Status: 01.06.2020

2.8 Chemical Mechanical Planarization (CMP)

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

2.8.1 Introduction

What is CMP

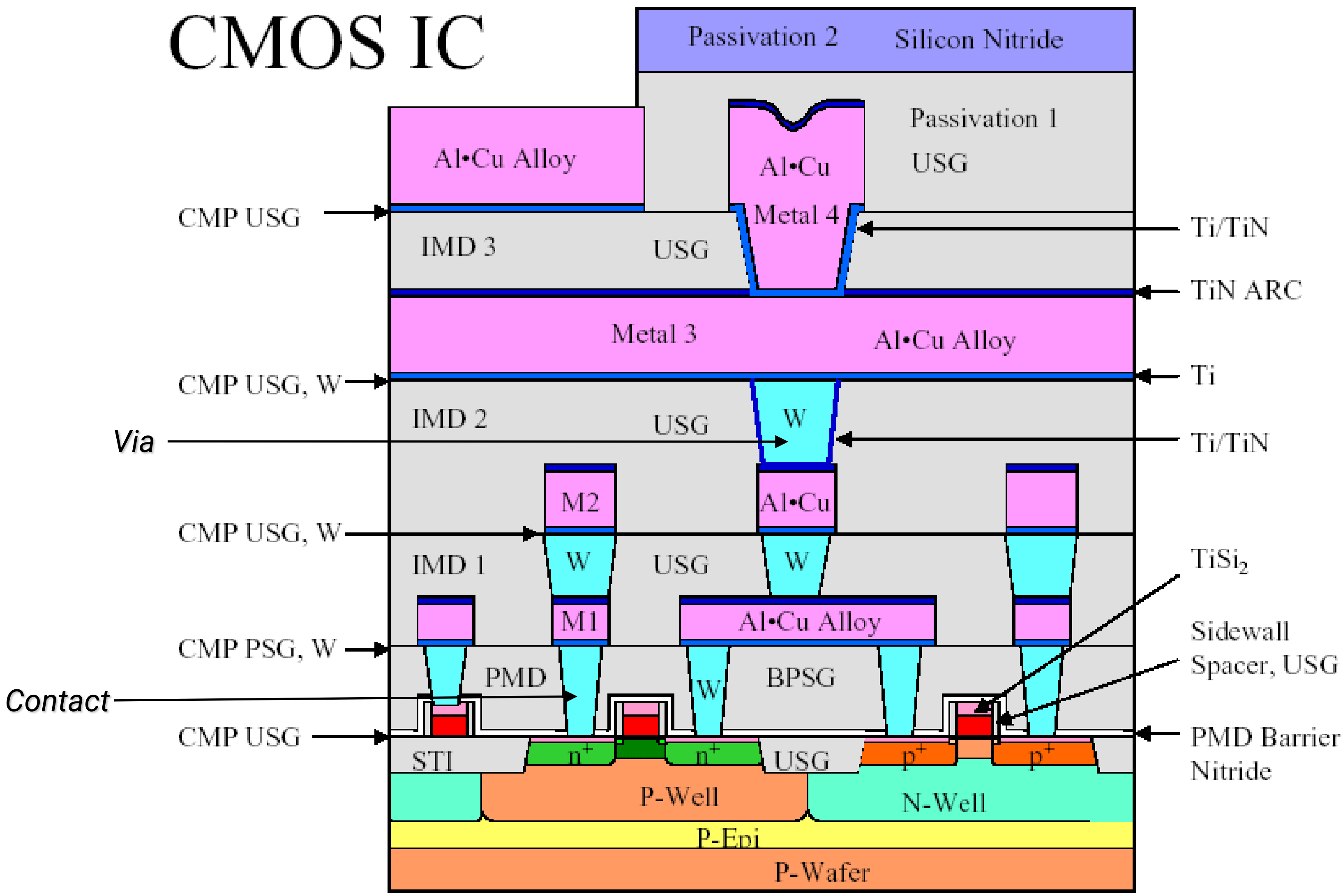
- *CMP is mechanically enhanced chemical etching or chemically enhanced mechanical grinding*
- *CMP is able to planarize surfaces by removal of material such that topography is eliminated or material is left at defined areas*
- *CMP provides local and global planarity*
- *CMP enables indirect patterning 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* $\lambda \downarrow$
- $DOF = k_2 \lambda / (NA)^2$*, both approaches to improve resolution reduce DOF (depth of focus)*
- *Planarization is inevitable for lithography for the 0.25 µm node and below*

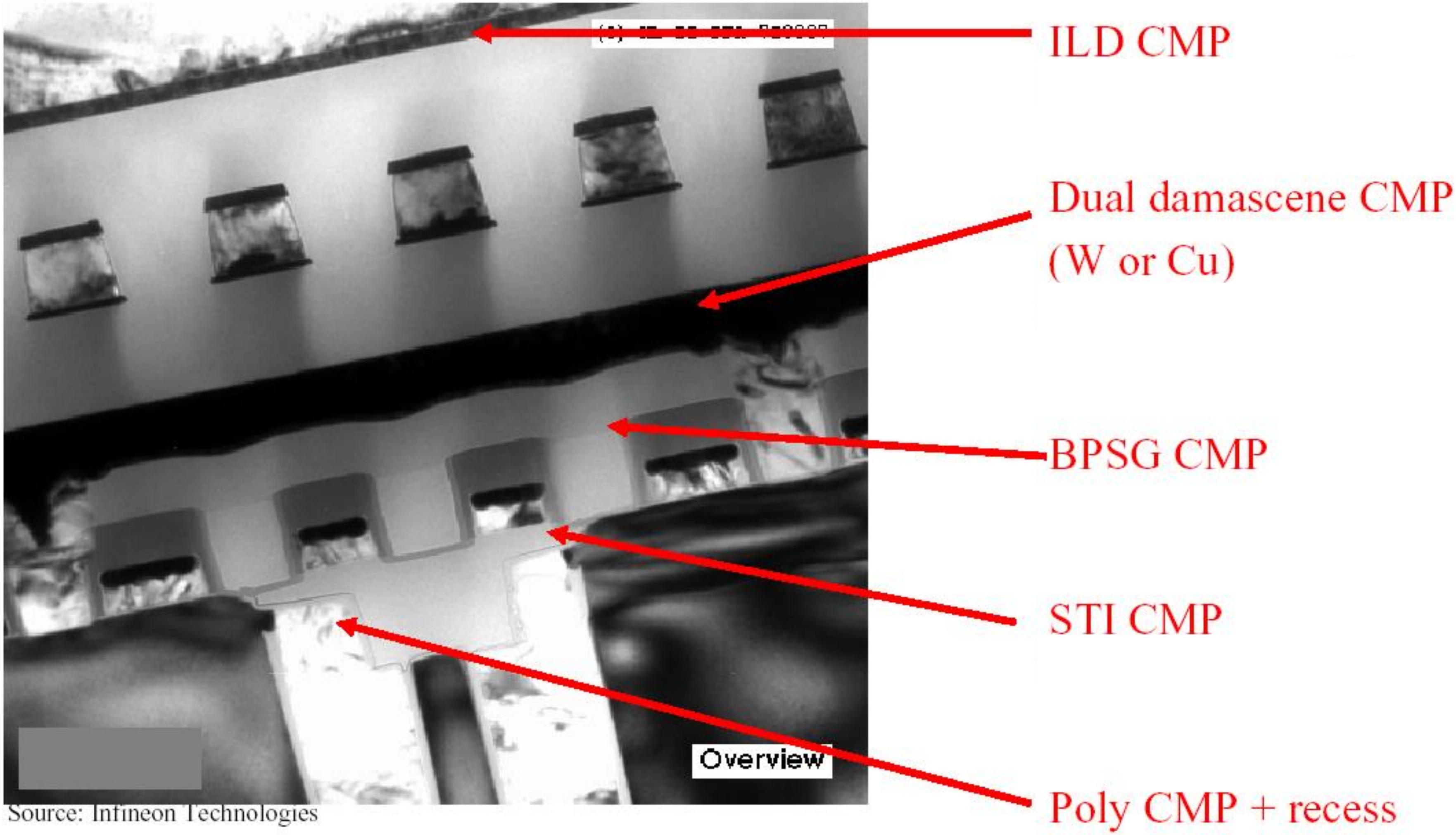
Application Examples of CMP

- *STI formation*
- *Tungsten plug formation for via/contact metallization (vertical interconnect)*
- *Deep trench capacitor*
- *Cu dual damascene*
- *Planarization of Pre-metal dielectric (PMD) and Interlevel dielectric (ILD)*



