3.8 Chemical Mechanical Planarization (CMP)

Outline:

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

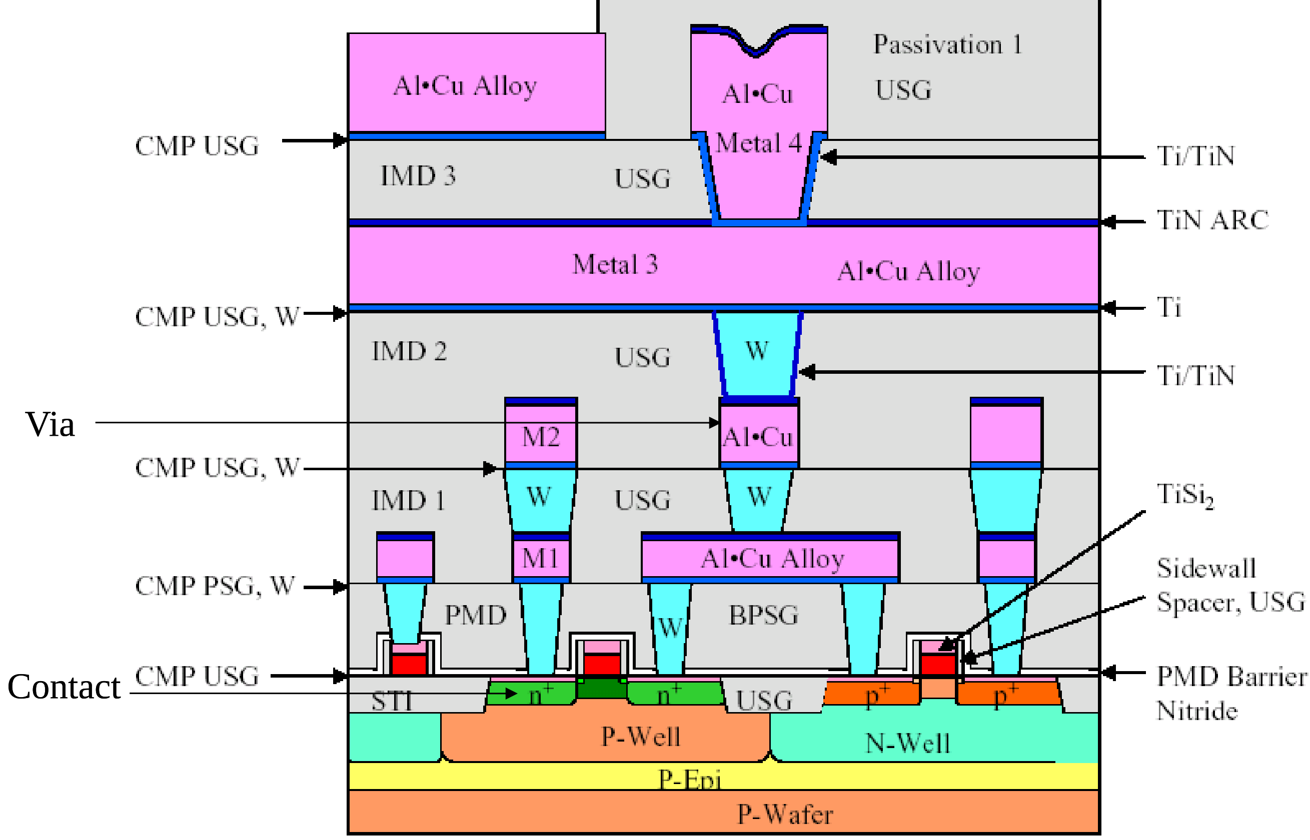
Necessity of CMP

- 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 µm node and below

Applications of CMP

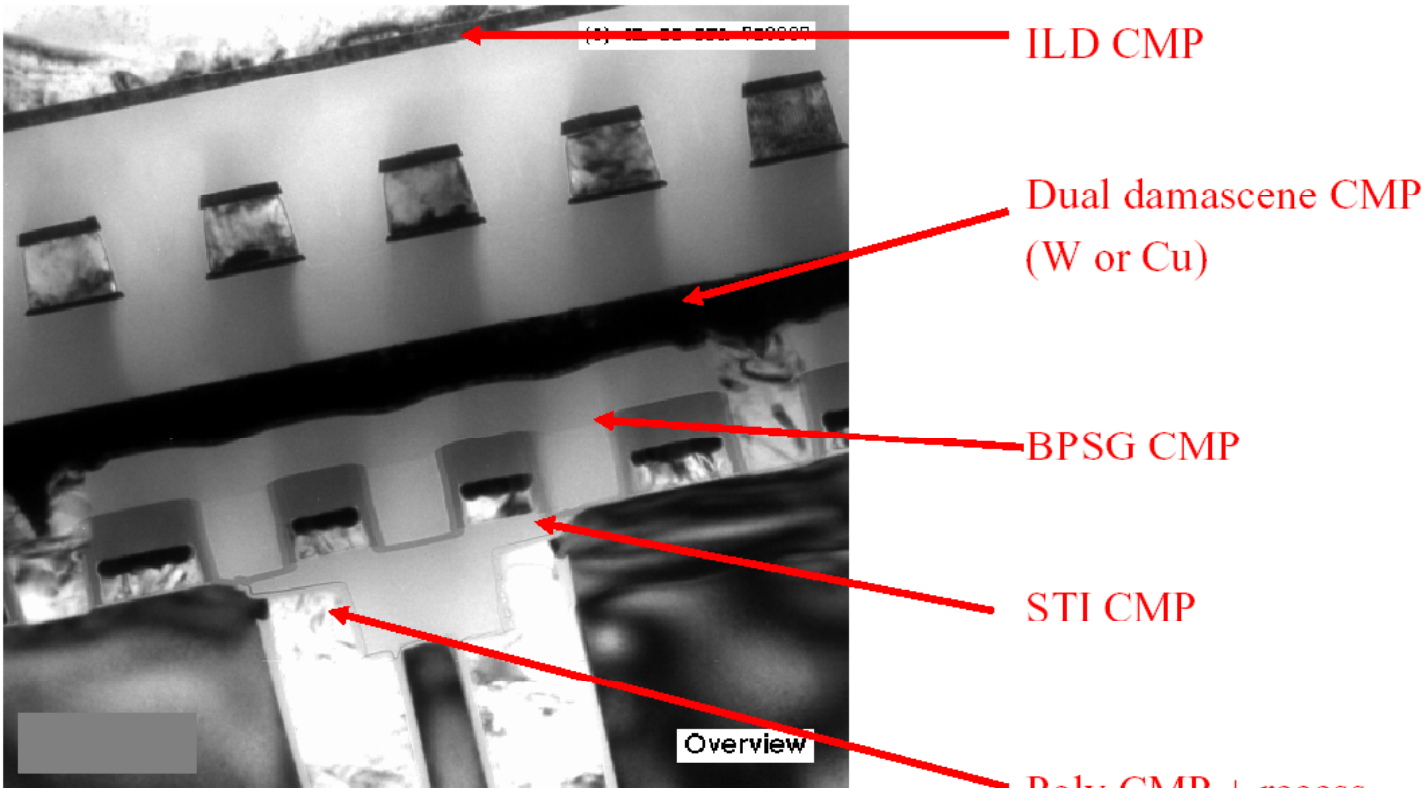
- STI formation
- Tungsten plug formation
- Deep trench capacitor
- Cu dual damascene
- ...

