Semiconductor Manufacturing Technology

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Chapter 18

Chemical Mechanical Planarization

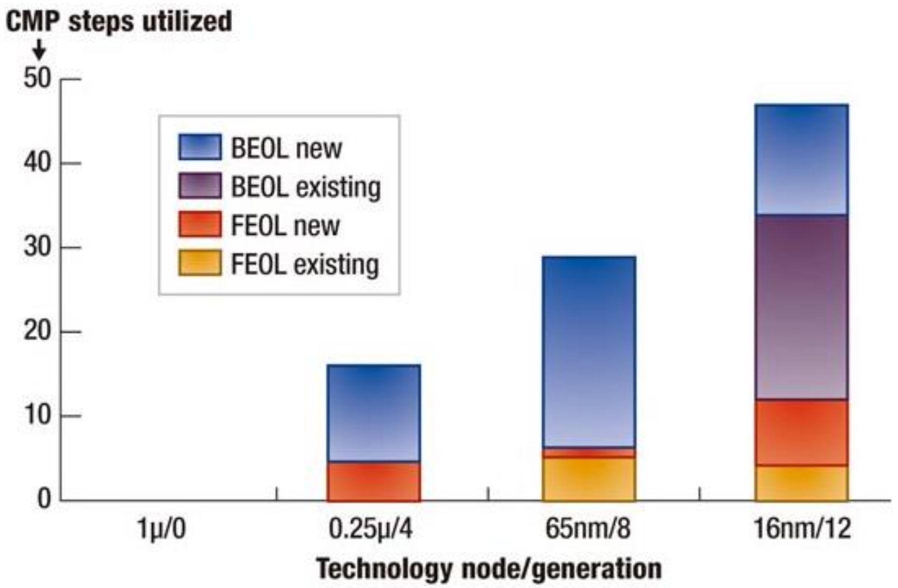
Objectives

After studying the material in this chapter, you will be able to:

1. Describe the terminology for planarization.
2. List and discuss three traditional types of planarization.
3. Discuss chemical mechanical planarization (CMP), the issues of wafer planarity and the advantage of CMP.
4. Describe the slurry and pad for both oxide and metal CMP.
5. Discuss CMP equipment, including endpoint detection and wafer carriers.
6. Explain the post-CMP clean procedure.
7. List and describe seven different CMP applications.

Introduction

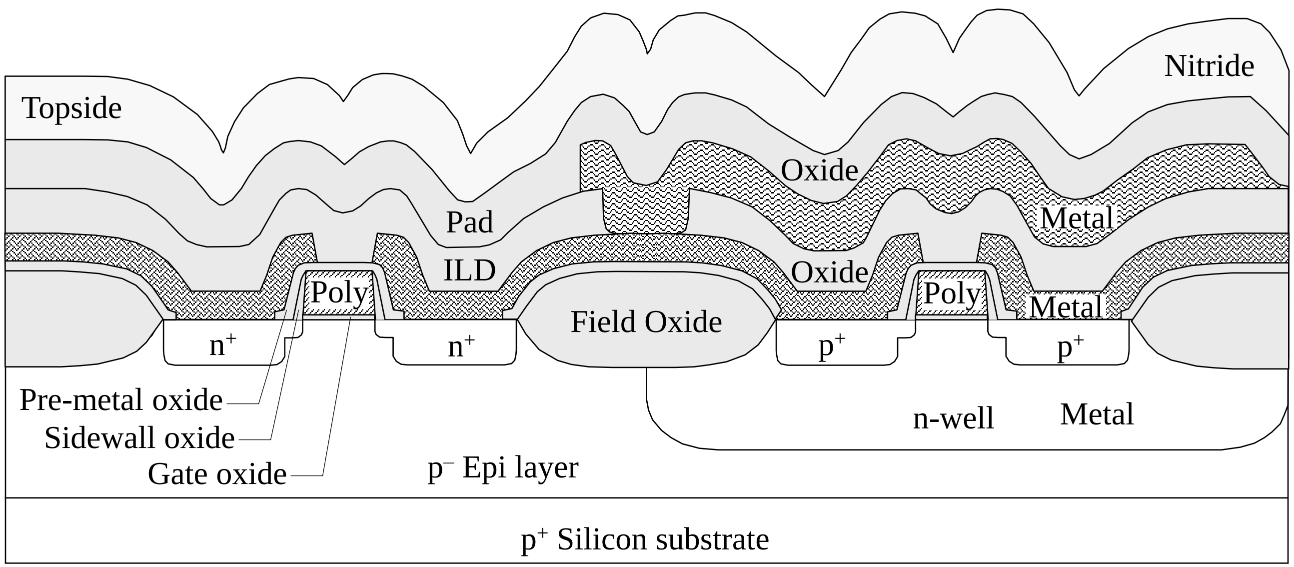
- Multilayer metal promotes higher device density because of its efficient use of vertical space on the chip surface
- But the wafer surface became nonplanar, which is undesirable for pattern because of the limiting depth of focus
- IBM developed in the late 1980s, and became the standard during 1990s



圖一：從0.25μm節點開始，每一個新的CMOS技術世代約增加四道新的CMP步驟

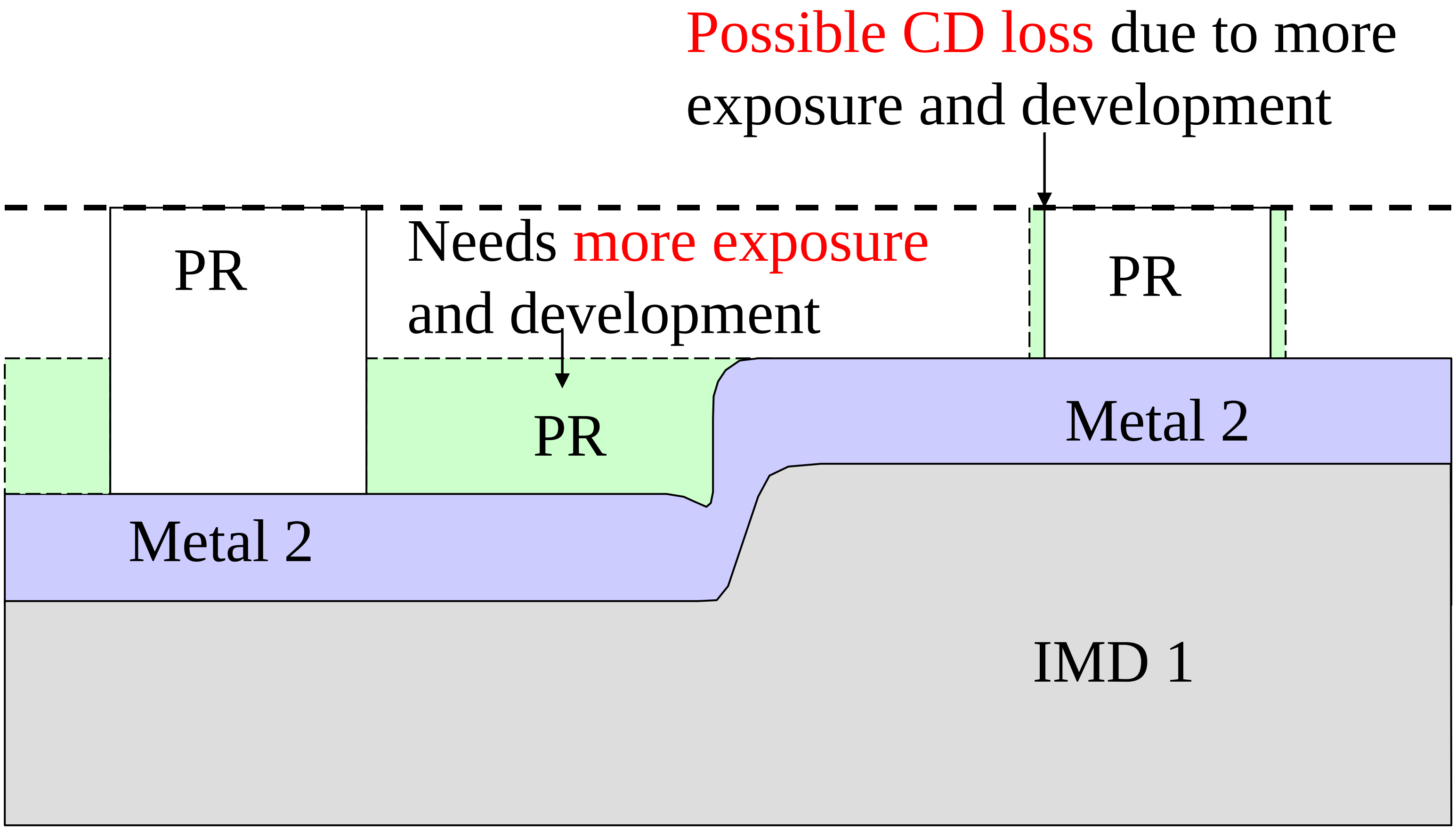
2010/12/29　來源：半導體科技

Single Metal Layer IC with Topography



- A major negative consequence of topography is **loss of line width control during photolithography**.
- The PR thickness variations due to topography are a major factor inhibiting subquarter micron lithography due to the depth-of-focus limitations of optical steppers
- A planarized wafer has a flat surface with minimal layer thickness variations on each layer
- Filling in low features or removing high features are two ways to planarized a wafer surface

- Over Exposure and Over Development

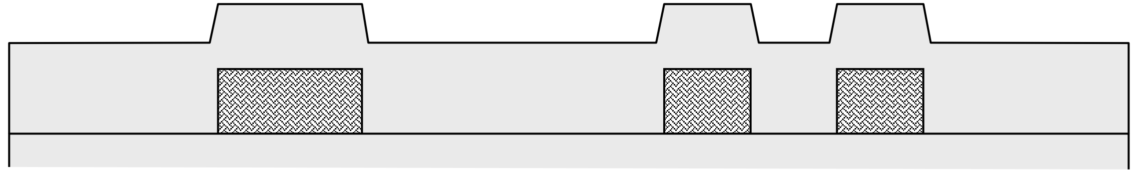


Terminology for Wafer Planarization

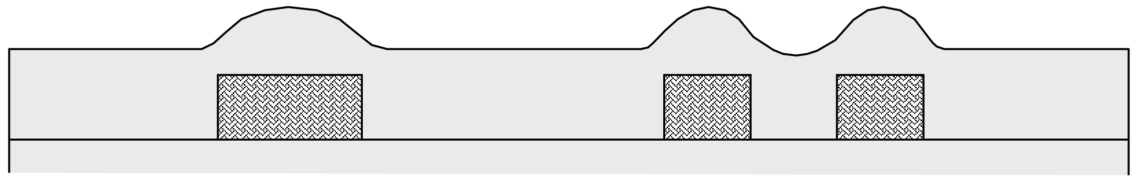
Type of Planarization	Description
Smoothing	Step height corners rounded and sidewalls sloped, but the height is not significantly reduced.
Partial Planarization	Smoothing plus a reduction in step height locally.
Local Planarization	Complete filling of smaller gaps (1 – 10 μm) or local areas within a die. The total step height to flat areas across the wafer is not significantly reduced.
Global Planarization	Achieves local planarization plus a significant reduction in the total step height across the entire wafer surface. This is also referred to as uniformity.

Qualitative Definitions of Planarization

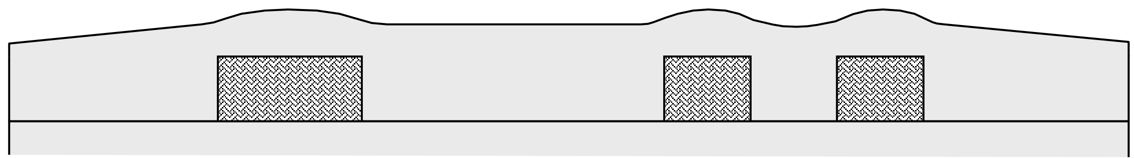
a) No planarization



b) Smoothing

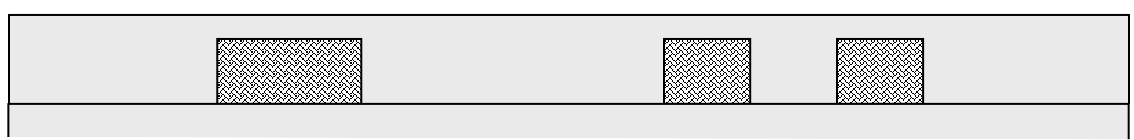


c) Partial planarization



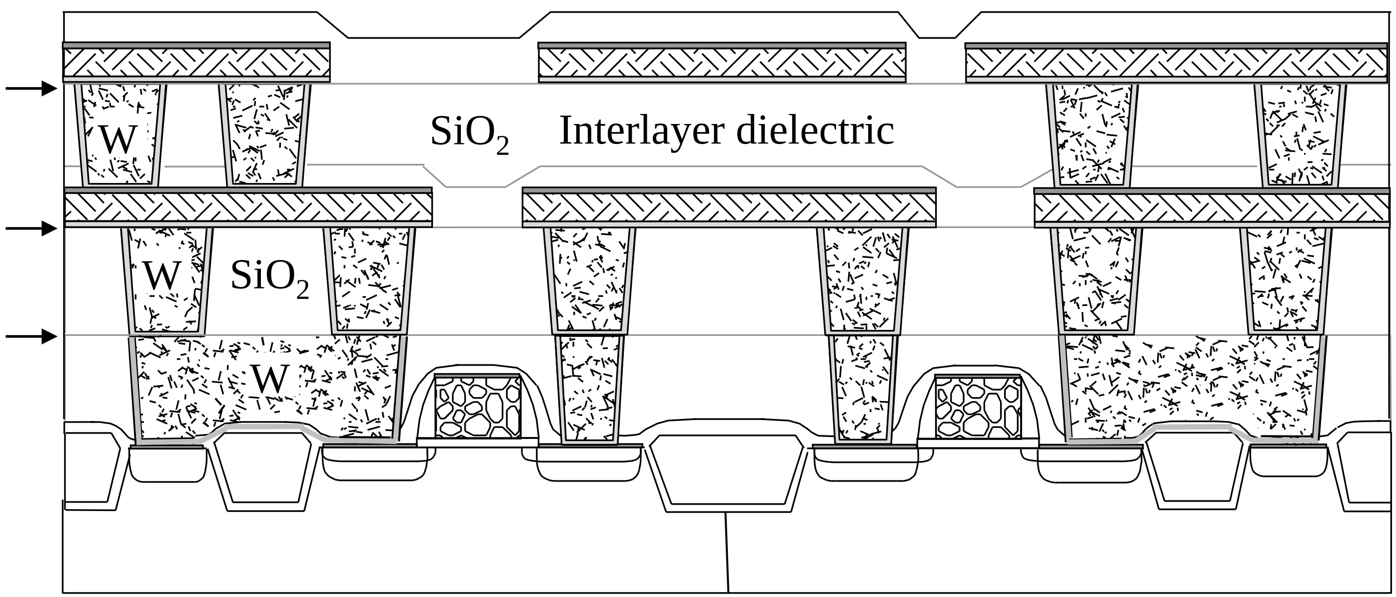
d) Local planarization

e) Global planarization



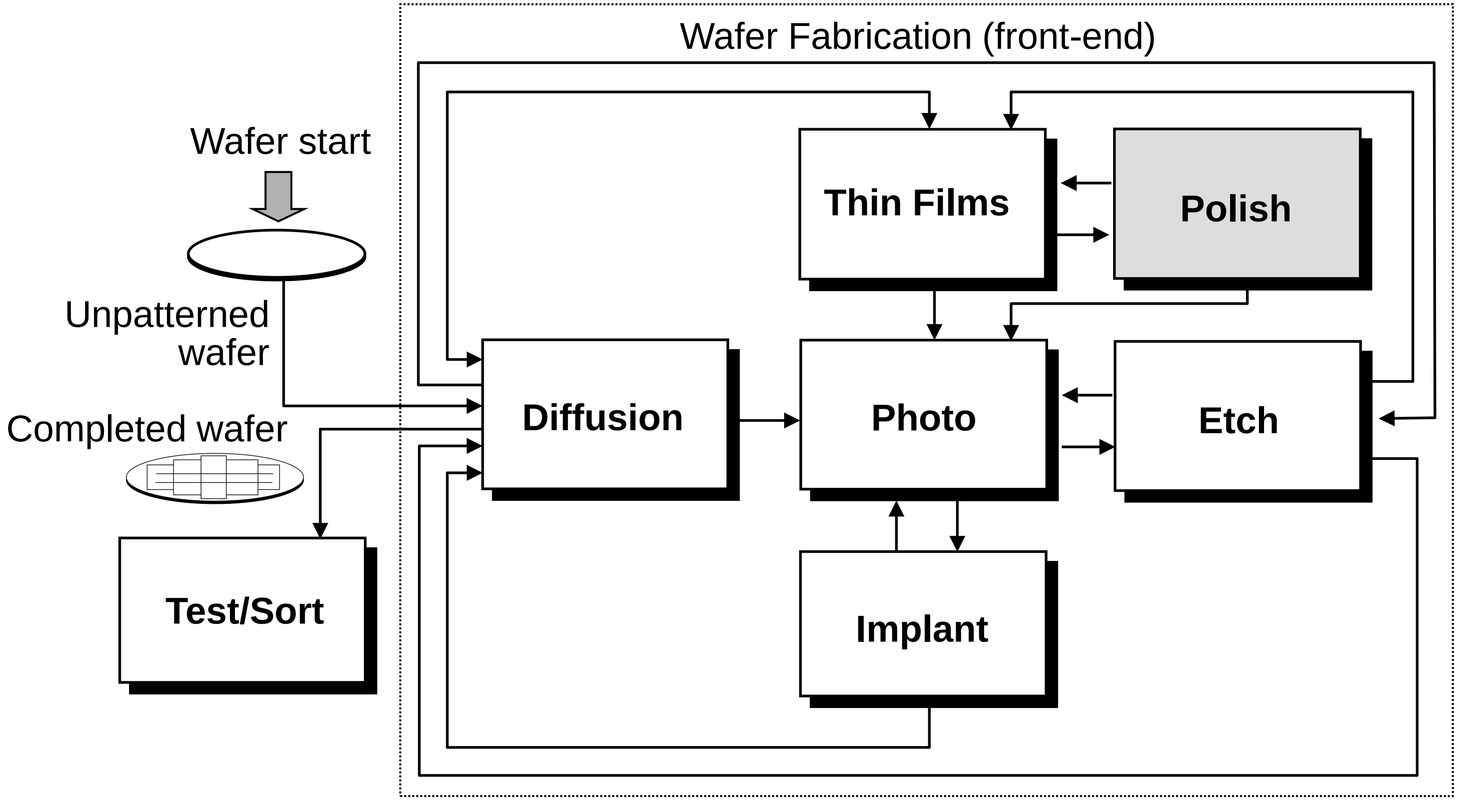
Multilayer Metallization with Chemical Mechanical Planarization (CMP)