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

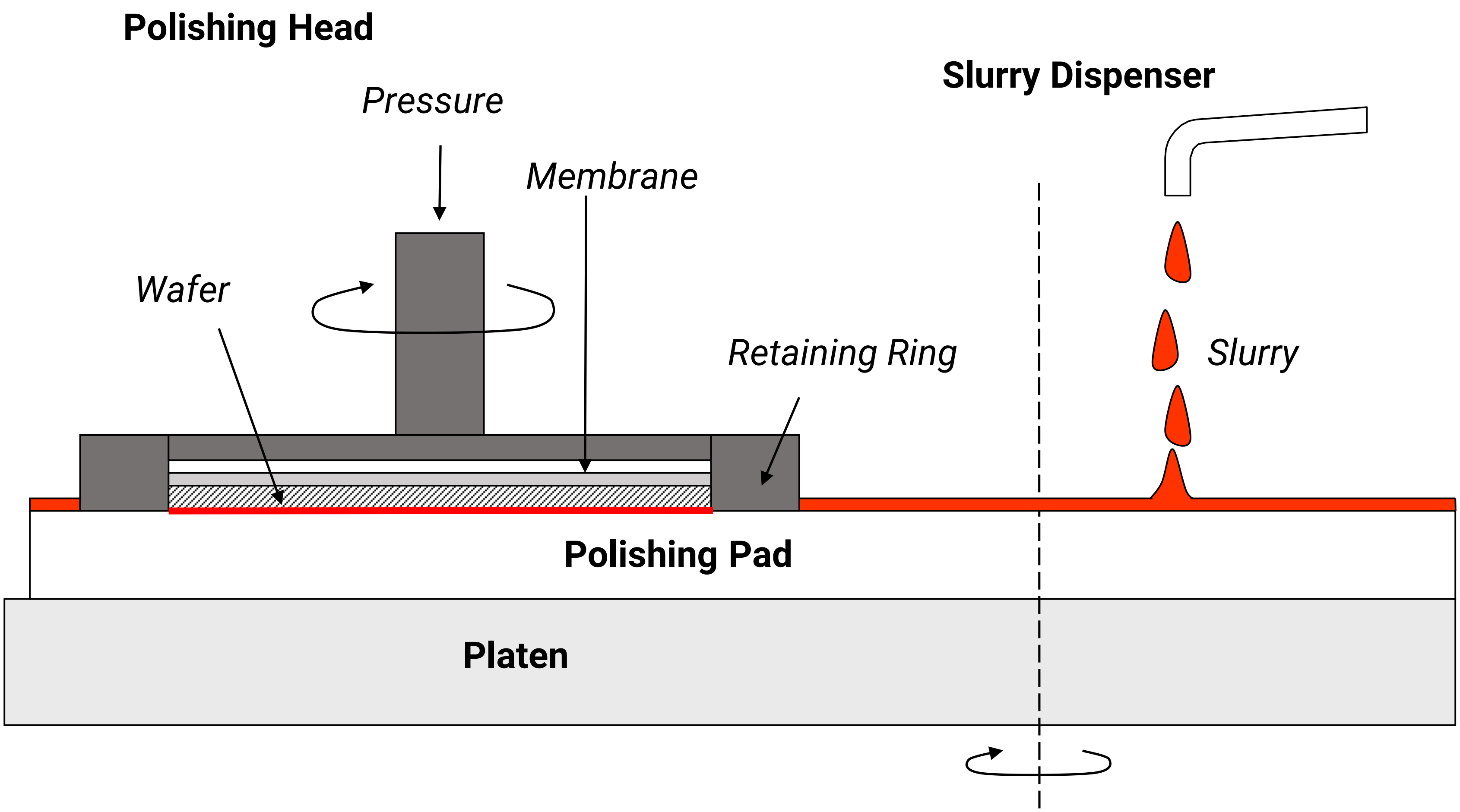
CMP in IC manufacturing



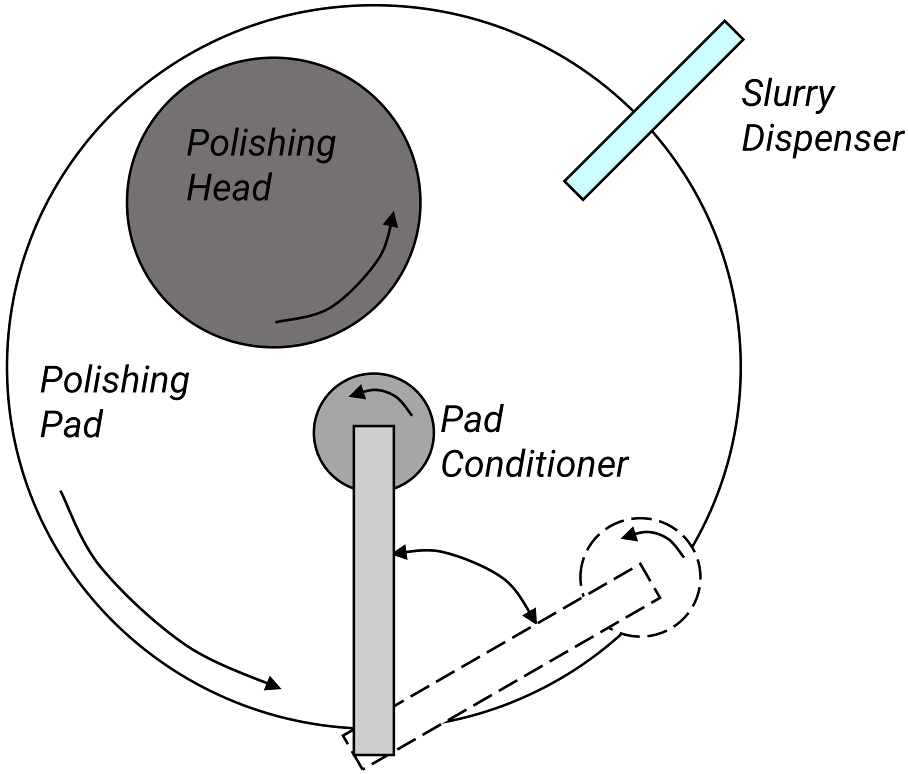
Source: Infineon Technologies

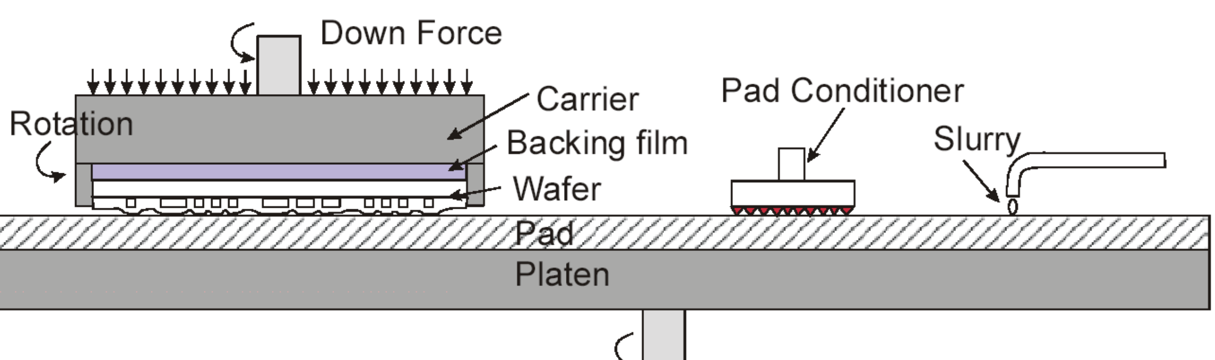
Cross section of trench type DRAM

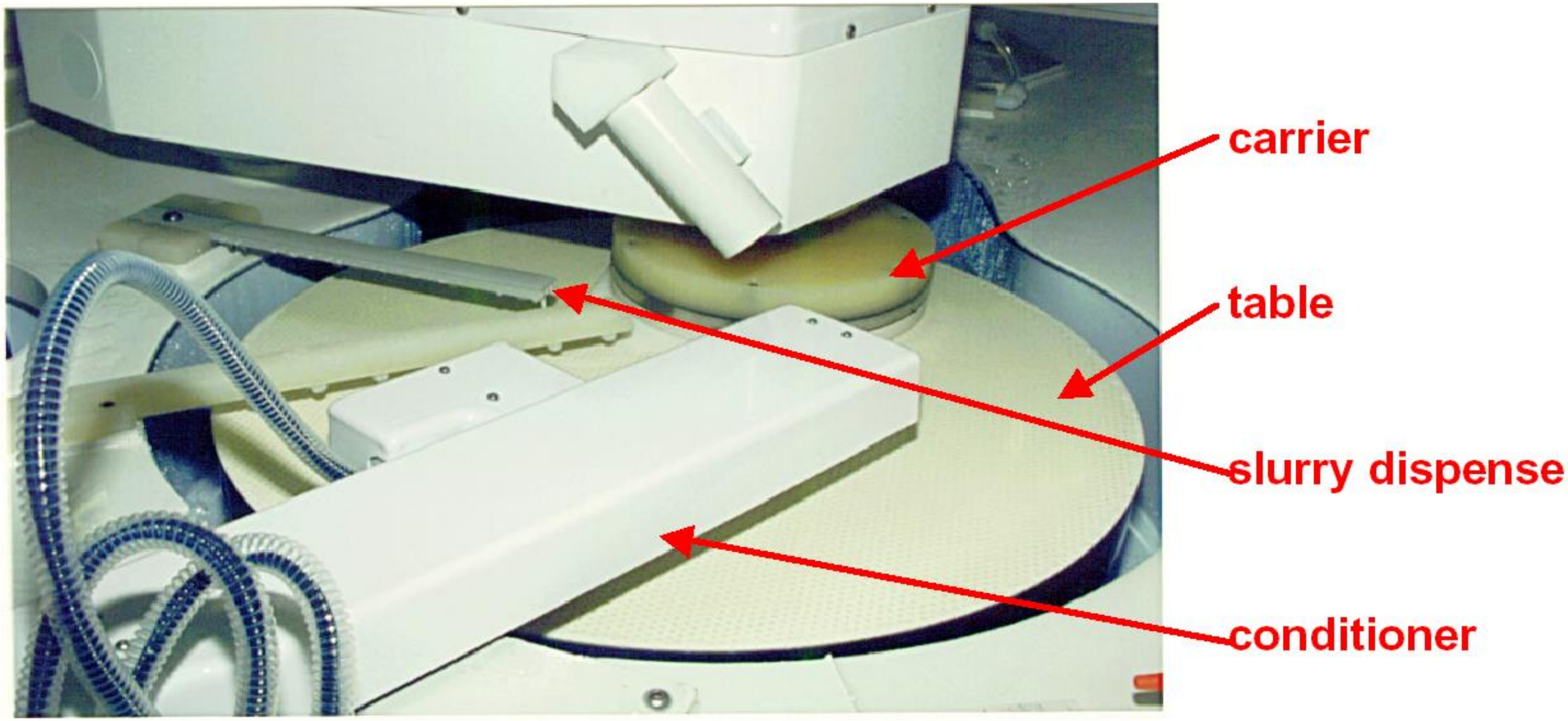