CMOS IC



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

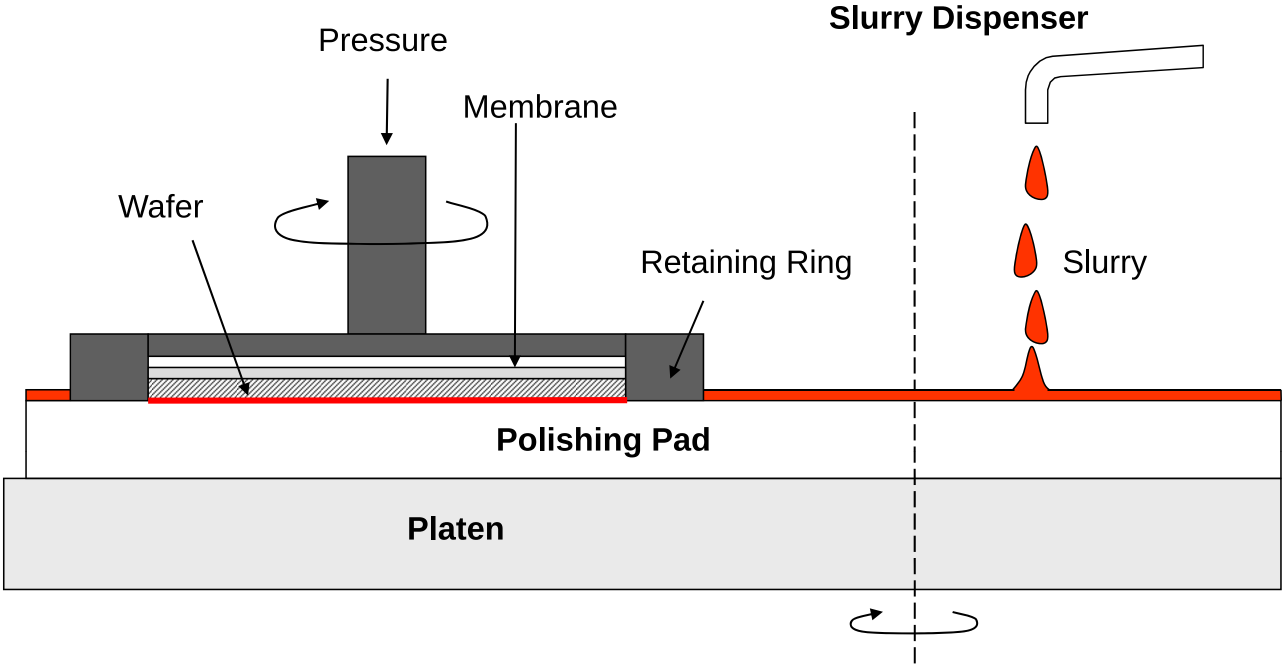
CMP in IC manufacturing



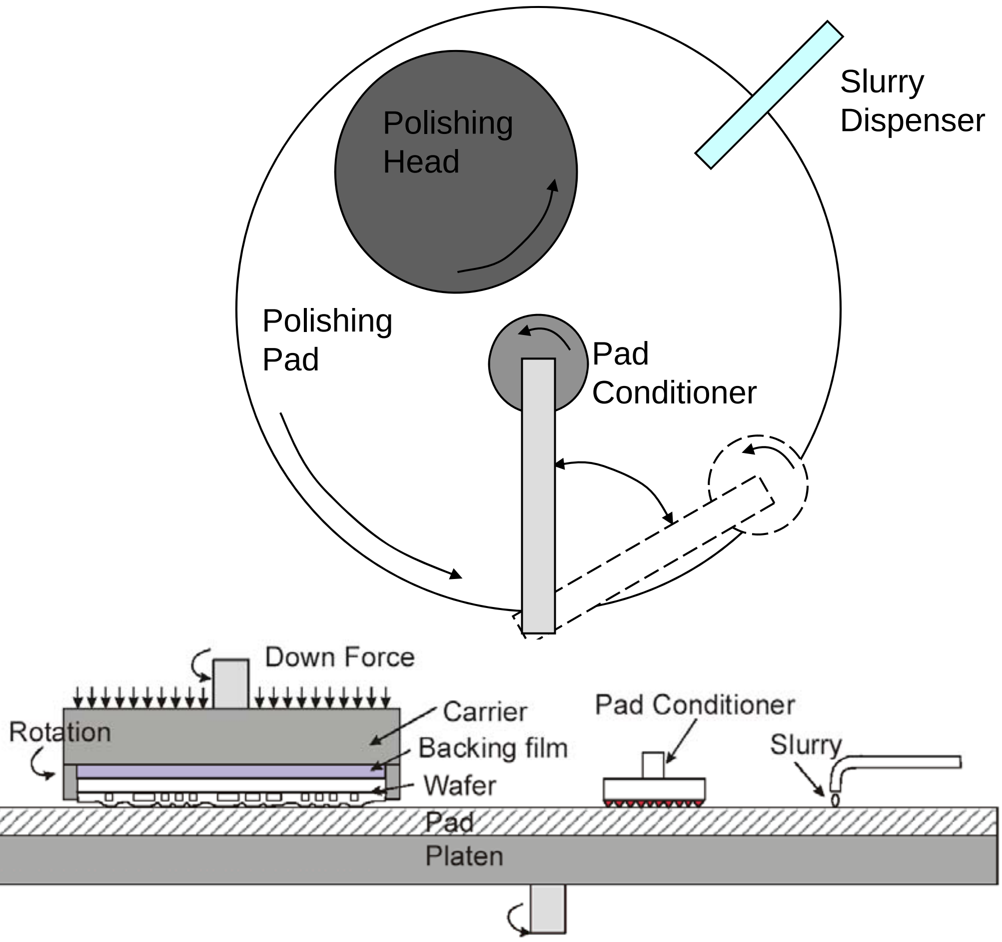
Source: Infineon Technologies

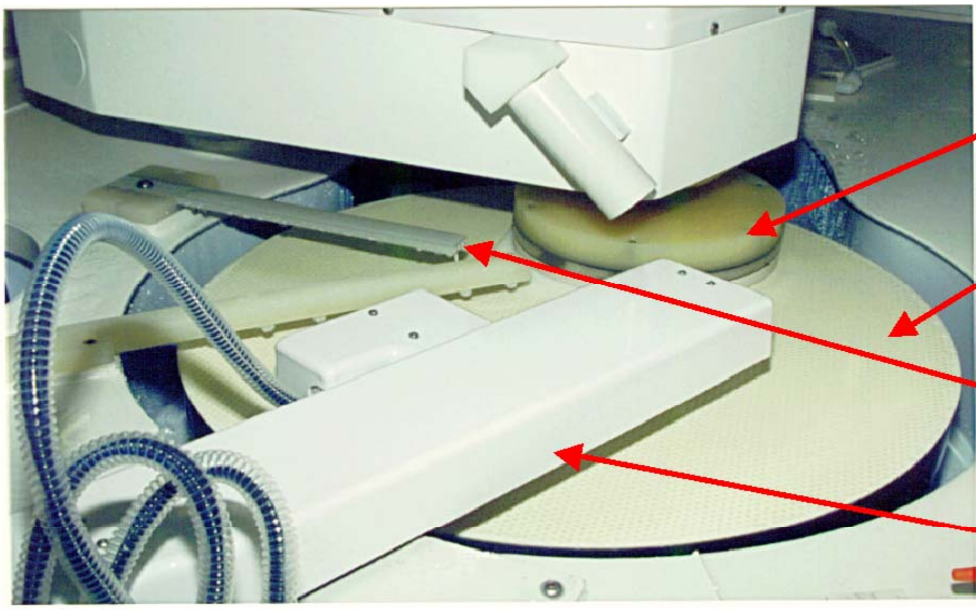
Cross section of trench type DRAM

3.8.2 Equipment configuration



Polishing Pad and Pad Conditioner





carrier

table

slurry dispense

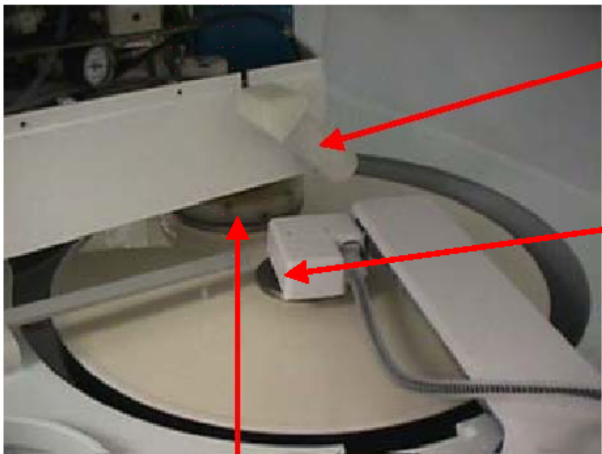
conditioner

source: SpeedFam-Ipec

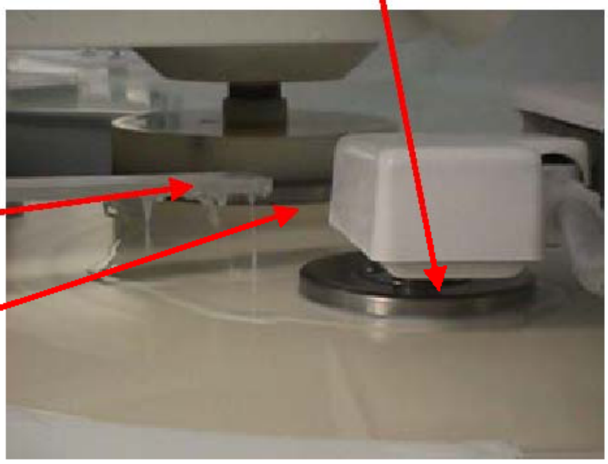
Single head two table (2nd table not visible) machine Ipec 472

