

## 3.8 Chemical Mechanical Planarization (CMP)

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Sources: – R&D results @ TU Chemnitz/ZfM and Fraunhofer ENAS (e.g. European Projects NanoCMOS and PULLNANO)  
 – chihiwu@cc.ee.ntu.edu.tw  
 – S. Beaudoin, D. Boning, S. Raghavan  
 NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

### 3.8.1 Introduction

#### What is CMP

- CMP is mechanically enhanced chemical etching or chemically enhanced mechanical grinding
- CMP is able to planarize surfaces by removal of material such that topography is eliminated or material is left at defined areas
- CMP provides local and global planarity
- CMP enables indirect patterning due to an adjustable polish selectivity between different materials

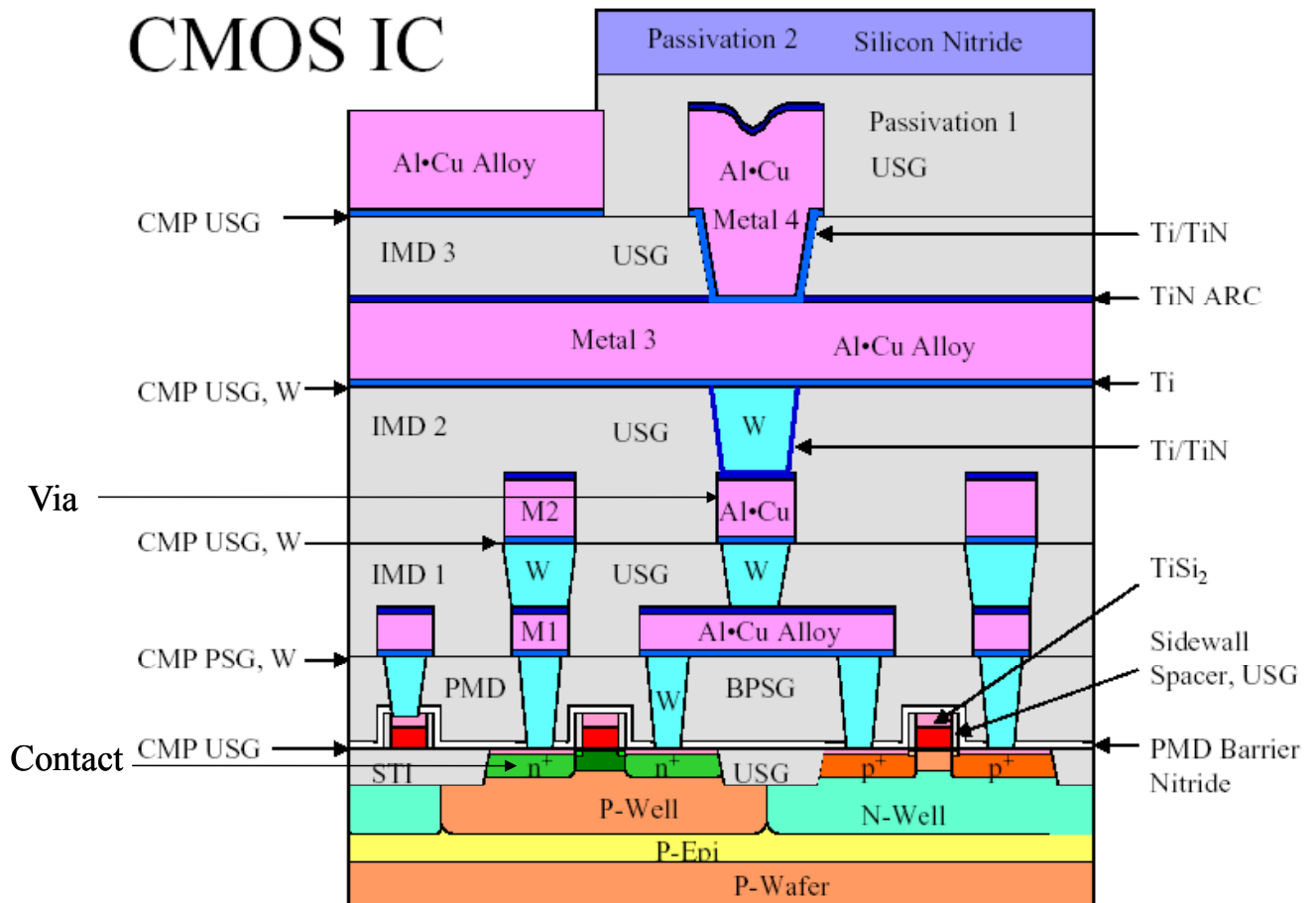
#### Necessity of CMP

- Photolithography resolution  $R = k_1 \lambda / NA$
- To improve resolution,  $NA \uparrow$  or  $\lambda \downarrow$
- $DOF = \pm k_2 \lambda / (NA)^2$ , both approaches to improve resolution reduce  $DOF$
- Planarization is inevitable for lithography for the 0.25  $\mu\text{m}$  node and below

#### Applications of CMP

- STI formation
- Tungsten plug formation
- Deep trench capacitor
- Cu dual damascene
- ...