2.8.2 Equipment configuration



Polishing Pad and Pad Conditioner

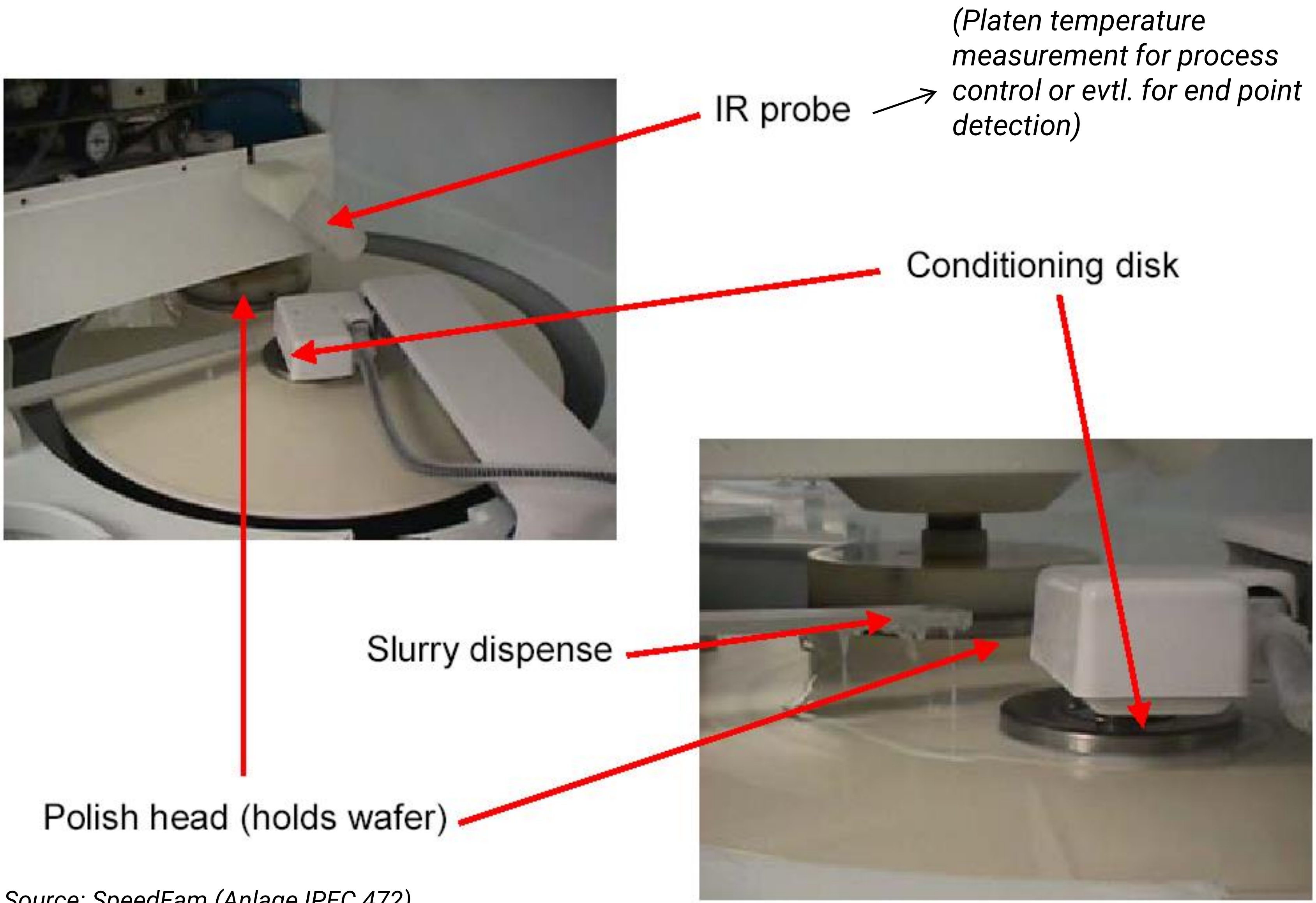






source: SpeedFam-Ipec

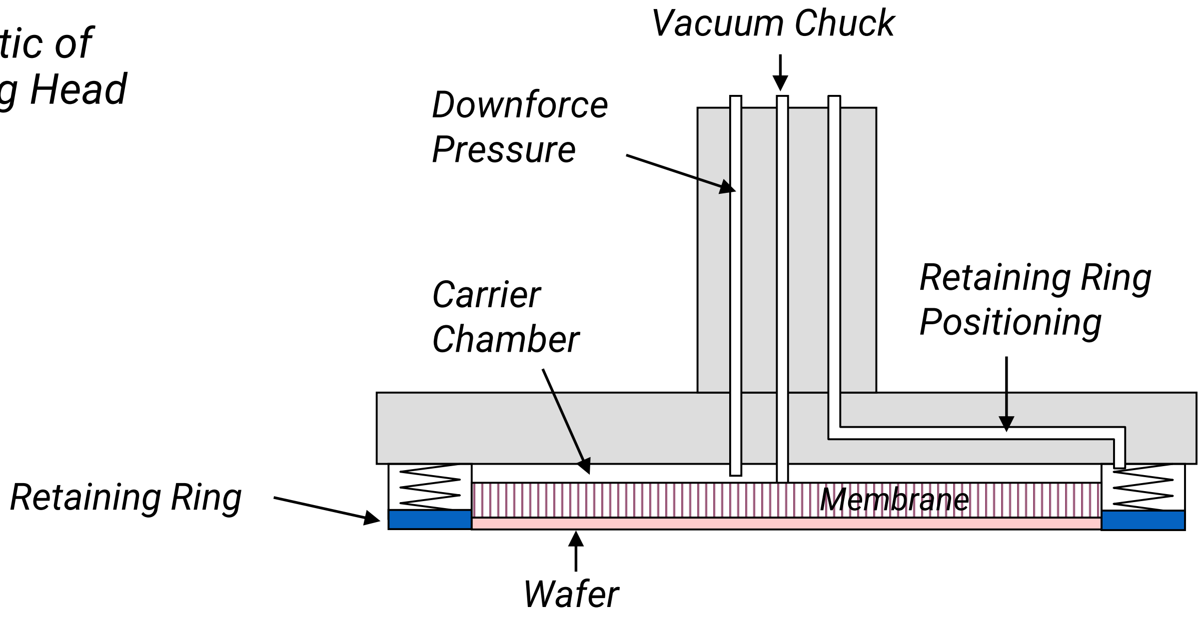
Single head two table (2nd table not visible) machine Ipec 472

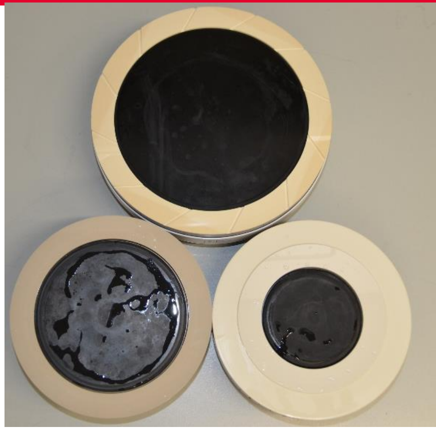


Source: SpeedFam (Anlage IPEC 472)