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

IR probe



Conditioning disk

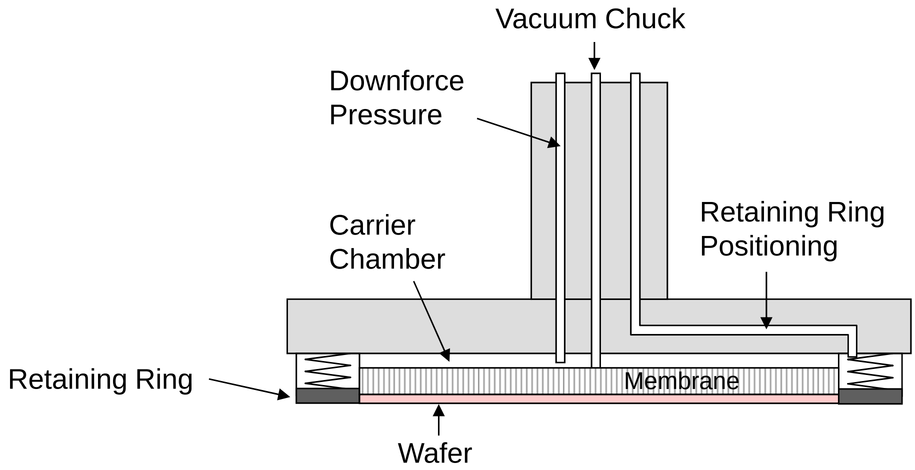


Slurry dispense

Polish head (holds wafer)

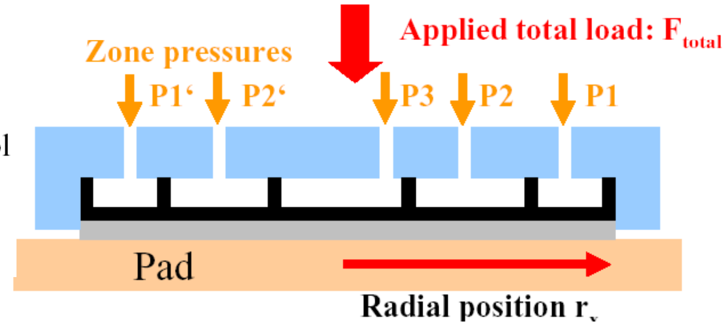
Source: SpeedFam (Anlage IPEC 472)

