal Load



Before



After

Figure. Images of the PMMA pin tip before and after the application of a normal load of 1 N.

Mechanical Properties

Table. Hardness and Young's modulus of a CMP pad (Pad A), polymer pins (PS and PMMA), and monolithic layers (Cu, low-*k* and SiO_2).

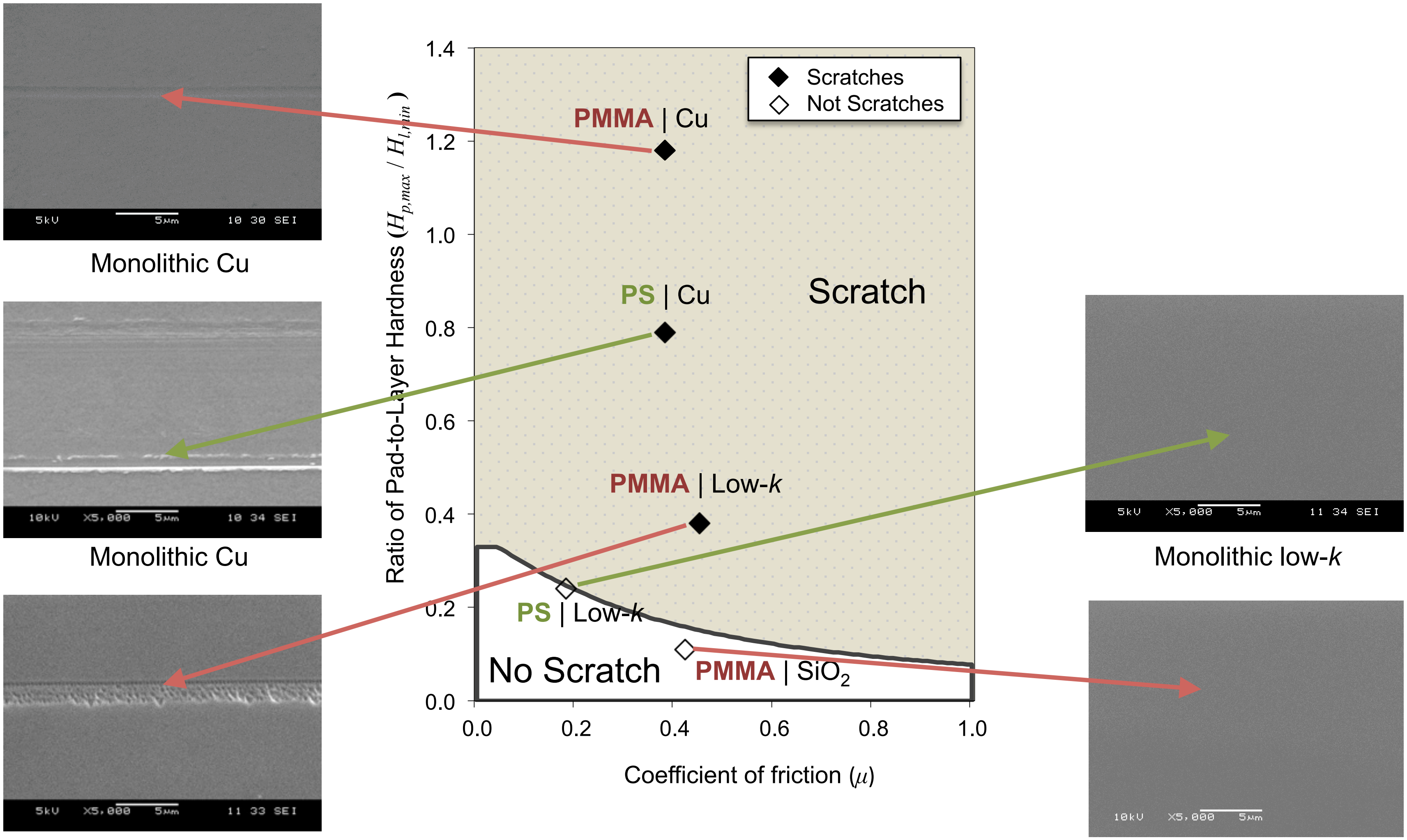
	Hardness (MPa)					Young's modulus (GPa)		
Material	Min.	Average	Max.	Std. Dev.	C.V.	Average	Std. Dev.	C.V.
PS	72	266	595	117	0.44	3.37	1.19	0.35
Pad A	23	293	915	220	0.75	2.21	1.59	0.72
PMMA	94	365	810	185	0.51	5.23	1.62	0.31
Cu	929	1,556	2,103	262	0.17	126.50	12.51	0.10
Low-*k*	2,379	2,473	2,548	47	0.02	26.38	0.45	0.02
SiO_2	7,781	8,002	8,212	108	0.01	76.10	0.80	0.01