- CMP, commonly referred to as chemical mechanical polish, has been used for many years for optical glass polishing and wafer polishing during silicon wafer production



Subquarter micron CMOS cross section

Wafer Process Flow with CMP



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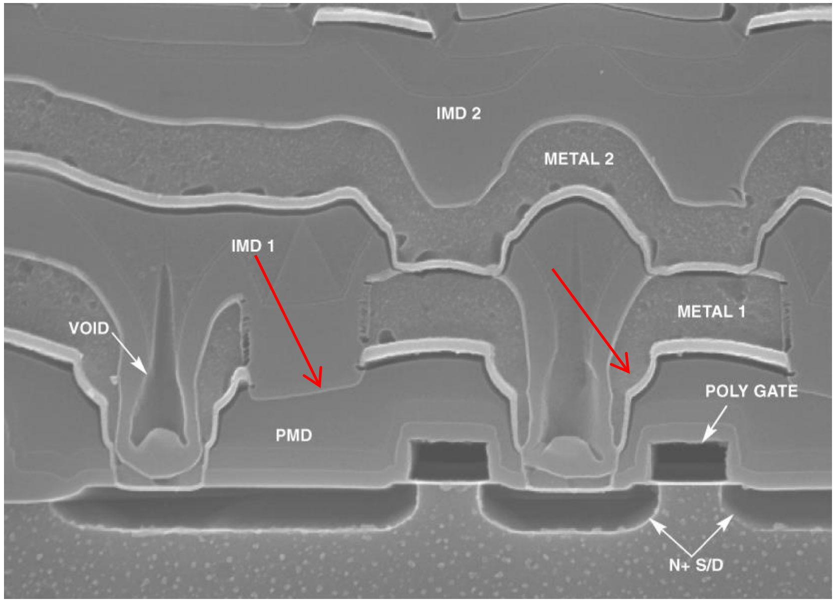
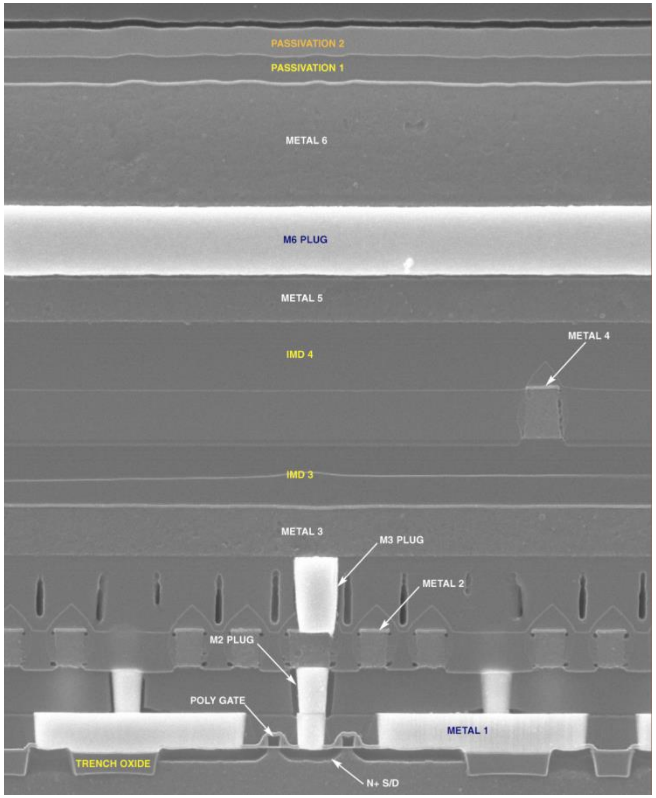
Multilayer Metallization with Non-planarized and Planarized Surfaces



Non-planarized IC product

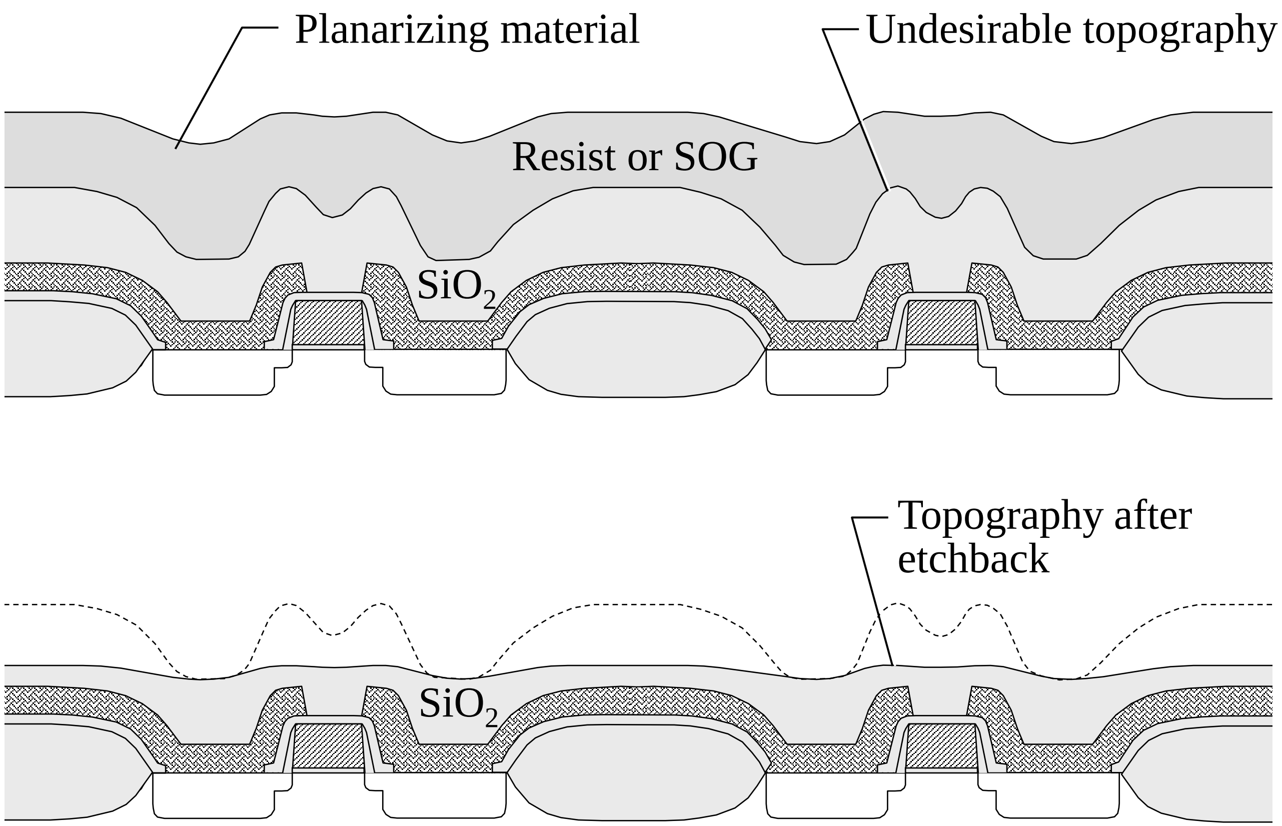


Planarized IC product

Traditional Planarization

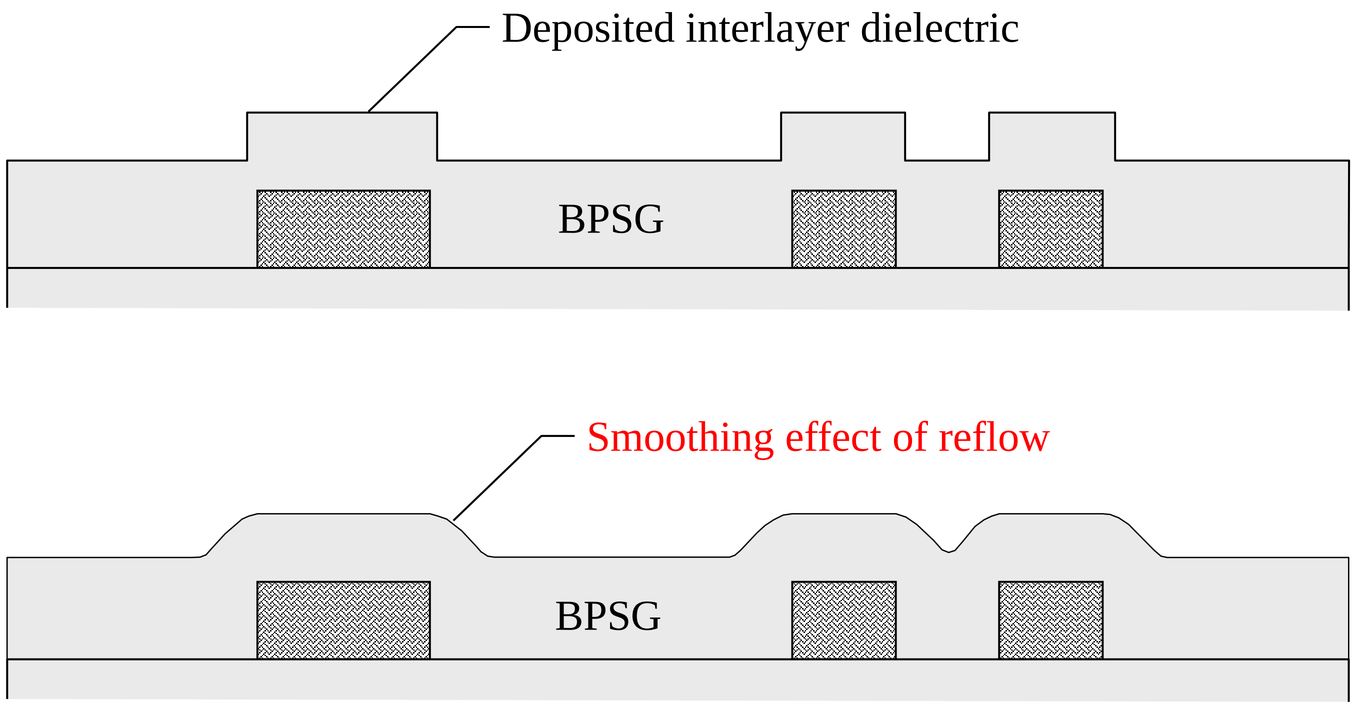
- Etchback
- Glass Reflow
- Spin-on-films

Etchback Planarization



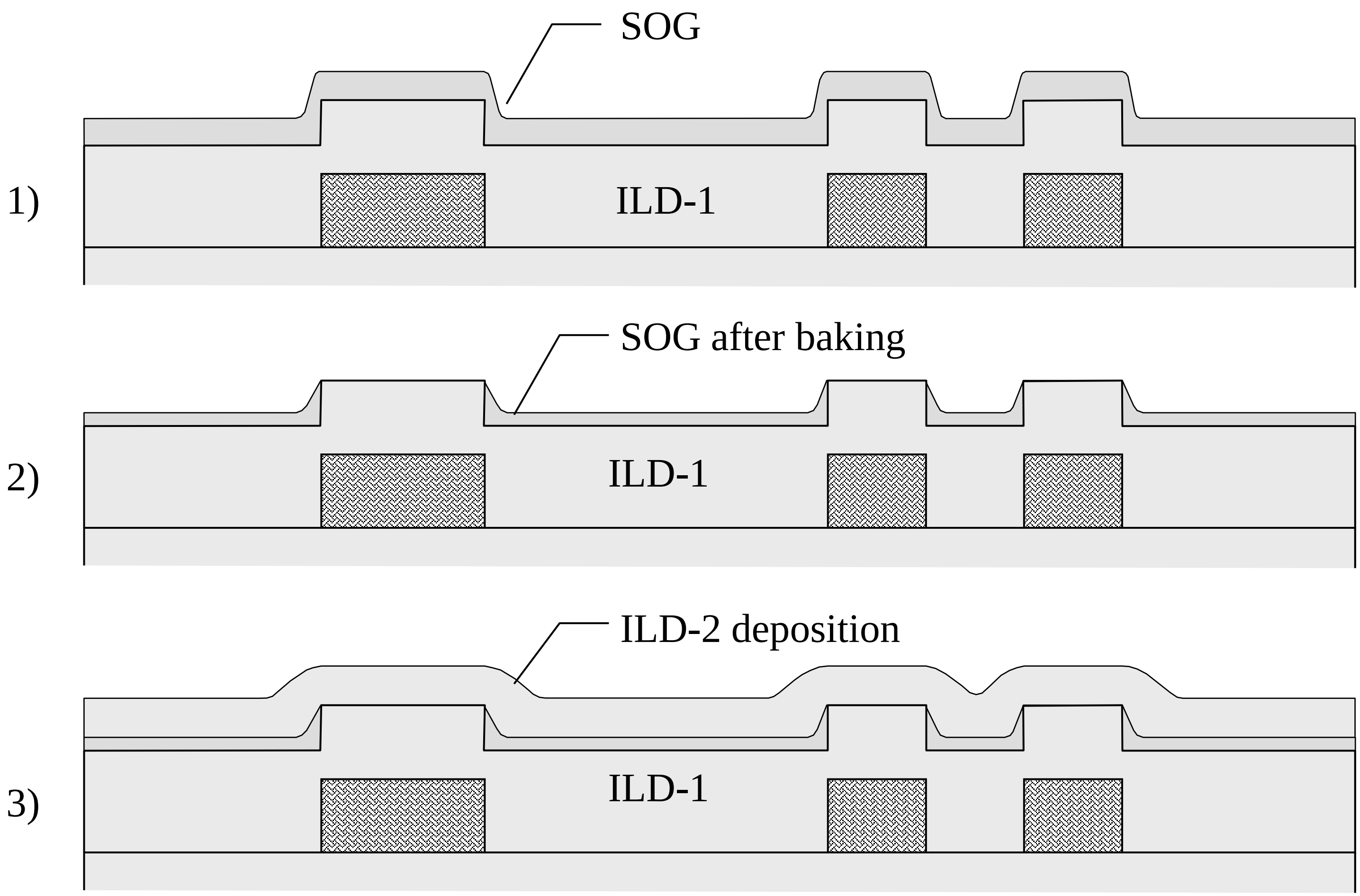
- The sacrificial material fills voids and the low spots on the surface.
- Etching of the sacrificial layer is then done using a dry etch to smooth the surface features by removing high feature at a faster rate than low features
- It is a local planarization.

BPSG Reflow Planarization



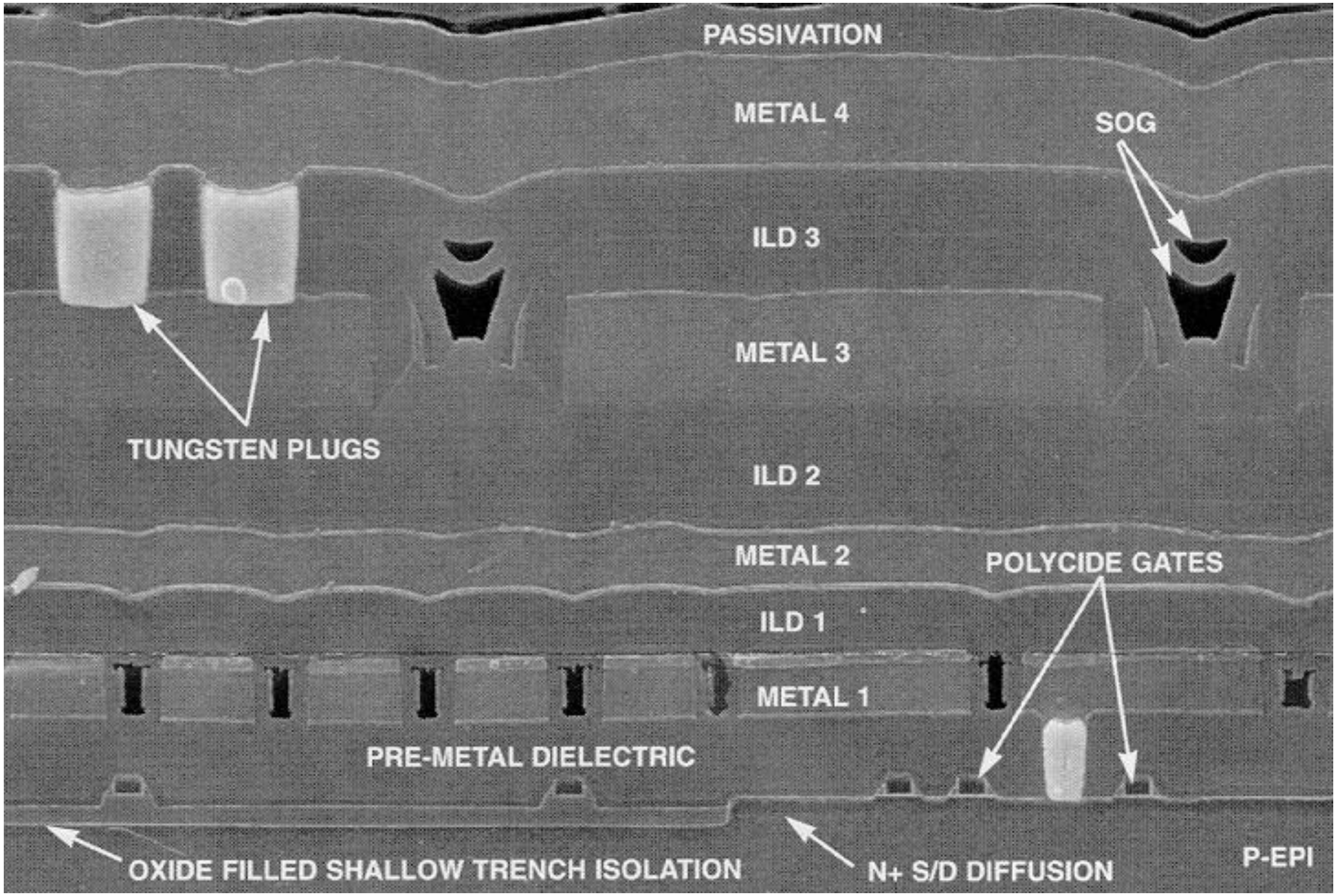
1. 850°C 30-min causes BPSG flow, resulting flow angle < 20°
2. It is not adequate for deep submicron ICs with multiple metals (high-temp)