# CMOS IC



source: chihwu@cc.ee.ntu.edu.tw

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## CMP in IC manufacturing



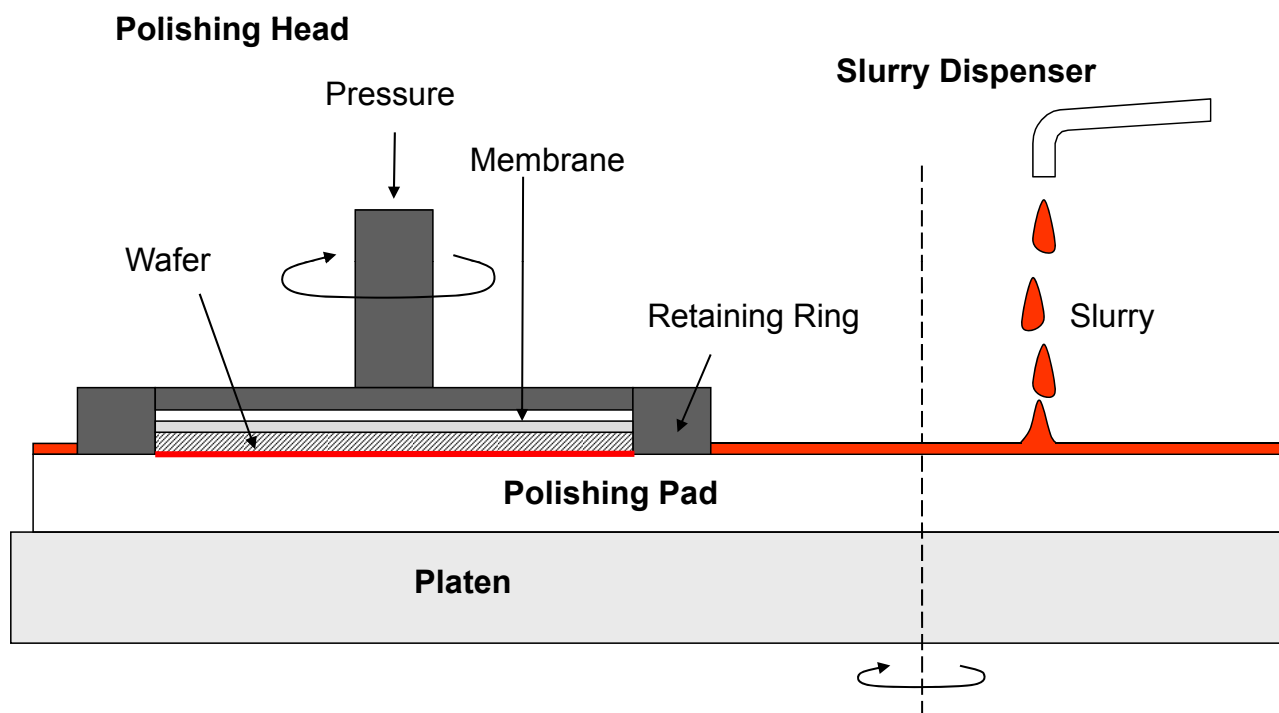
Source: Infineon Technologies

## Cross section of trench type DRAM

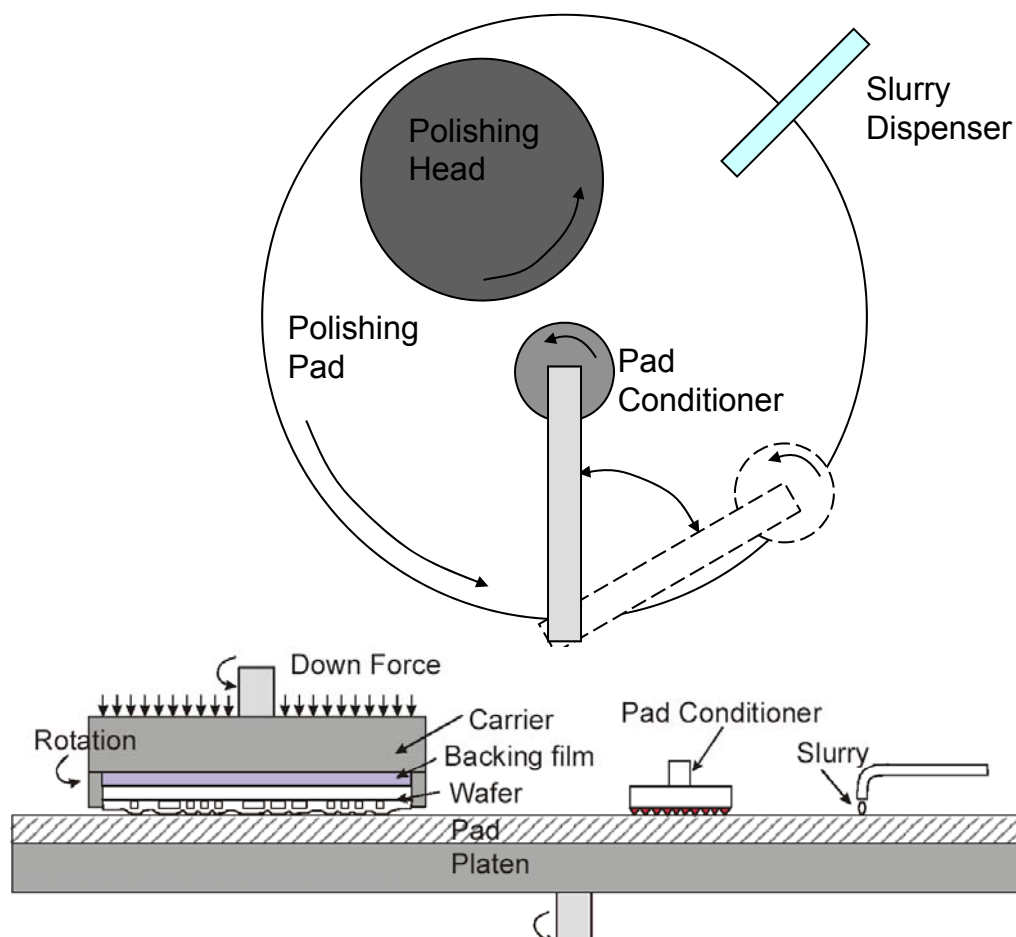
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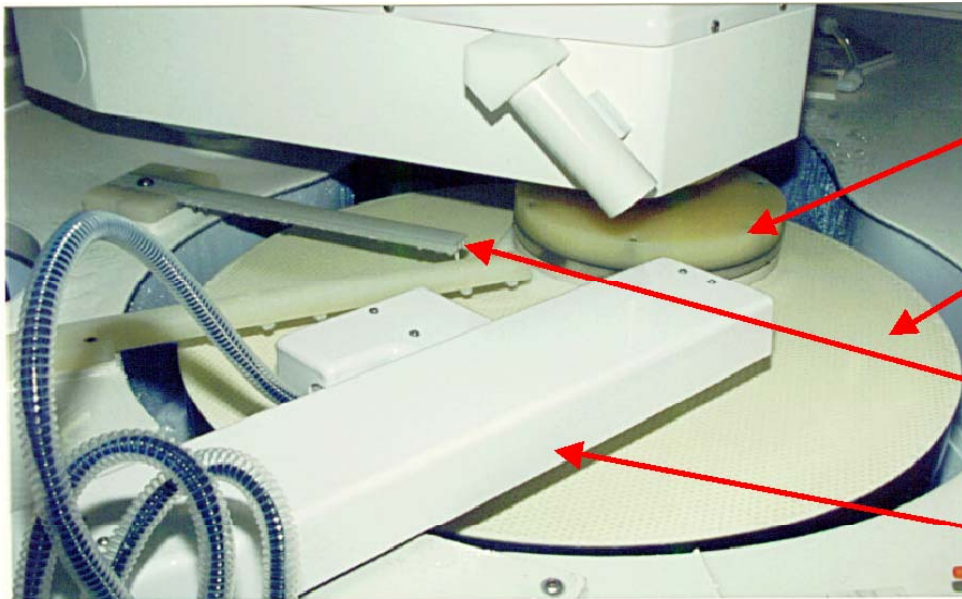
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### 3.8.2 Equipment configuration



### Polishing Pad and Pad Conditioner





carrier

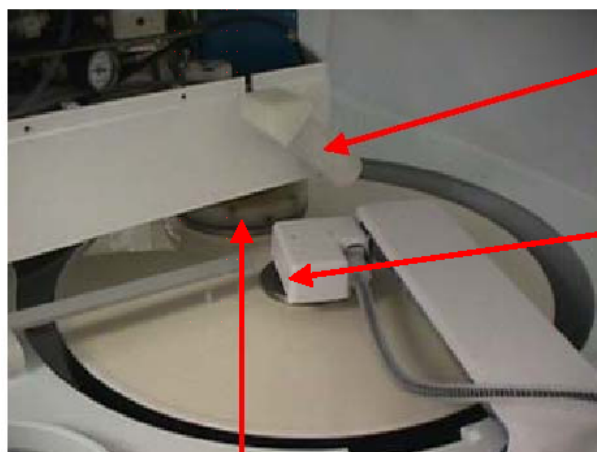
table

slurry dispense

conditioner

source: SpeedFam-Ipec

**Single head two table (2nd table not visible) machine Ipec 472**



IR probe

(Platen temperature  
measurement for process  
control or evtl. for end  
point detection)