* All properties were determined by nano-indentation using a Berkovich indenter.
* C.V. : coefficient of variation = (stdandard deviation / average)

Linewidths of Tested Patterned Cu/Dielectric Layers

Pattern	Subdie no.	Cu linewidth (µm)	Dielectric linewidth (µm)
Cu/SiO_2	S1	100	100
	S2	25	25
	S3	2	2
	S4	0.5	0.5
Cu/Low-*k*	K1	4.5	4.5
	K2	0.35	0.35
	K3	0.05	0.05

Scratch-Regime Map of Monolithic Layers



Monolithic Cu

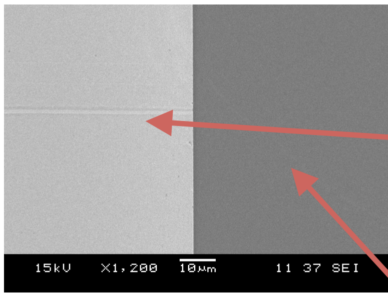
Monolithic Cu

Monolithic low-*k*

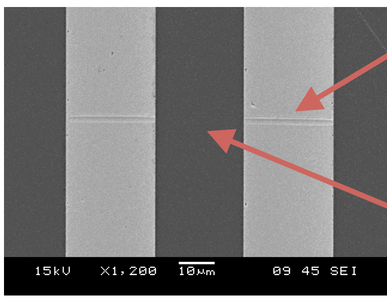
Monolithic low-*k*

Monolithic SiO_2

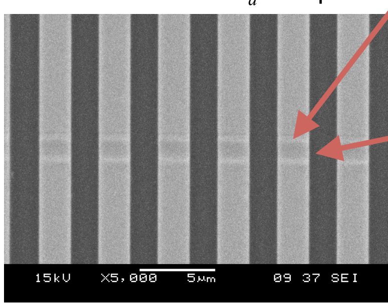
Scratch-Regime Map of Patterned Layers with Wide Cu and Dielectric Lines: w_{Cu} and w_d > 1 µm