Spin On film with Etchback



- The most common method for planarization and gap-fill at 0.35 μm and larger
- Possible formulation: 80% solvent and 20% SiO_2
- It is important for low-k deposition

- SOG Etchback

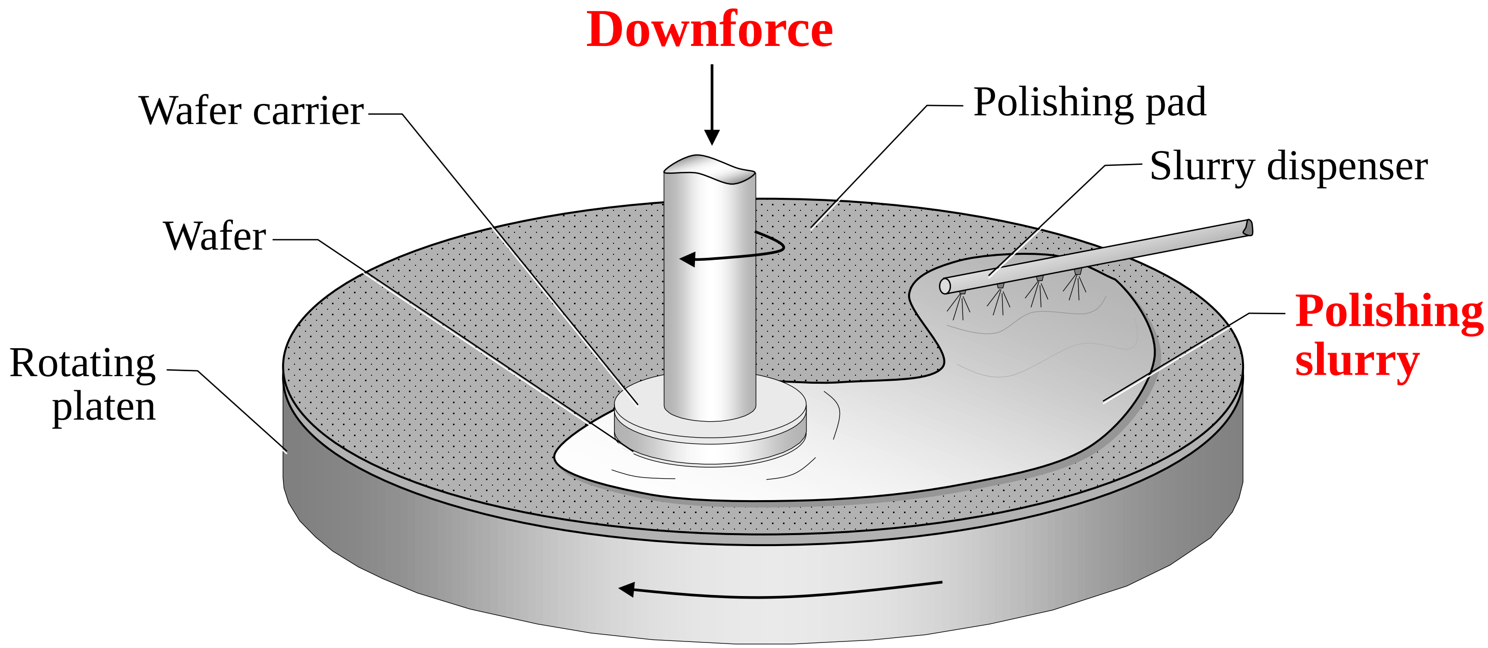


Chemical Mechanical Planarization

- CMP Planarity
- Advantages of CMP
- CMP Mechanisms
- CMP Slurry and Pad
- CMP Equipment
- CMP Clean
- CMP Equipment Manufacturers

Schematic of Chemical Mechanical Planarization (CMP)

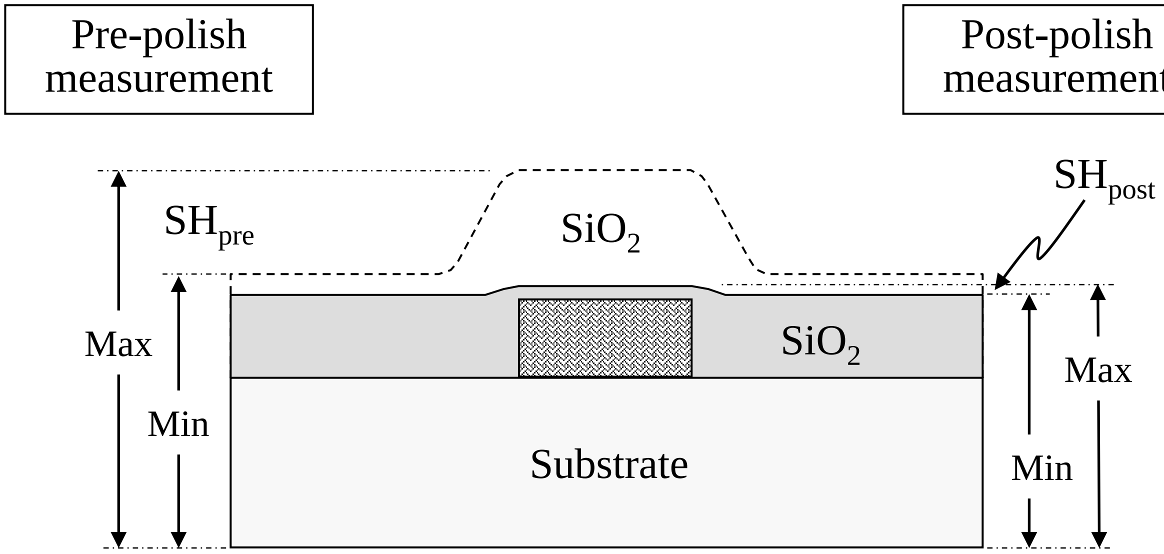
Step height: etchback ~ 7000Å vs. CMP ~ 50Å



- CMP achieves wafer planarity by removing high features on the surface more quickly relative to the low feature (high pressure by Preston's eq.)
- Both metal and dielectric layers can be removed

Wafer Measurements for Degree of Planarization

$$DP(\%) = \left(1 - \frac{SH_{post}}{SH_{pre}}\right) \times 100$$



- Planarity: surface topography variation
- Uniformity: film thickness variation
- Perfect flat: DP is 100%. If SH post=1 μm, pre is 20 μm, then DP(%) is 95%.

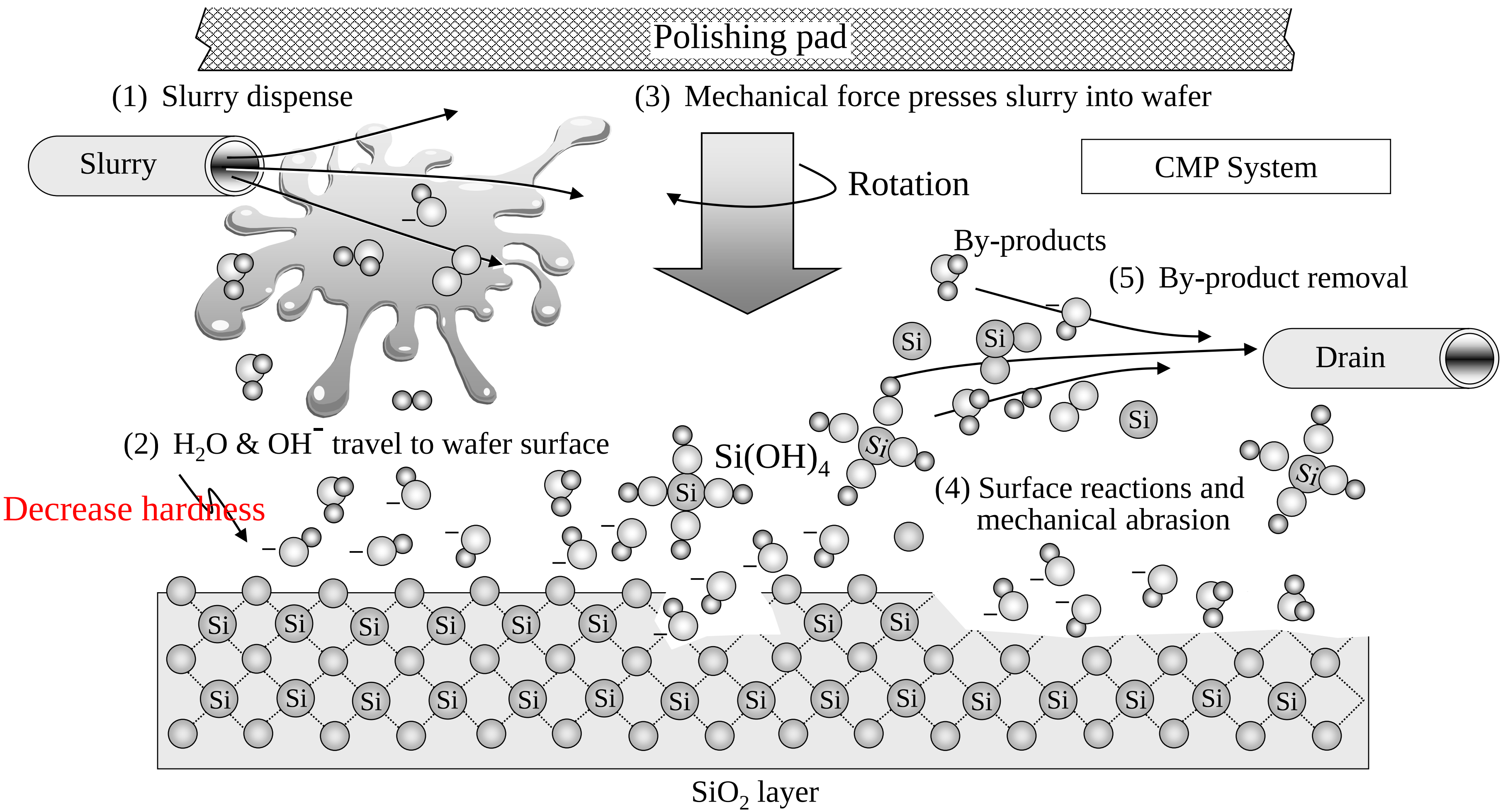
Advantages of CMP

Benefits	**Remarks**
1. Planarization	Achieves global planarization.
2. Planarize different materials	Wide range of wafer surfaces can be planarized.
3. Planarize multi-material surfaces	Useful for planarizing multiple materials during the same polish step.
4. Reduce severe topography	Reduces topography to allow for fabrication with tighter design rules and additional interconnection levels.
5. Alternative method of metal patterning	Provides an alternate means of patterning metal (e.g., Damascene process), eliminating the need of the plasma etching for difficult-to-etch metals and alloys.
6. Improved metal step coverage	Improves metal step coverage due to reduction in topography.
7. Increased IC reliability	Contributes to increasing IC reliability, speed and yield (lower defect density) of sub-0.5μm devices and circuits.
8. Reduce defects	CMP is a subtractive process and can remove surface defects.
9. No hazardous gases	Does not use hazardous gases common in dry etch process.

Disadvantages of CMP

Disadvantages	Remarks
1. New technology	CMP is a new technology for wafer planarization. There is relatively poor control over the process variables with a narrow process latitude.
2. New defects	New types of defects from CMP can affect die yield. These defects become more critical for sub-0.25 μm feature sizes.
3. Need for additional process development	CMP requires additional process development for process control and metrology. An example is the endpoint of CMP is difficult to control for a desired thickness.
4. Cost of ownership is high	CMP is expensive to operate because of costly equipment and consumables. CMP process materials require high maintenance and frequent replacement of chemicals and parts.

CMP Oxide Mechanism
(surface hydration by Cook's theory)

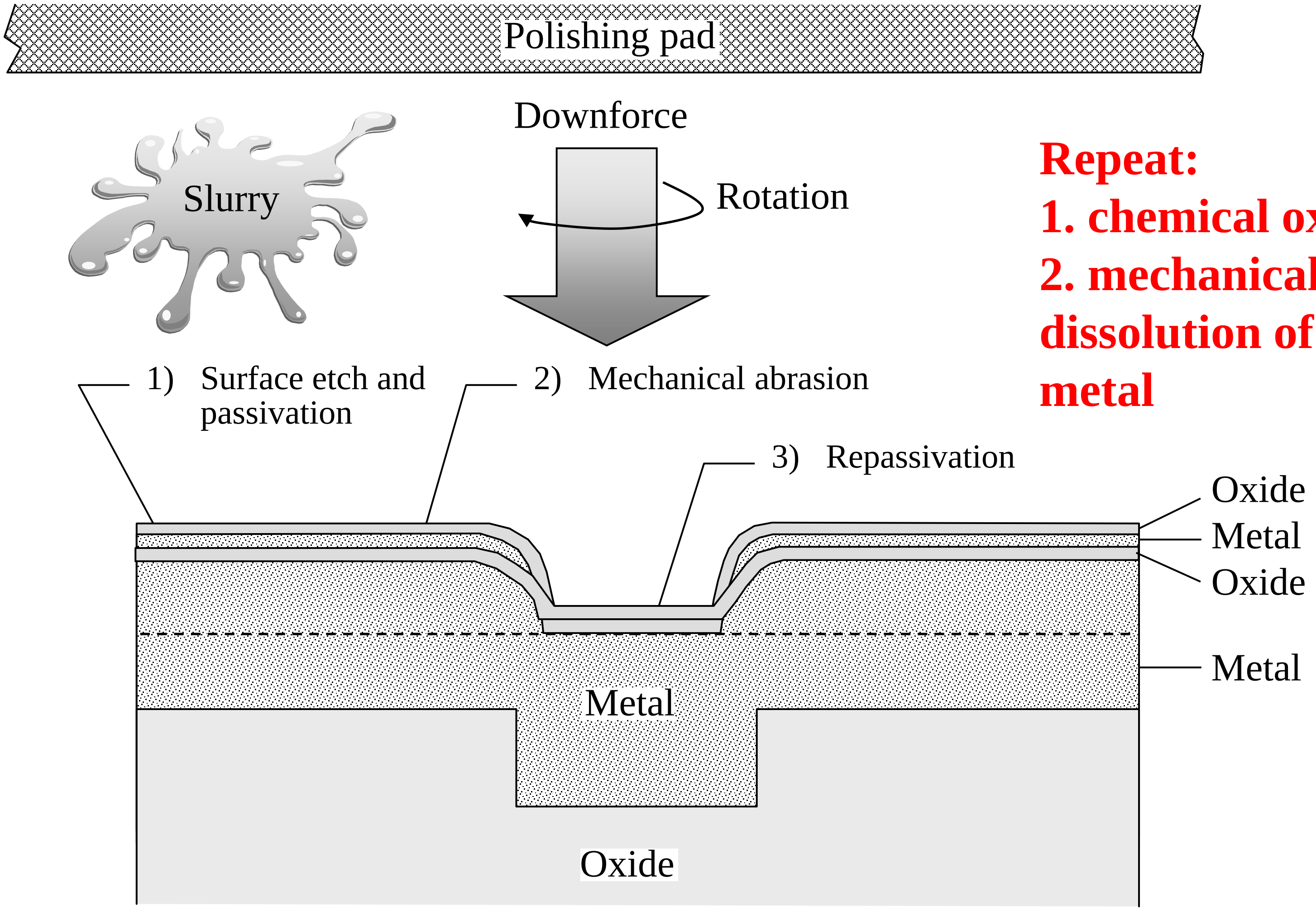


- Chemical: slurry chemistry forms a wafer surface that is easy to remove.
- Mechanical: slurry abrasive component and applied pressure and relative velocity

Oxide Polish

- To planarize the ILD
- Speed of removal is given by Preston's eq.
  - $R=kPv$
  - Where P is applied pressure
  - v is relative velocity between wafer and and pad
  - k: constant depends on oxide hardness, slurry, and pad

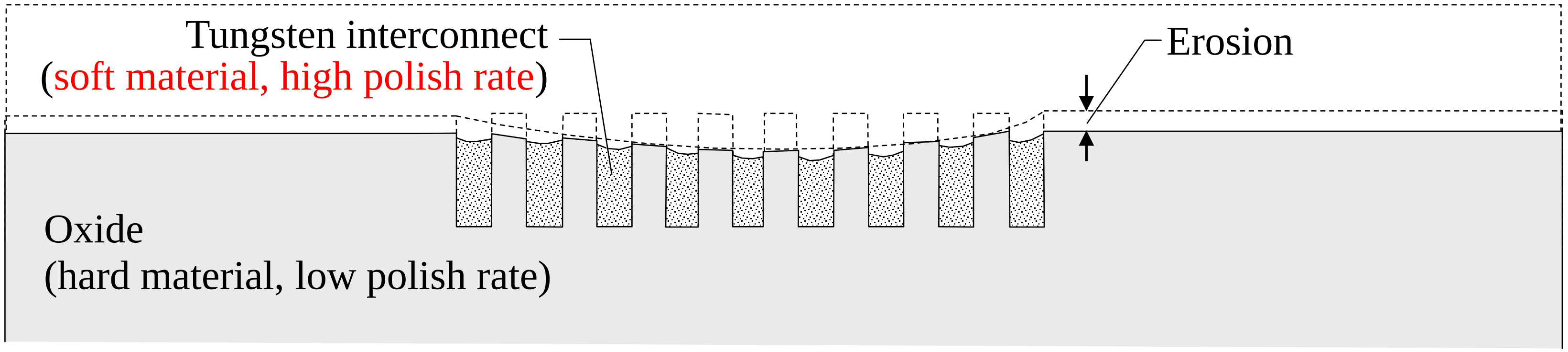
Mechanism for Metal CMP



Repeat:
1. chemical oxidation and
2. mechanical abrasion or dissolution of the oxidized metal