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

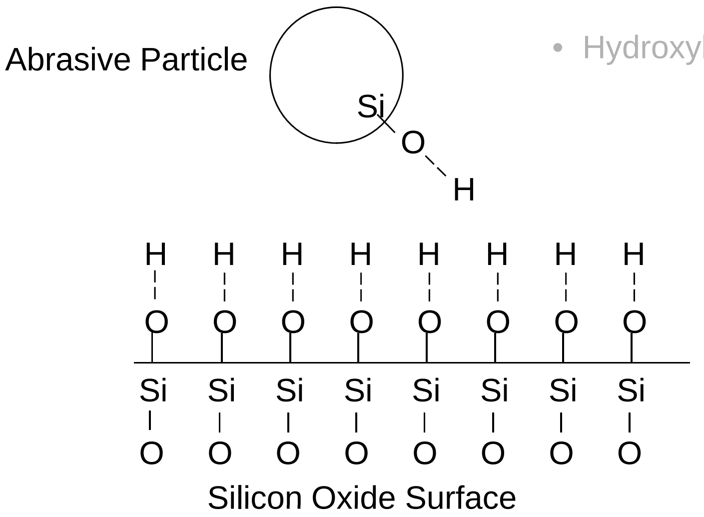
3.8.3.1 Slurries

- 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

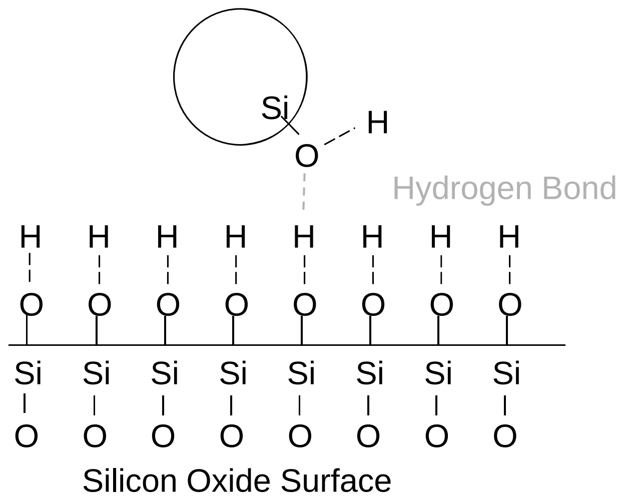
Slurries for oxide (SiO_2) polishing

- 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

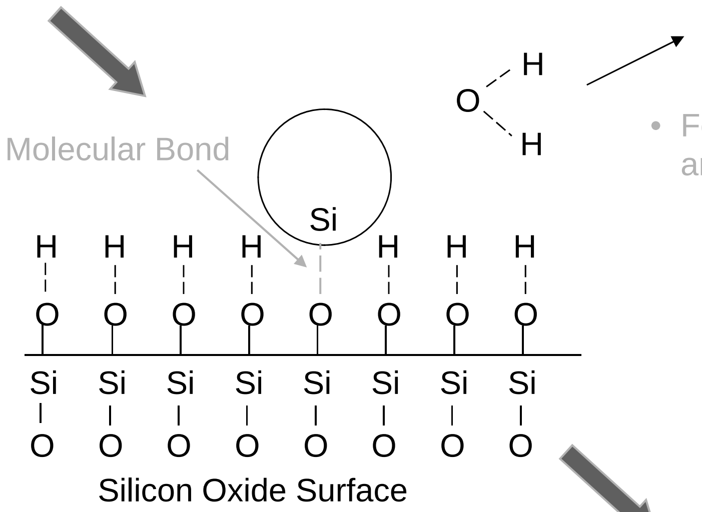


- Hydroxyls on both film and silica surfaces

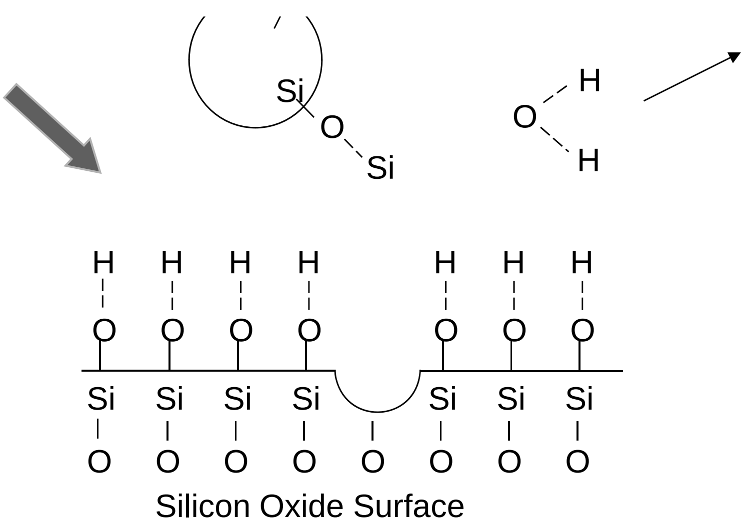


- Formation of hydrogen bonds of silica and surface

Removal mechanism for oxide (SiO_2) polishing



- Formation of molecular bonds of silica and surface

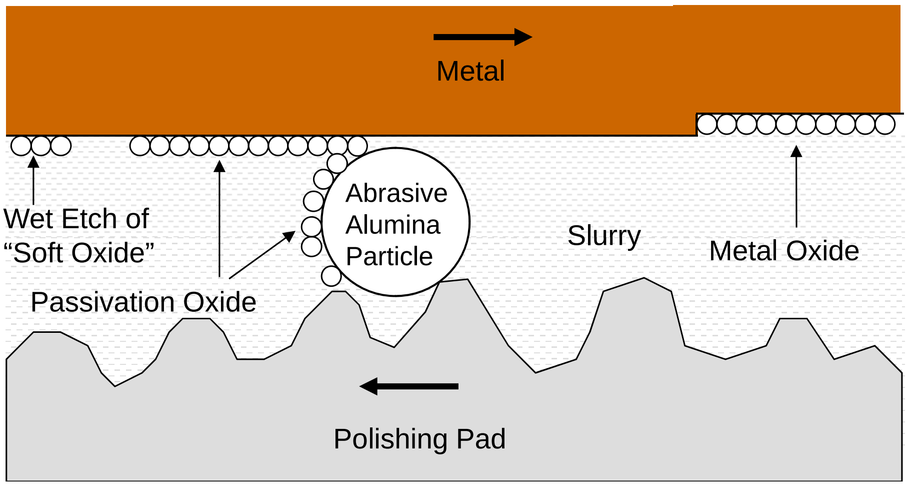


- Mechanical removal of the particles bonded with wafer surface