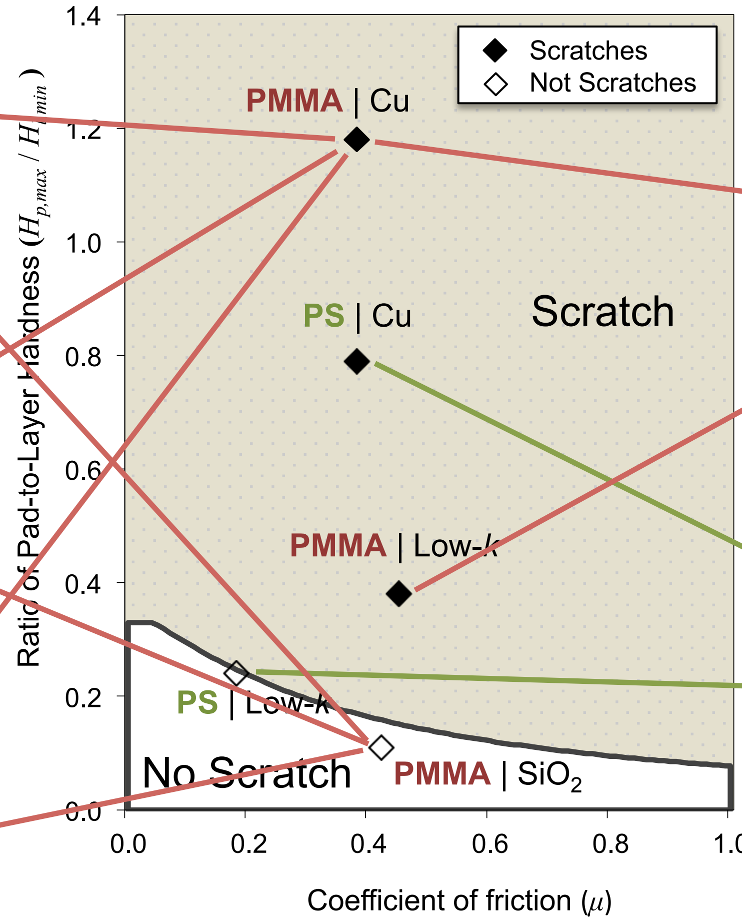
Cu/SiO_2 : w_{Cu}= 100 µm
w_d= 100 µm

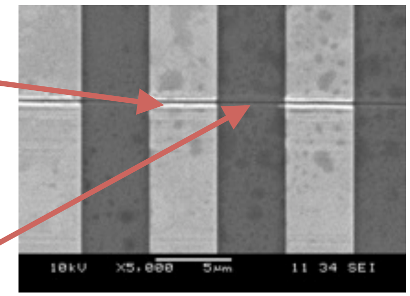


Cu/SiO_2 : w_{Cu}= 25 µm
w_d= 25 µm

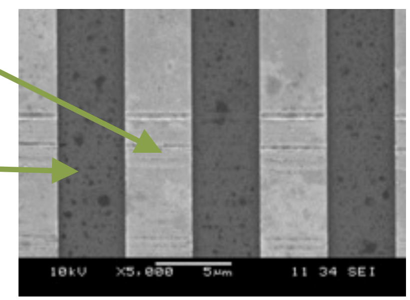


Cu/SiO_2 : w_{Cu}= 2 µm