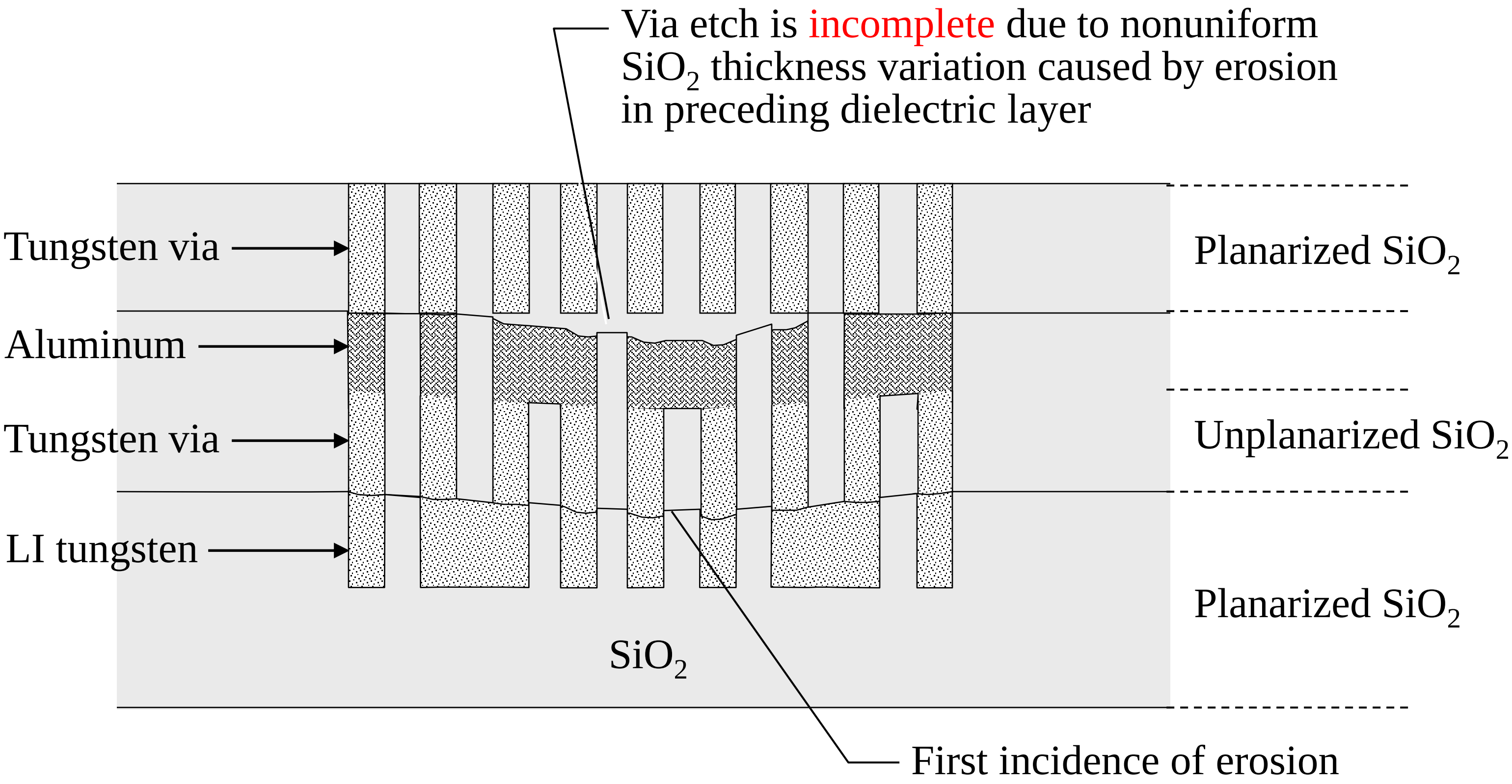
For example: Cu CMP, CuO or Cu2O or Cu(Oh)2 are formed

CMP Erosion in High Wiring Density

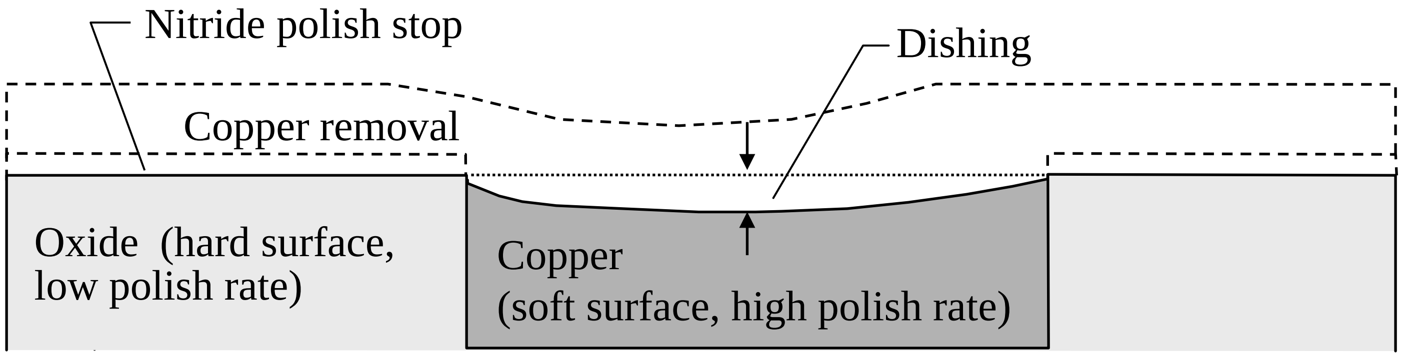


- Narrowly spaced feature often polish at a greater rate than widely spaced feature.
- Small isolated raised feature encounter greater pressure during planarization and polish at a high rate.
- To solve: shorten the overpolish time, and another oxide polish at elevated region.

Incomplete Via Etch due to Erosion



CMP Dishing in a Large Feature

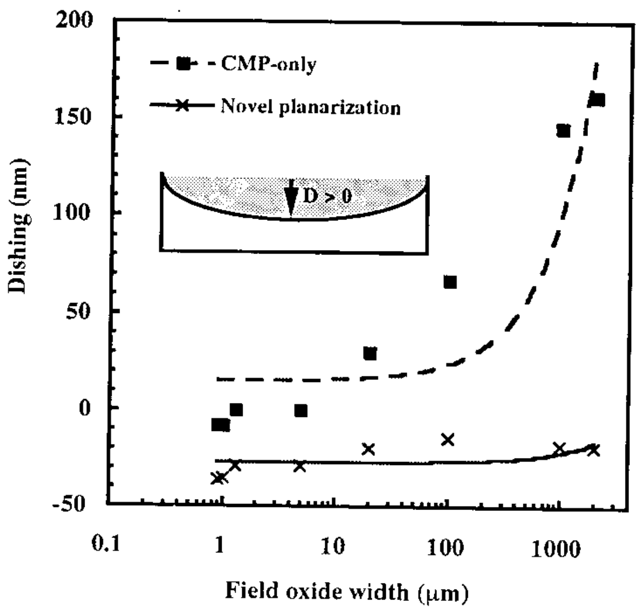


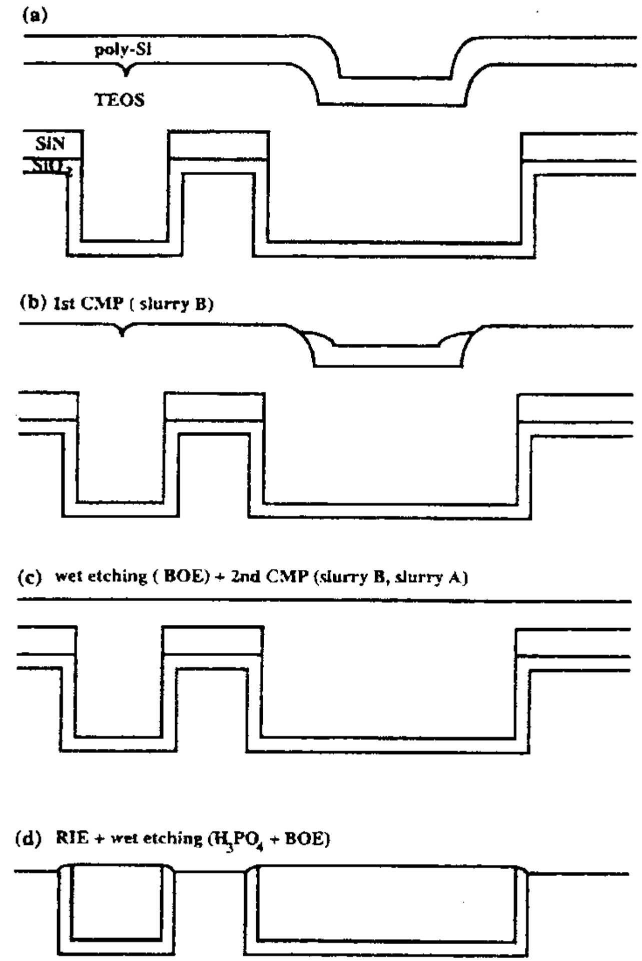
- Wider lines having more tendency to dish
- Softer polishing pads bend into the soft metal line and exert pressure to causes dishing

A Novel Planarization of Oxide-filled STI

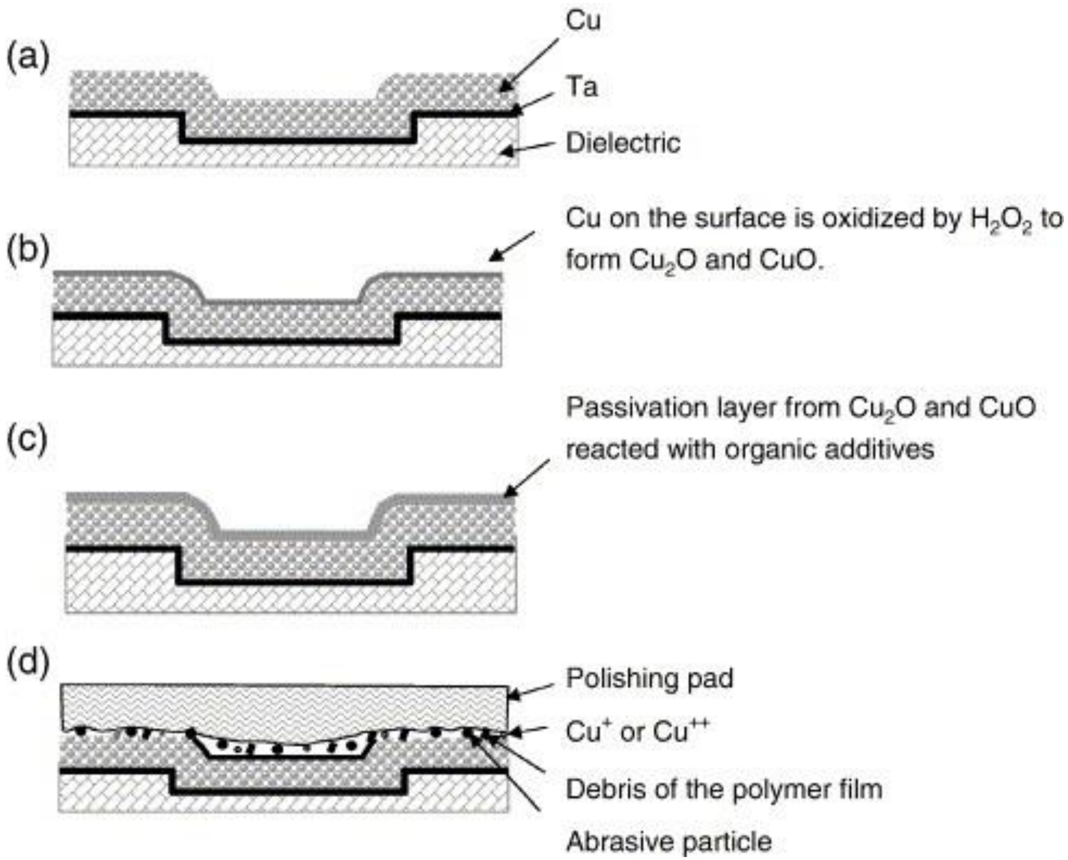
(J. Electrochem. Soc., 1997, p.315)

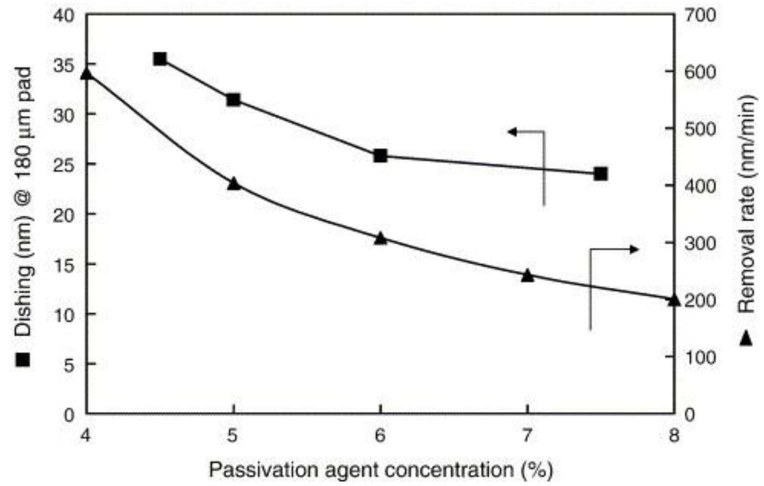
- Using high selectivity CMP on poly-Si/oxide
- Dishing effect in wide field regions is improved





Novel slurry solution for dishing elimination in copper process beyond 0.1-μm technology (Thin Solid Films, 498, p.50, 2006)



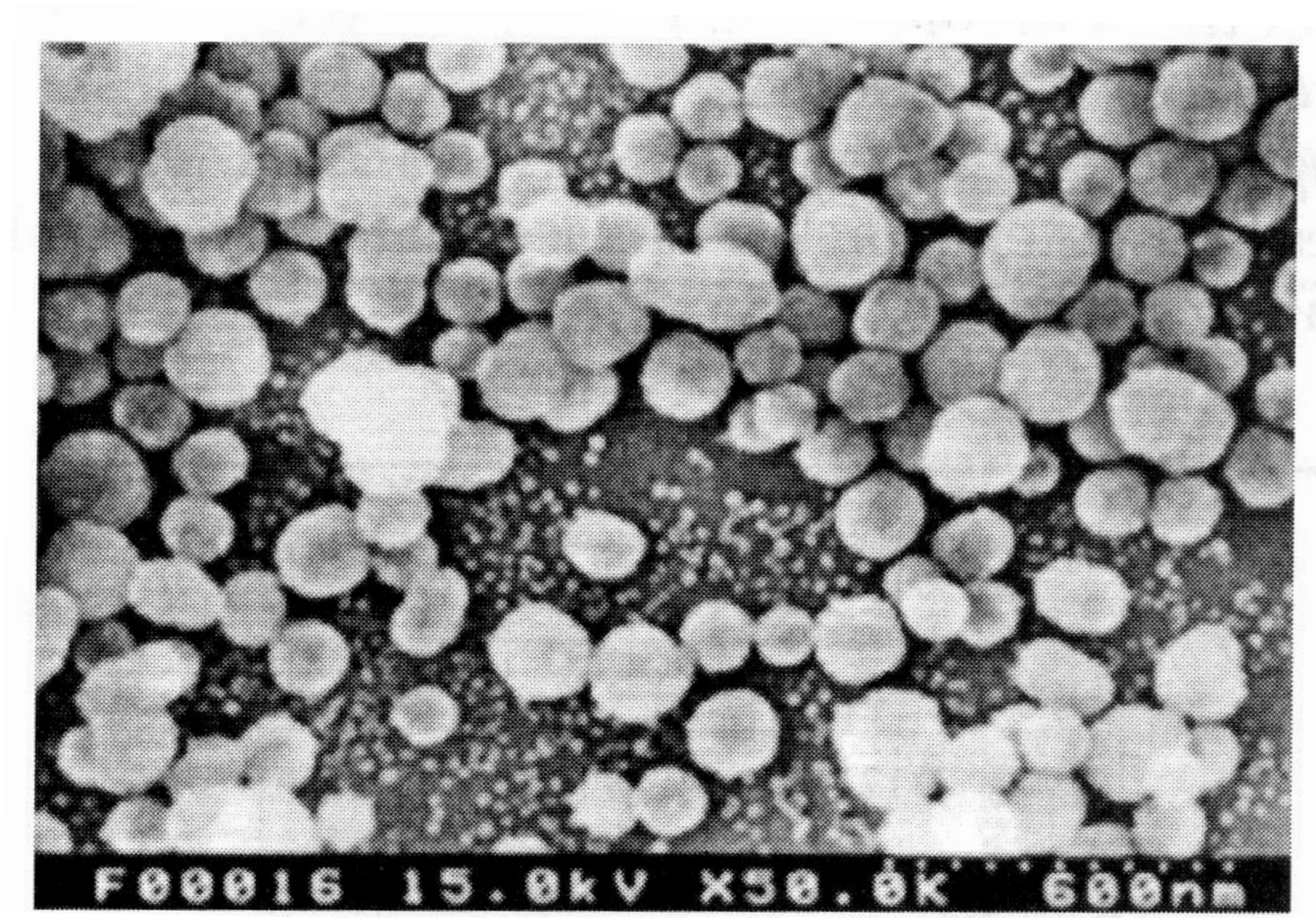


- inhibitor of copper corrosion due to its active adsorption ability on the copper surface to prevent the copper oxidation