- Tearing away of atoms or molecules from film on wafer surface

Advanced Integrated Circuit Technology

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



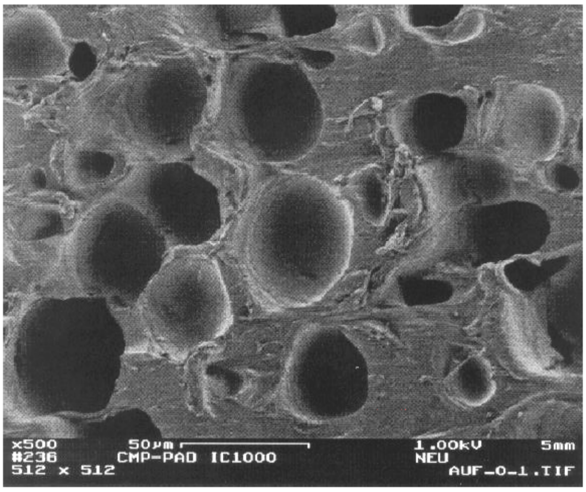
TECHNISCHE UNIVERSITÄT CHEMNITZ
ZfM

Advanced Integrated Circuit Technology

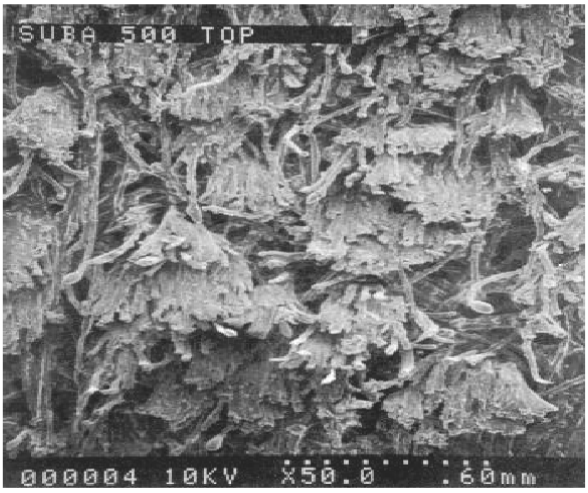
3.8.3.2 Pads

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



source: Rodel

„hard pad" IC1000 by Rodel
-> good planarization performance

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

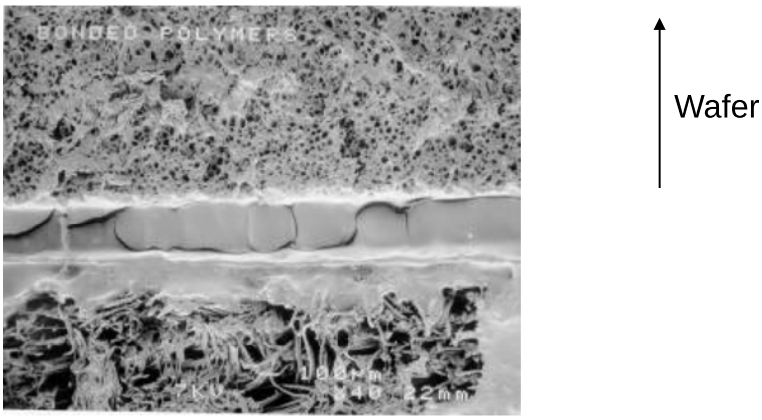
Advanced Integrated Circuit Technology

- 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)

