Chapter 12
Chemical Mechanical Polishing

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www2.austin.cc.tx.us/HongXiao/Book.htm

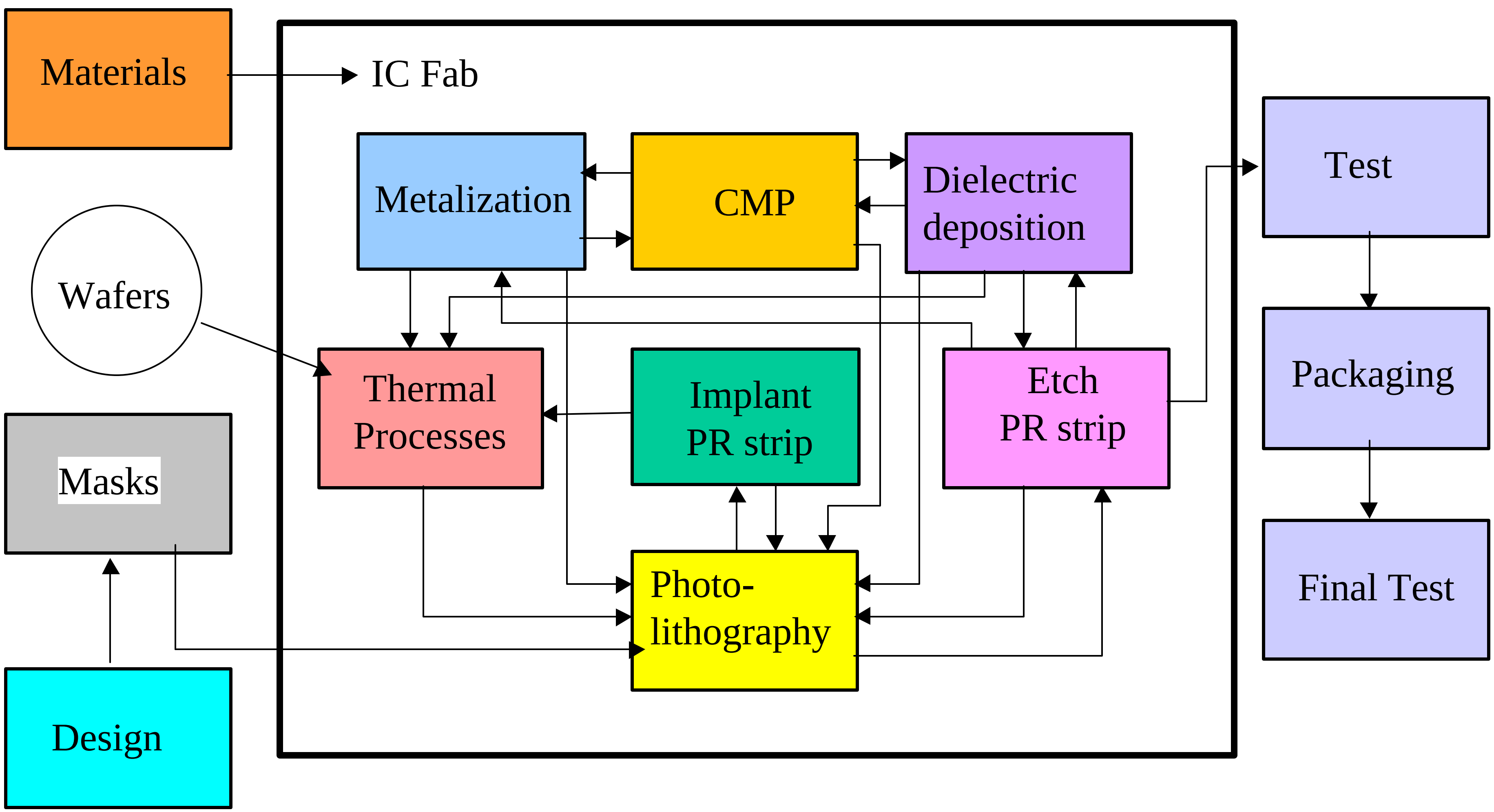
Objectives

- List applications of CMP
- Describe basic structure of a CMP system
- Describe slurries for oxide and metal CMP
- Describe oxide CMP process.
- Describe metal polishing process.
- Explain the post-CMP clean

Overview

- Multi layer metal interconnection
- Planarization of dielectric layers
- Depth of focus require flat surface to achieve high resolution
- The rough dielectric surface can also cause problems in metallization

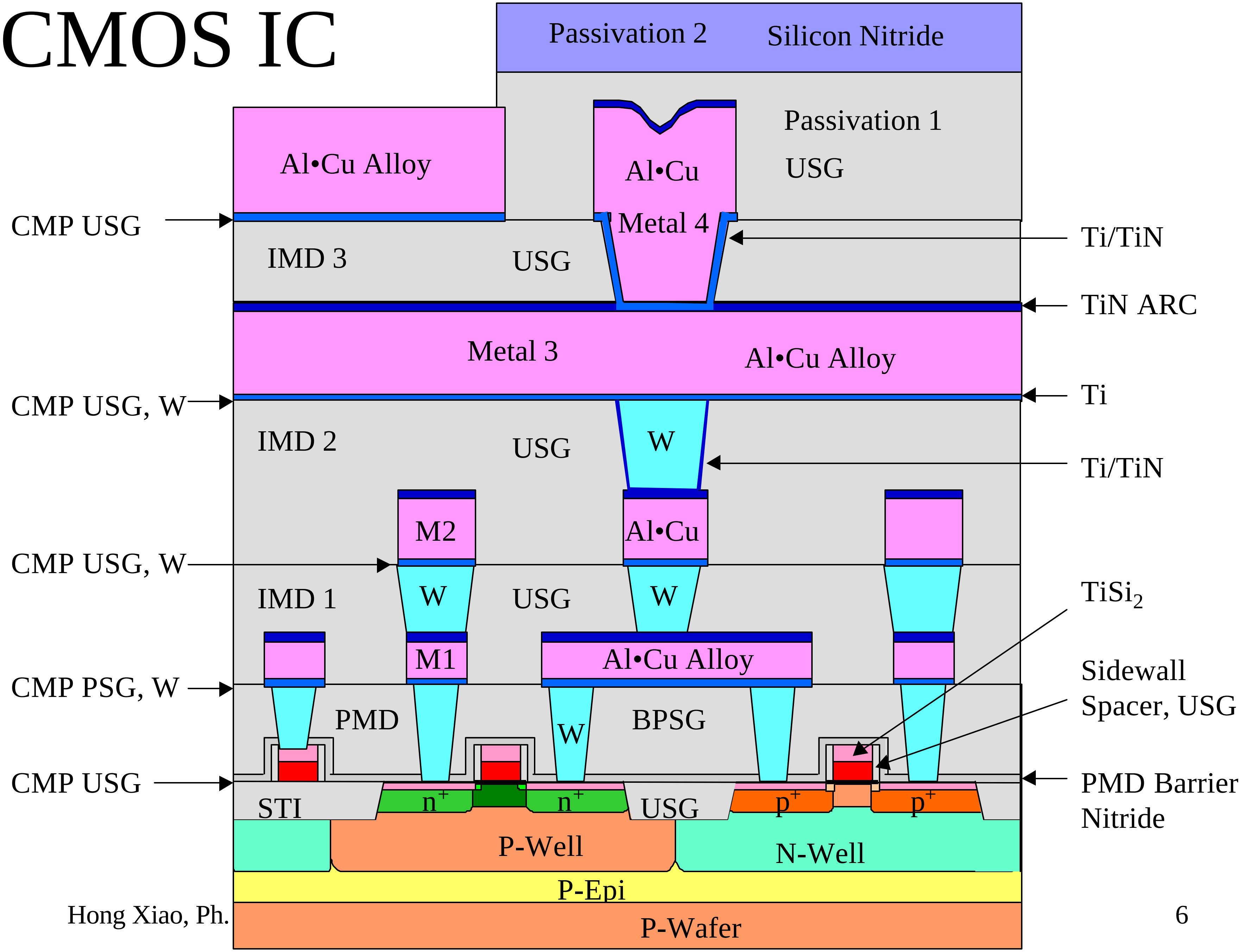
Wafer Process Flow



Tungsten CMP

- Tungsten has been used to form metal plugs
- CVD tungsten fills contact/via holes and covers the whole wafer.
- Need to remove the bulk tungsten film from the surface
- Fluorine based plasma etchback processes
- Tungsten CMP replaced etchback

CMOS IC

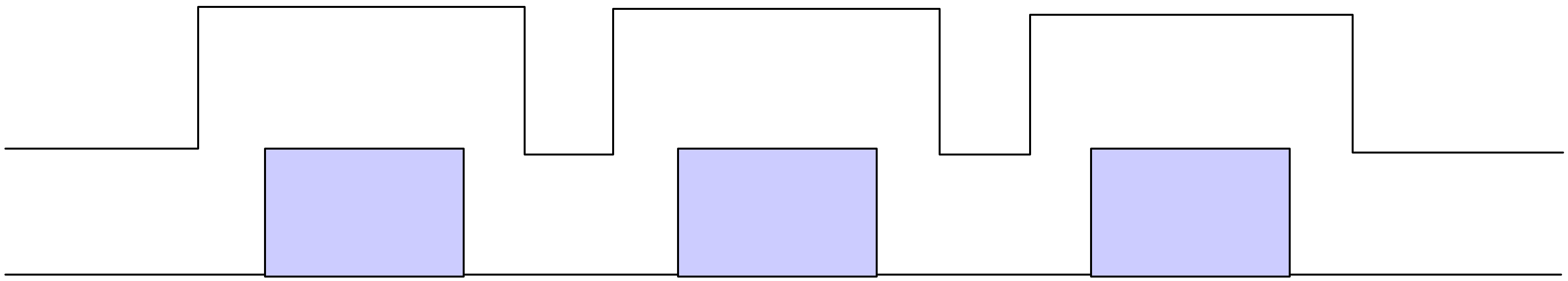


Passivation 2
Silicon Nitride
Passivation 1
USG
Al•Cu Alloy
Al•Cu
Metal 4
CMP USG
IMD 3
USG
Ti/TiN
TiN ARC
Metal 3
Al•Cu Alloy
Ti
CMP USG, W
IMD 2
USG
W
Ti/TiN
M2
Al•Cu
CMP USG, W
IMD 1
W
USG
W
TiSi2
M1
Al•Cu Alloy
Sidewall
Spacer, USG
CMP PSG, W
PMD
W
BPSG
CMP USG
PMD Barrier
Nitride
STI
n+
n+
USG
p+
p+
P-Well
N-Well
P-Epi
P-Wafer

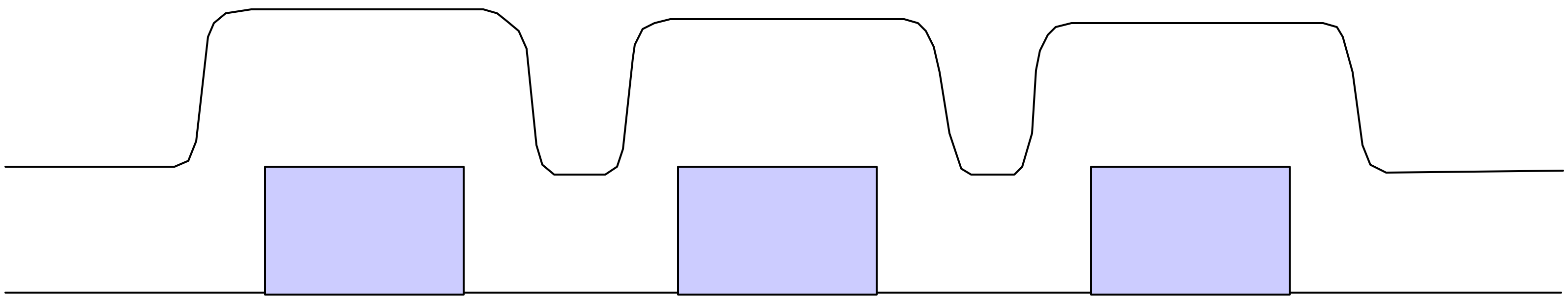
Definition of Planarization

- Planarization is a process that removes the surface topologies, smoothes and flattens the surface
- The degree of planarization indicates the flatness and the smoothness of the surface