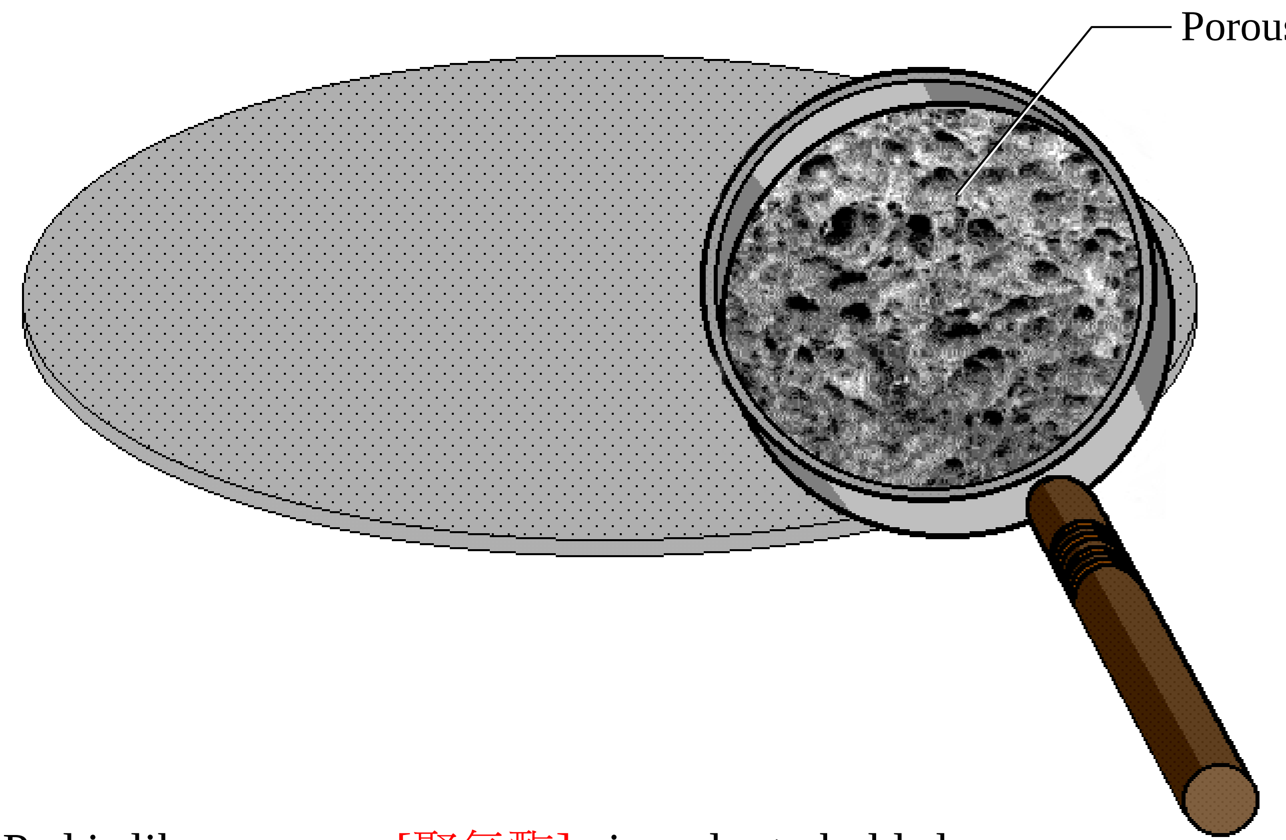
Slurry

- Slurry is a mixture of fine abrasive particles and chemicals
- Precise slurry mixing, uniform suspended and uniformly distribution are important
- Oxide slurry: silica colloidal + KOH or NH_4OH (pH ~ 10-11). KOH is preferred for its stable colloidal suspension, but K is mobile ion. BPSG as the gettering layer.
- W-slurry: fine Al_2O_3 or silica (more soft, less scratch) + H_2O_2. Oxidizes the W as WO_3 (soft and remove)
- Cu-slurry: NH_4OH+alumina powder

Silica Particulates

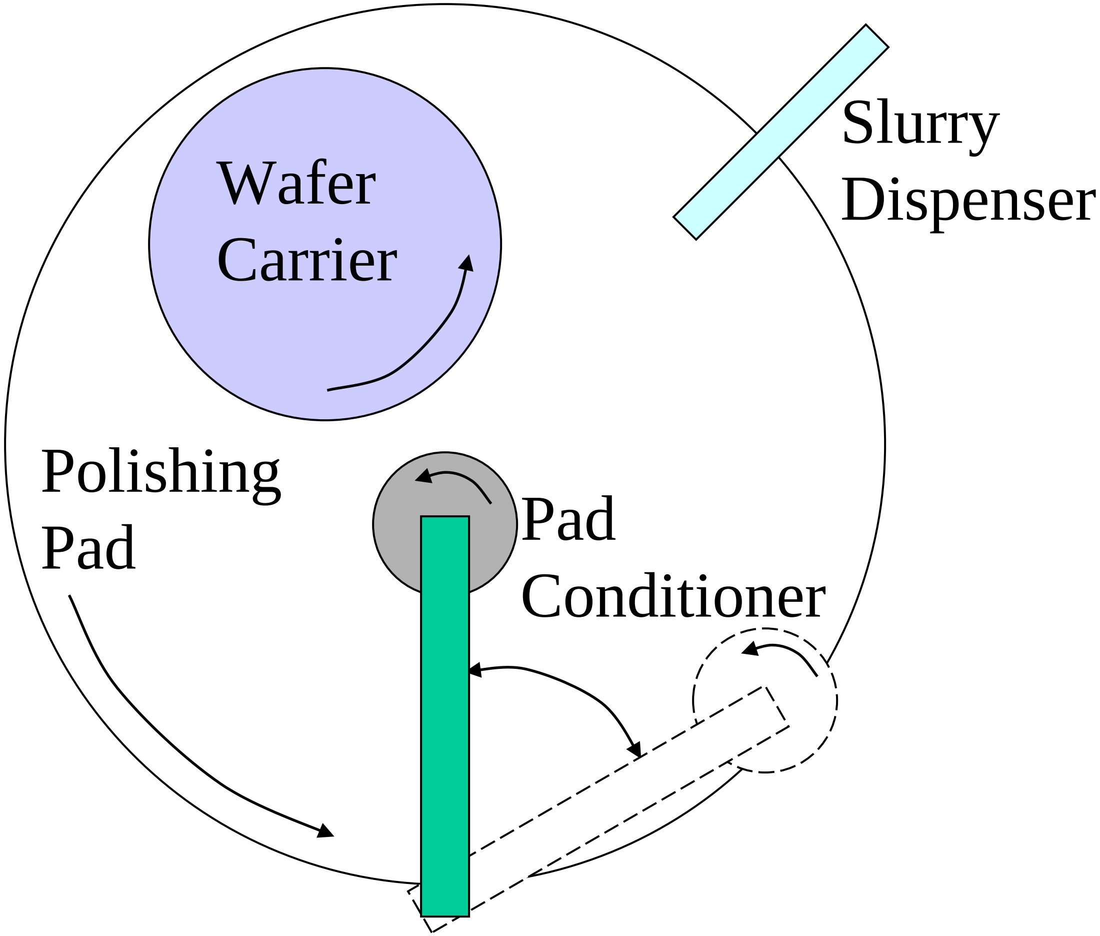


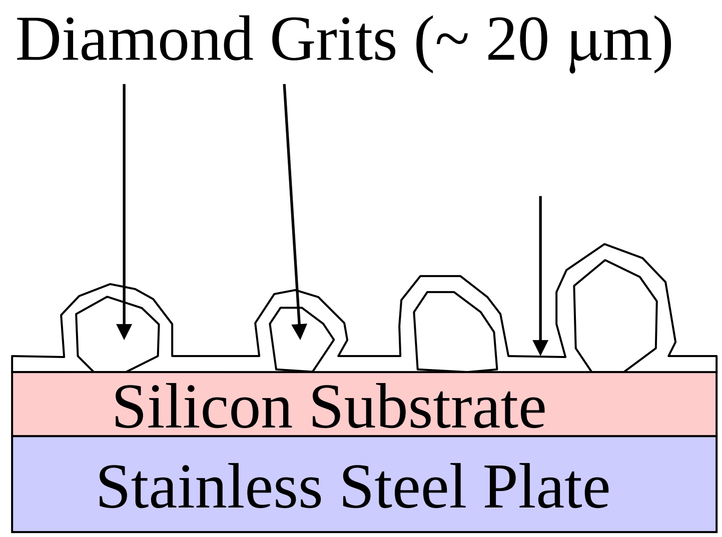
CMP Polishing Pad



- Pad is like a sponge [聚氨酯] , in order to hold slurry.
- After polishing for a long time, the pad surface becomes flatted and smooth → glazing
- Needs conditioning to slow down the glazing: abrasion or DI water jet spray

- Polishing Pad and Pad Conditioner





Diabond

CMP Polishing Pad

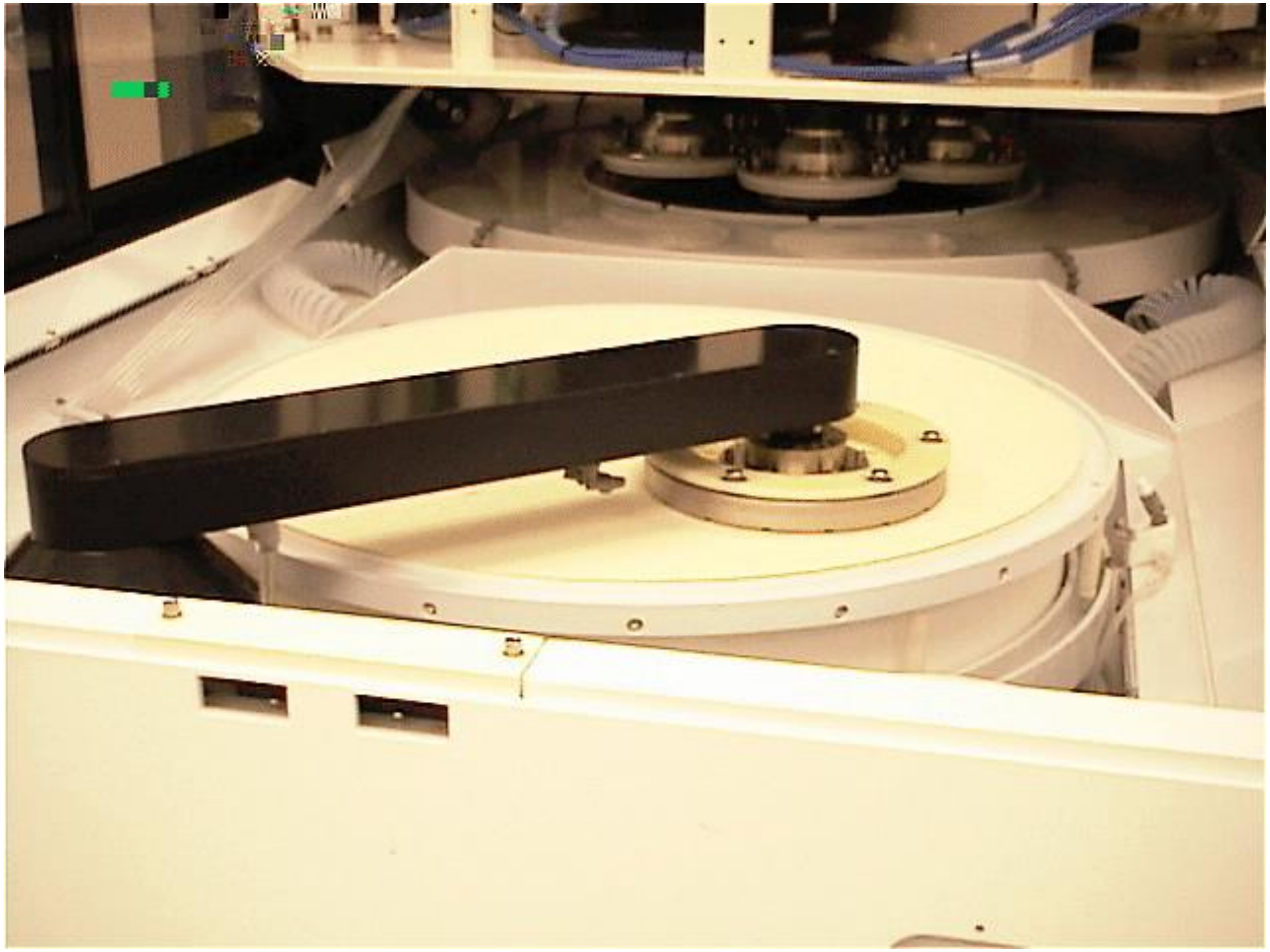
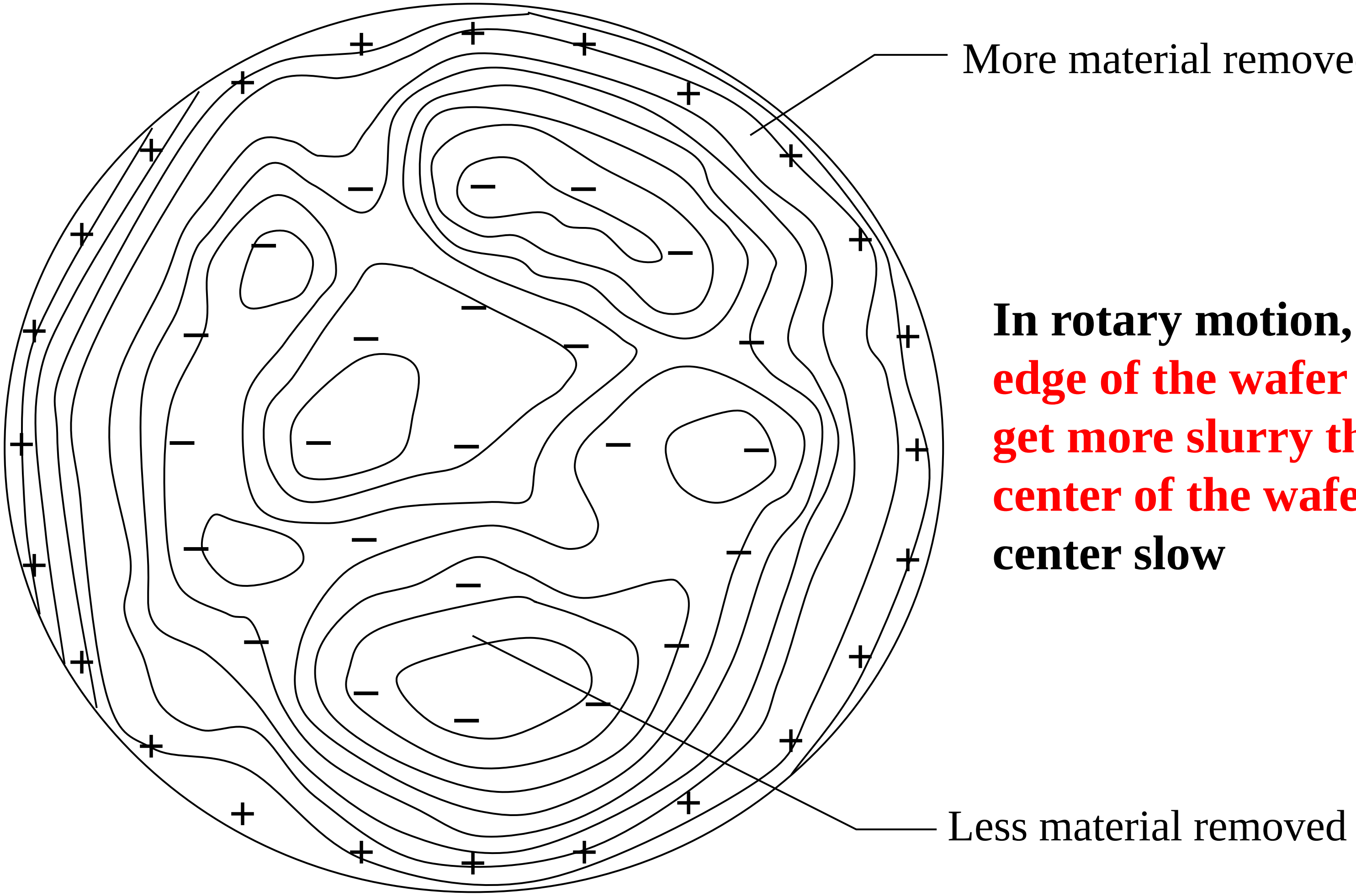


Photo courtesy of Speedfam-IPEC

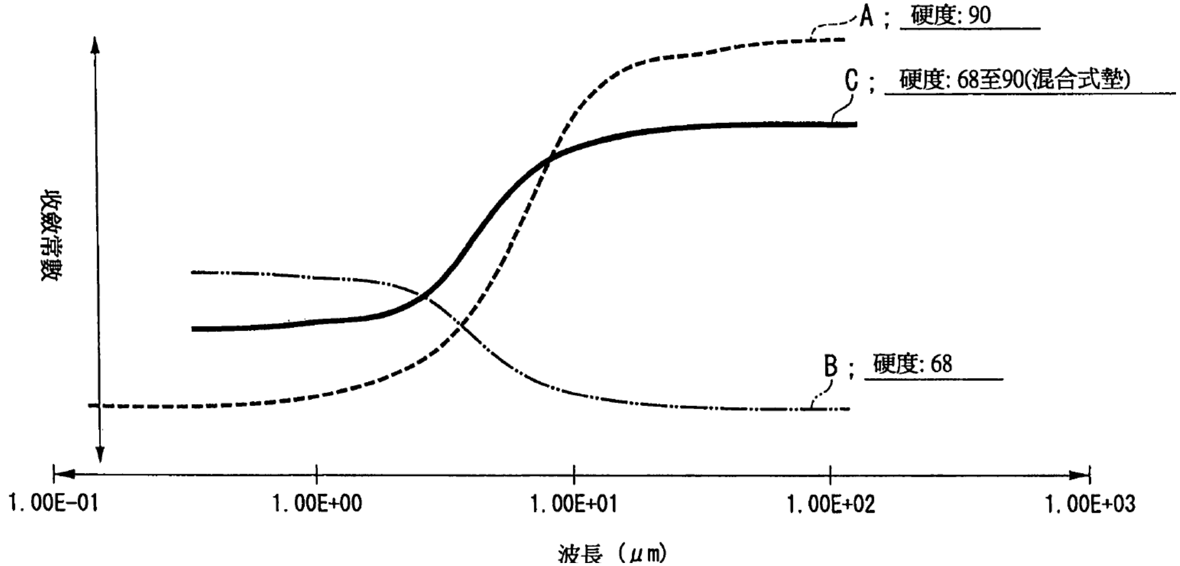
CMP Contour Plot for Center Slowness

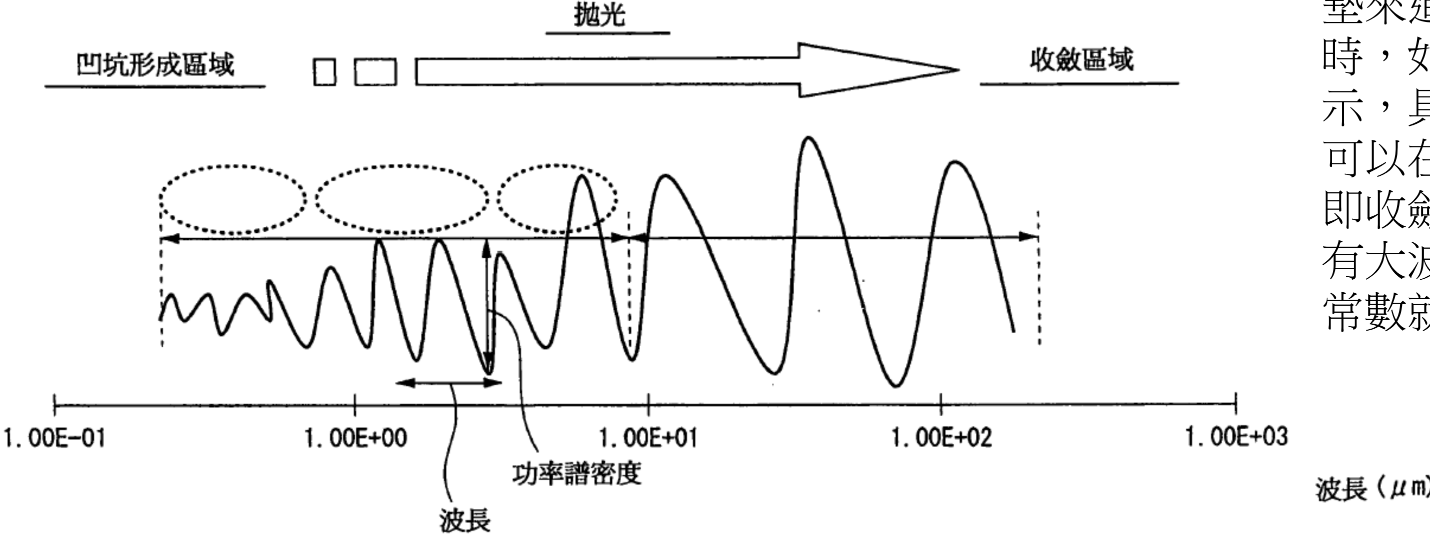


In rotary motion, the edge of the wafer may get more slurry than the center of the wafer → center slow