Conditioning disk

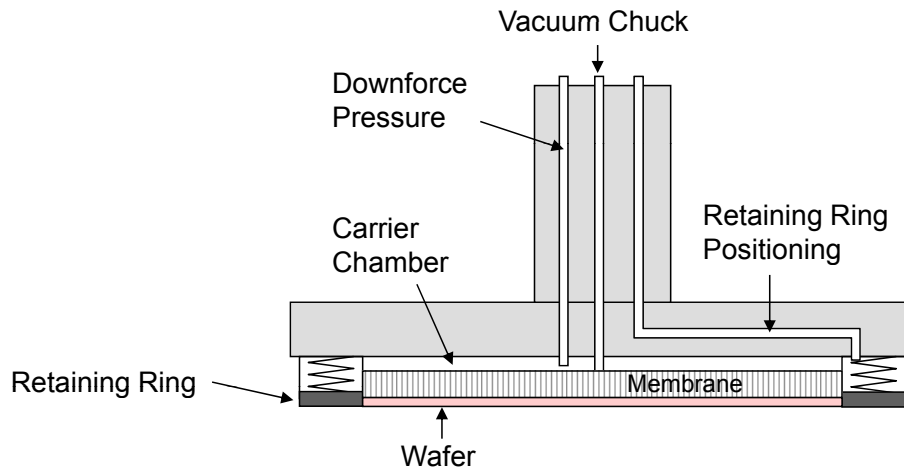
Slurry dispense

Polish head (holds wafer)



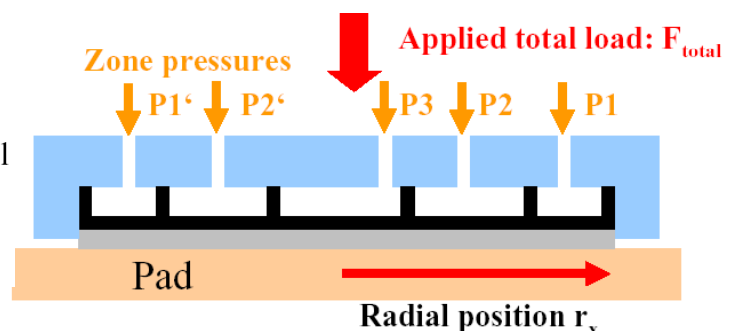
Source: SpeedFam (Anlage IPEC 472)

## Schematic of Polishing Head



## Uniformity Control

Wafer carrier with pressure zone control  
for example: SFI Momentum,  
Ebara F-Rex200 or  
Applied Materials Mirra



## 3.8.3 Consumables

### 3.8.3.1 Slurries

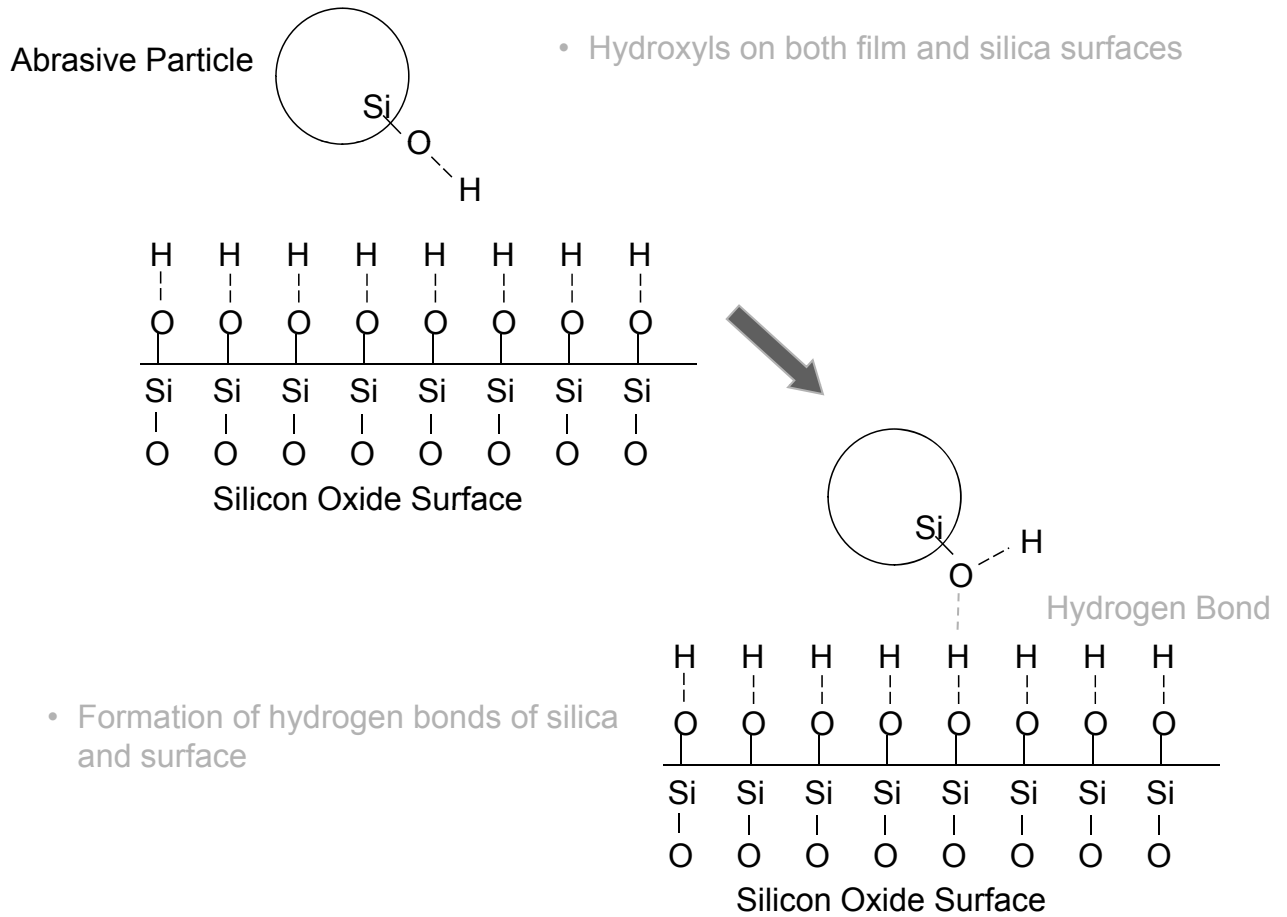
- Chemicals in the slurry react with surface materials, form chemical compounds that can be removed by abrasive particles
- Particles in slurry mechanically abrade the wafer surface and remove materials
- Oxide slurry: alkaline solution with silica
- Metal slurry: acidic solution with alumina
- Additives control the pH value of slurries
  - oxide, pH at 10 to 12
  - metal, pH at 6 to 2