Definition of Planarization

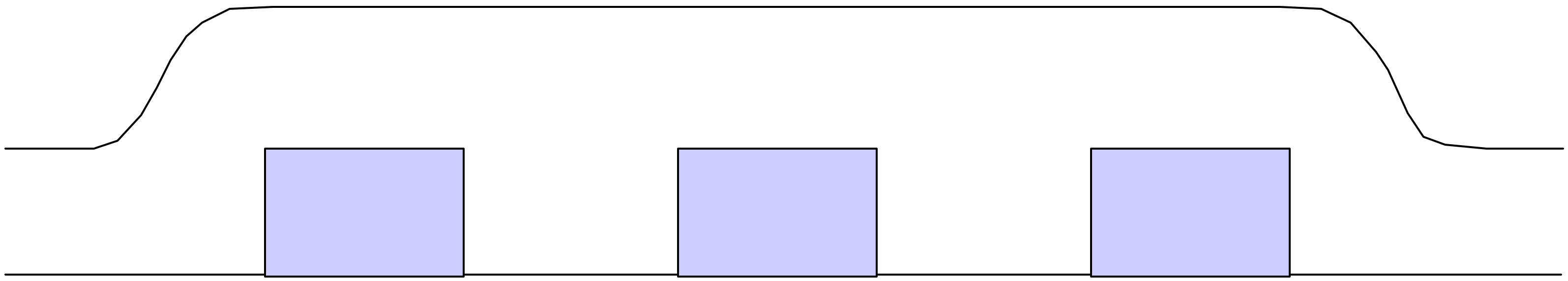


Completely Conformal Film, No Planarization

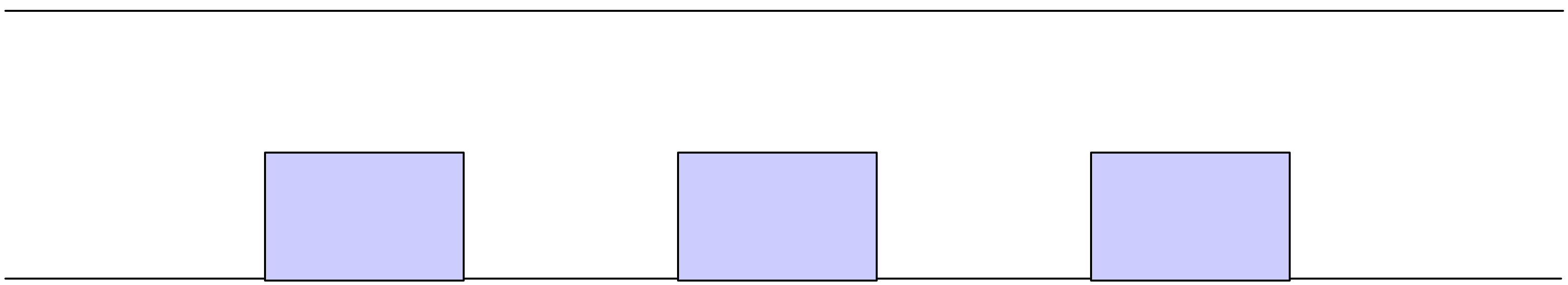


Conformal and Smooth, No Planarization

Definition of Planarization



Partial Planarization

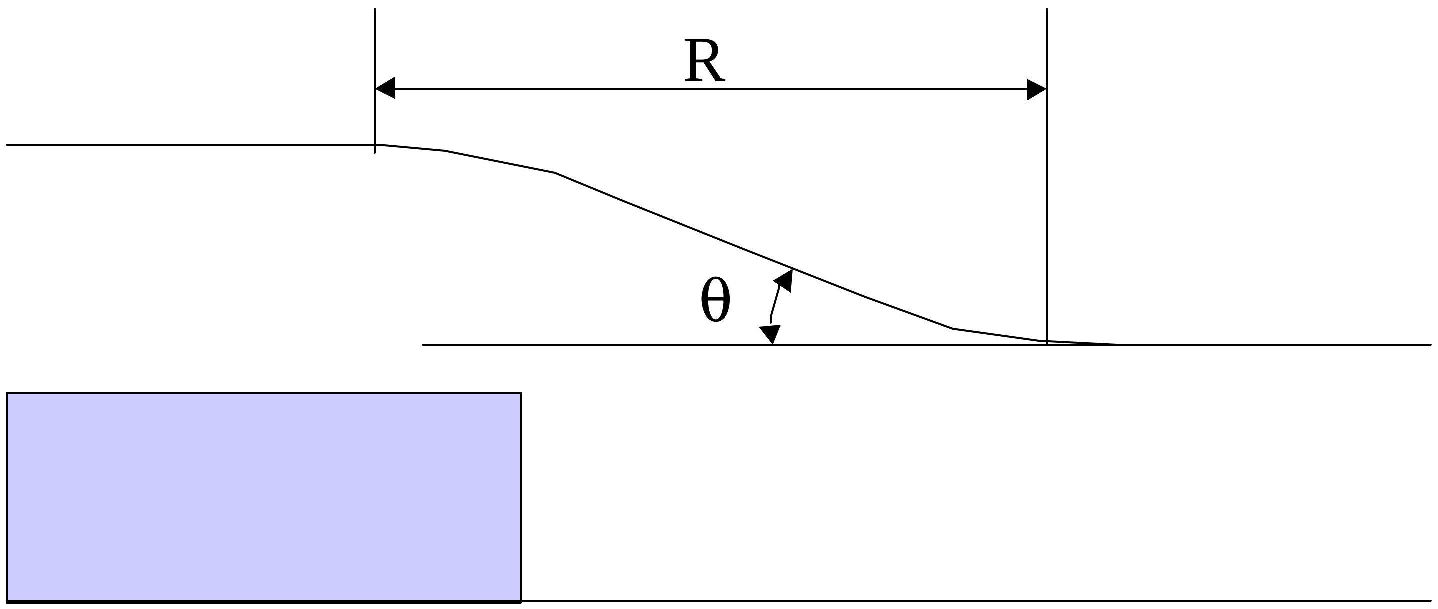


Global Planarization

Degrees of Planarity

Planarity	R(μm)	θ
Surface Smoothing	0.1 to 2.0	> 30
Local Planarization	2.0 to 100	30 to 0.5
Global Planarization	> 100	< 0.5

Definition of Planarity



Planarization

- Smoothing and local planarization can be achieved by thermal flow or etchback
- Global planarization is required for the feature size smaller than 0.35 μm, which can only be achieved by CMP

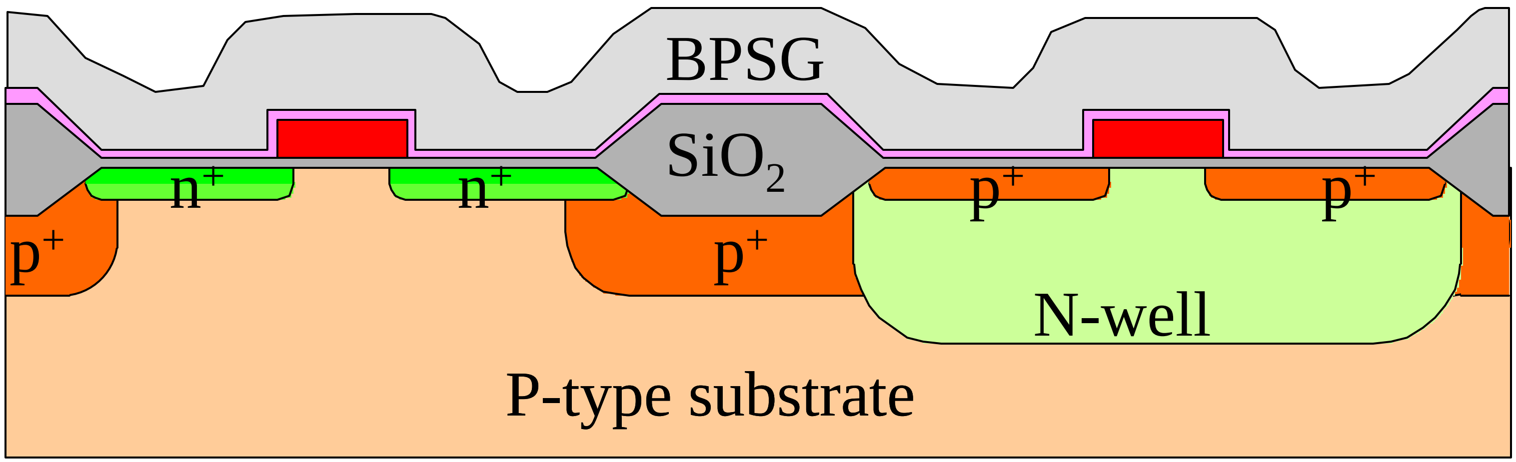
Other Planarization Methods

- Thermal flow
- Sputtering etchback
- Photoresist etchback,
- Spin-on glass (SOG) etchback

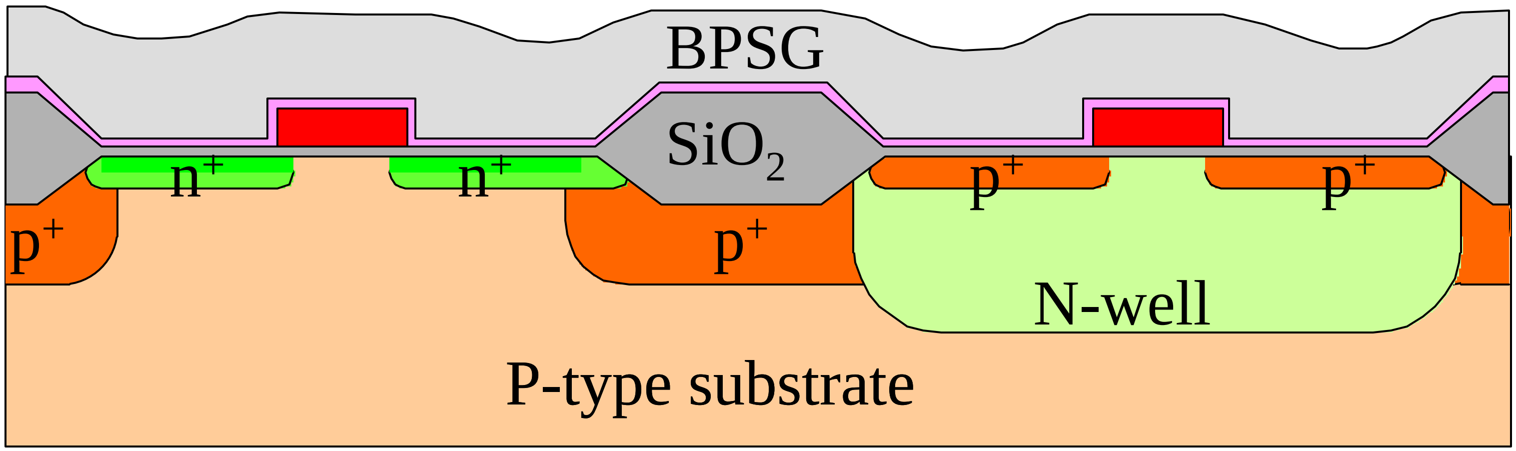
Thermal Flow

- Dielectric planarization
- Pre-metal dielectric
- High temperature, ~1000 °C
- PSG or BPSG, become soft and start to flow due to the surface tension
- Smooth and local planarization