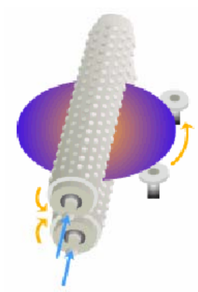
Bonding epoxy layer
(thickness ~ 300 mm)

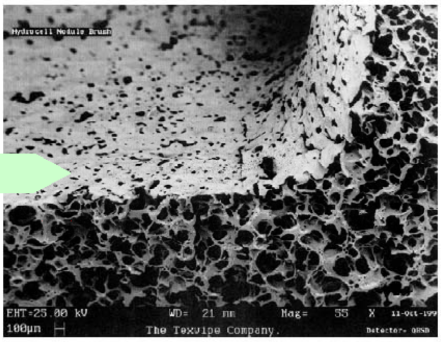
SubaIV layer
(thickness ~ 1.24 mm)



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

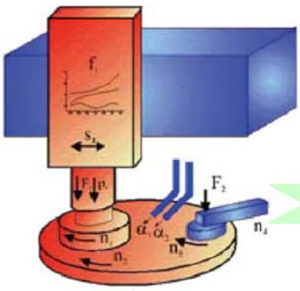
3.8.3.3 Brushes and Conditioner



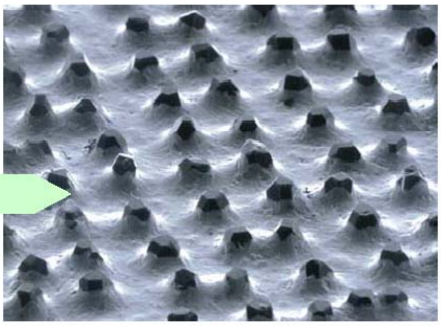


PVA brush for post CMP cleaning
- water / chemistry supply and particle transportation
- application of mechanical forces to particle

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

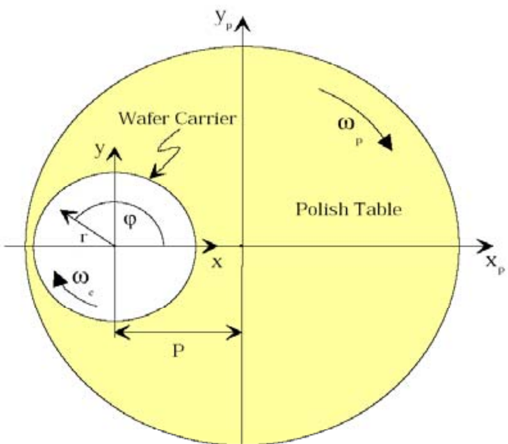
3.8.4 Process Issues

3.8.4.1 Removal rate

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

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

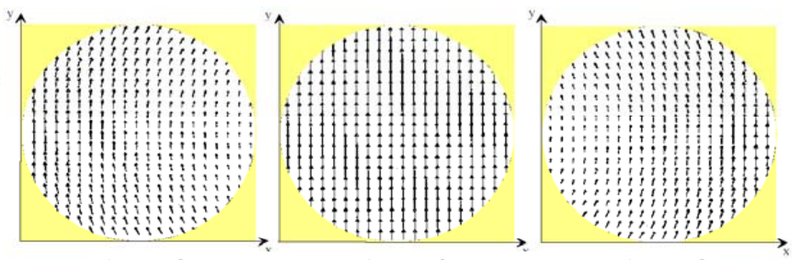
gives only *very crude estimates* for the blanket removal rate
- p is the polishing pressure
- Δv is relative velocity of wafer and pad
- K_p is the Preston coefficient (closely related to the coefficient of friction, depends in reality both on p and Δv)



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

Pressure zone control

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



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

source: Infineon

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
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

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

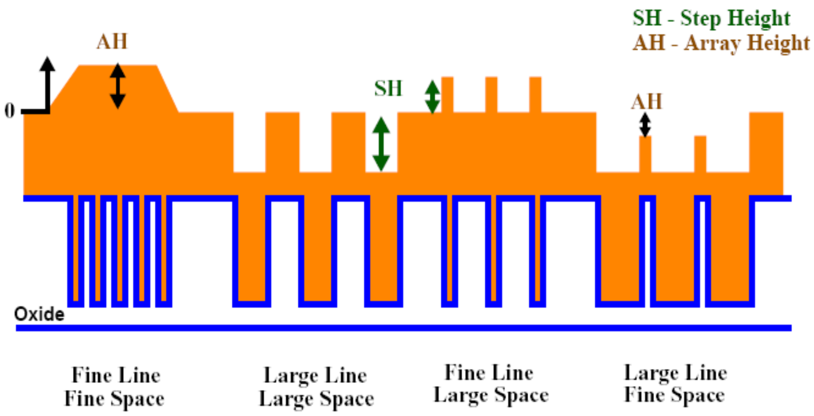
Pattern erosion

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

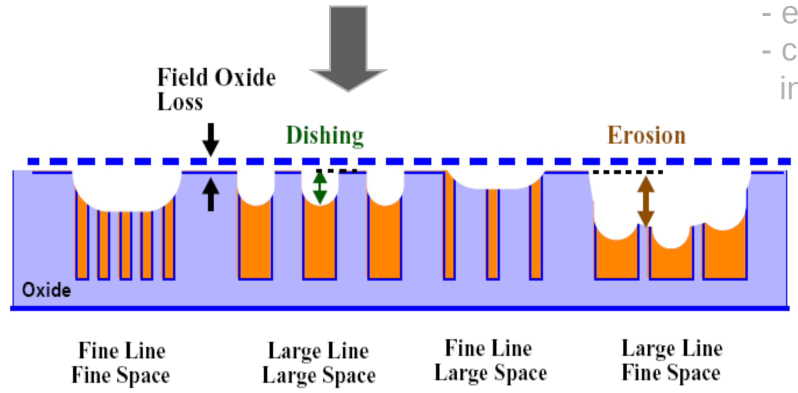
Edge effect

- 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



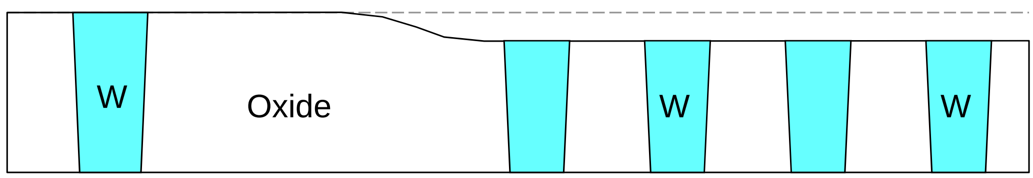
Post-ECP Topography (Park, MIT 2002)