### **Slurries for oxide ( $\text{SiO}_2$ ) polishing**

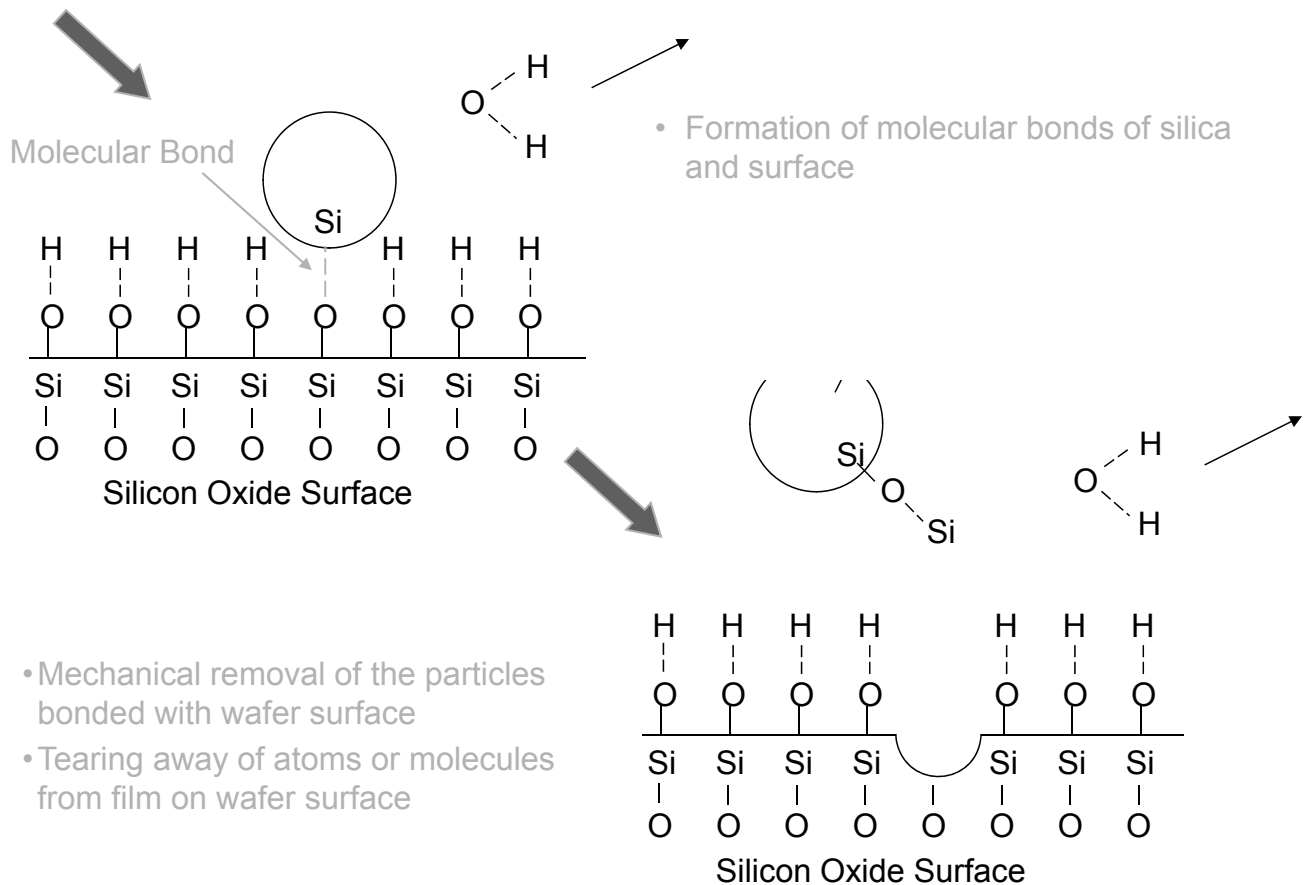
- suspension of colloidal/fumed silica particles in alkaline medium
- hydroxyl ions attack  $\text{SiO}_2$ , causing softening and chemical dissolution
- particles range from 10 to 3000 nm, mean size 160 nm
- 12% (wt) particles, KOH or  $\text{NH}_4\text{OH}$  used to set pH ~11
- other concerns: particle size distribution (scratching), particle shape, particle agglomeration



## Removal mechanism for oxide ( $\text{SiO}_2$ ) polishing



## Removal mechanism for oxide ( $\text{SiO}_2$ ) polishing



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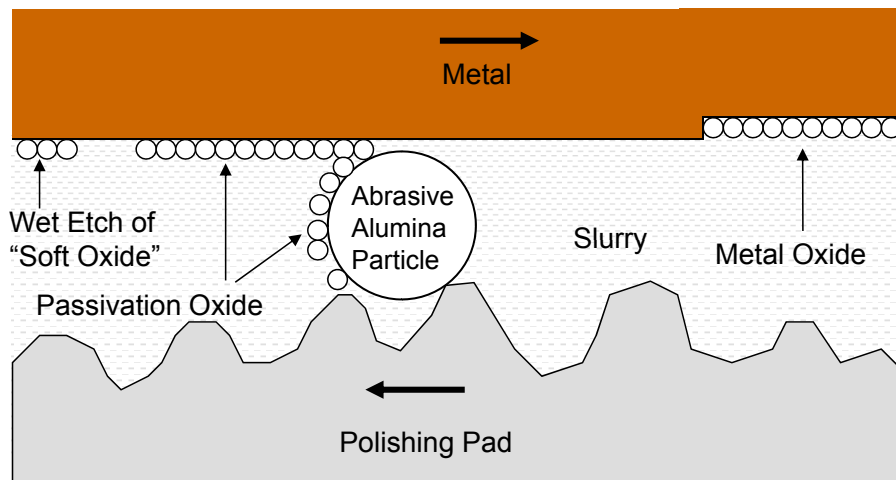
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## Slurries for metal (W, Al, Cu) polishing

- Metal CMP process is similar to the metal wet etch process
  - Oxidant cause metal dissolution and passivation (reactions to form protective layer on metal surface)
  - Metal oxide is removed by abrasive particles (typically alumina particles,  $\alpha$  or  $\gamma$ )
  - Repeated metal oxidation and oxide removal
- W polishing examples:
 

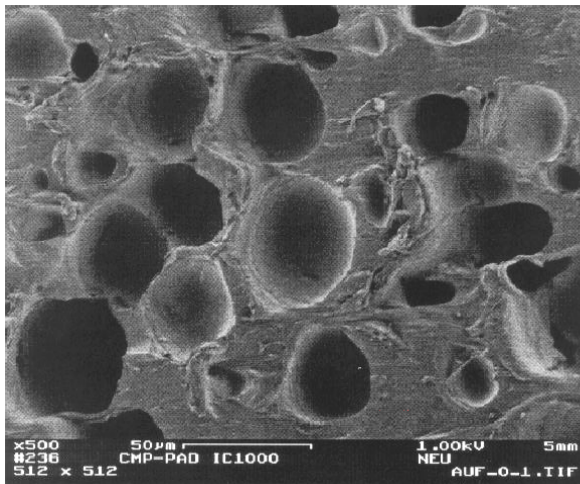
- alumina / peroxide:	1 part slurry, 1 part 50% $\text{H}_2\text{O}_2$ ,	pH 3.7 - 4.0
- alumina / ferric nitrate:	6% alumina solids, 5% $\text{Fe}(\text{NO}_3)_3$ ,	pH 1.5
- alumina / potassium iodate:	6% alumina solids, 2 - 8% $\text{KIO}_3$ ,	pH 4.0
- Al polishing: peroxide or iodate-based slurries
- Cu polishing:  $\text{H}_2\text{O}_2$  or ammonia-based solutions, passivating agents