As Deposited



After Thermal Flow



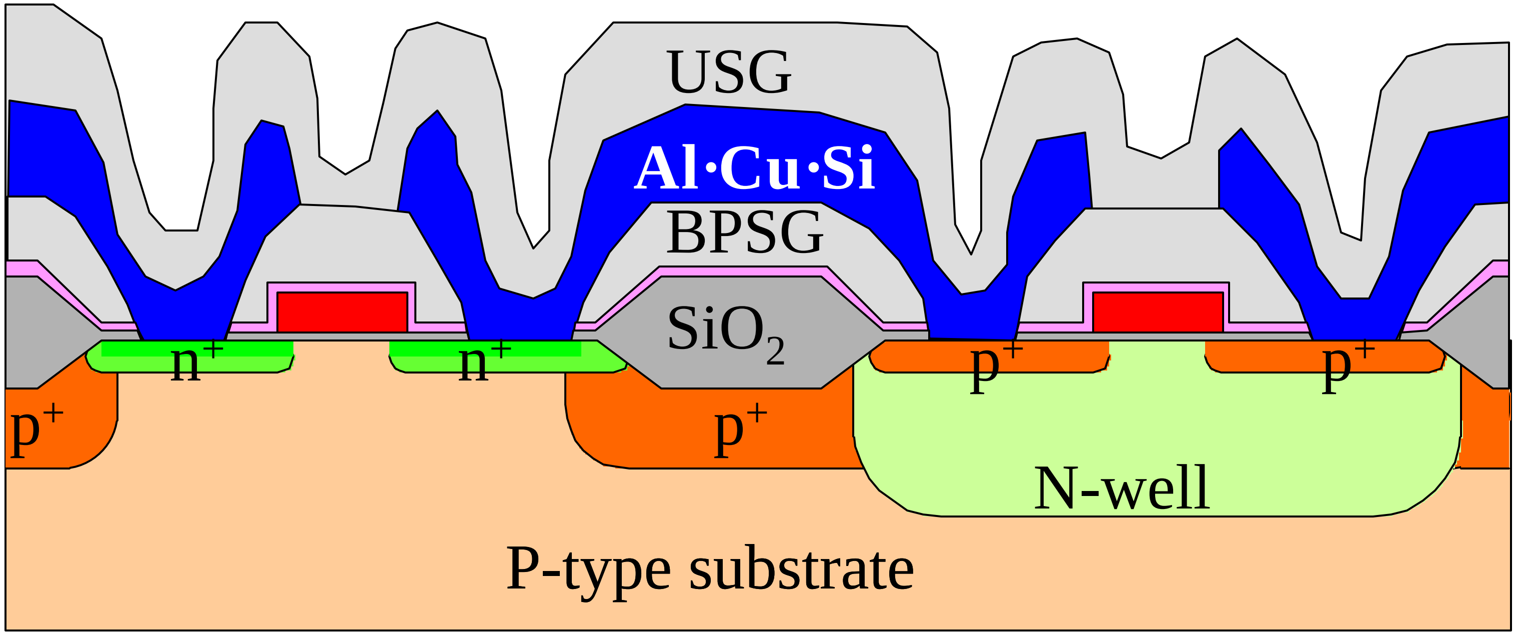
Etch Back

- Reflow temperature is too high for IMD
  - can melt aluminum
- Other planarization method is needed for IMD
- Sputtering etch back and reactive etch back

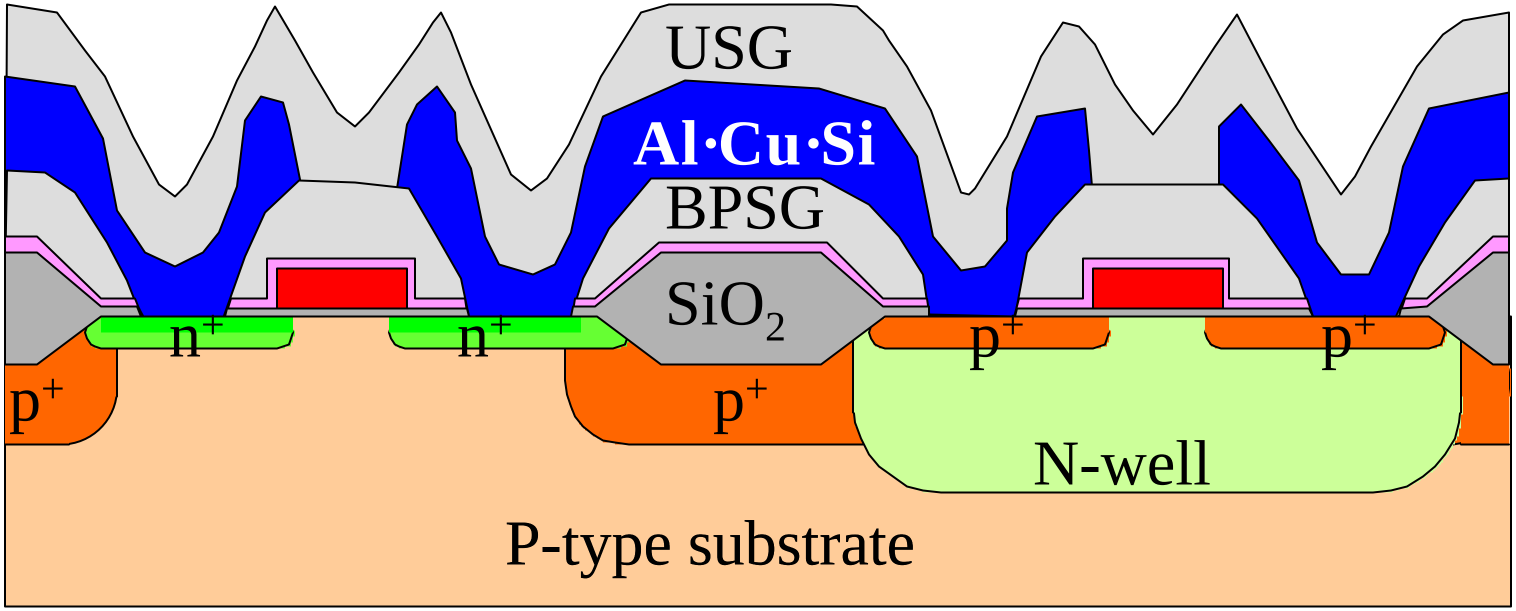
Etch Back

- Argon sputtering etchback chip off dielectric at corner of the gap and taper the openings
- Subsequent CVD process easily fills the gap with a reasonable planarized surface
- Reactive ion etchback process with CF_4/O_2 chemistry further planarizes the surface