w_d= 2 µm



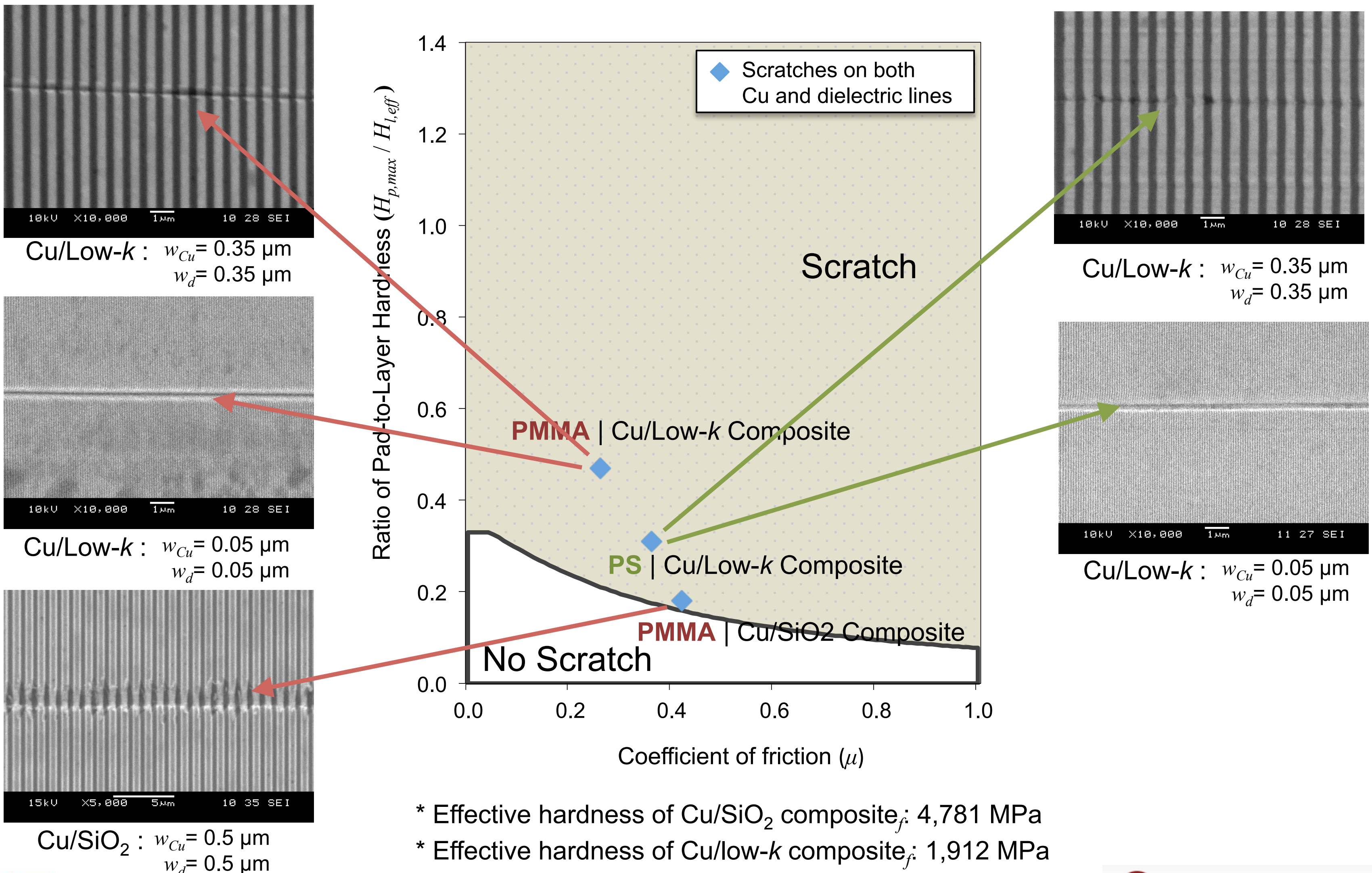


Cu/Low-*k* : w_{Cu}= 4.5 µm
w_d= 4.5 µm



Cu/Low-*k* : w_{Cu}= 4.5 µm
w_d= 4.5 µm

Scratch-Regime Map of Patterned Layers with Narrow Cu and Dielectric Lines: w_{Cu} and w_d < 1 µm