Equipment configuration

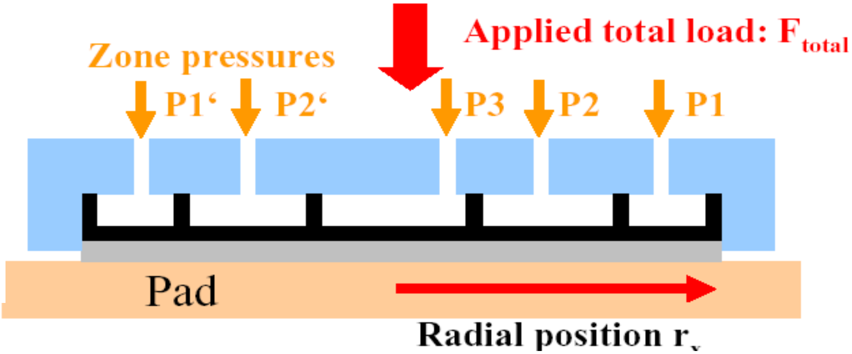
Schematic of Polishing Head





Uniformity Control

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



2.8.3 Consumables

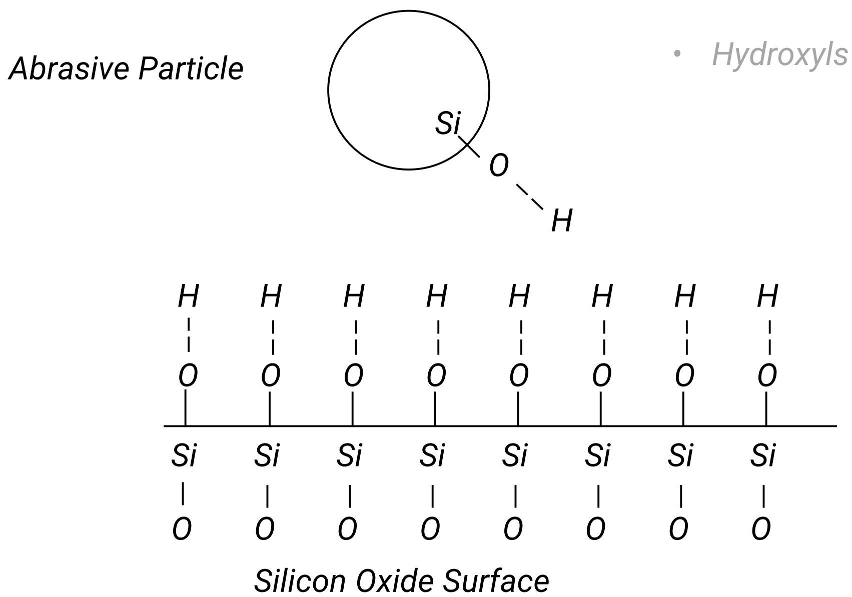
2.8.3.1 Slurries

- *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*

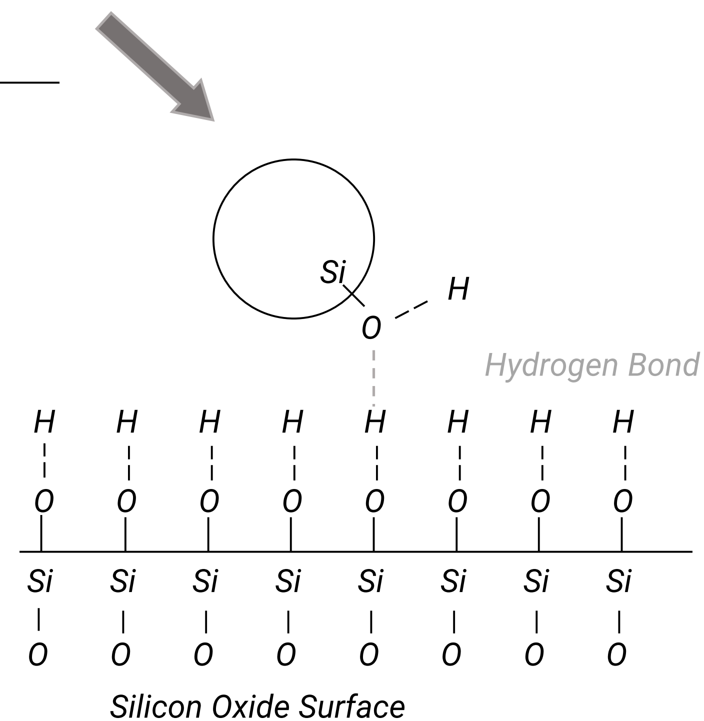
Slurries for oxide (SiO_2) polishing

- *suspension of colloidal/fumed silica particles in alkaline medium*
- *hydroxyl ions attack SiO_2, causing softening and chemical dissolution*
- *particles range from 10 to 3000 nm, mean size 160 nm*
- *12% (wt) particles, KOH or NH_4OH used to set pH ~11*
- *other concerns: particle size distribution (scratching), particle shape, particle agglomeration*

Removal mechanism for oxide (SiO_2) polishing

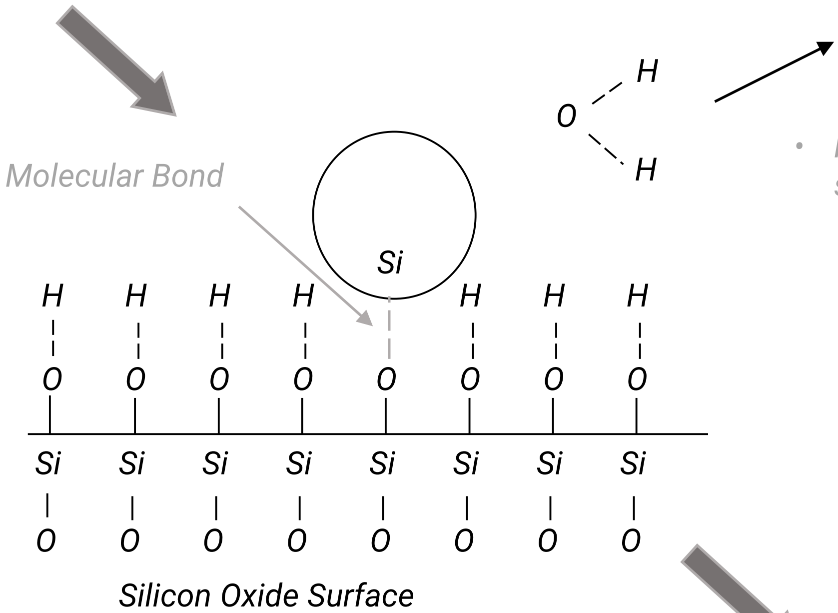


- *Hydroxyls on both film and silica surfaces*

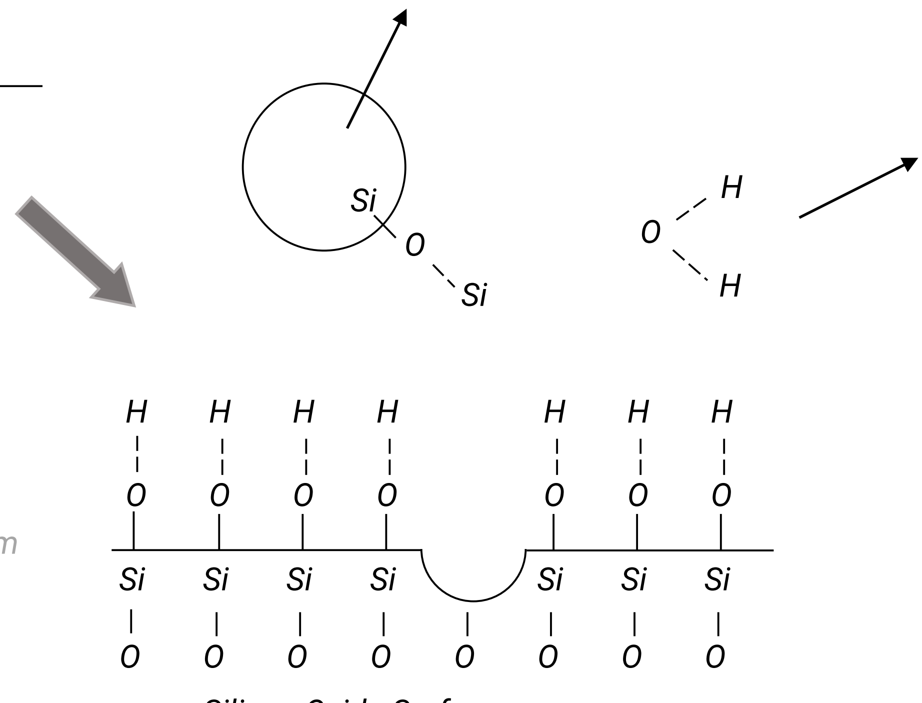


- *Formation of hydrogen bonds of silica and surface*

Removal mechanism for oxide (SiO_2) polishing



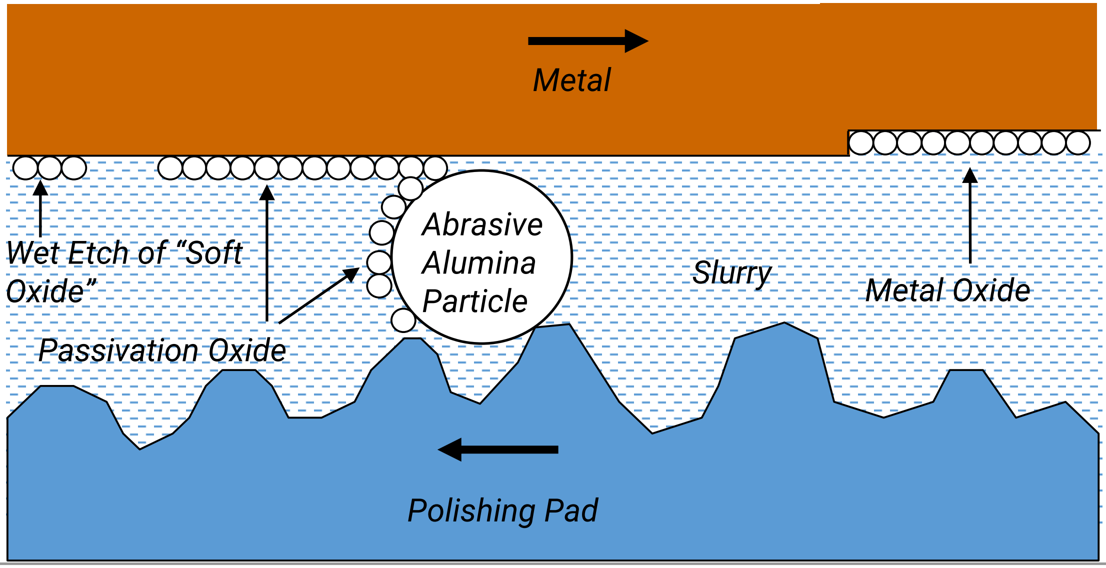
- *Formation of molecular bonds of silica and surface*



- *Mechanical removal of the particles bonded with wafer surface*
- *Tearing away of atoms or molecules from film on wafer surface*