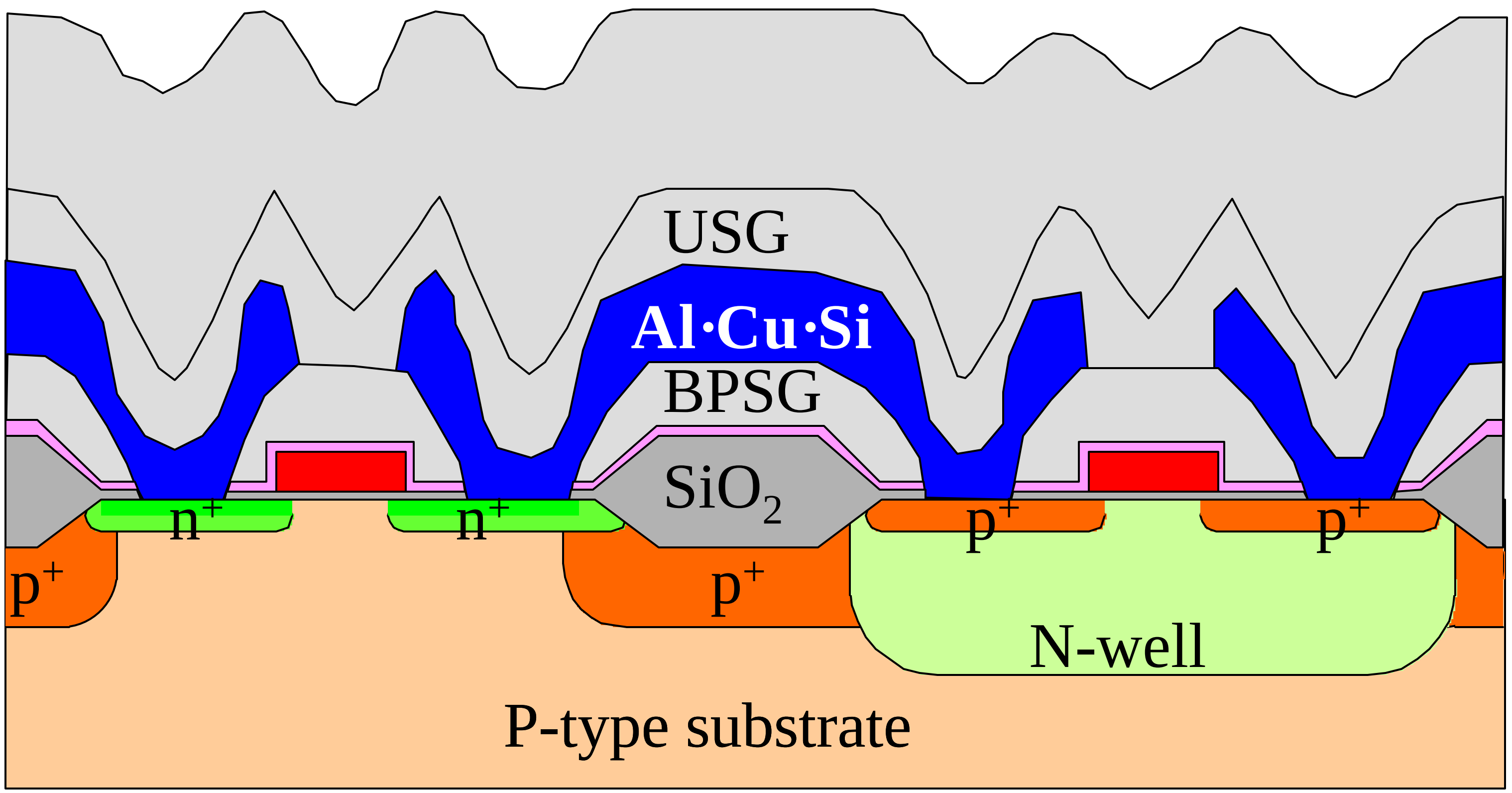
CVD USG



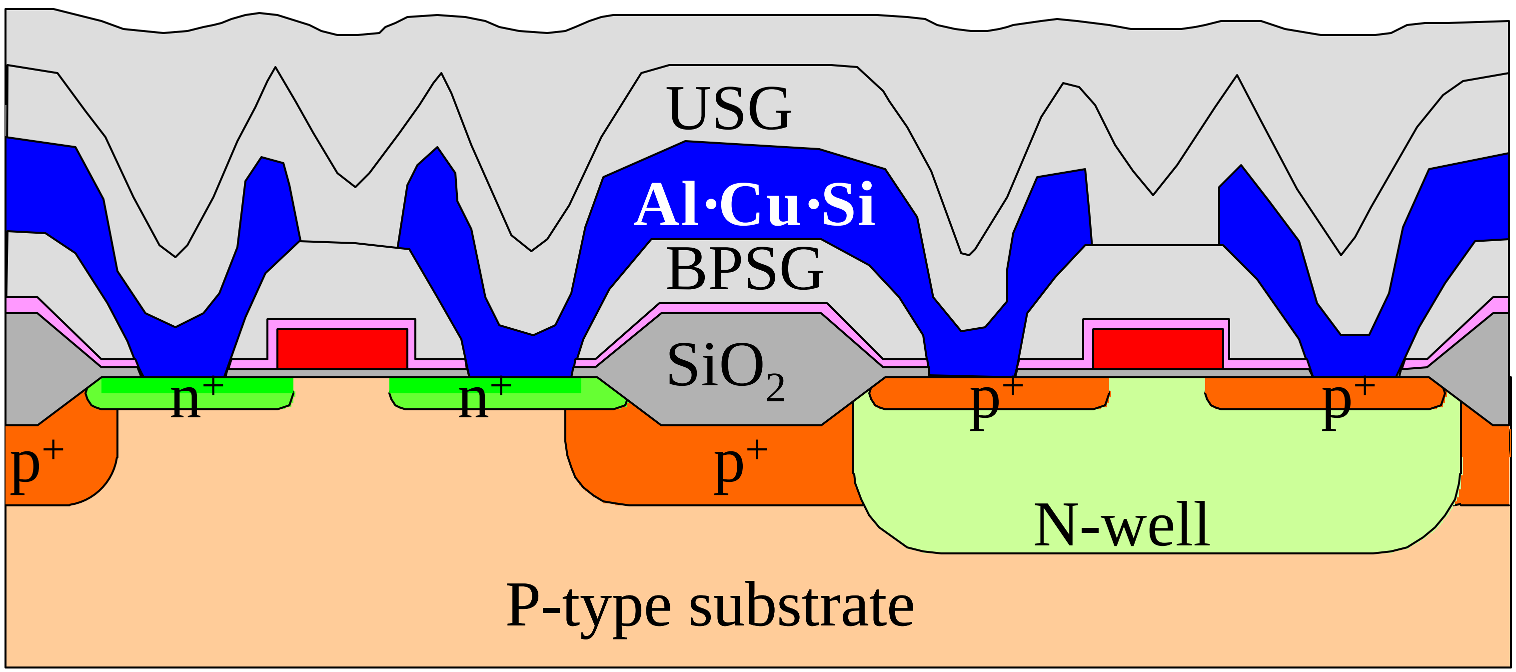
Sputtering Etch Back of USG



CVD USG



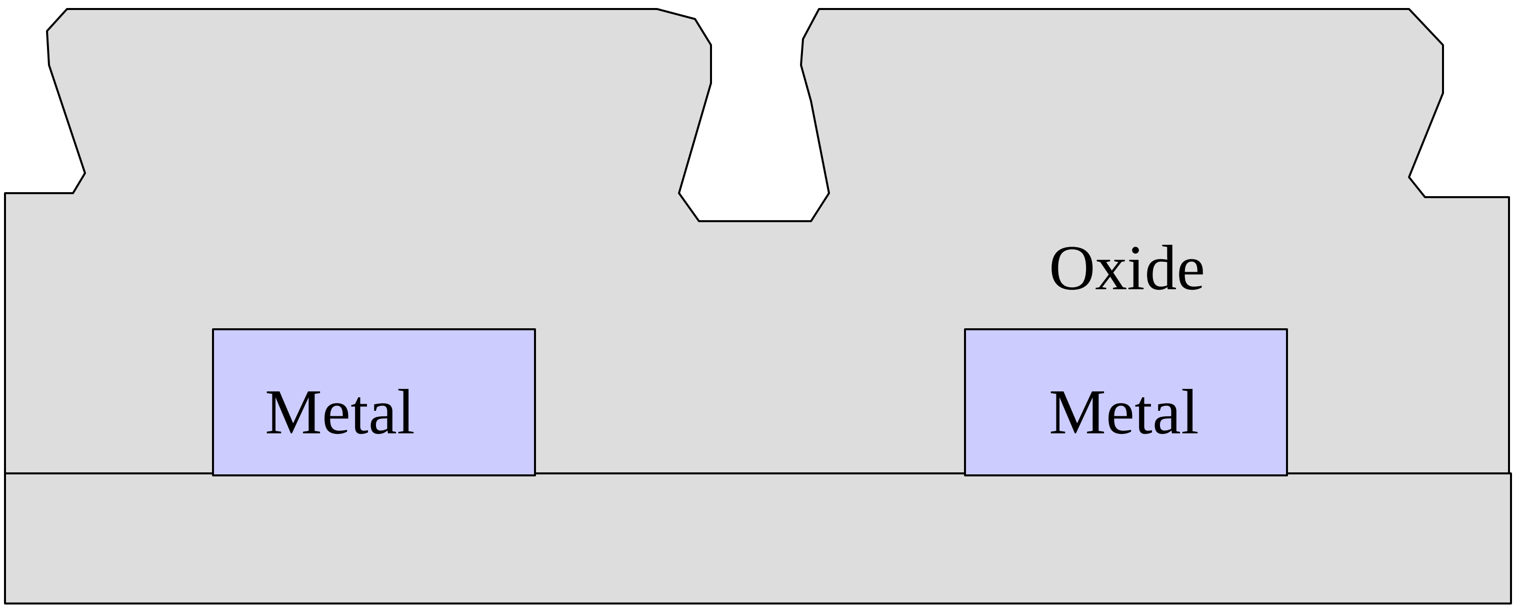
Reactive Etch Back of USG



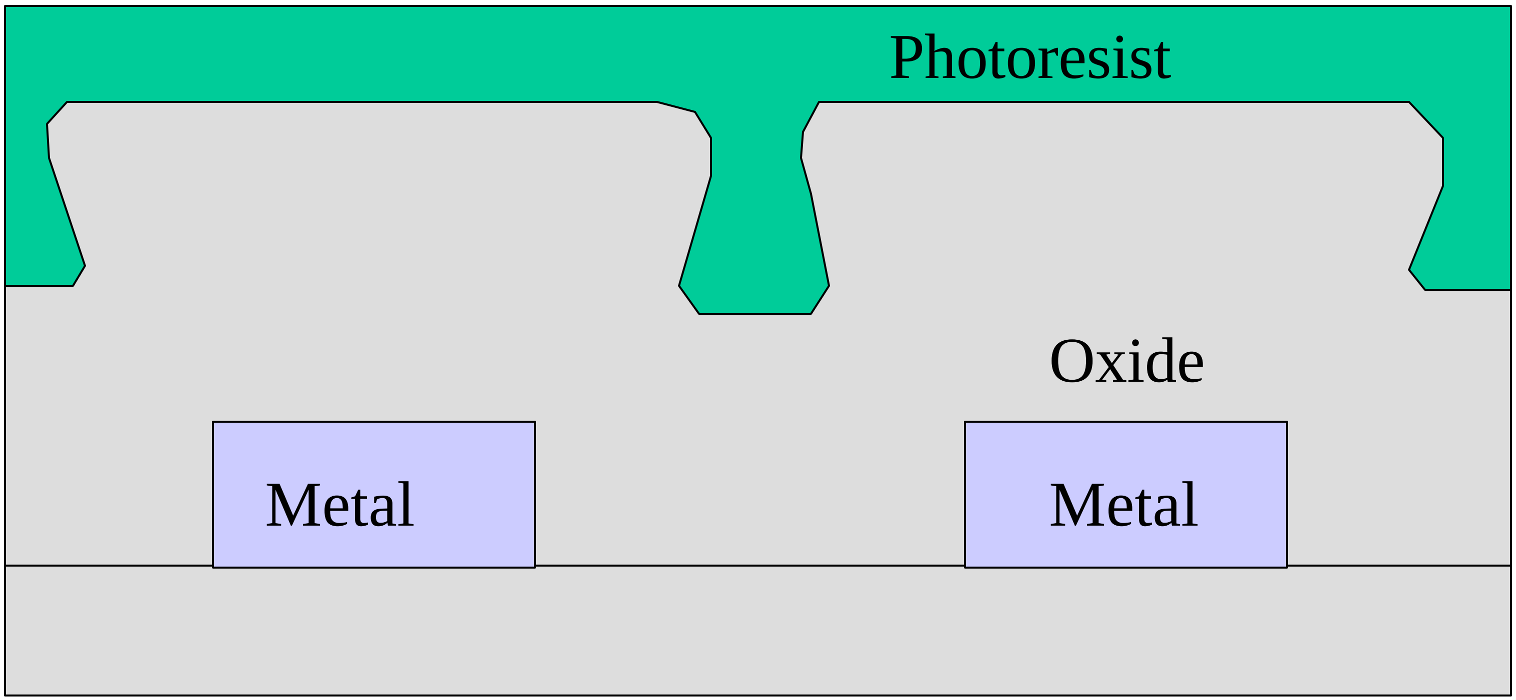
Photoresist Etchback

- PR spin-coats can baking
- Planarized solid thin film on wafer surface
- Plasma etch process with CF_4/O_2 chemistry
- Oxide etched by F and PR by O
- Adjusting CF_4/O_2 flow ratio allows 1:1 of oxide to PR selectivity.
- Oxide could be planarized after etchback