### 3.8.3.2 Pads

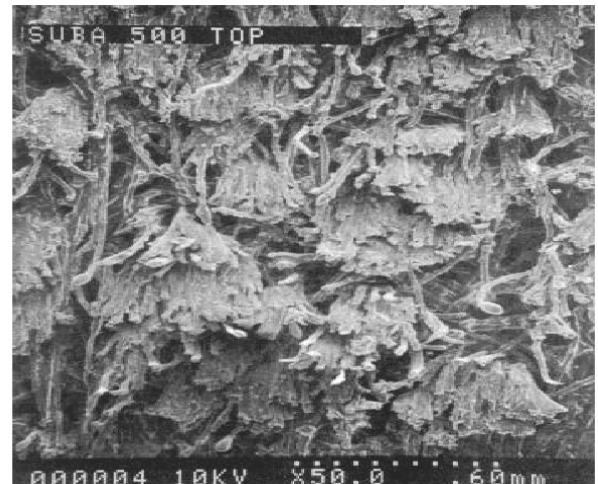
#### Structural classification

- Solid Polyurethane Sheet
  - Example: IC2000
- Polyurethane with voids
  - Isolated void; e.g., IC1000, FX 9
  - Interconnected void
- Polyurethane with abrasives
  - Fixed abrasive pad / table
- Felt impregnated with polyurethane
  - TWI: 817, 813, hard porous pads
  - Rodel: Suba series
  - Pad properties can be tailored for specific applications by adjusting porosity, ratio of polyurethane to fiber.
- Poromeric
  - TWI: BP-30
  - Rodel: Politex



source: Rodel

**„hard pad“ IC1000 by Rodel**  
**-> good planarization performance**



source: Rodel

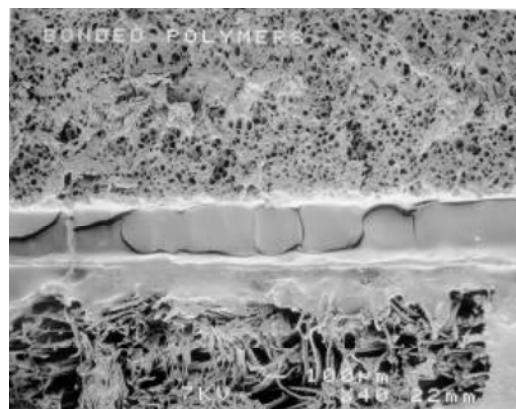
**„soft pad“ Suba series by Rodel**  
**-> low surface roughness but poor planarization performance**

- thickness ~ 1 - 3 mm
- hardness affects planarization and nonuniformity --> stacked pads
- surface treatment (conditioning) required to control polish rate and slurry transport  
 --> scraping pad surface with hard edge to remove debris and open pores
- pads wear out quickly (100-1000 wafers/pad!)
- use of perforated, grooved pads for improved slurry transport and uniformity

IC1000 layer  
 (thickness ~ 1.37 mm)

Bonding epoxy layer  
 (thickness ~ 300 µm)

SubaIV layer  
 (thickness ~ 1.24 mm)

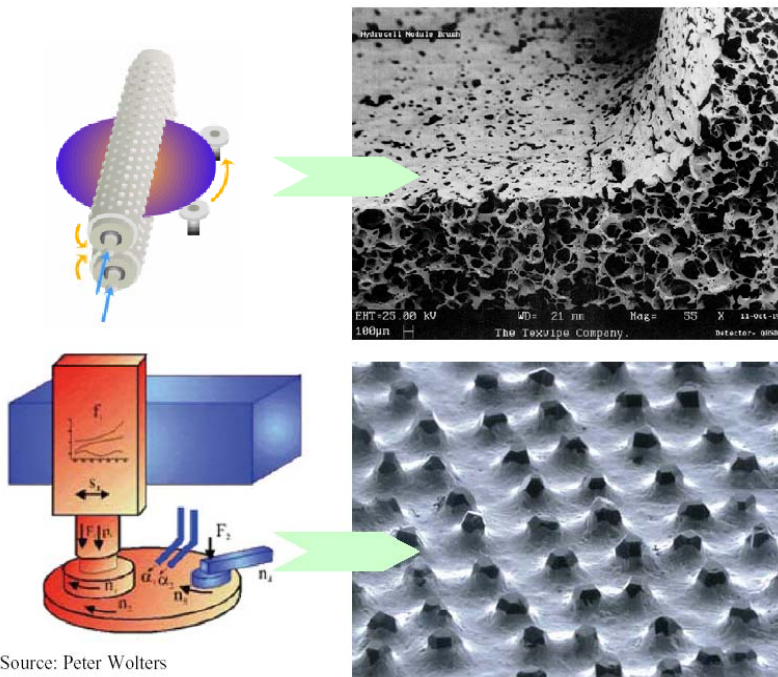


↑  
 Wafer

SEM cross section of a two pad  
 composite (IC1000/ SubaIV).



### 3.8.3.3 Brushes and Conditioner



Source: Peter Wolters

- PVA brush for post CMP cleaning
- water / chemistry supply and particle transportation
  - application of mechanical forces to particle

Source: Metron Technologies

- Diamond type of conditioner
- “pad grinding” between or while polishing
  - flattening and cleaning of pad