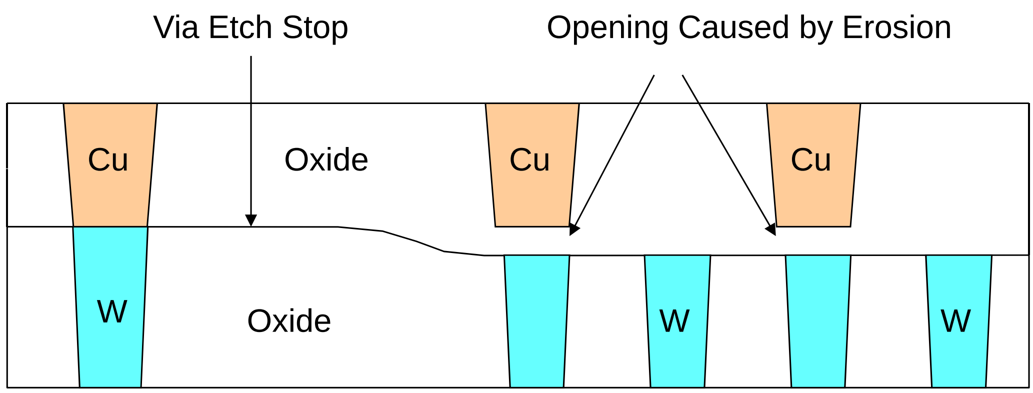
Post-CMP Topography (Park, MIT 2002)

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

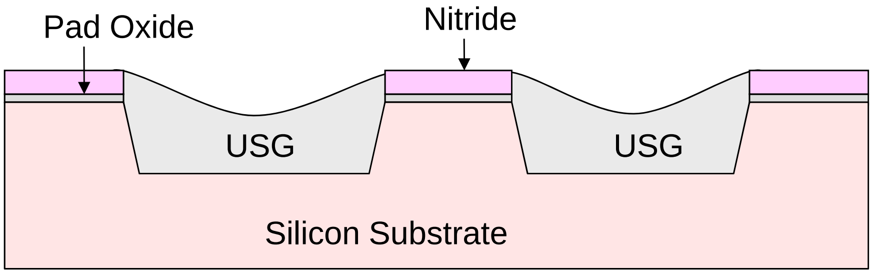
Erosion Caused by High Pattern Density



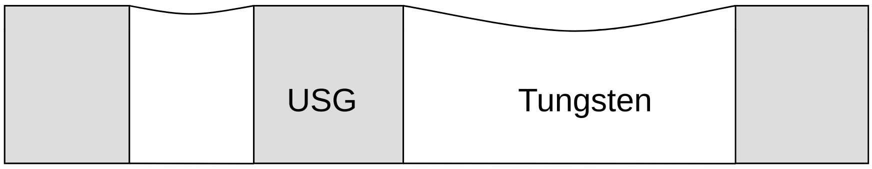
Circuit Opening Caused by Erosion



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

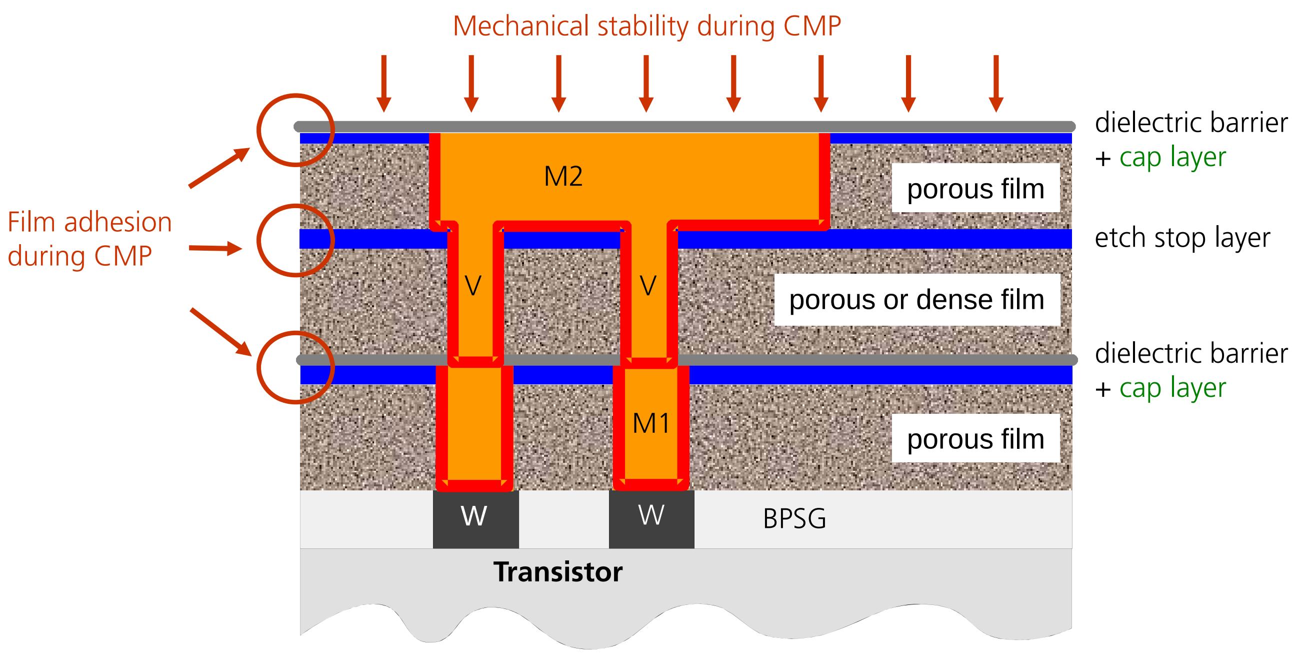
IC Layout and Erosion

- 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.