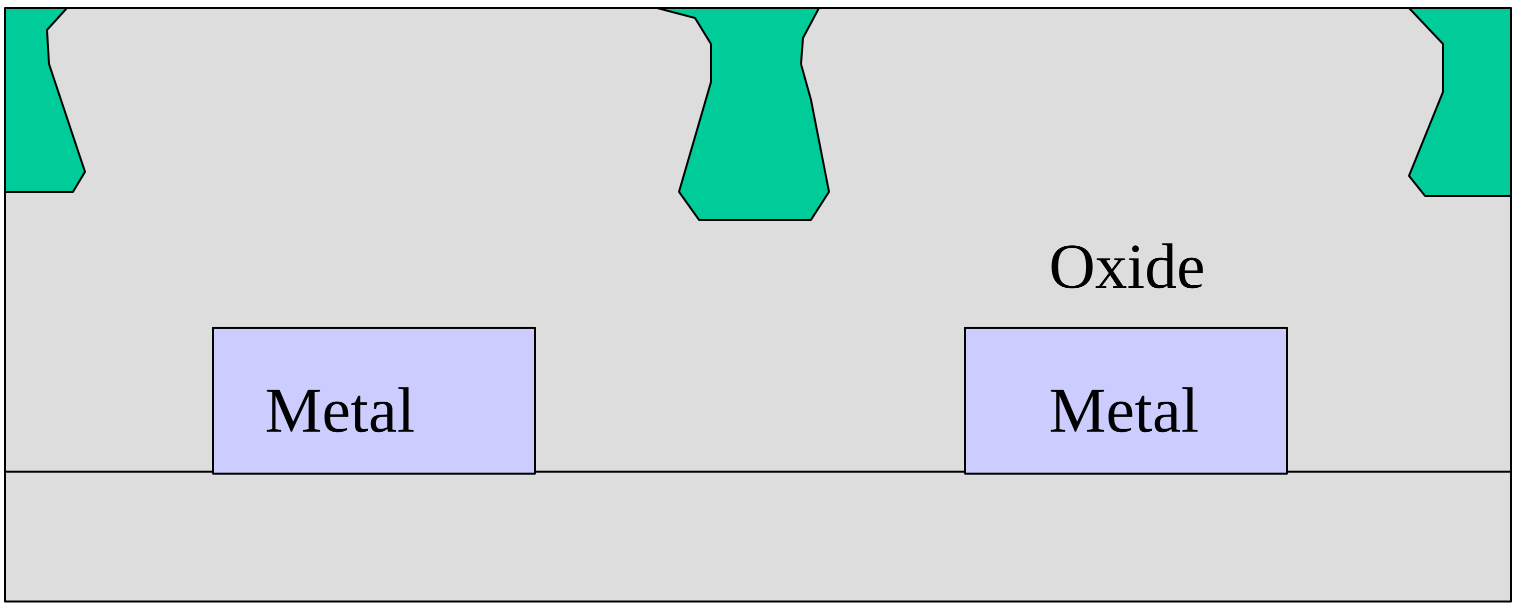
After Oxide Deposited



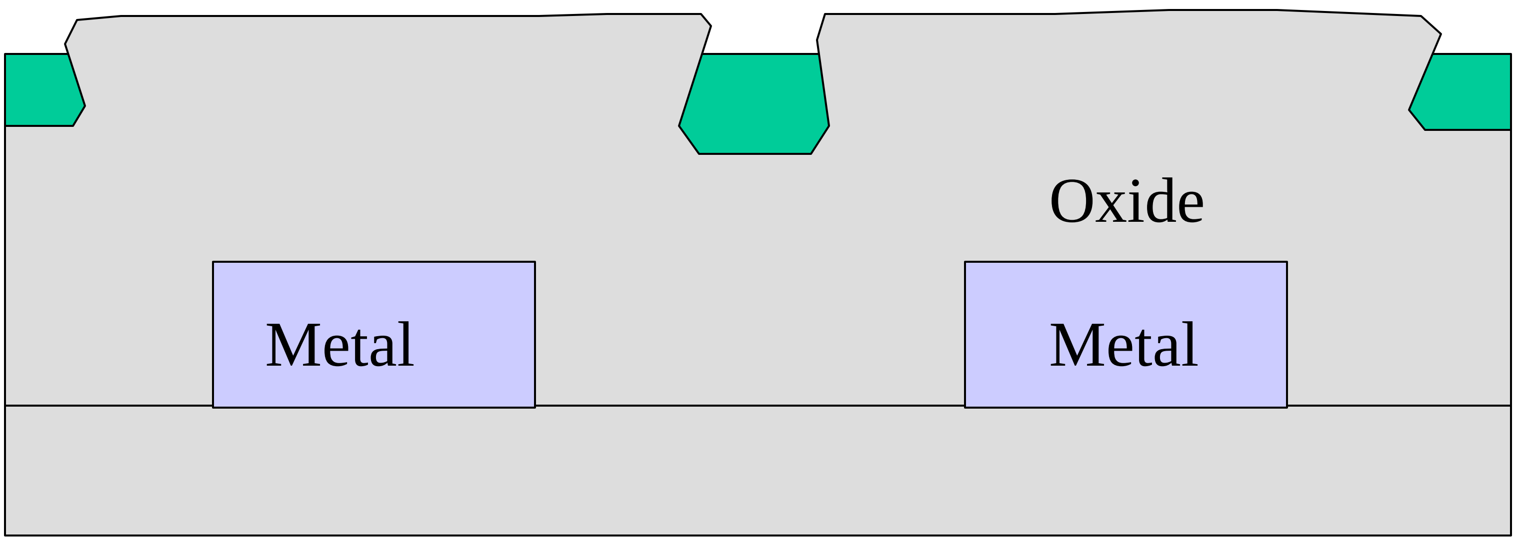
Photoresist Coating and Baking



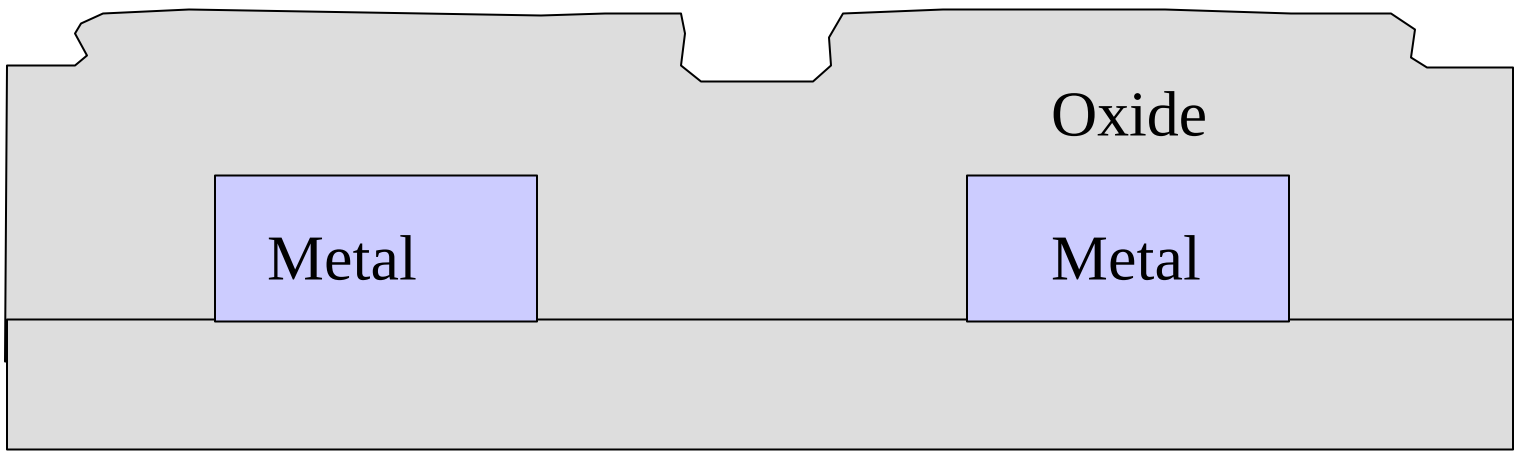
Photoresist Etchback



Photoresist Etchback



Photoresist Etchback



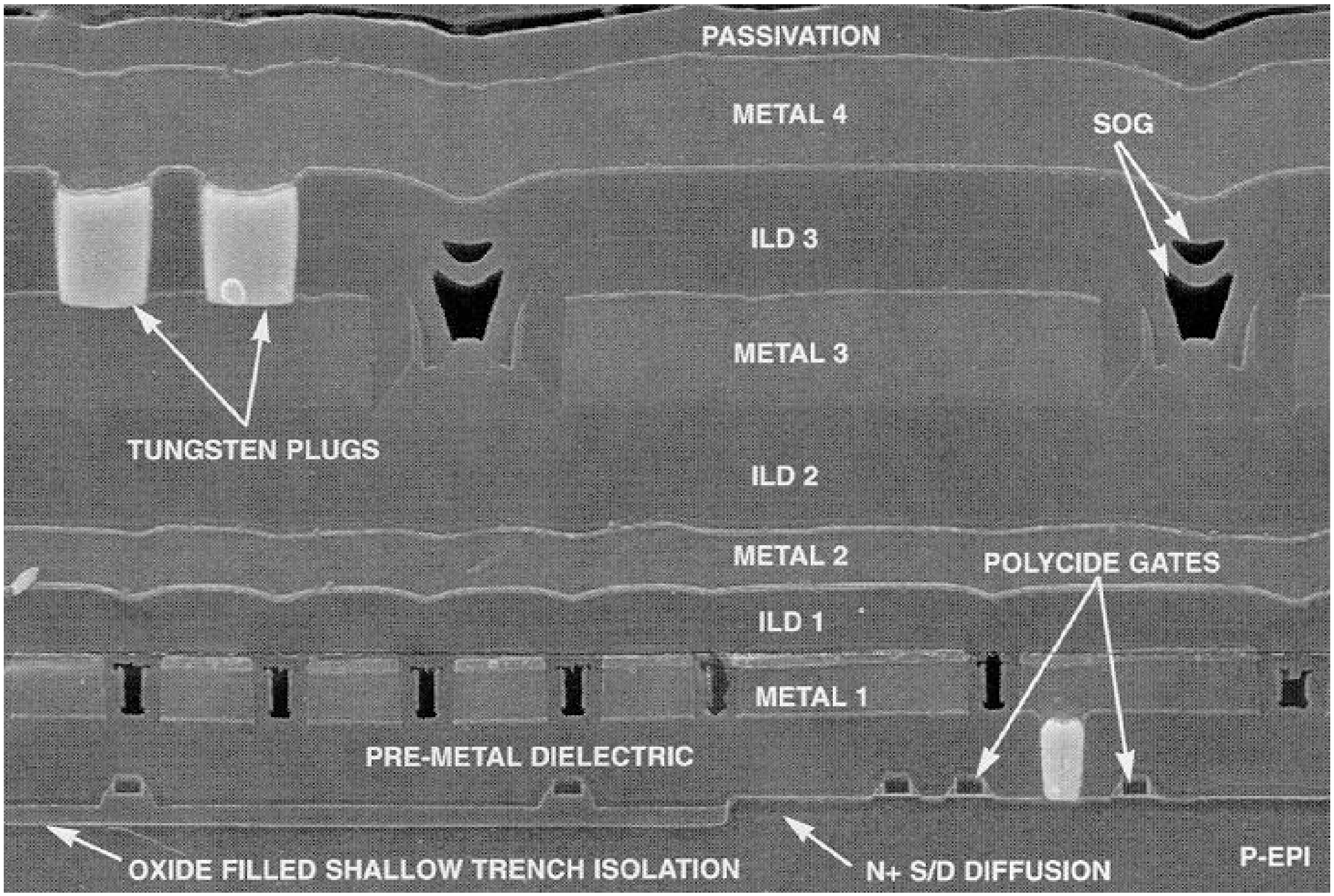
Photoresist Etchback

- When F etch oxide, O will be released
- Higher PR etch rate due to extra oxygen
- PR etchback can't planarize very well
- After the PR etchback, dielectric film surface is flatter than it is just deposited.
- In some cases, more than one PR etchback is needed to achieve required flatness

SOG Etchback

- SOG replaces PR
- Advantage: some SOG can stay on the wafer surface to fill the narrow gaps
- PECVD USG liner and cap layer
- USG/SOG/USG gap fill and surface planarization
- Sometimes, two SOG coat, cure and etchback processes are used

SOG Etchback



Necessity of CMP

- Photolithography resolution $R = K_1 l/NA$
- To improve resolution, $NA\uparrow$ or $l\downarrow$
- $DOF = K_2 l/2(NA)^2$, both approaches to improve resolution reduce *DOF*
- DOF is about 2,083 Å for 0.25 μm and 1,500 Å for 0.18 μm resolution.
- Here we assumed $K_1=K_2$, $l=248$ nm (DUV), and $NA=0.6$