Source: Abrasive Technologies

PVA = Polyvinyl Alcohol

## 3.8.4 Process Issues

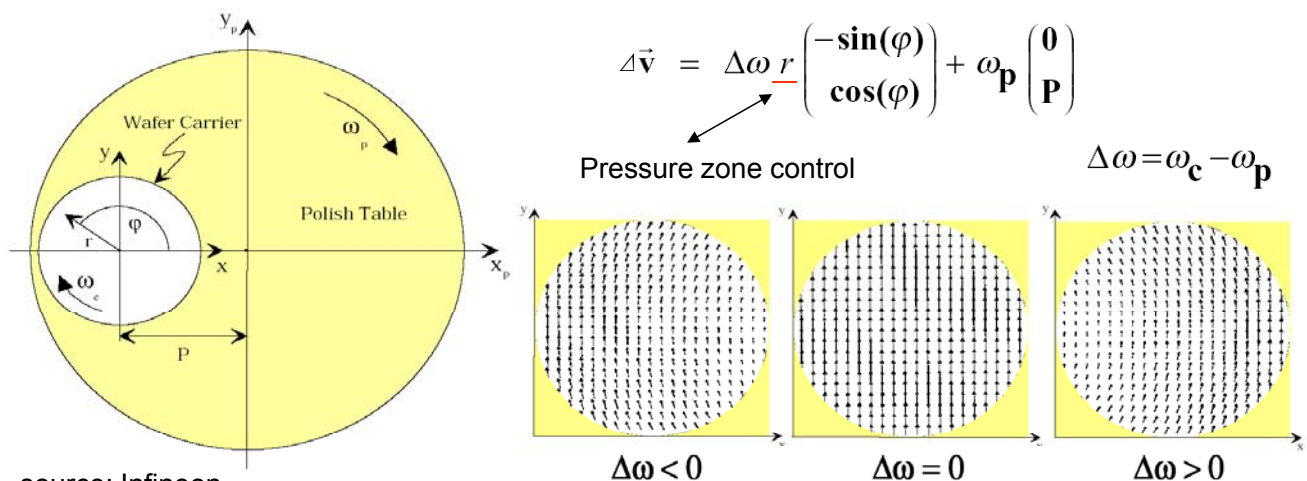
### 3.8.4.1 Removal rate

- Removal rate law was found by Preston 1927 for glass polishing
- The Preston equation

$$R = K_p \cdot p \cdot \Delta v$$

gives only very crude estimates for the blanket removal rate

- $p$  is the polishing pressure
- $\Delta v$  is relative velocity of wafer and pad
- $K_p$  is the Preston coefficient (closely related to the coefficient of friction, depends in reality both on  $p$  and  $\Delta v$ )



source: Infineon

### 3.8.4.2 Selectivity

- Ratio of removal rates of different materials
- Affect CMP defects, such as erosion or dishing
- The slurry chemistry is the primary factor that affects removal selectivity of CMP process
- STI oxide CMP require high oxide to nitride selectivity, from 100:1 to 300:1
- For metal CMP process, selectivity to oxide, nitride, and barriers is very important.
- Example for Cu CMP:

	EPOCH Cu bulk slurry	Rohm and Haas Cu clearing slurry	RR* [nm/min]	Rohm and Haas barrier slurry
Cu-RR* [nm/min]	500 ... 1000	500 ... 650	TiN	150 ... 200
Select. Cu : SiC	> 55	> 600	TaN	100 ... 150
Cu : SiN	> 110	> 60	Cu	40 ... 50
Cu : HM	> 1000	> 1000	SiC	3 ... 4
Cu : TaN	> 100	> 300	SiN	6 ... 8
Cu : TiN	> 14	> 10	MSQ-HM	22 ... 25
			SiO <sub>2</sub>	7 ... 8

\* depending on pattern factor, determined at 2 psi down force and 200 ml/min slurry flow

### 3.8.4.3 Dishing and Erosion

#### Main Kinds of Nonuniformity:

#### Dishing

- reduction in thickness of large features consisting of softer material towards the center of the features (More materials are removed from the center, cross-section view looks like a dish)
- Usually happens at a larger opening area
  - large metal pads
  - STI oxide in the trenches.
- caused by differences in polishing rates of different materials

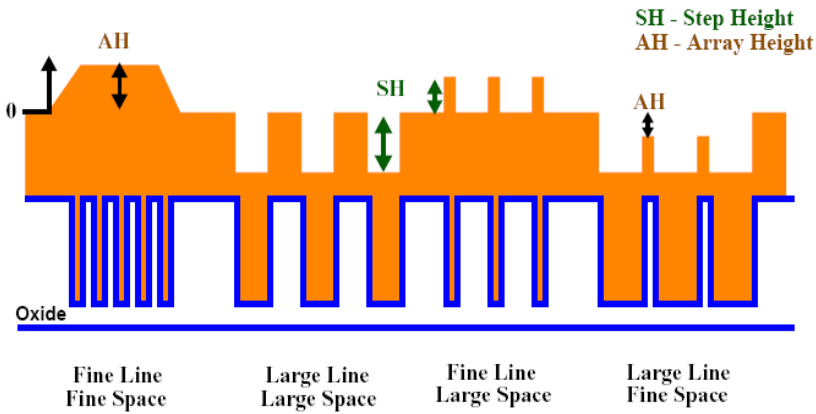
#### Pattern erosion

- thinning of oxide and metal in a patterned area
- increases with pattern density

#### Edge effect

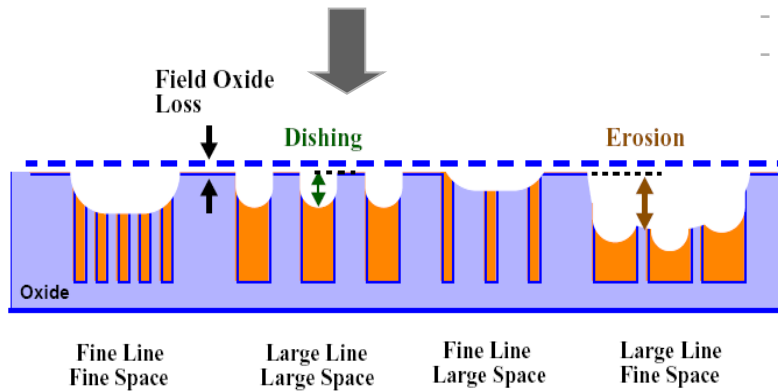
- variations in removal rate due to stress variations with radial distance across wafer (3 - 6 mm edge exclusion required)

## Issues with systematic Cu and oxide thickness variations in damascene process



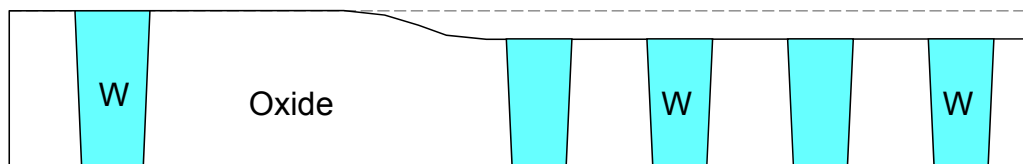
Post-ECP Topography (Park, MIT 2002)

Across-chip thickness variation  
- eats away depth of focus (DOF)  
- causes RC variations and inaccurate timing