Slurries for metal (W, Al, Cu) polishing

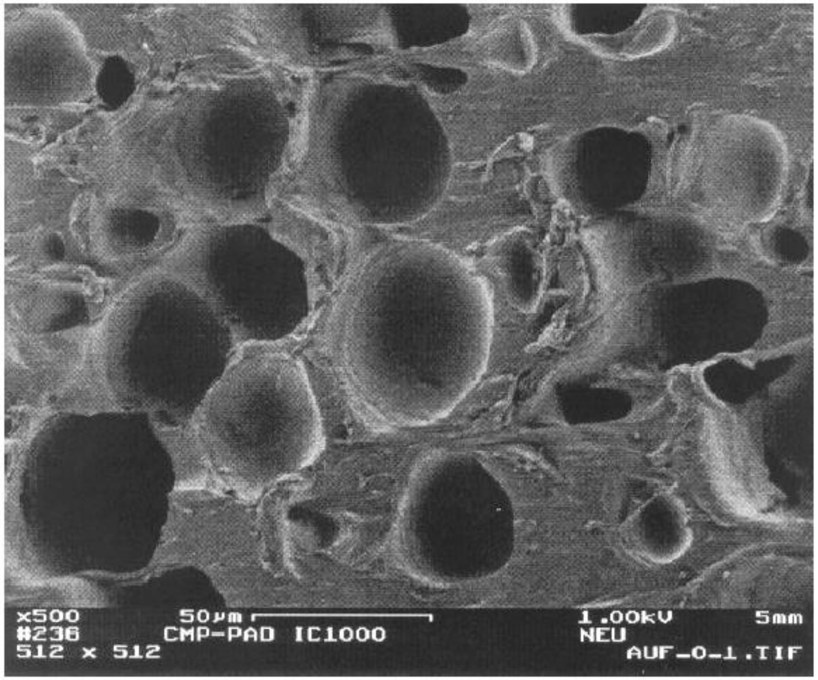
- Metal CMP process is similar to the metal wet etch process
  - Oxidant cause metal dissolution and passivation (reactions to form protective layer on metal surface)
  - Metal oxide is removed by abrassive particles (typically alumina particles, α or γ)
  - Repeated metal oxidation and oxide removal
- W polishing examples:
  - alumina / peroxide: 1 part slurry, 1 part 50% H_2O_2, pH 3.7 - 4.0
  - alumina / ferric nitrate: 6% alumina solids, 5% $Fe(NO_3)_3$, pH 1.5
  - alumina / potassium iodate: 6% alumina solids, 2 - 8% KIO_3, pH 4.0
- Al polishing: peroxide or iodate-based slurries
- Cu polishing: H_2O_2 or ammonia-based solutions, passivating agents



2.8.3.2 Pads

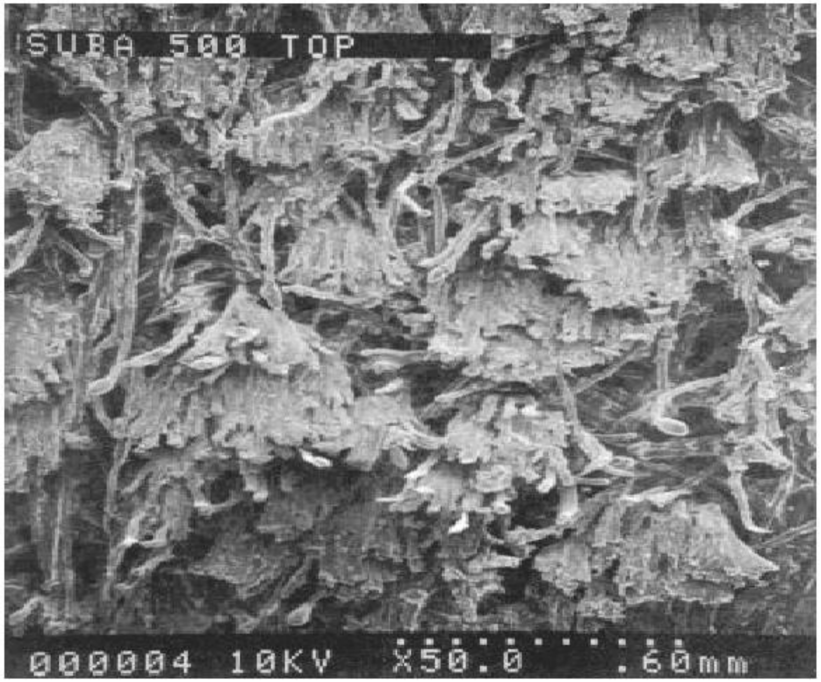
Structural classification

- *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

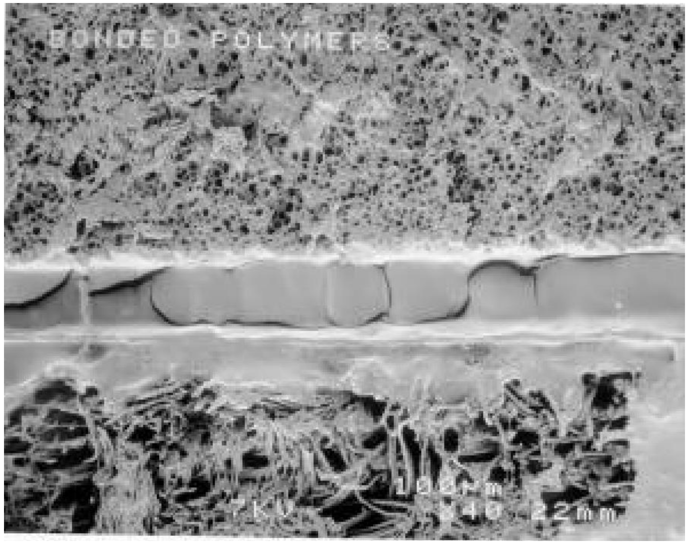
„soft pad" Suba series by Rodel
-> low surface roughness but poor planarization performance

- *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 mm)

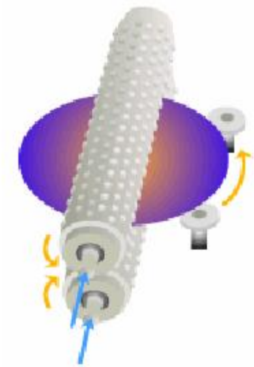
SubaIV layer (thickness ~ 1.24 mm)

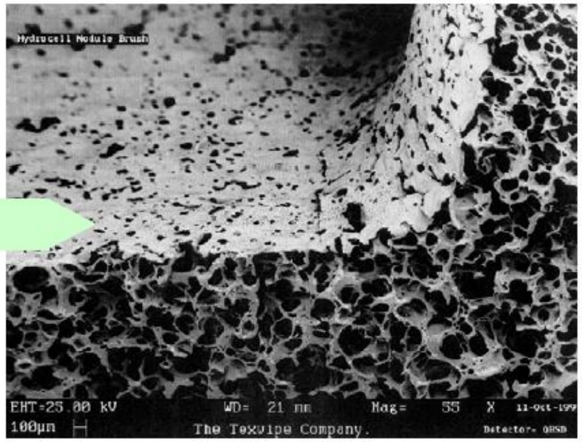


Wafer

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

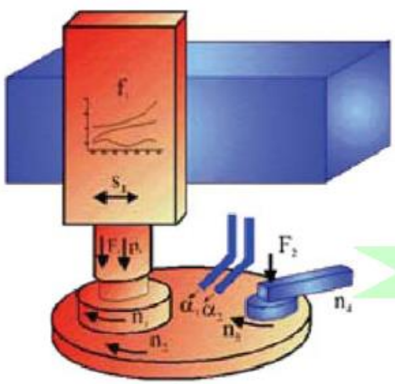
2.8.3.3 Brushes and Conditioner



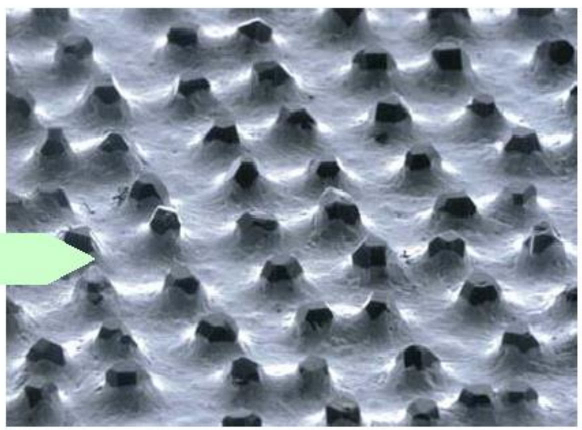


PVA brush for post CMP cleaning
- water / chemistry supply and particle transportation
- application of mechanical forces to particle