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

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

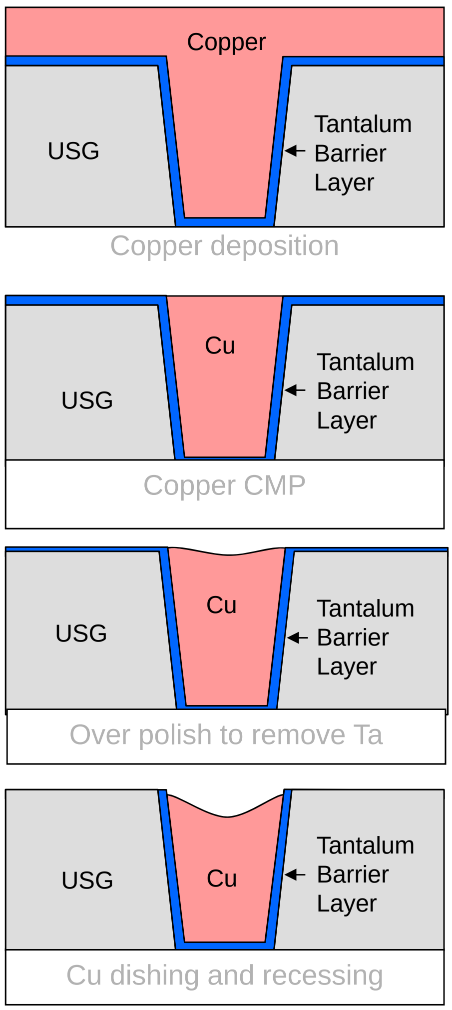
- Amorphous silica abrasives
- Abrasive concentration: <3% (by weight)
- Abrasive size: 20 …25 nm
- Dilution ratio 9:1 (water : slurry)
- Oxidizer type: H_2O_2
- Oxidizer concentration 1.5% (by weight)
- Acidic chemistry
- pH value 4.2 (ready to use mixture)
- 2.0 … 2.5 psi for Cu bulk removal
- 1.0 … 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

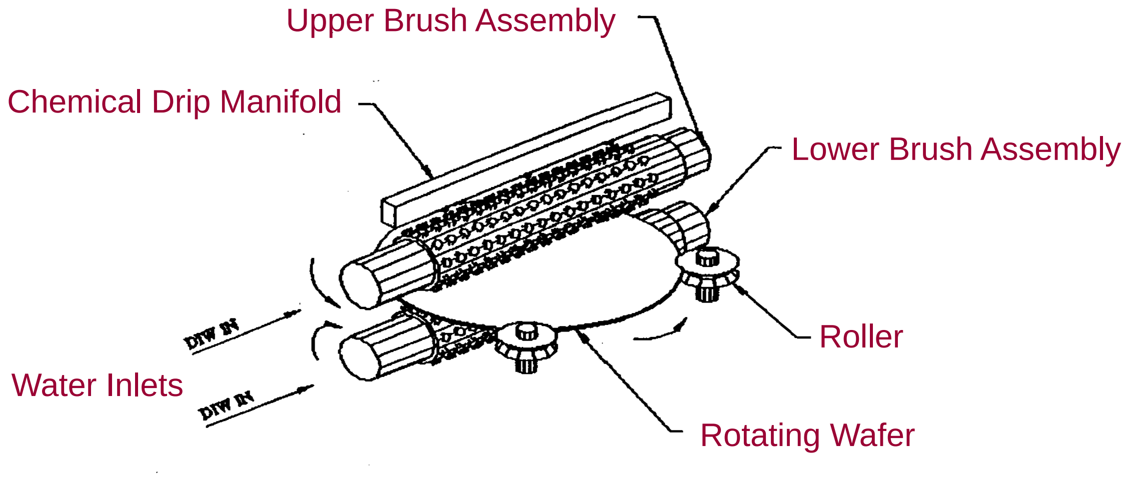


3.8.5 Post CMP Cleaning

- 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 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

Advanced Integrated Circuit Technology

Brush Box



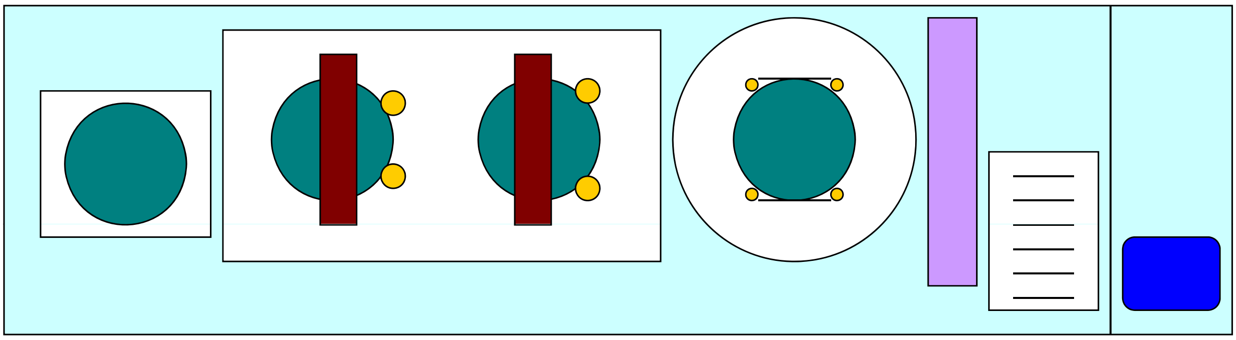
[OnTrak Systems, Inc.]

ZfM Fraunhofer ENAS

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 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