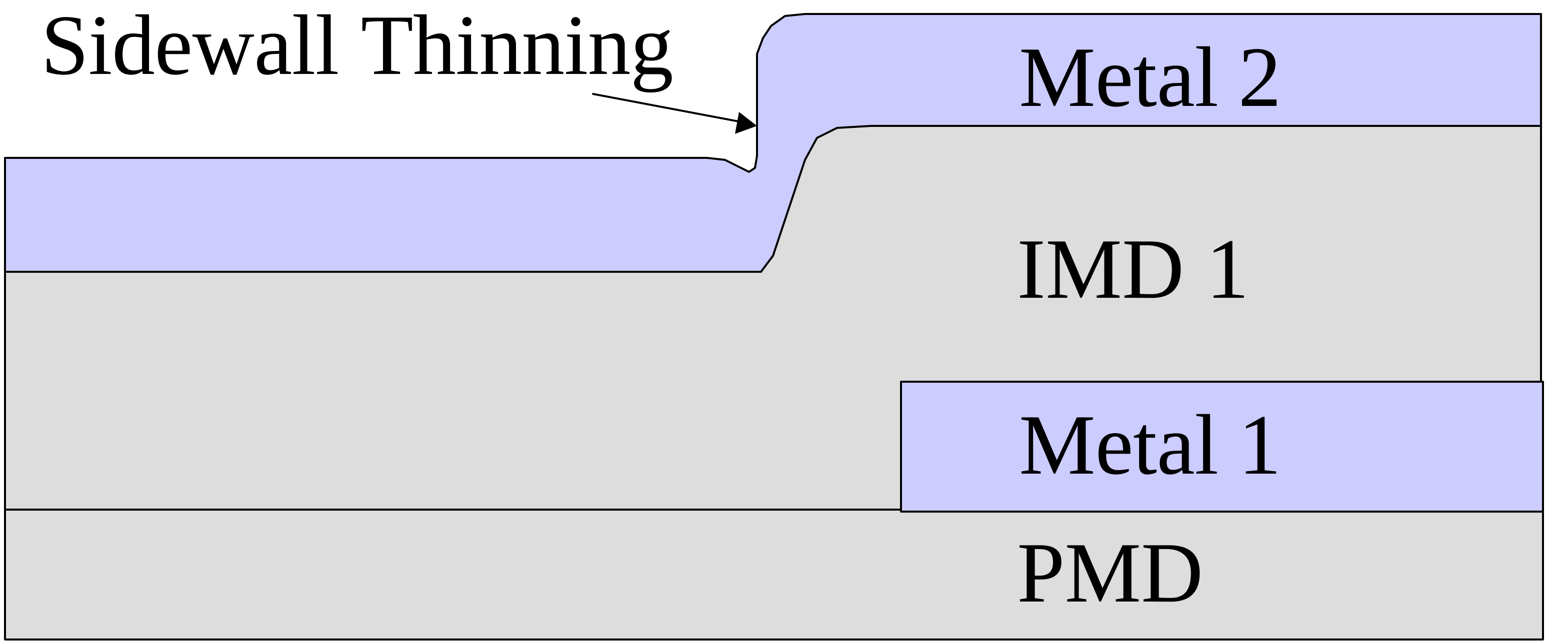
Necessity of CMP

- 0.25 μm pattern require roughness < 2000 Å
- Only CMP can achieve this planarization
- When feature size > 0.35 μm, other methods can be used

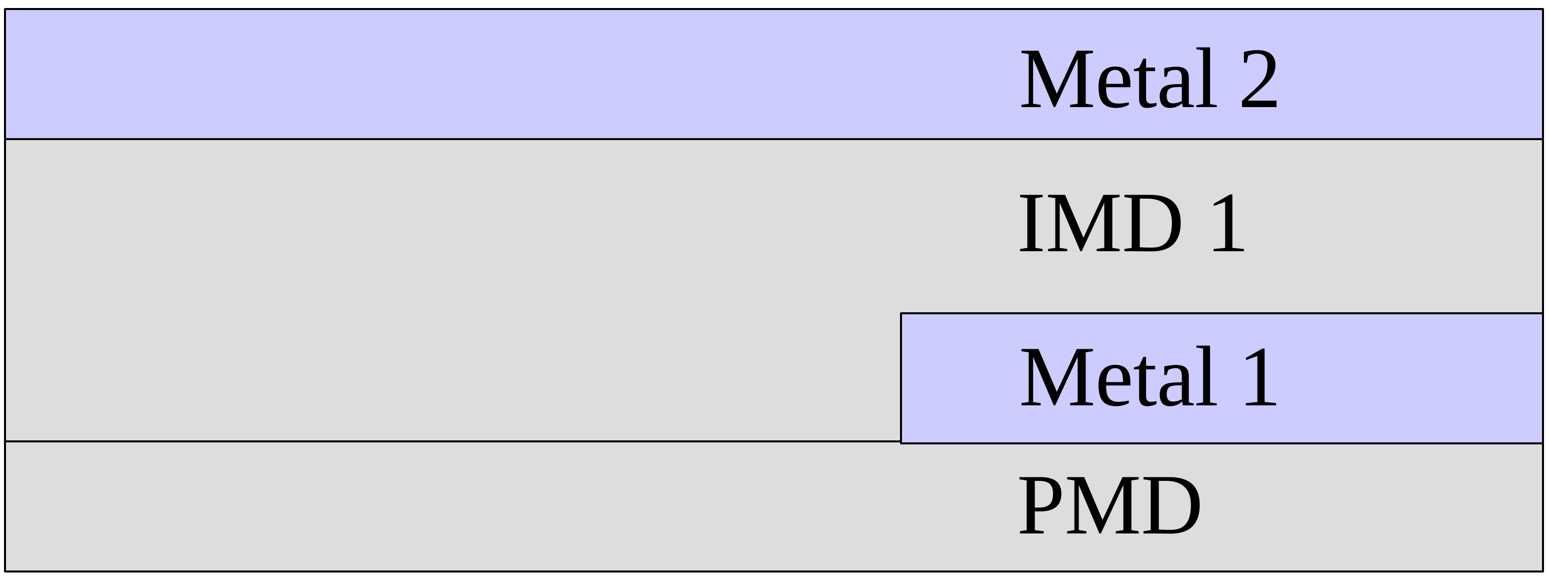
Advantages of CMP

- Planarized surface allows higher resolution of photolithography process
- The planarized surface eliminates sidewall thinning because of poor PVD step coverage

Metal Line Thinning Due to the Dielectric Step



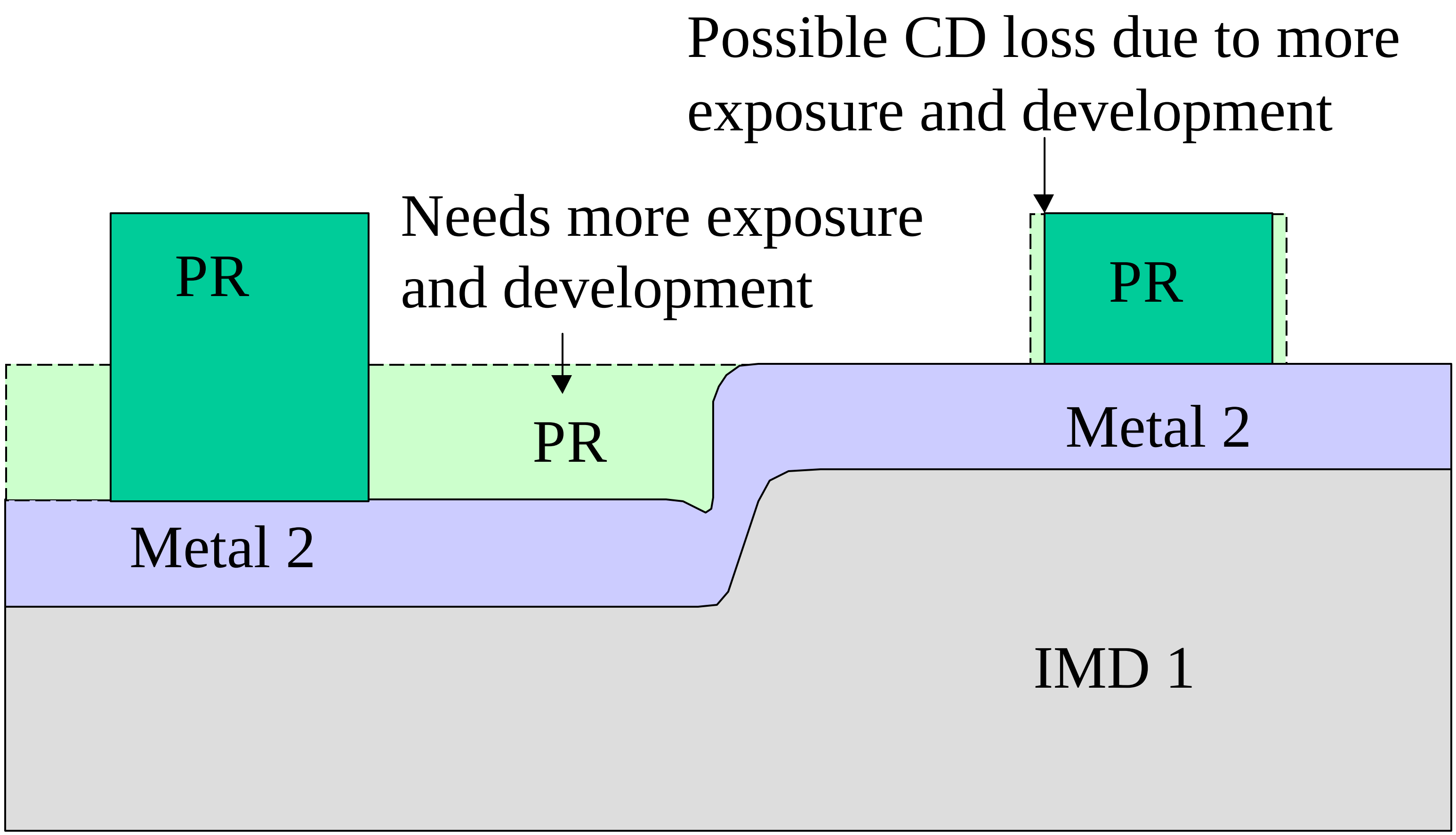
Planarized Dielectric Surface, no Metal Line Thinning Effect