Source: Metron Technologies



Source: Peter Wolters



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

Source: Abrasive Technologies

PVA = Polyvinyl Alcohol

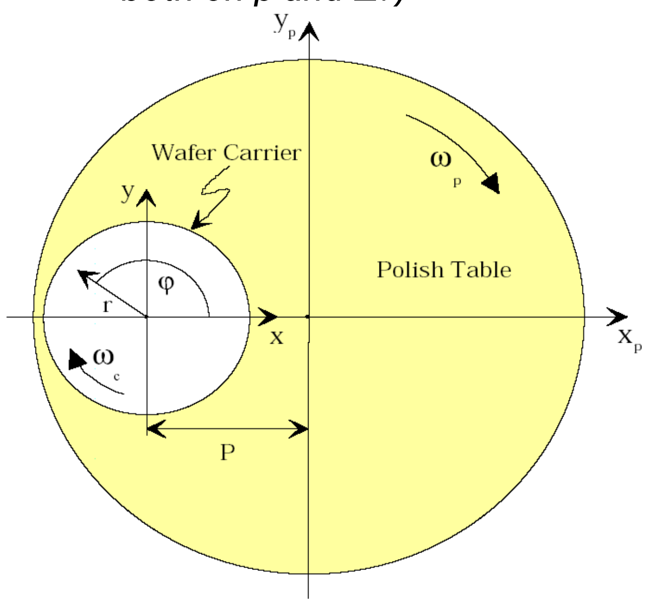
2.8.4 Process Issues

2.8.4.1 Removal rate

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

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

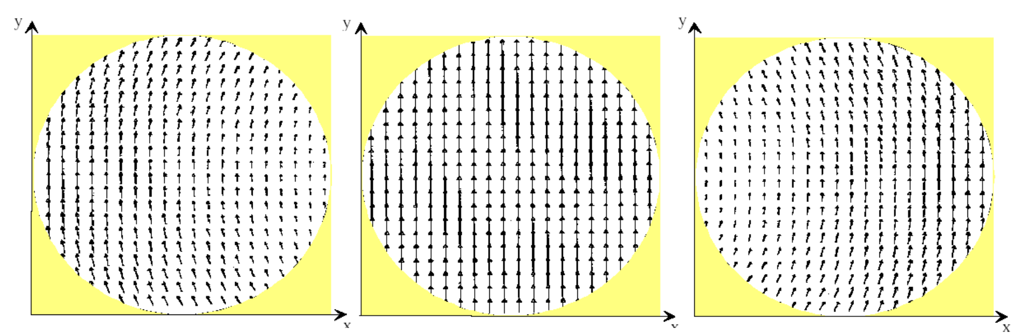
gives only <u>very crude estimates</u> for the blanket removal rate
  - *p is the polishing pressure*
  - *Δv is relative velocity of wafer and pad*
  - *K_p is the Preston coefficient (closely related to the coefficient of friction, depends in reality both on p and Δv)*



$$\Delta\vec{\mathbf{v}} = \Delta\omega\, r \begin{pmatrix} -\sin(\varphi) \\ \cos(\varphi) \end{pmatrix} + \omega_{\mathbf{p}} \begin{pmatrix} \mathbf{0} \\ \mathbf{P} \end{pmatrix}$$

Pressure zone control

$$\Delta\omega = \omega_{\mathbf{c}} - \omega_{\mathbf{p}}$$



$\Delta\omega < 0$ $\Delta\omega = 0$ $\Delta\omega > 0$

source: Infineon

2.8.4.2 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
Cu-RR* [nm/min]		500 … 1000	500 … 650
Select.	Cu : SiC	> 55	> 600
	Cu : SiN	> 110	> 60
	Cu : HM	> 1000	> 1000
	Cu : TaN	> 100	> 300
	Cu : TiN	> 14	> 10

RR* [nm/min]	Rohm and Haas barrier slurry
TiN	150 … 200
TaN	100 … 150
Cu	40 … 50
SiC	3 … 4
SiN	6 … 8
MSQ-HM	22 … 25
SiO_2	7 … 8

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

2.8.4.3 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*

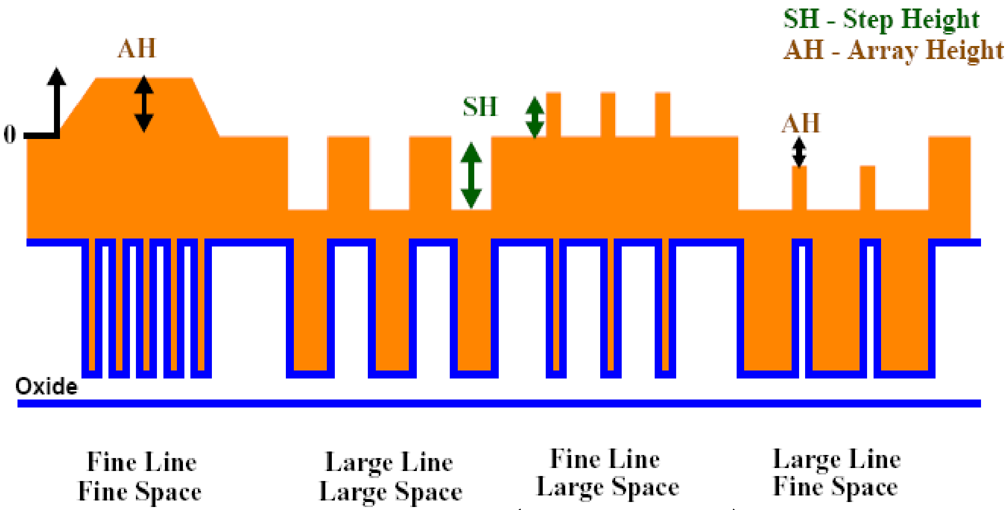
Pattern erosion

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

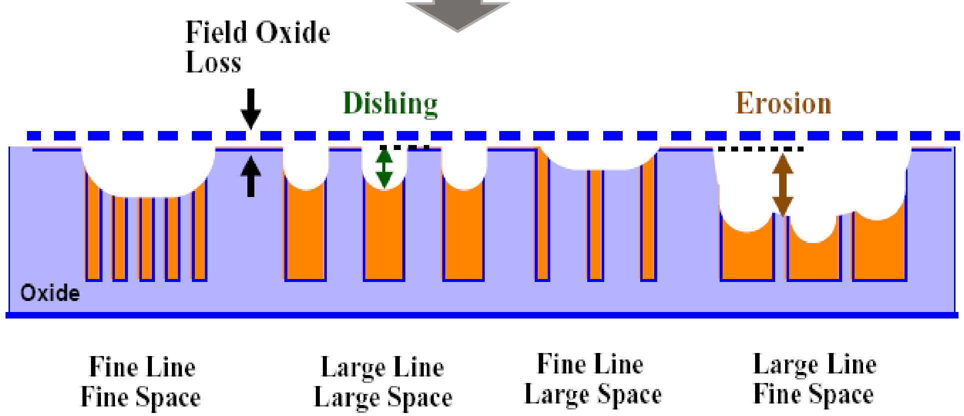
Edge effect

- *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



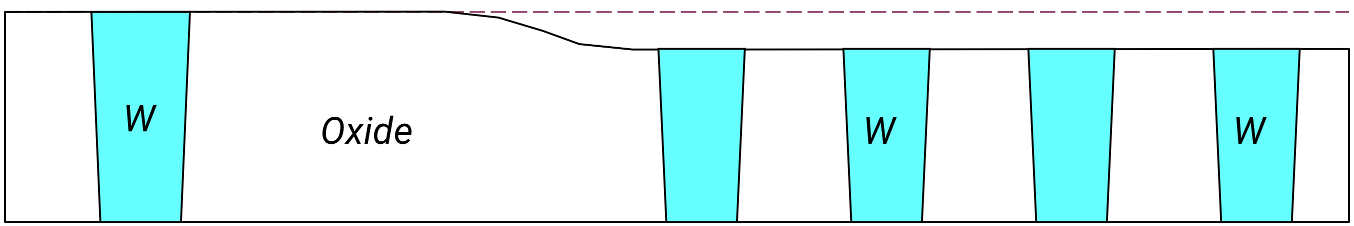
Post-ECP Topography (Park, MIT 2002)



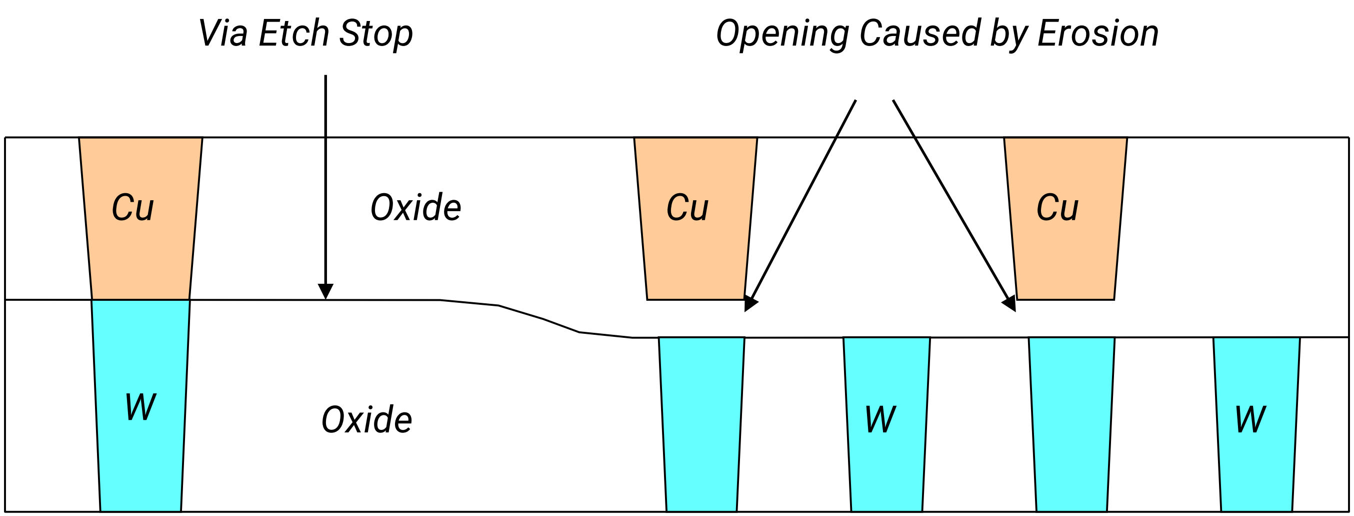
Post-CMP Topography (Park, MIT 2002)