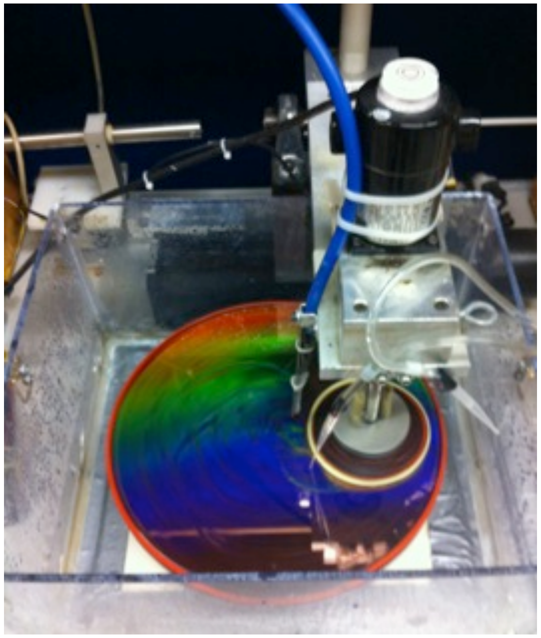


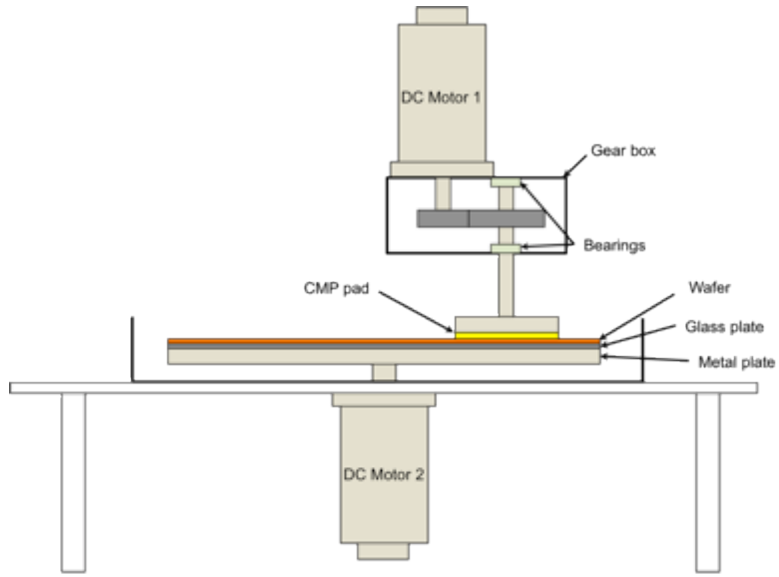
* Effective hardness of Cu/SiO$_2$ composite$_f$: 4,781 MPa

* Effective hardness of Cu/low-*k* composite$_f$: 1,912 MPa

Scratching Experiments using CMP Pads

Face-up "Polishing" Experiments





Schematic of face-up polisher.

Table: Experimental conditions.

Parameter	Value
Normal load	24 N
Nominal contact area	0.002 – 0.003 m^2
Nominal pressure	6 – 12 kPa
Rotational speed	90 rpm
Relative velocity	0.75 m/s
Duration	5 min

* Deionized water was used as a "lubricant."