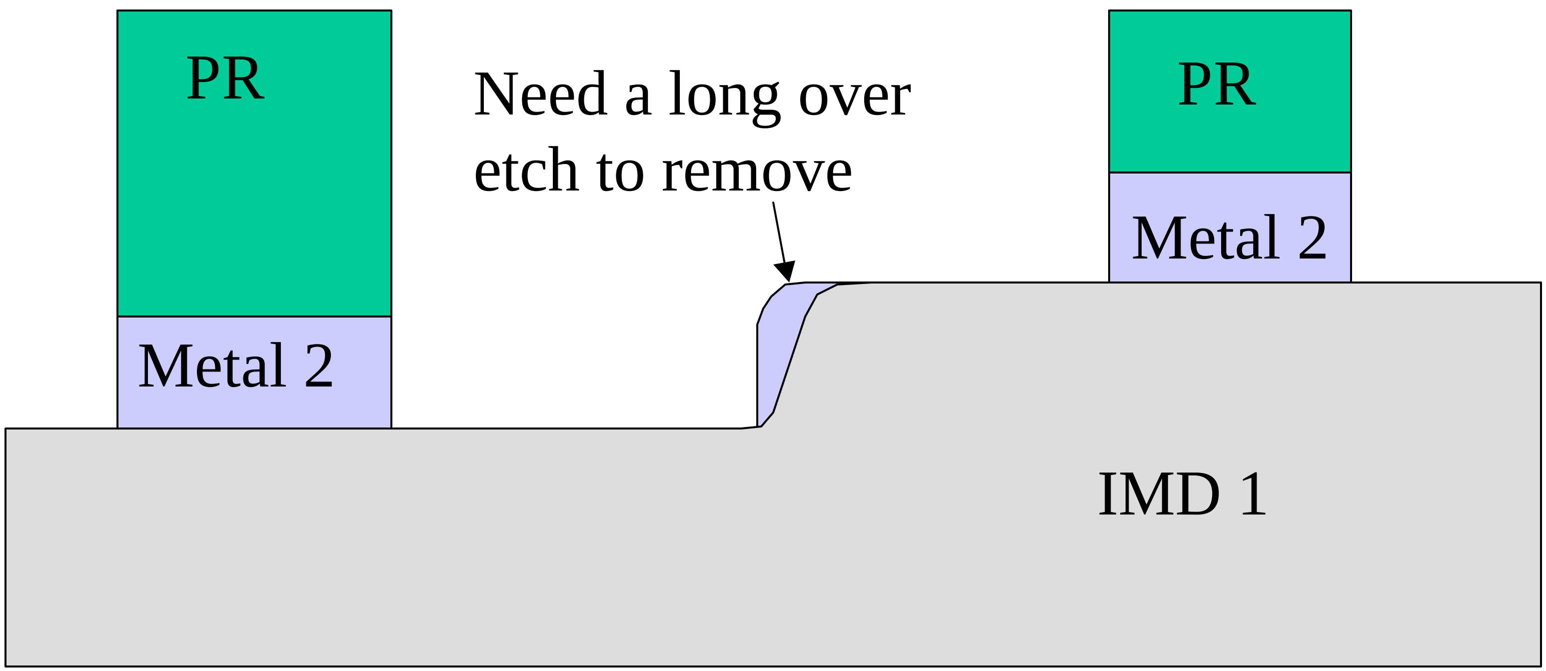
Advantages of CMP

- Eliminate the requirement of excessive exposure and development to clear the thicker photoresist regions due to the dielectric steps
  - This improves the resolution of via hole and metal line pattering processes
- Uniform thin film deposition
  - Reduce required over etch time
  - Reduce chance of undercut or substrate loss

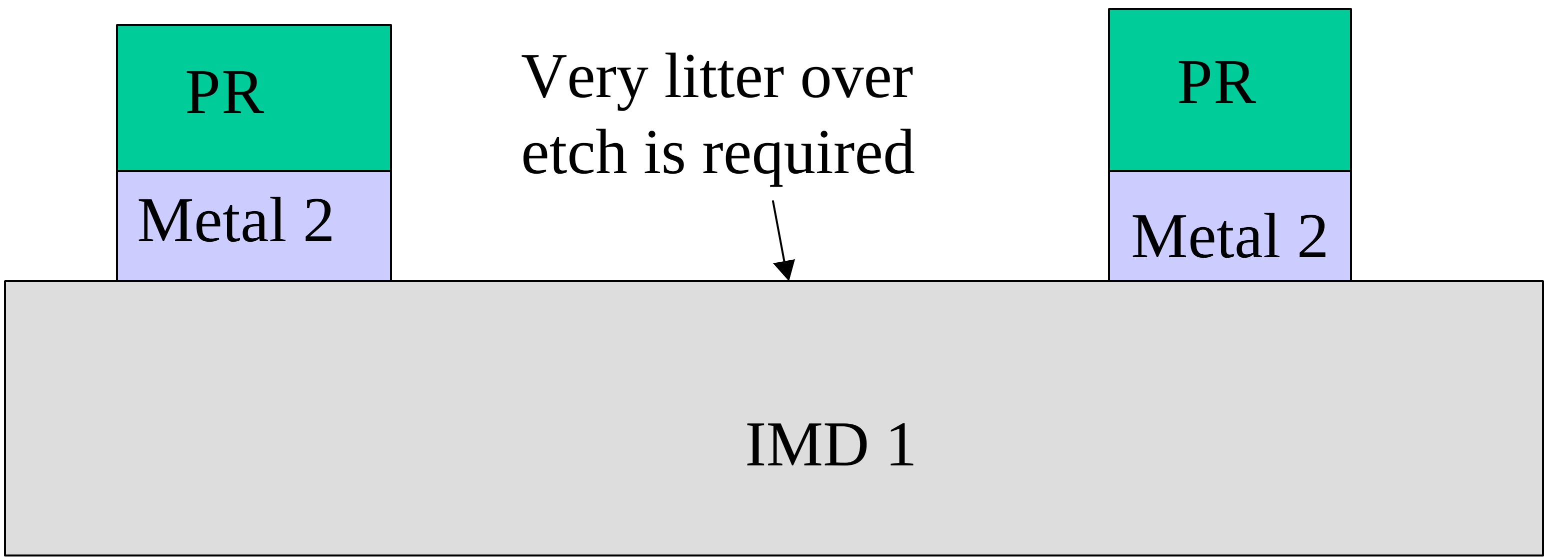
Over Exposure and Over Development



Rough Surface, Long Over Etch



Flat Surface, Short Over Etch



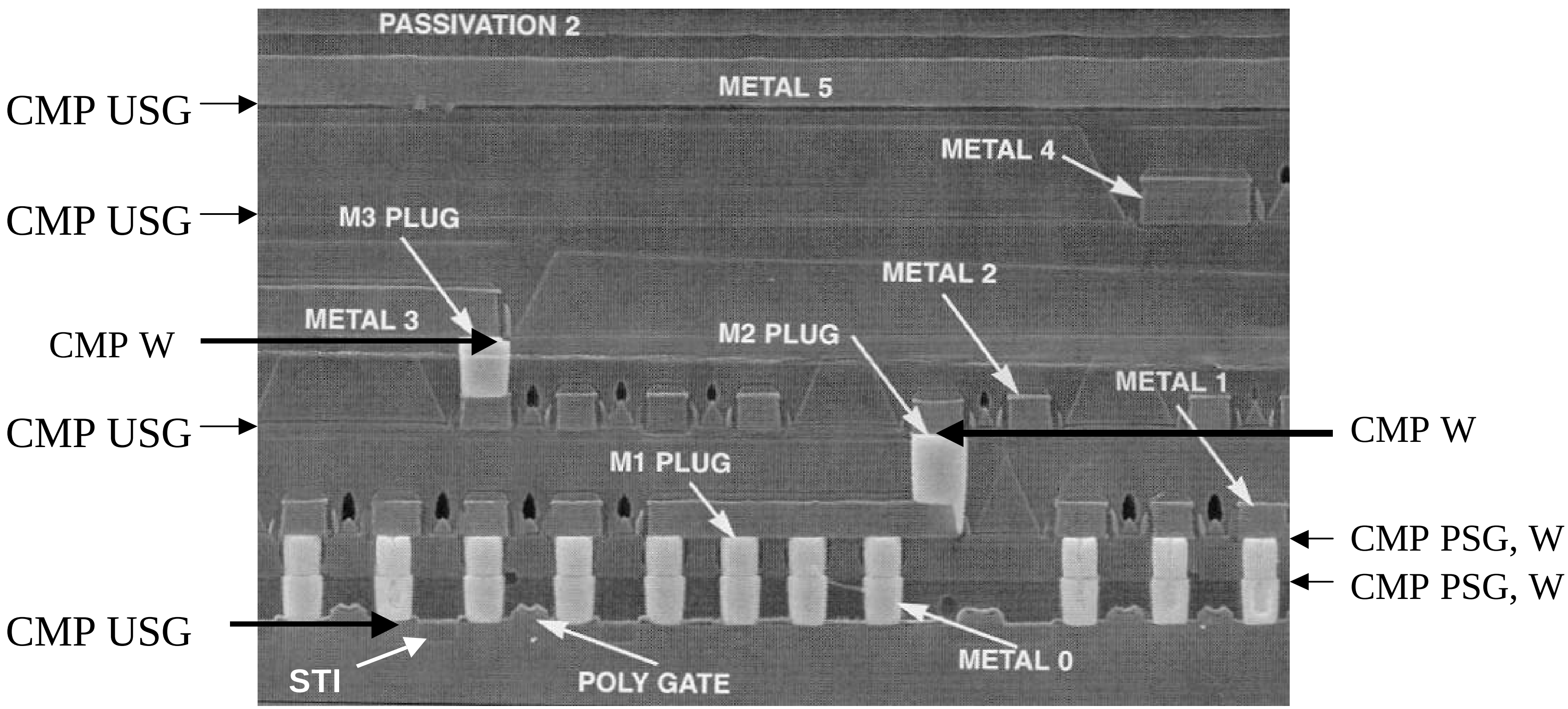
Advantages of CMP

- CMP reduce defect density, improve yield
  - Reducing the process problems in thin film deposition, photolithography, and etch.
- CMP also widens IC chip design parameters
- CMP can introduce defects of its own
- Need appropriate post-CMP cleaning

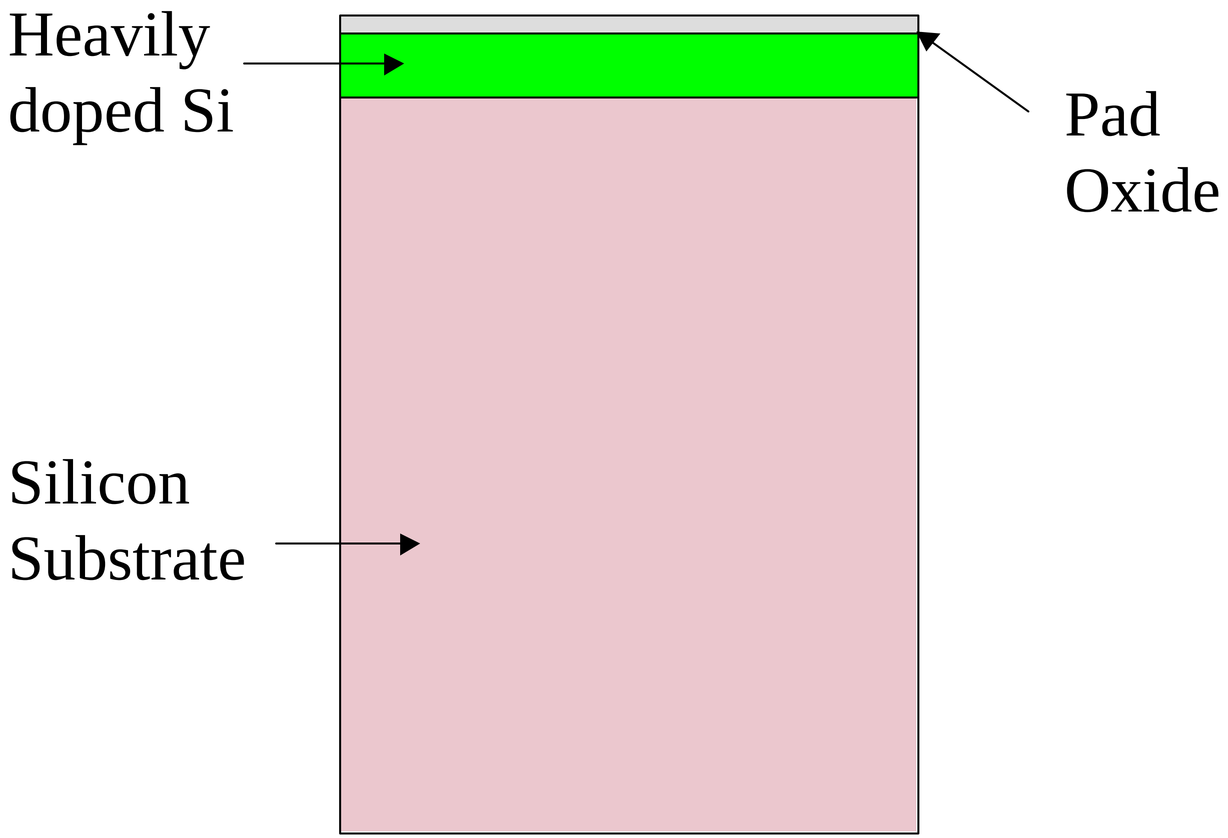
Applications of CMP

- STI formation
- Dielectric layer planarization
  - PMD and IMD
- Tungsten plug formation
- Deep trench capacitor