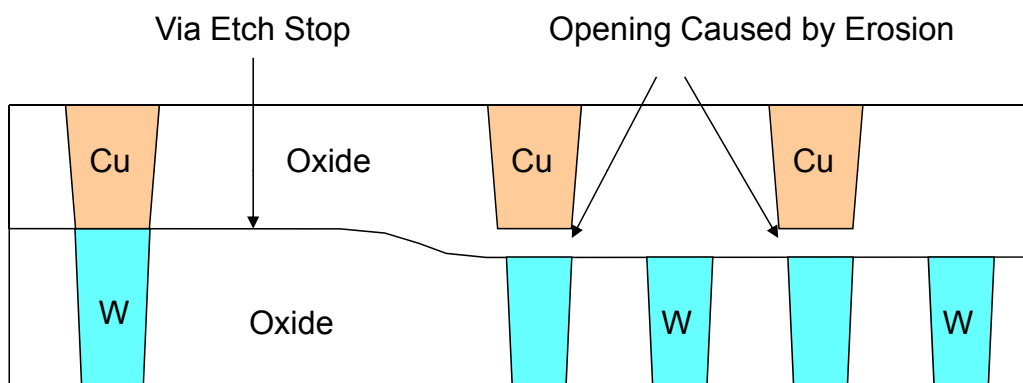


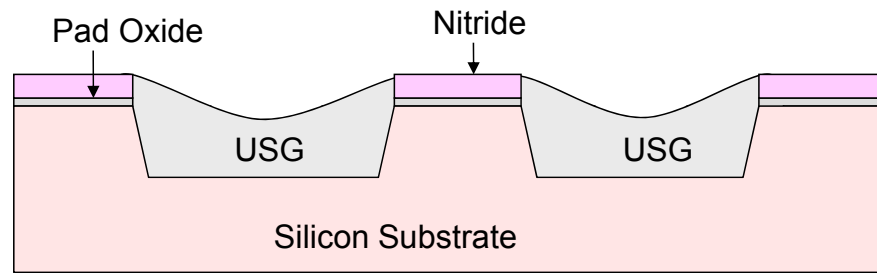
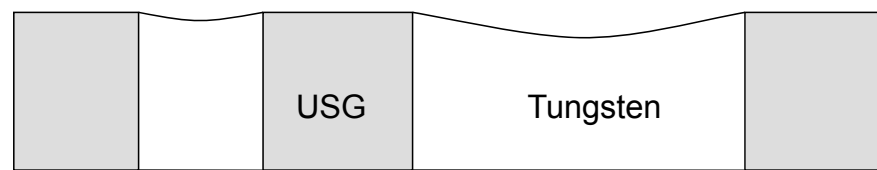
Post-CMP Topography (Park, MIT 2002)

## Erosion Caused by High Pattern Density

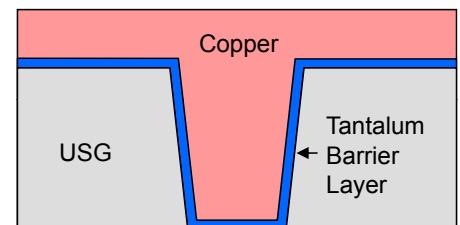


## Circuit Opening Caused by Erosion

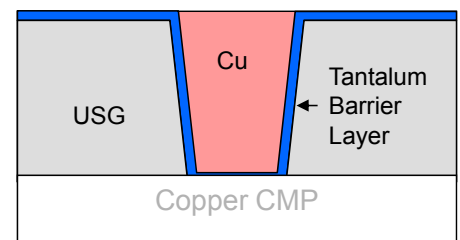


Dishing Effect of STI USGDishing Effect of W CMPDishing Effect of Cu CMP

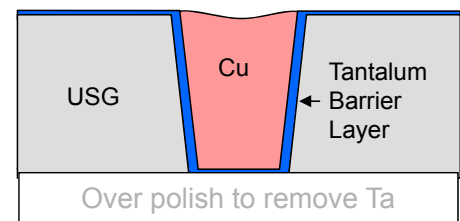
- Dual-damascene copper metallization requires that both bulk Cu and barrier Ta layer need to be removed by the CMP process.
- Cu slurry can't effectively remove Ta, the lengthy over polishing step for Ta removal can cause copper recess and dishing effects



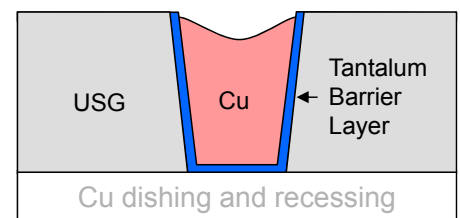
Copper deposition



Copper CMP



Over polish to remove Ta



Cu dishing and recessing

Dishing / Erosion and Selectivity

- Both dishing and erosion effects are related to the removal selectivity
- Metal CMP process:
  - If metal to oxide selectivity is too high, more metal removal, causes dishing and recessing
  - If the selectivity is not high enough, both oxide and metal will be polished, causes erosion

IC Layout and Erosion

- IC design layout can directly affect the erosion problems
- Designing opening area less than 30% of the chip surface can help to solve the erosion problem
- Erosion will be decreased by reducing the structure density variation across the chip. Homogenization of structure density is achieved by the inclusion of dummy structures.



zfm



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3.8.5 Polishing Copper and Porous Low-k Materials

- Development Trend: More widely use of copper and low-k dielectrics in future BEOL interconnection schemes. This requires
  - low-k dielectric CMP
  - copper and barrier layer CMP processes with high selectivity to low-k dielectric
- Low-k and ultra low-k dielectrics can be obtained using material with less polar bonds and / or an introduced porosity.
- The physical properties of such materials can be very different from that what is known from traditional dielectrics like silicon oxide or silicon nitride.
- Moreover, the variety of materials and integration concepts thwarts “standard” process solutions.
- Major challenges for CMP are the low mechanical strength and the partly low adhesion of low-k / ultra low-k materials.
- Common approach to handle low-k / ultra low-k integration schemes:
  - Low down force CMP
  - Protection of low-k / ultra low-k materials by cap layers
  - Use of optimized consumables