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

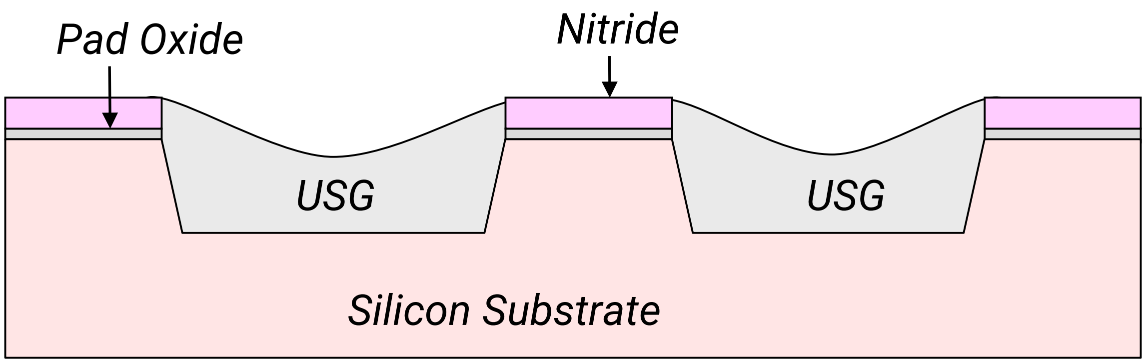
Erosion Caused by High Pattern Density



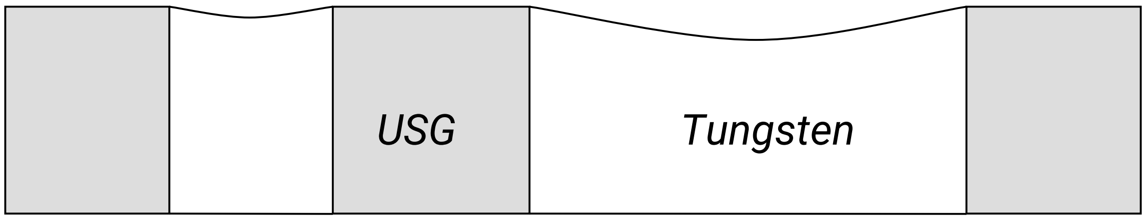
Circuit Opening Caused by Erosion



Dishing Effect of STI USG



Dishing Effect of W CMP



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*

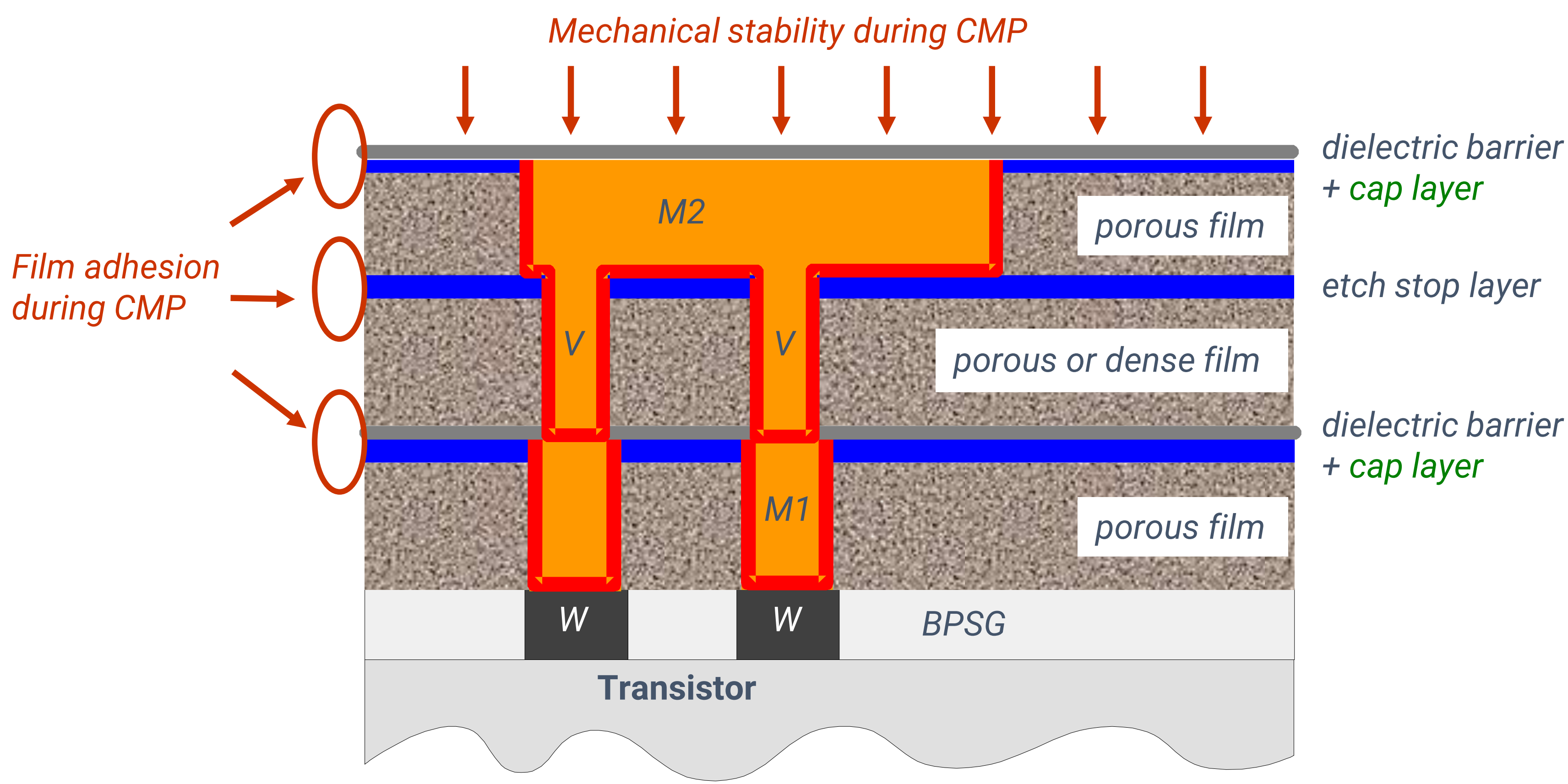
IC Layout and Erosion

- *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.*

2.8.4.4 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*

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



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

CMP consumables for low-k based integration schemes - Polish Pads

Hard pads (stiff pads)

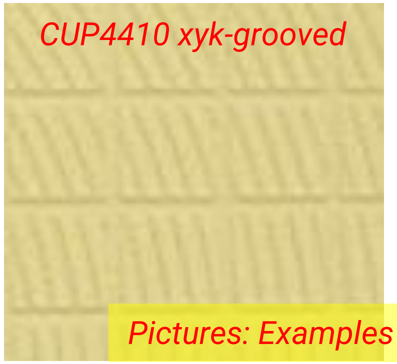
- *Polyurethane based materials (hard foam)*
- *Consists of one or two layers (single pads, stacked pads)*
- *Specific grooving:*
  - *k-grooved*
  - *xy-k-grooved*
  - *spiral grooved*
- *Excellent planarization behavior*
- *Critical regarding defectivity*

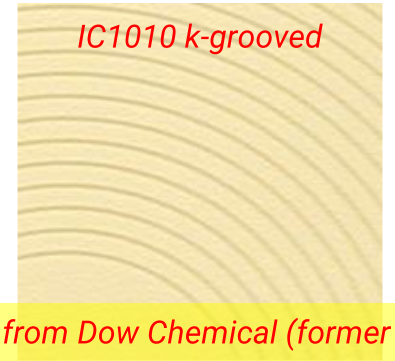
→ Cu and barrier CMP

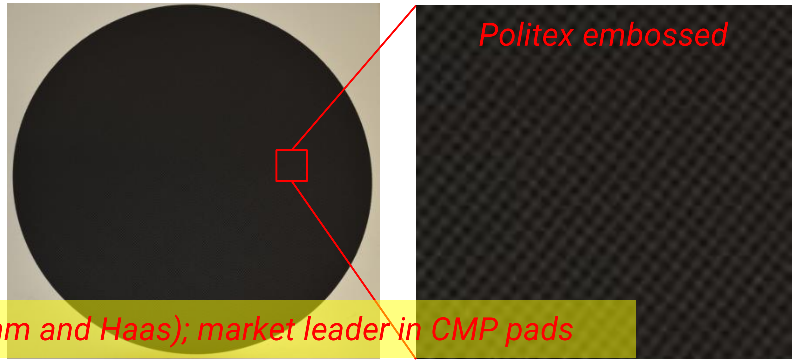
Soft pads (flexible pads)

- *Poromeric based materials (mixture of polyurethane and polyester – textile character)*
- *Single layer pads*
- *With / without embossing*
- *Poor planarization behavior*
- *Outstanding low defectivity*

→ Barrier and dielectric CMP







Pictures: Examples from Dow Chemical (former Rohm and Haas); market leader in CMP pads

Tendency: *pad materials with excellent planarization behavior and low defectivity*

CMP consumables for low-k based integration schemes – Slurries I

Common / general status

- *High number of dedicated copper and barrier slurries available on the market*
    - ❖ *Dow Chemical, Cabot, Fujimi, Air Products, Anji, BASF, ….*
- *Acidic and alkaline chemistries*
- *Different types of abrasives (polish particles)*
    - ❖ *Silica (colloidal, fumed, amorphous)*
    - ❖ *Alumina*
    - ❖ *Ceria*