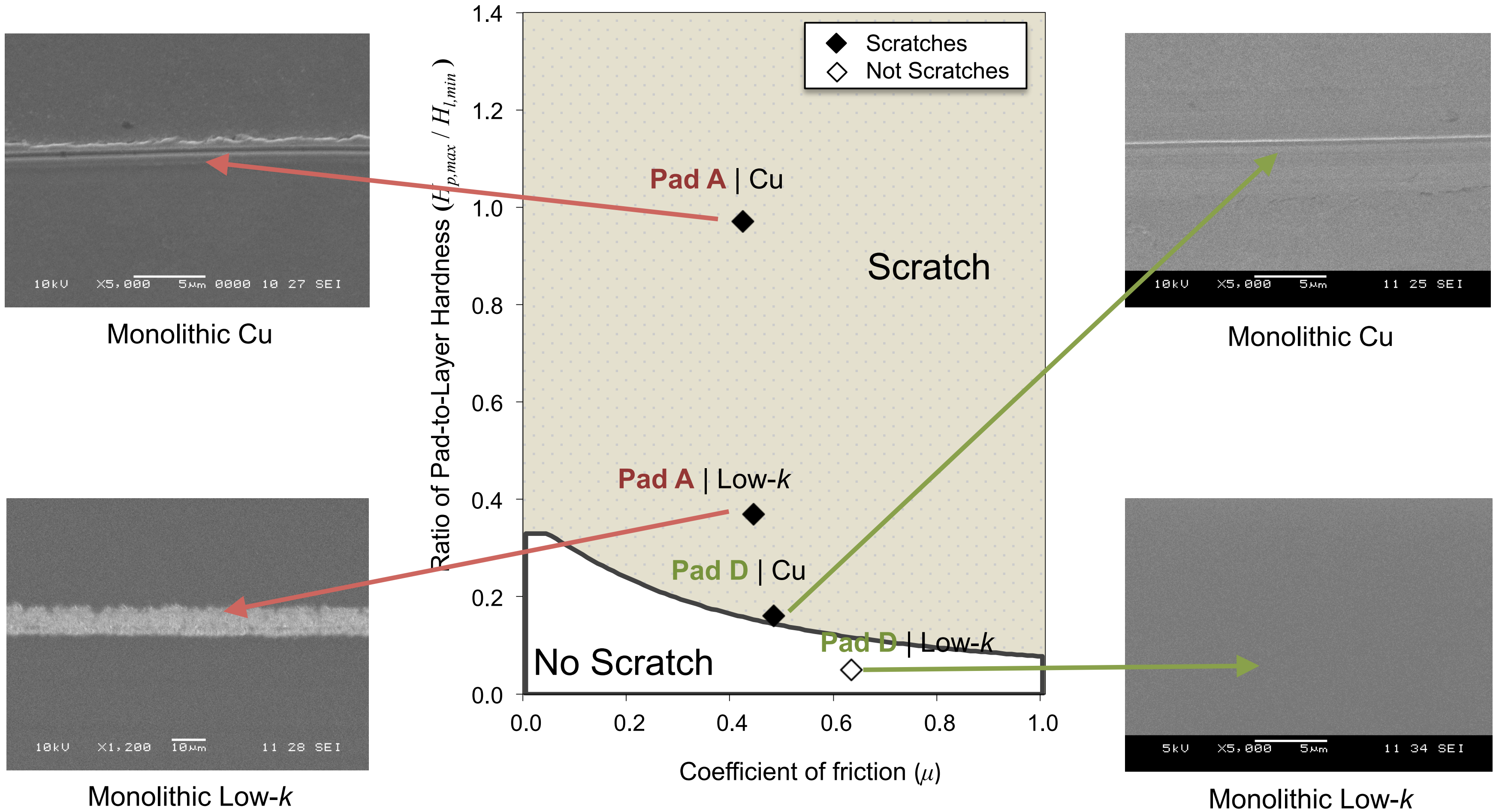
Mechanical Properties

Table. Hardness and Young's modulus of CMP pads (Pad A and D) and monolithic layers (Cu and low-*k*).

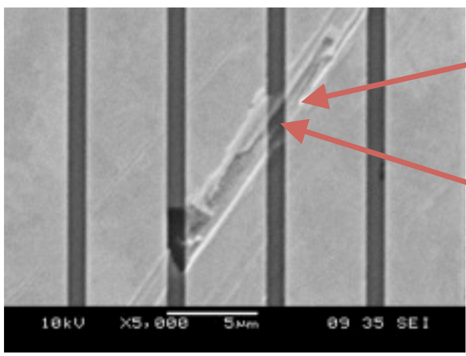
	Hardness (MPa)					Young's modulus (GPa)		
Material	Min.	Average	Max.	Std. Dev.	C.V.	Average	Std. Dev.	C.V.
Pad A	13	28	159	19	0.70	0.14	0.12	0.81
Pad D	23	293	915	220	0.75	2.21	1.59	0.72
Cu	929	1,556	2,103	262	0.17	126.50	12.51	0.10
Low-*k*	2,379	2,473	2,548	47	0.02	26.38	0.45	0.02

* All properties were determined by nano-indentation using a Berkovich indenter.
* C.V. : coefficient of variation = (stdandard deviation / average)