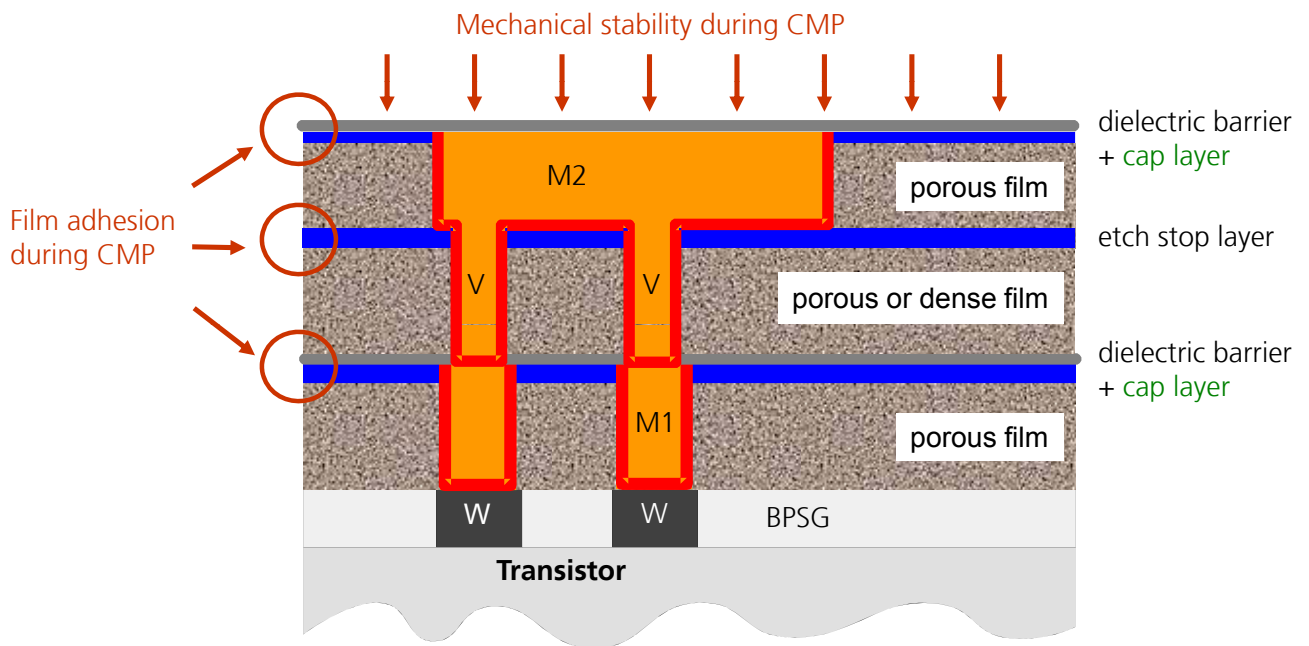
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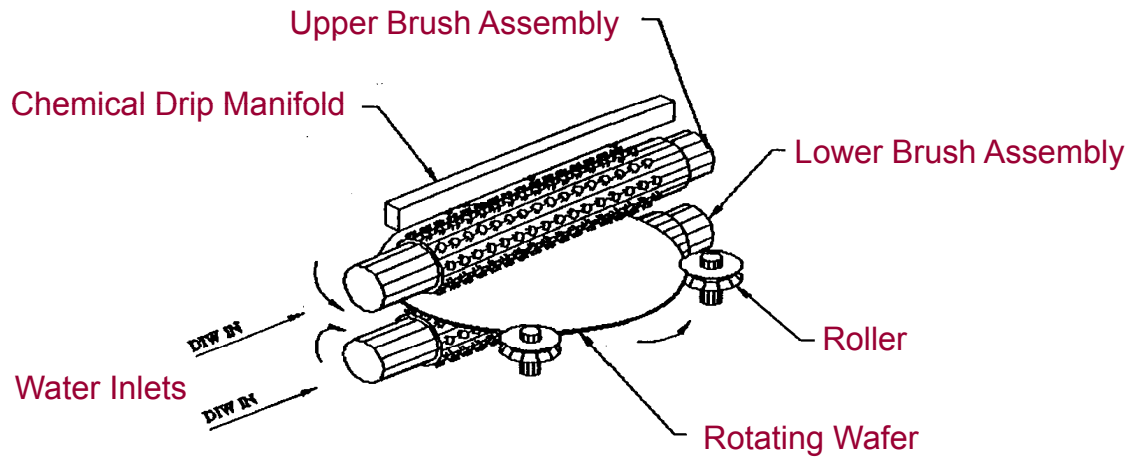
**CMP related issues of porous low-k materials in damascene architectures**

How to overcome? – Low down-force processes and tuned consumables!

**3.8.5 Post CMP Cleaning**

- Removes particles and chemical contamination after CMP
- Involves buff, brush clean, megasonic clean, spin-rinse dry steps
- Buffing:
  - after main polish, wafers “polished” using soft pads
  - used following metal CMP
  - oxide slurries, DI water, or  $\text{NH}_4\text{OH}$  used
    - changes pH of system to reduce adhesion of metal particles
    - removes metal particles embedded in wafers
  - can reduce cleaning loads
- Brush cleaning
  - brushes made from PVA with 90% porosity
  - usually double sided scrubbing, roller or disk-type
  - brushes probably make direct contact with wafer
  - $\text{NH}_4\text{OH}$  (1-2%) added for particle removal (prevents redeposition), **citric acid (0.5%) added for metal removal**, HF etches oxide to remove subsurface defects
- Megasonic cleaning
  - sound waves add energy to particles, thin boundary layers
  - cleaning chemicals added (TMAH, SC1, etc.)
  - “acoustic streaming” induces flow over particles
  - importance uncertain

## Brush Box

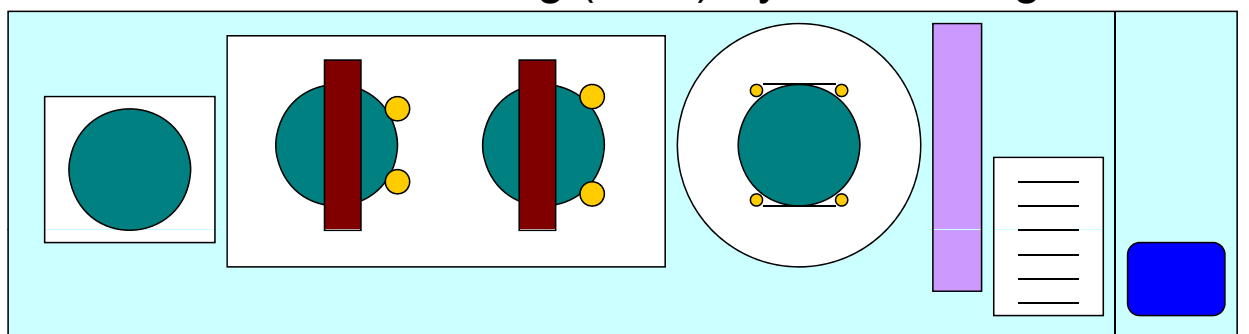


[OnTrak Systems, Inc.]

## Post CMP Cleaning (cont'd)

- Spin-rinse drying
  - following cleaning, wafers rotated at high speed
  - water and/or cleaning solution (SC1) sprayed on wafer at start
  - hydrodynamics drain solutions from wafer
  - probably no effect on cleaning, but ensures that particles dislodged from wafer during preceding steps do not resettle on wafer

## Double Side Scrubbing (DSS) System Configuration



Wet Sand  
Indexer

Dual Brush Module

Rinse, Spin  
Dry Station  
(Megasonic)

Edge  
Handling  
Receive  
Station

User  
Interface

(OnTrak Systems, Inc.)

### 3.8.6 Summary

- Main applications of CMP are dielectric planarization and bulk film removal
  - STI, PMD and IMD planarization, tungsten plugs, and dual damascene copper interconnections.
- Need CMP for  $< 0.25 \mu\text{m}$  features patterning due to depth-of-focus requirement
- Advantages of CMP: high-resolution patterning, higher yield, lower defect density
- A CMP system usually consists of wafer carrier, a polishing pad on a rotating platen, a pad conditioner, and a slurry delivery system
- Oxide slurries: alkaline solutions at  $10 < \text{pH} < 12$  with colloidal suspension silica abrasives
- Tungsten slurries are acidic solutions at  $4 < \text{pH} < 7$  with alumina abrasives
- Copper slurries: acidic with alumina abrasives
- The removal selectivity is mainly determined by the slurry chemistry
- Oxide CMP process: silica particles form chemical bonds with surface atoms and abrade removal of materials from the surface
- Two metal removal mechanisms in metal CMP process: wet etch and passivation/abrasion
- Endpoint detection methods:
  - Optical
    - Thickness measurement for dielectric film
    - Reflectivity measurement for metal film
  - Motor current
- Post-CMP clean reduces defects and improves yield



**ZfM**

**Fraunhofer**  
EMAS

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