Requests coming from the device manufactures (IDMs)

- *Tunable removal rates for Cu slurries (Cu bulk removal / Cu clearing)*
- *Tunable selectivity for Cu and barrier slurries (selective / non-selective approaches*
- *2 Platen processes: P1 – Cu bulk and clearing / P2 – barrier removal*
- *Low defectivity*
- *Low cost of ownership*
- *Environmental friendly*

Tendency: *highly concentrated slurries, to be diluted at the point of use*

CMP consumables for low-k based integration schemes – Slurries II

Example for a state of the art slurry system form Cabot Microelectronics (2014)

EPOCH™ C8917 Cu slurry

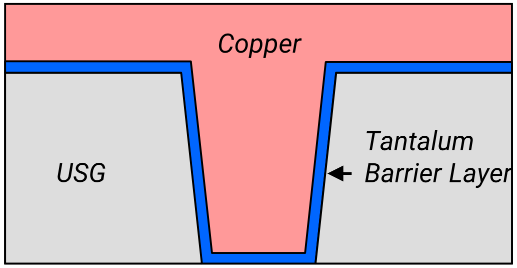
- *Amorphous silica abrasives*
- *Abrasive concentration: <3%* (by weight)
- *Abrasive size: 20 …25 nm*
- *Dilution ratio 9:1 (water : slurry)*
- *Oxidizer type: H_2O_2*
- *Oxidizer concentration 1.5%* (by weight)
- *Acidic chemistry*
- *pH value 4.2 (ready to use mixture)*
- *2.0 … 2.5 psi for Cu bulk removal*
- *1.0 … 1,5 psi for Cu clearing*
- *Slurry flow 200 ml/min*
- *in-situ conditioning at 5 psi*
- *Removal rate about 600 nm/min*
- *Selectivity Cu:Ta = 1000:1*

ICUE™ B7002 barrier slurry (Ta)

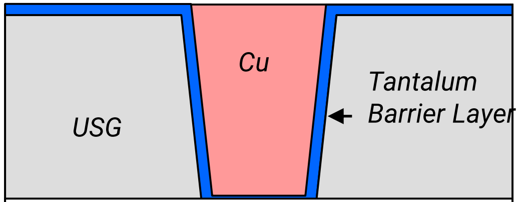
- *Colloidal silica abrasives*
- *Abrasive concentration 14%* (by weight)
- *Abrasive size: 110 nm*
- *Ready to use (non-dilutable)*
- *Oxidizer type: H_2O_2*
- *Oxidizer concentration 1.0%* (by weight)
- *Alkaline chemistry*
- *pH value 10 (ready to use mixture)*
- *1.0 … 1,5 psi for Ta removal*
- *Slurry flow 200 ml/min*
- *ex-situ conditioning at 5 psi (10s)*
- *Removal rate about 60nm/min*
- *Tunable selectivity to Cu, low-k, and TEOS by downforce anc chemistry*

Dishing Effect of Cu CMP

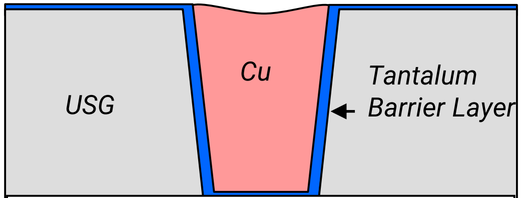
- *Dual-damascene copper metallization requires that both bulk Cu and barrier Ta layer need to be removed by the CMP process.*
- *Cu slurry cannot effectively remove Ta, the lengthy over polishing step for Ta removal can cause copper recess and dishing effects*



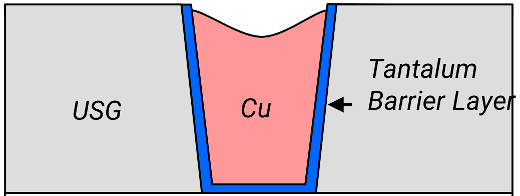
Copper deposition



Copper CMP



Over polish to remove Ta

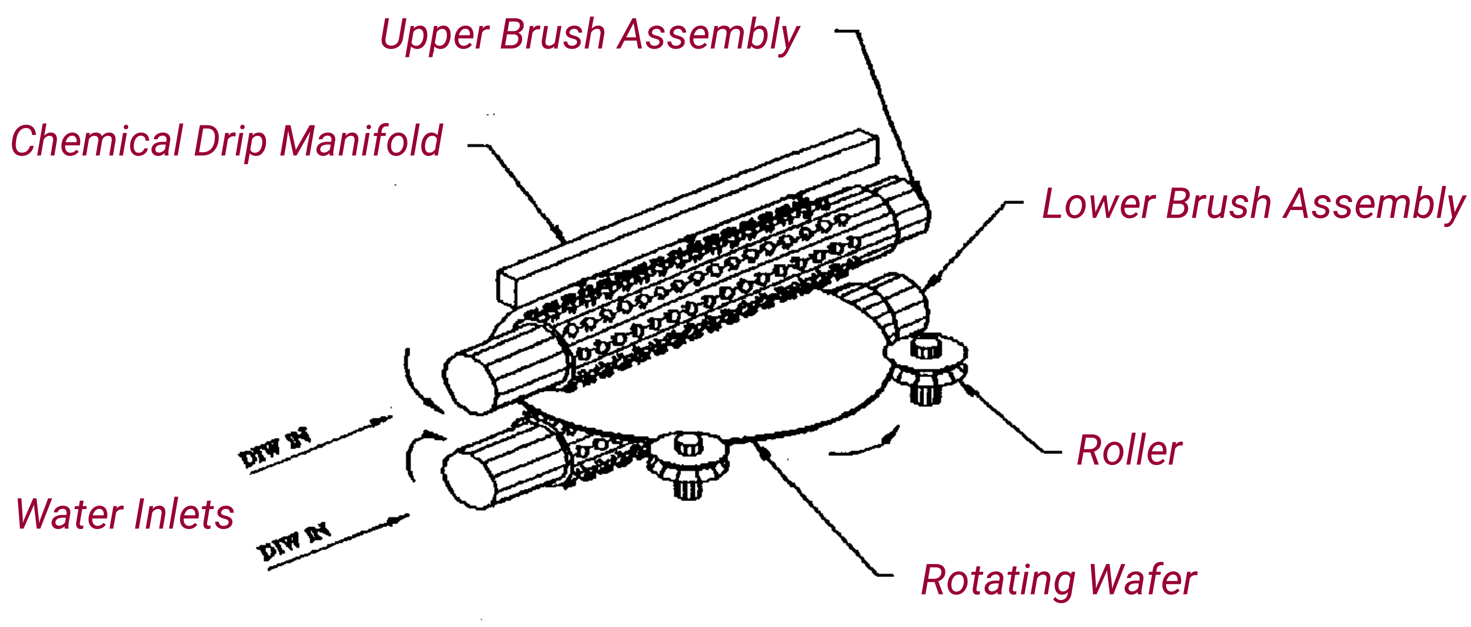


Cu dishing and recessing

2.8.5 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 NH_4OH 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*
  - *NH_4OH (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

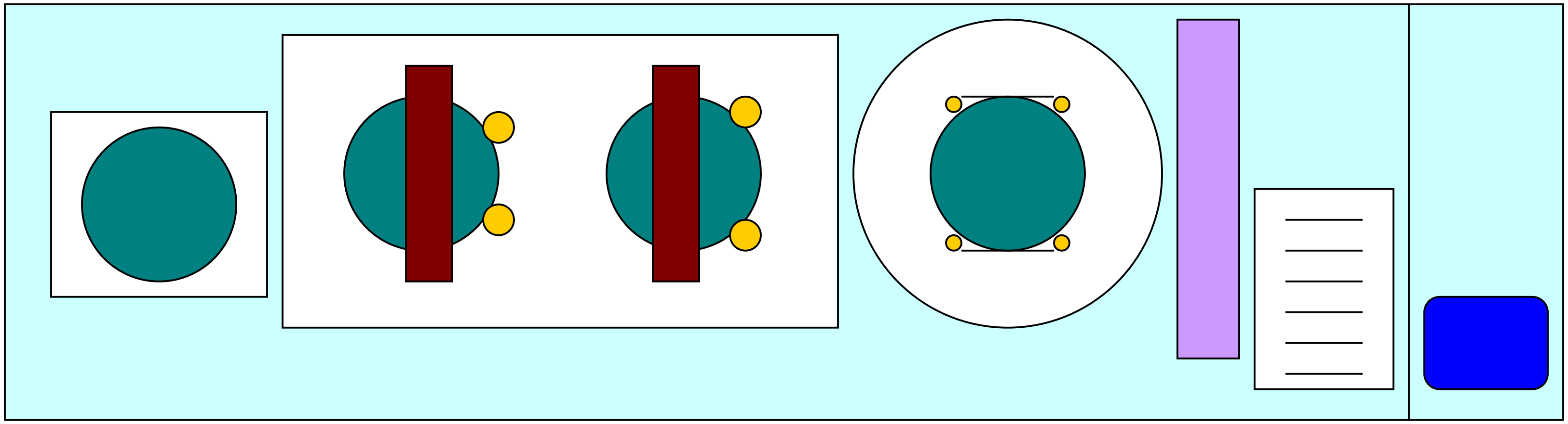


[OnTrak Systems, Inc.]

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.)

2.8.6 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 μm 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 < pH < 12 with colloidal suspension silica abrasives*
- *Tungsten slurries are acidic solutions at 4 < 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*