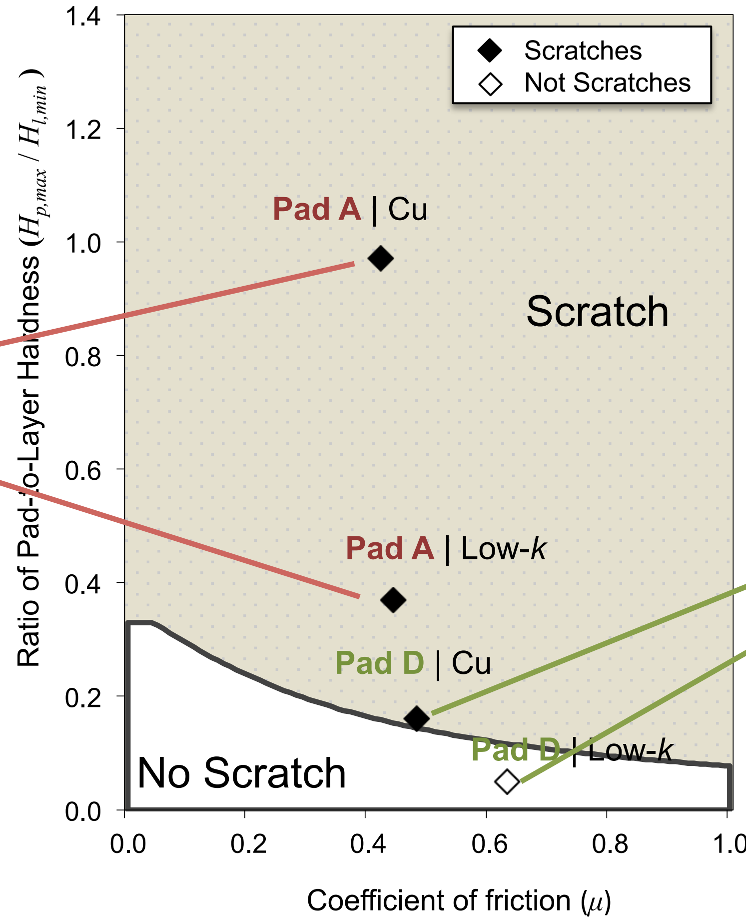
Scratch-Regime Map of Monolithic Layers

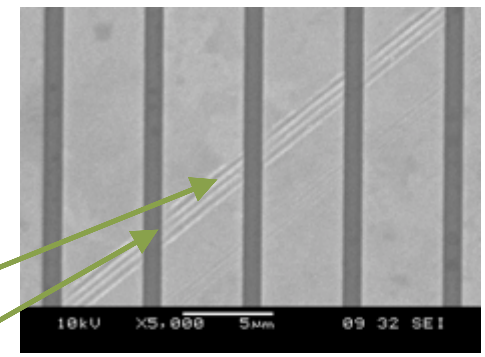


Scratch-Regime Map of Patterned Layers with Wide Cu and Dielectric Lines: w_{Cu} and w_d > 1 μm