Polish Rate and Uniformity

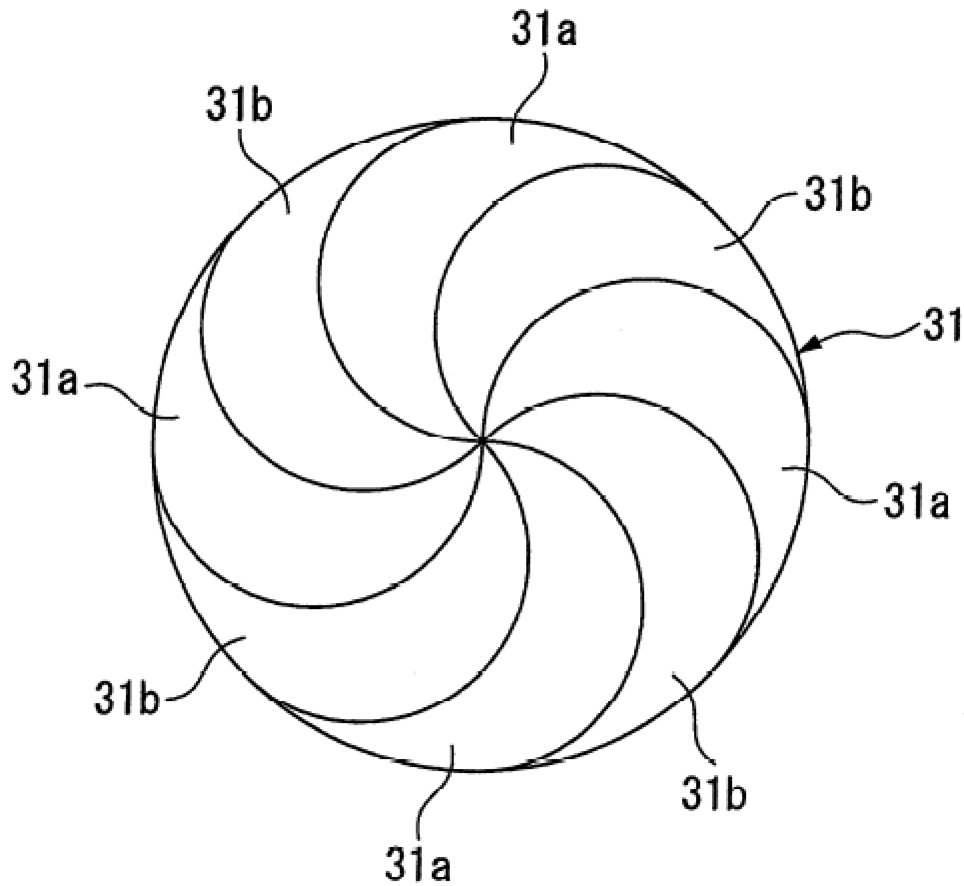
- **A hard polishing generally promotes local wafer planarization**
- **A soft polishing pad will reduce the scratches**
- **Higher down force and rotational speed will increase the removal rates, at the expense of uniformity and scratches**
- **In many cases, the best planarity : a hard polishing pad and low pressure**
- **Selectivity: one for simultaneous polishing of multiple materials; but high for metal/ILD to minimize erosion**
- **To reduce polishing time, it needs to minimizing the overburden thickness. For example, ILD polish on metal.**





由硬度90之發泡胺甲酸乙酯製成習用硬拋光墊來進行晶圓表面拋光時，如第2A圖中曲線A所示，具有大波長的部份可在短時間內移除(亦即收斂常數較大)，而具有短波長的部份的收斂常數就較小。再者，其發現，在使用由硬度68之麂皮製成的習用軟拋光墊來進行晶圓表面拋光時，如第2A圖中曲線B所示，具有小波長的部份可以在短時間內移除(亦即收斂常數較大)，而具有大波長的部份的收斂常數就較小

習知的拋光製程中，其係使用一設有硬拋光墊的晶圓拋光裝置來進行第一拋光製程，以移除晶圓表面上的粗糙不均勻度，使該表面平坦，再使用一設有軟拋光墊的晶圓拋光裝置來進行第二拋光製程，以消除晶圓表面上的小凹坑，而將該晶圓表面加工成平直而無應變的表面

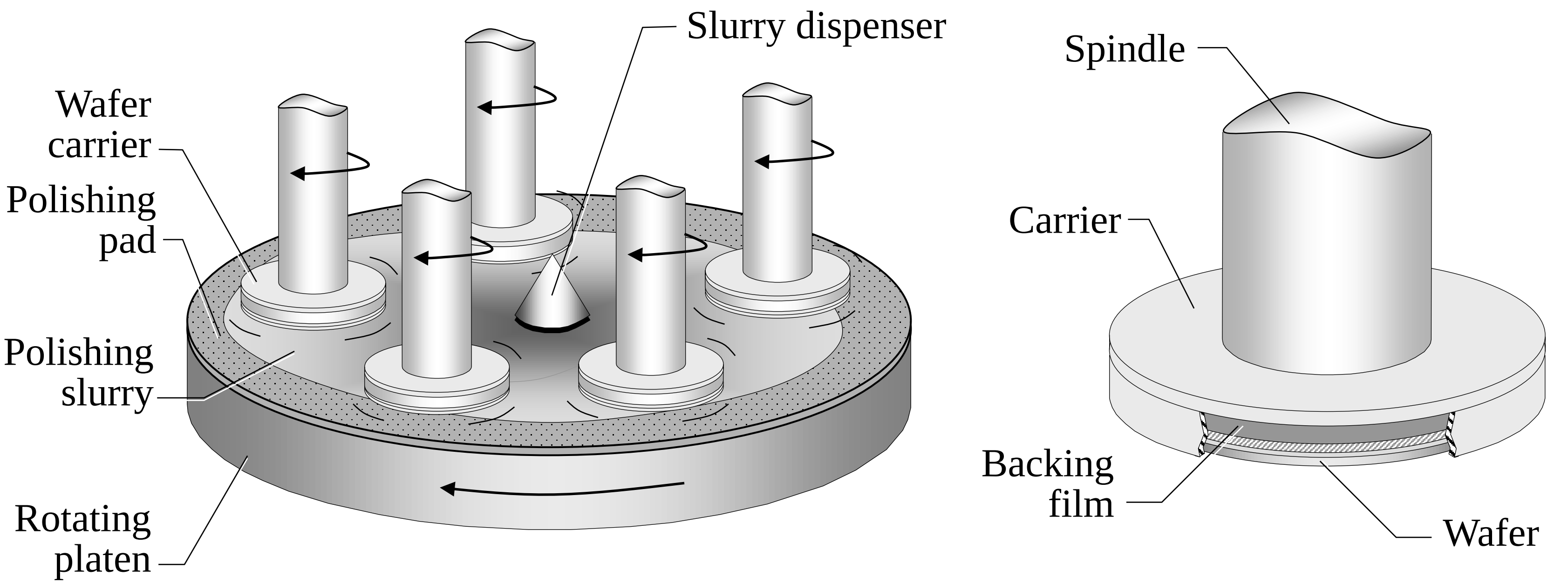


包括硬度不同之第一區域及第二區域等多個區域的拋光墊係被加以轉動，而一轉動中的矽晶圓則被壓貼並磨擦該拋光墊，以透過該拋光墊將晶圓表面上的粗糙不均勻度及小凹坑加以移除，因此不再需要如同習用般針對要移除粗糙不均勻度的情形或是要消除小凹坑的情形來更換晶圓拋光裝置及拋光墊，且可以減少拋光晶圓所需的設備及拋光材料，因之可以簡化拋光製程及縮短晶圓的拋光週期，因此之故可以更有效率地拋光晶圓

CMP Parameters

Parameter	Planarization Results on Wafer
Polish time	• Amount of material removed • Planarity
Pressure on wafer carrier (downforce)	• Removal rate • Planarization and non-uniformity
Platen speed	• Removal rate • Non-uniformity
Carrier speed	• Non-uniformity
Slurry chemistry	• Material selectivity • Removal rate
Slurry flow rate	• Affects how much slurry is on the pad and the lubrication properties of the system
Pad conditioning	• Removal rate • Non-uniformity • Stability of CMP process
Wafer/slurry temperature	• Removal rate
Wafer back pressure	• Center slowness/non-uniformity • Wafer breakage

CMP Tool with Multiple Wafer Carriers



- Most difficult: endpoint detection which is the ability of the CMP tool to detect when the planarization process has polished the materials to the correct thickness

CMP Tool

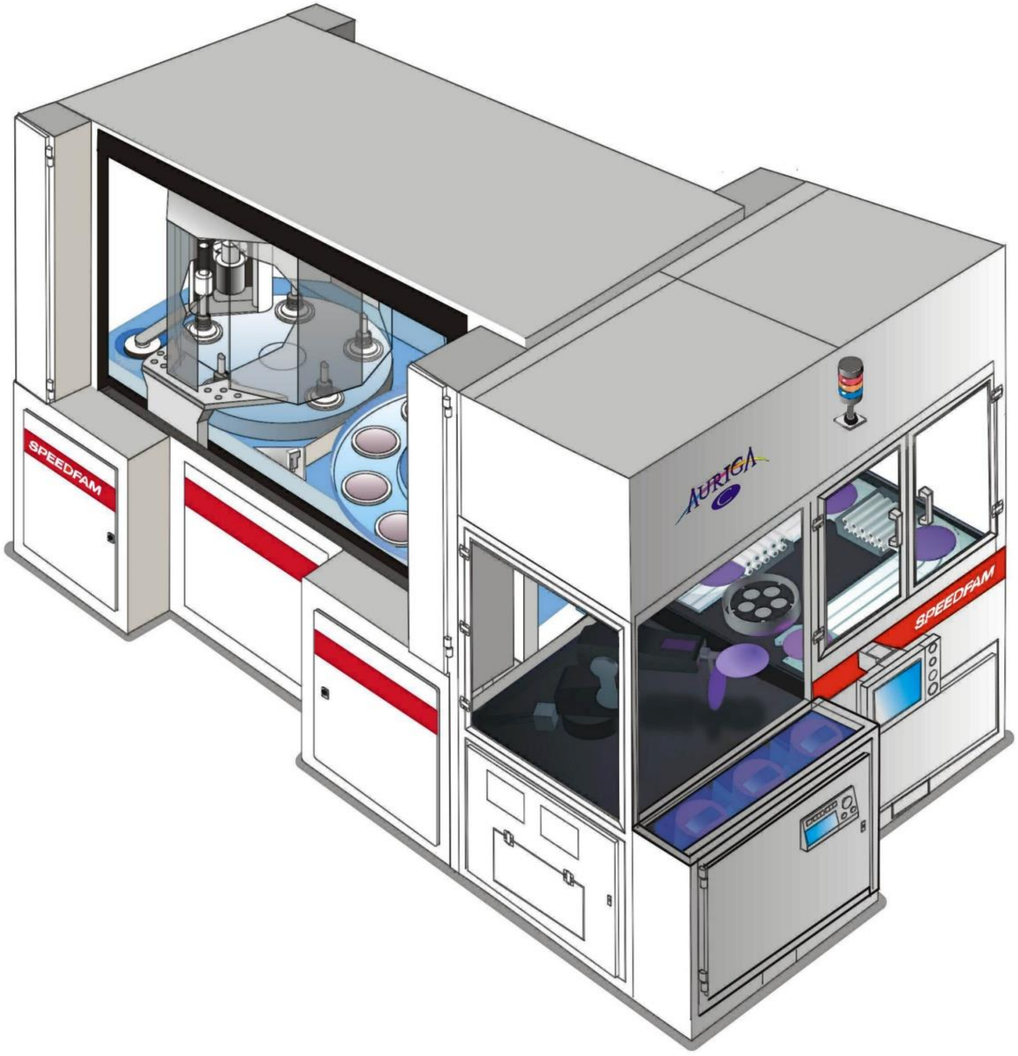
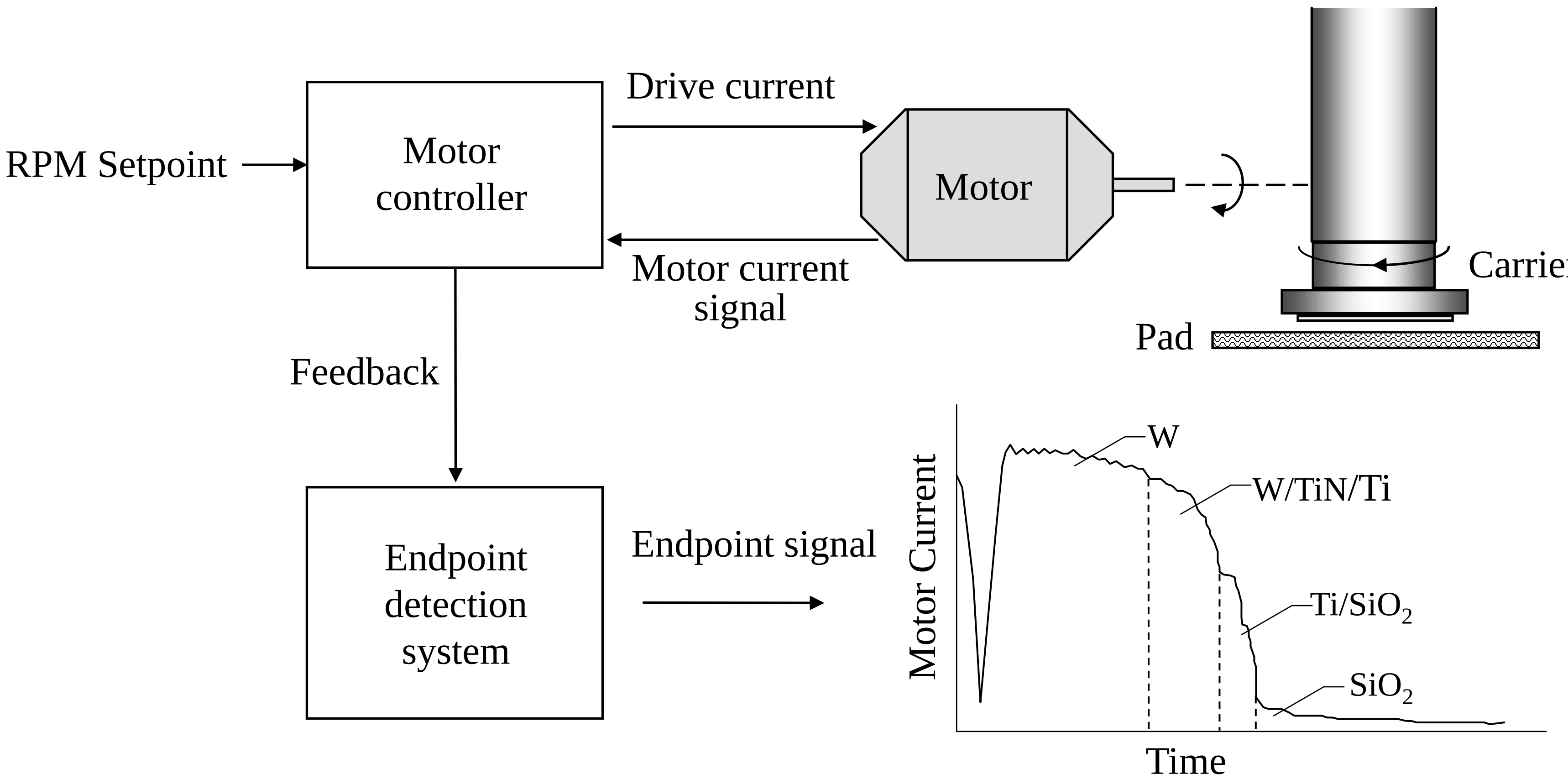


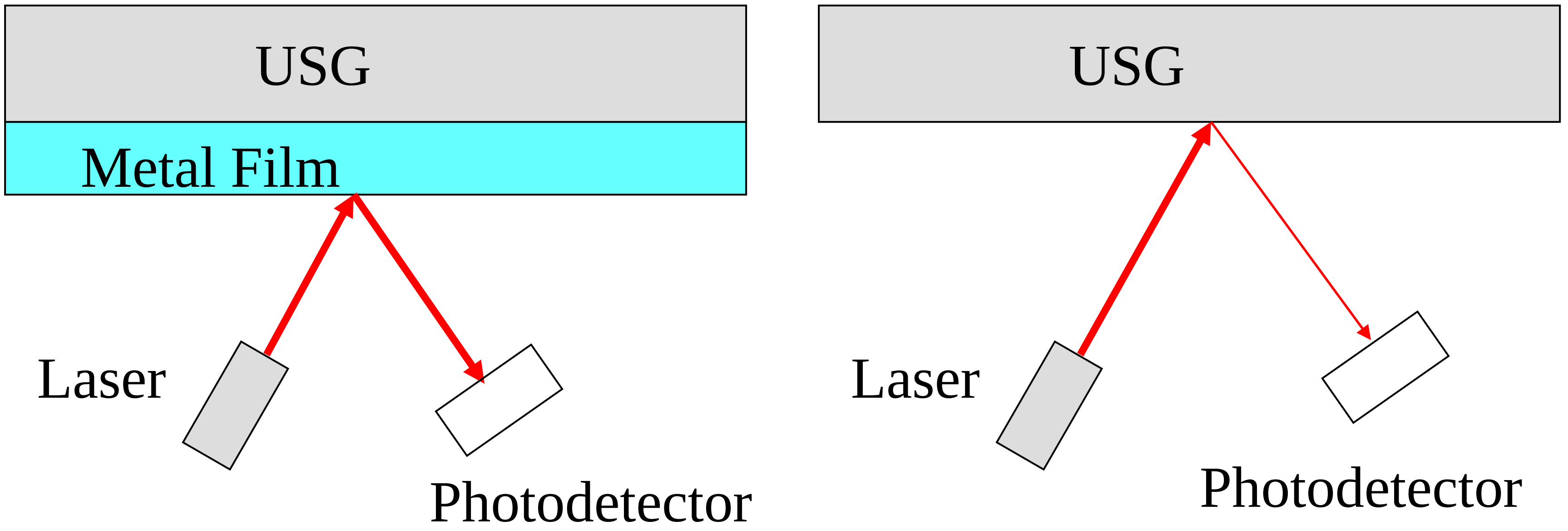
Photo courtesy of Speedfam-IPEC

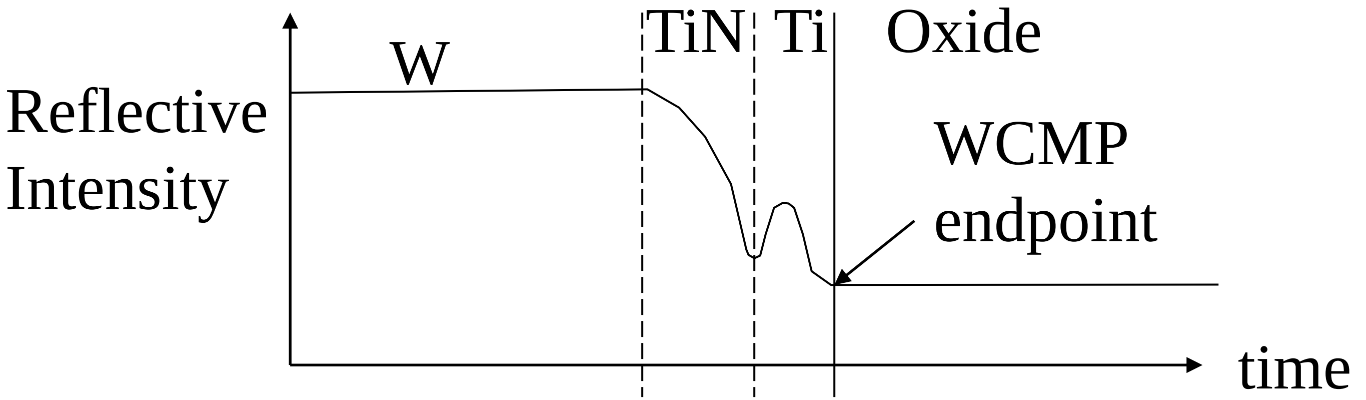
Motor Current Endpoint Detection



- Wafer carrier rotates at a constant speed, so the drive current is sensitive to changes at the wafer surface due to friction or surface roughness
- This is not the case for CMP ILD, a predetermined oxide thickness needs to leave

- Endpoint of Metal CMP

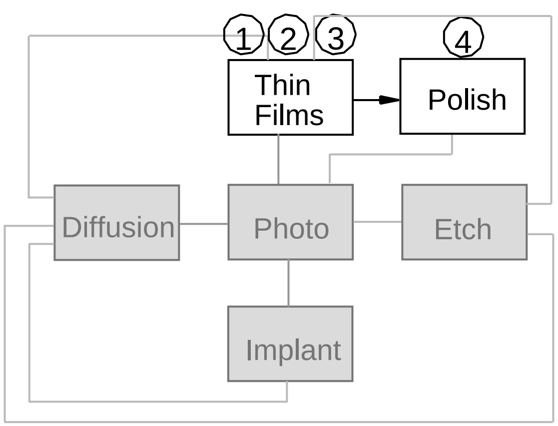




LI Metal Formation

Ti/TiN is used: Ti for adhesion and TiN for diffusion barrier

Tungsten (W) is preferred over Aluminum (Al) for LI metal due to its ability to fill holes without leaving voids



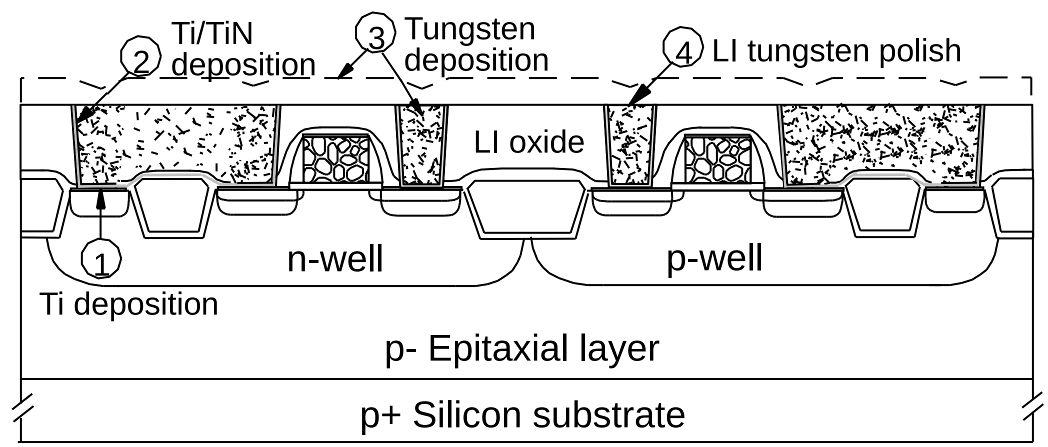
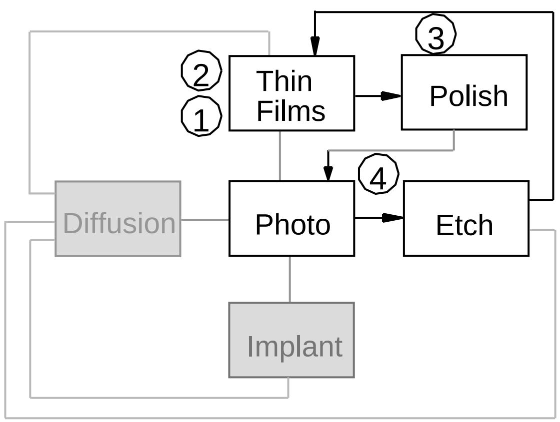


Figure 9.22

LI Oxide Dielectric Formation

1. **Nitride: protect active region**
2. **Doped oxide**
3. **Oxide polish**
4. **9th mask**



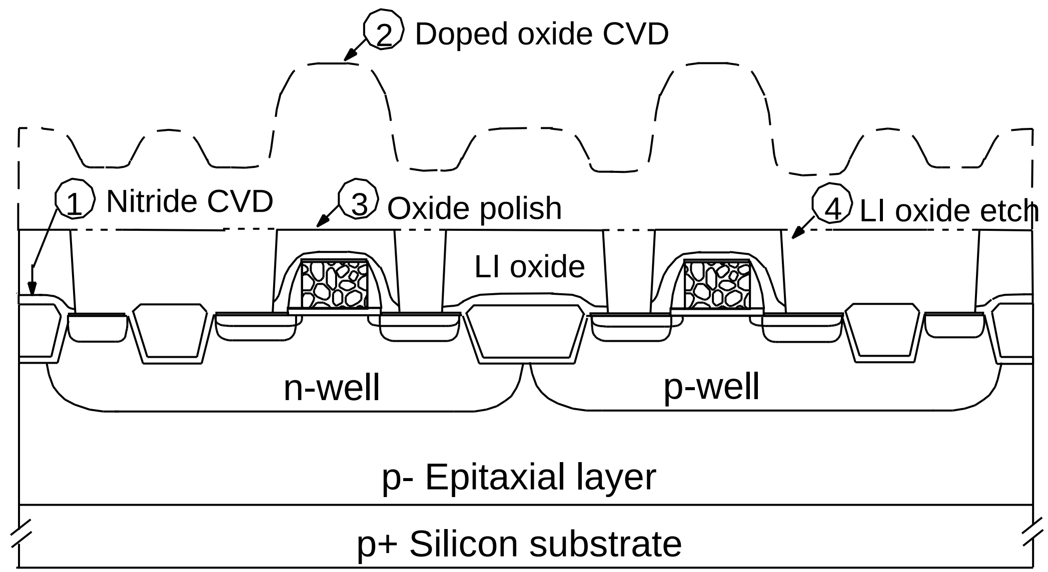
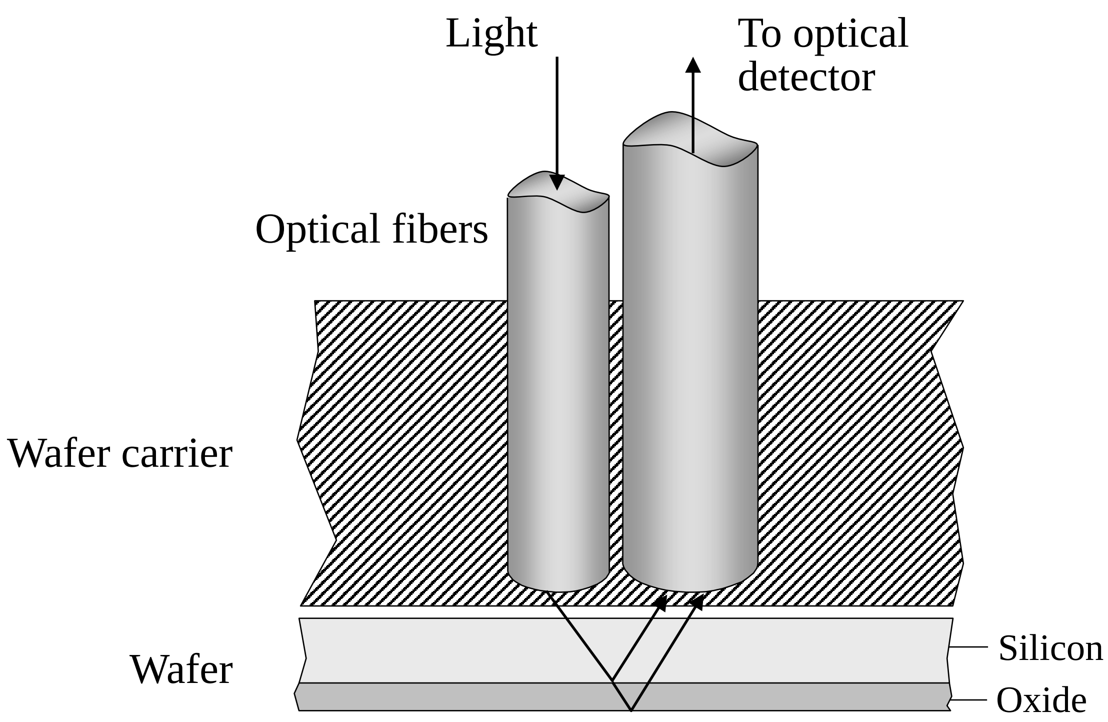


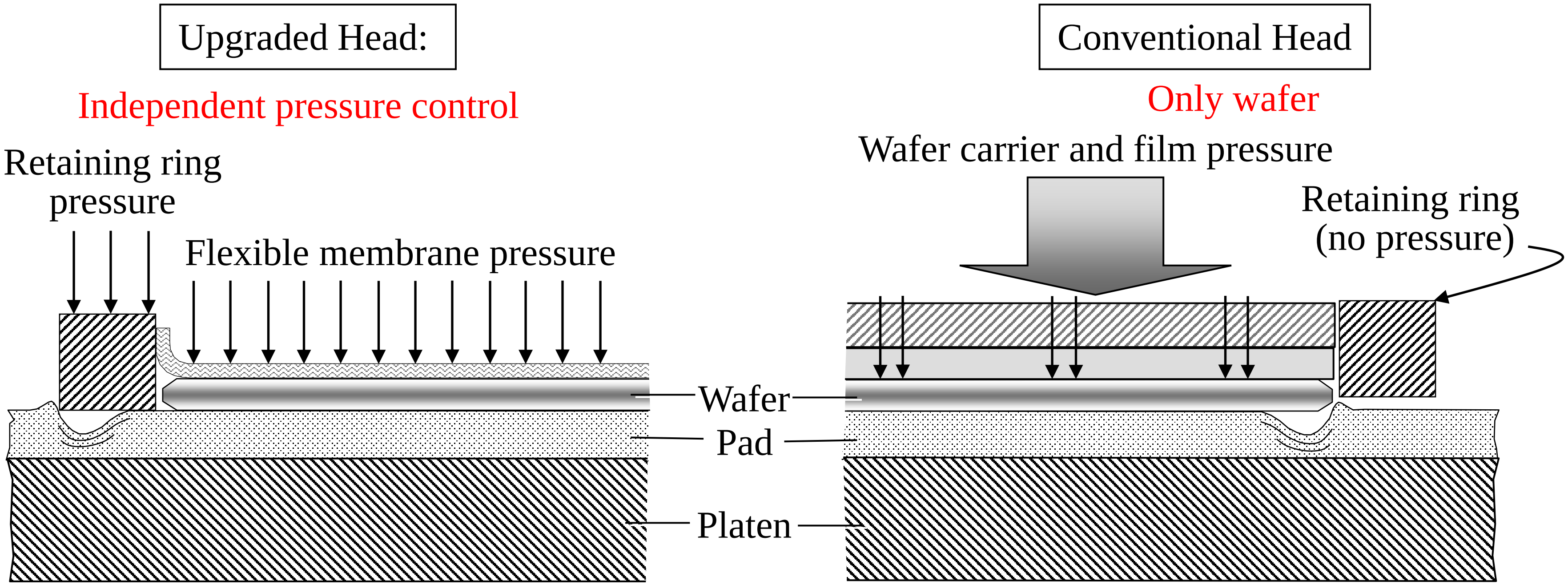
Figure 9.21

Optical Interferometry for Endpoint Detection



- Based on light reflectance
- For example, endpoint detection of STI, oxide over nitride is within ±100 Å

CMP Head Carrier Design and Wafer Edge Nonuniformity

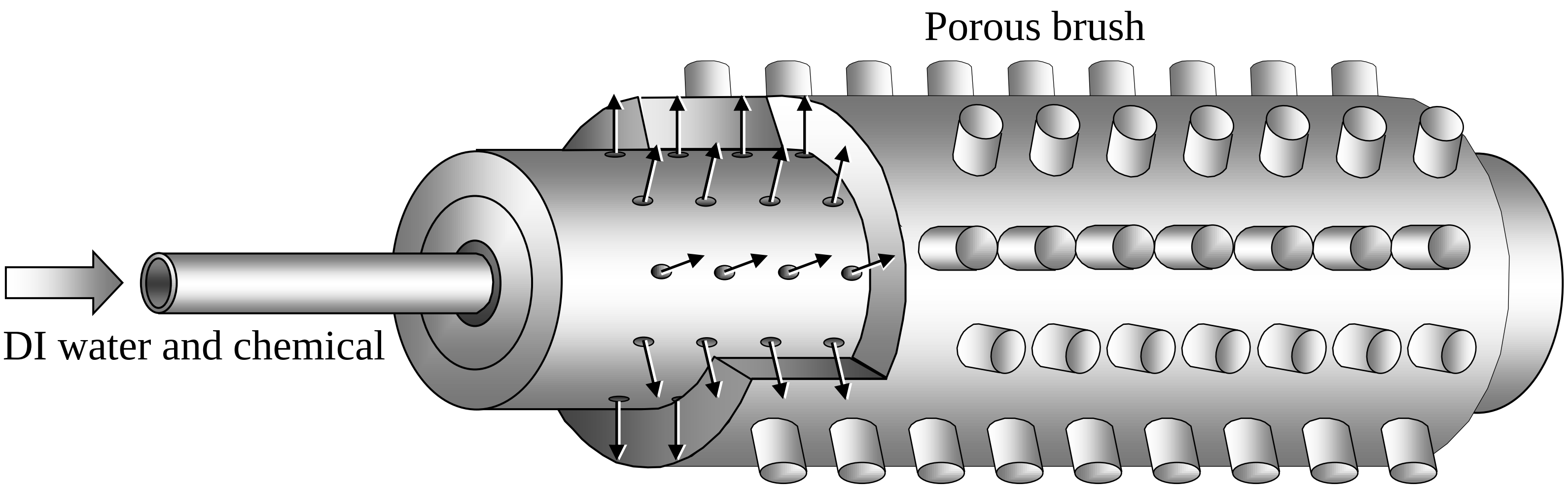


Edge exclusion: 3 mm for high density ICs

Evolution of Post-CMP Cleaning

	Wet bench with megasonics	Doublesided scrubber + DI water	DSS + NH_4OH	DSS + NH_4OH and HF	DSS + Additional Chemistries
Oxide CMP	√	√	√	√	
Tungsten CMP			√	√	
Copper CMP					√

Through-the-Brush Chemical Delivery for Post-CMP Cleaning



Redrawn from D. Hynes, et al, "Brush Scrubbing Emerges as Future Wafer-Cleaning Technology, *Solid State Technology*, (July 1997): p. 210.