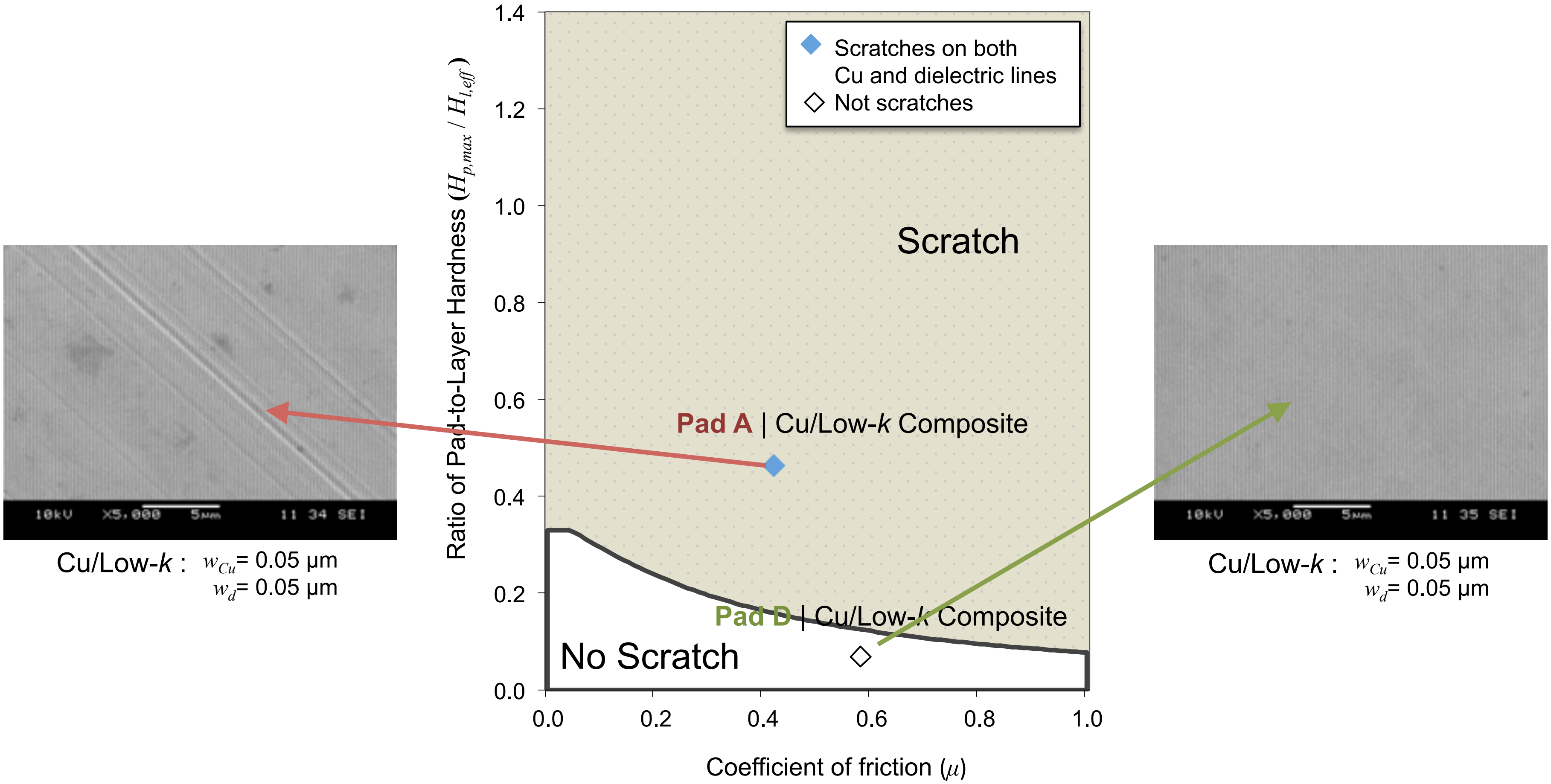
Cu/Low-*k* : w_{Cu}= 4.5 μm
w_d= 1.0 μm





Cu/Low-*k* : w_{Cu}= 4.5 μm
w_d= 1.0 μm

Scratch-Regime Map of Patterned Layers with Narrow Cu and Dielectric Lines: w_{Cu} and w_d < 1 μm



* Effective hardness of Cu/low-*k* composite$_f$: 1,912 MPa

Conclusions

- For pads with exponentially distributed asperity heights, most pad asperities deform plastically, and several asperities will reach the extreme case: fully-plastically deformation.
- Scratching criteria and scratching-regime map for monolithic layers under fully-plastically deformed asperities were developed based on pad-to-layer hardness ratio and coefficient of friction.
- Scratch models for patterned Cu/dielectric layers by fully-plastically deformed pad asperities were advanced.
- Scratching experiments using polymer pins and CMP pads were conducted to validate the models.

Acknowledgments

- Thanks are due the Samsung Electronics Company, Ltd. for its financial support.