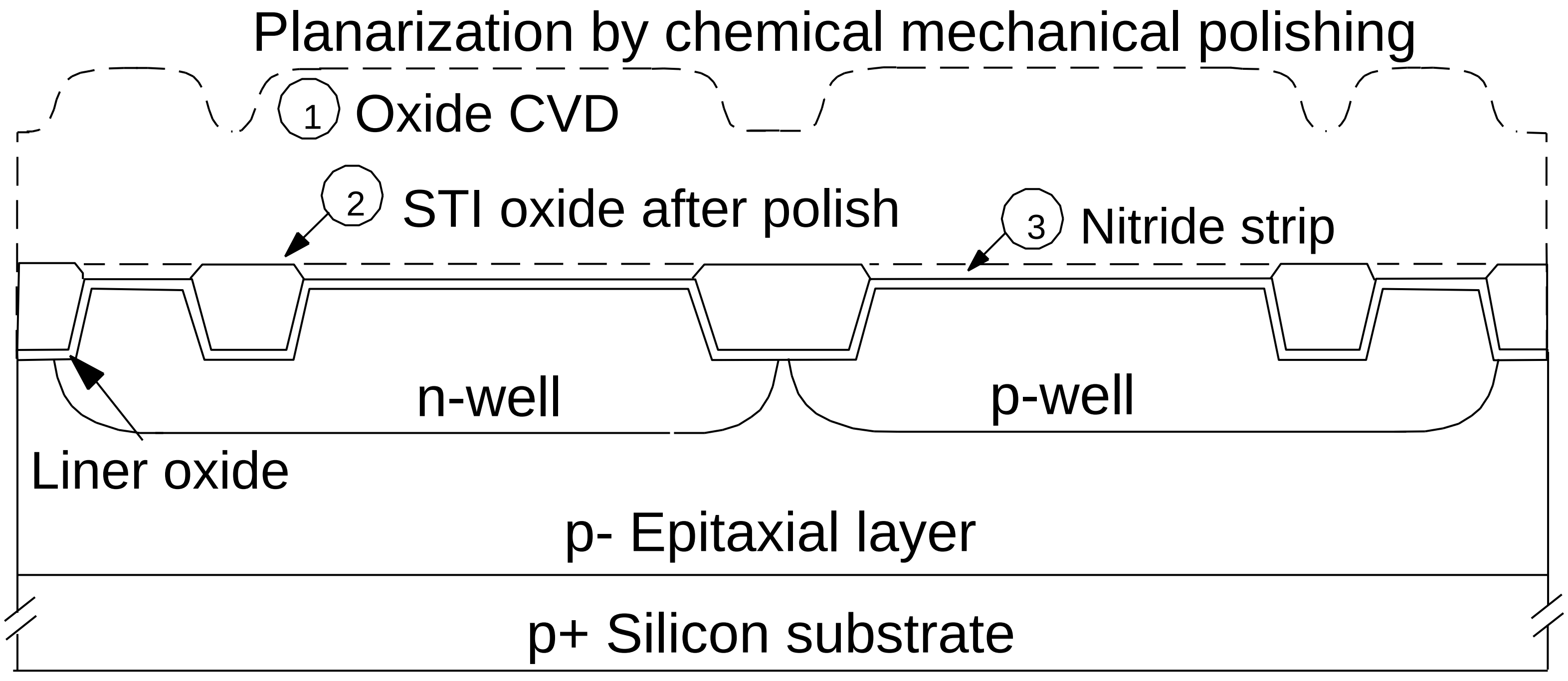
Examples of Some Commercial CMP Equipment Systems

Supplier / Model	Type of Motion	No. of Platens/Dia. (in.)	# of Wafer Carriers (or heads)	Dry-In/ Dry-Out	Endpoint Detection
Applied Materials Mirra 3400	Rotary	3 / 20"	4	Yes	Yes
Ebara EPO-222	Rotary	2 / 23.6"	1	Yes	Yes
Speedfam-IPEC Avanti 472 Avanti 672 IPEC 676/776 Auriga-C	Orbital Orbital Orbital Rotary	2 / 22.5" 3 or 6 / 32" 4 / 16"	1 3 or 6 4	Yes Yes Yes	Yes Yes Yes
Lam Teres	Linear	2 belts	4	Yes	Yes
SpeedFam Auriga	Orbital	2 / 32"	5	Yes	Yes
Strasbaugh Symphony	Rotary	3 / 32"	4	Yes	Yes

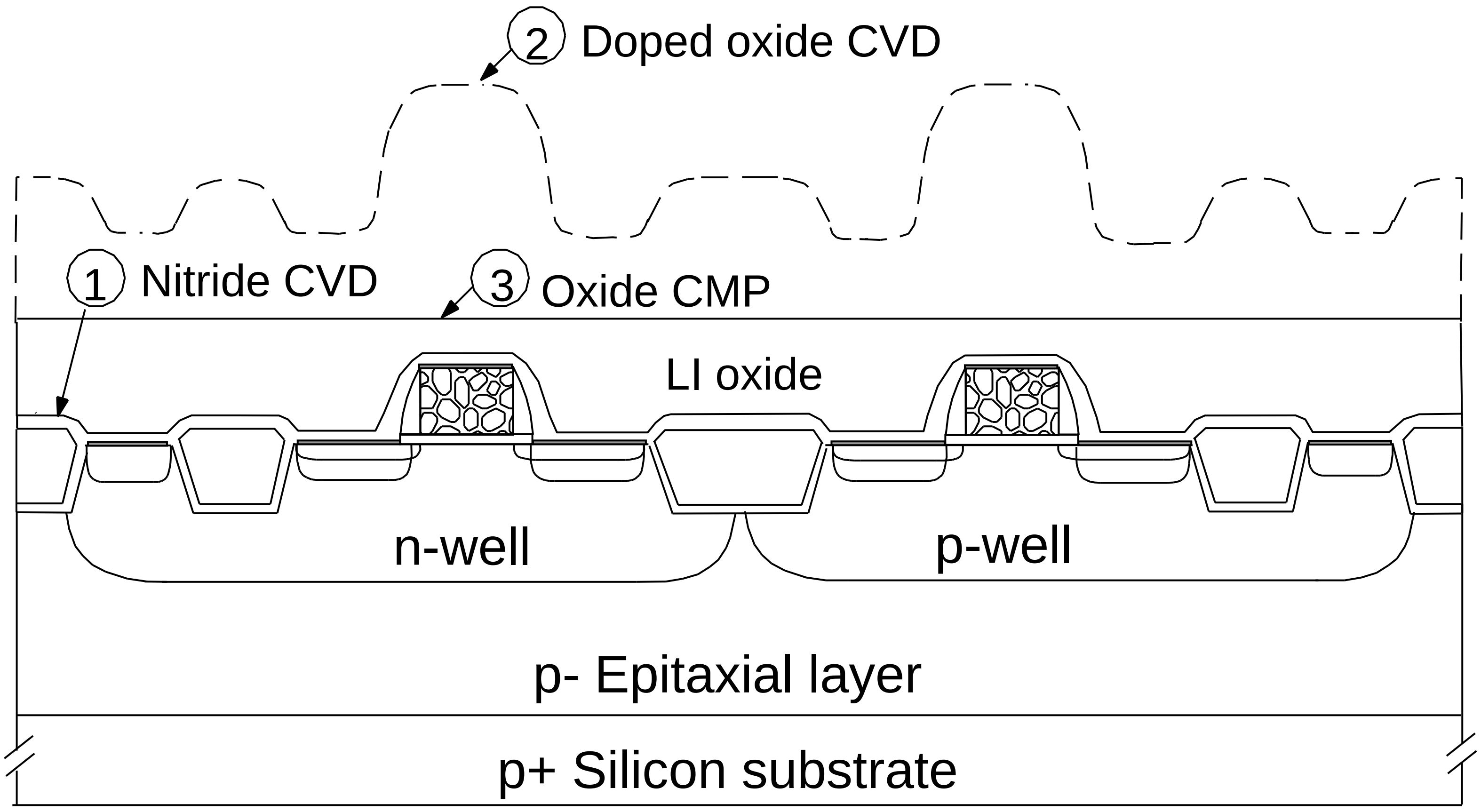
CMP Applications

- STI oxide polish
- ILD-1 oxide polish
- LI tungsten polish
- ILD oxide polish
- Tungsten plug polish
- Dual Damascene copper polish

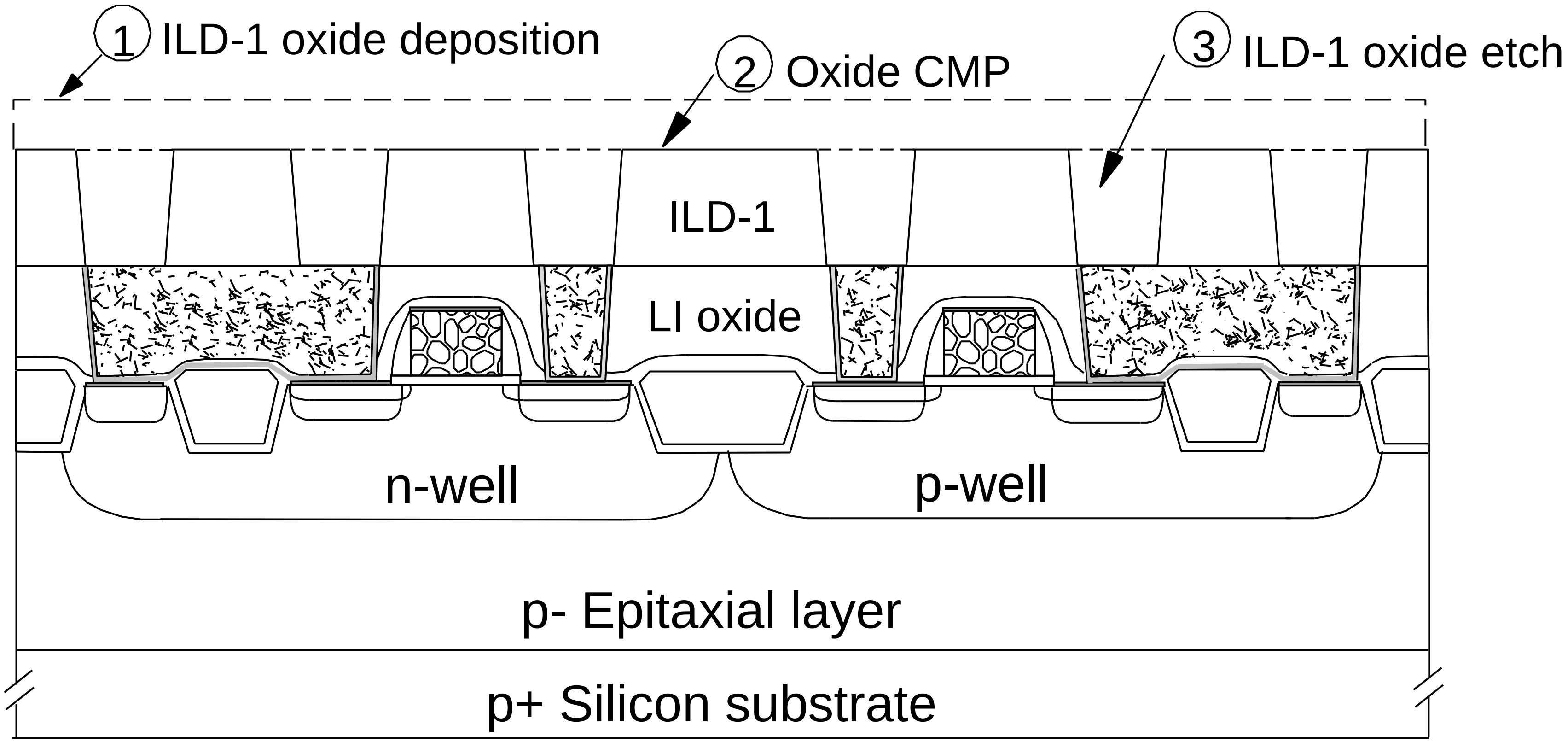
CMP for Oxide Fill of STI



LI Oxide before and after CMP Planarization

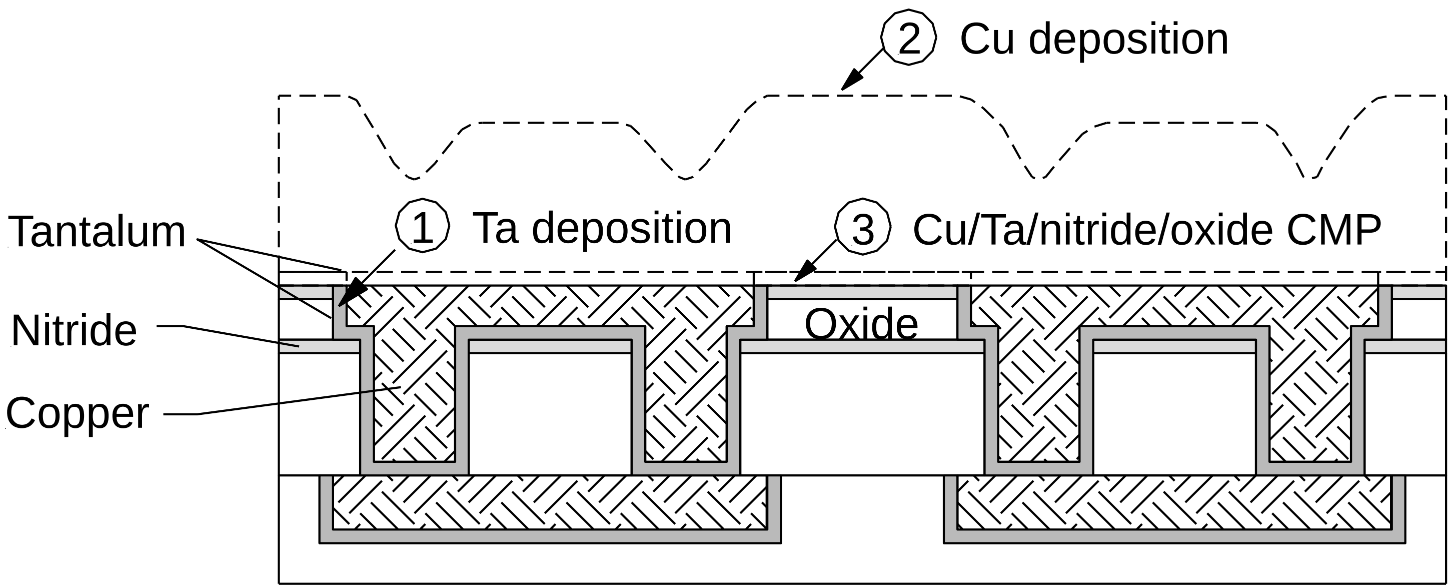


ILD Oxide Polish

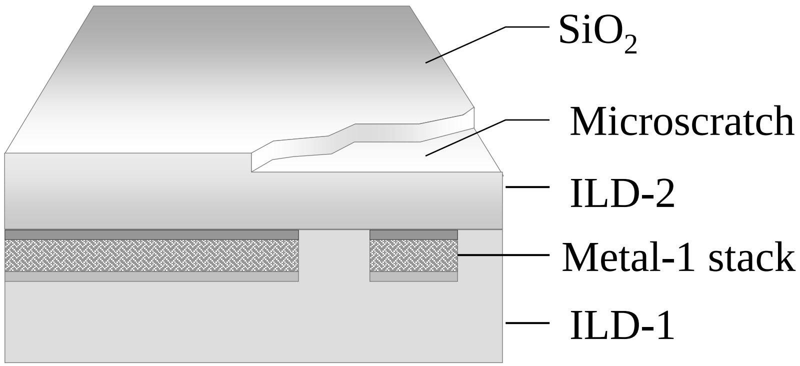


CMP for Dual Damascene Copper Metallurgy

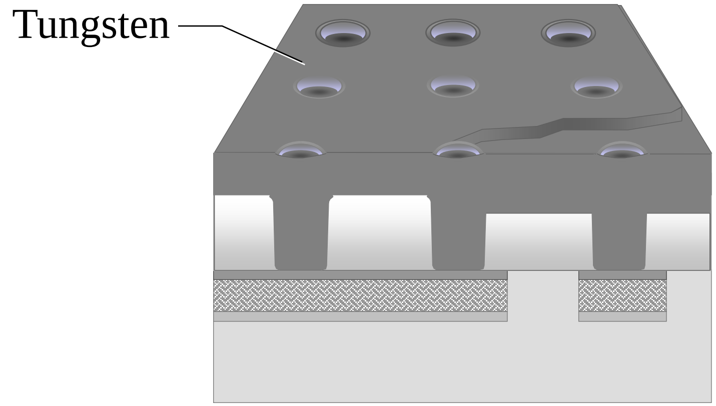
- Via and trench patterns are first formed in the ILD material by lithography and dry etching
- A barrier metal (~ 75Å), followed by a thin copper seed layer (~ 500Å)
- The selectivity of Cu and Ta affects how well planarity quality
- A two-step process, one for Cu and another for Ta



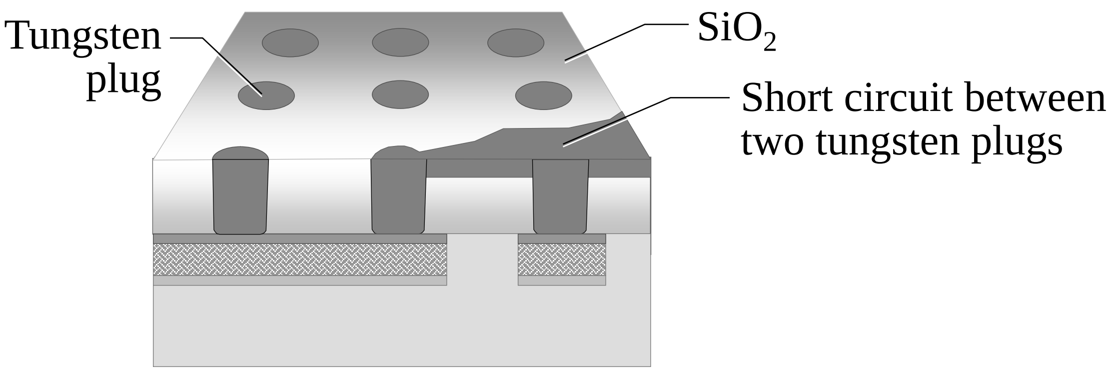
Results of CMP Micro-Scratch



1) SiO_2 deposition followed by CMP



2) Via etch followed by tungsten via fill



3) Tungsten CMP