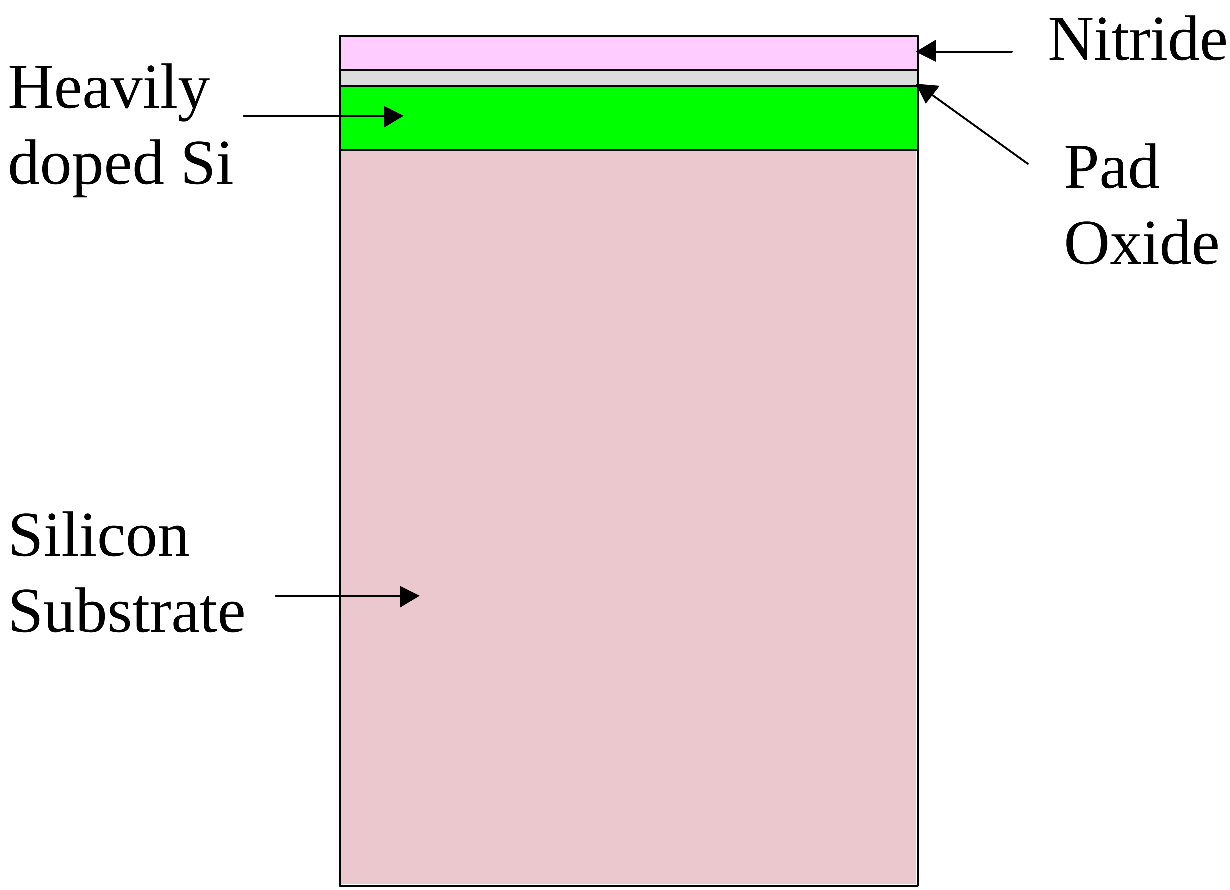
Applications of CMP



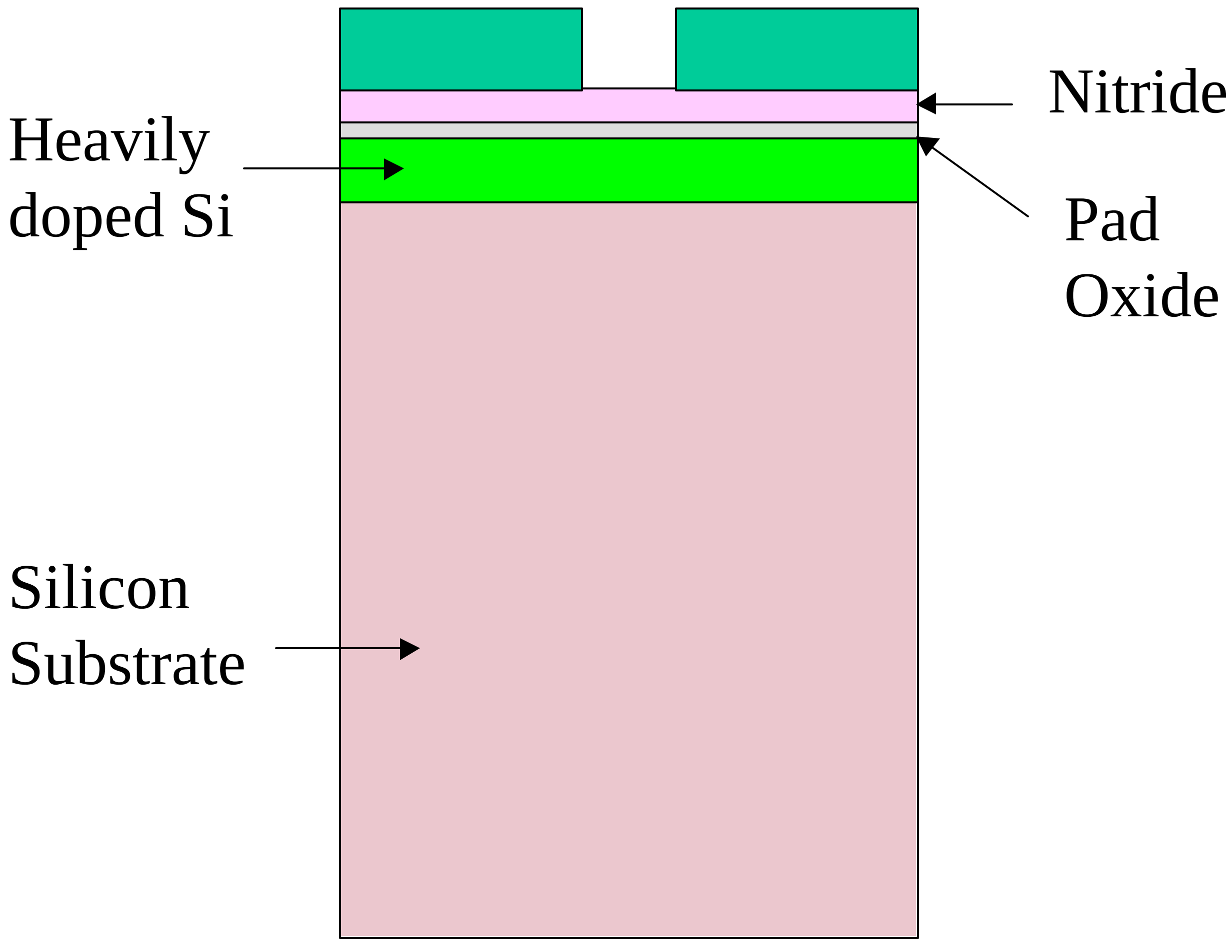
Deep Trench Capacitor



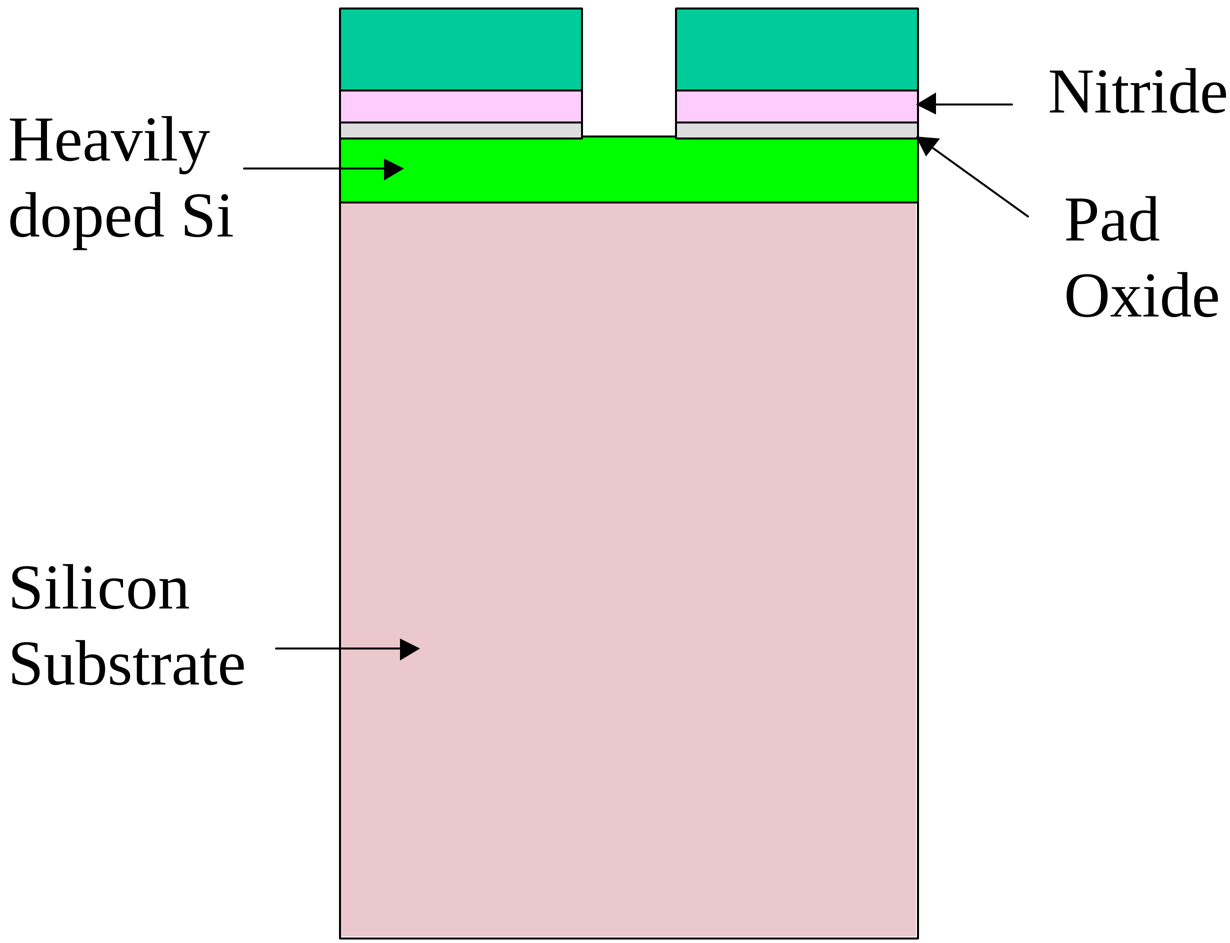
Deep Trench Capacitor



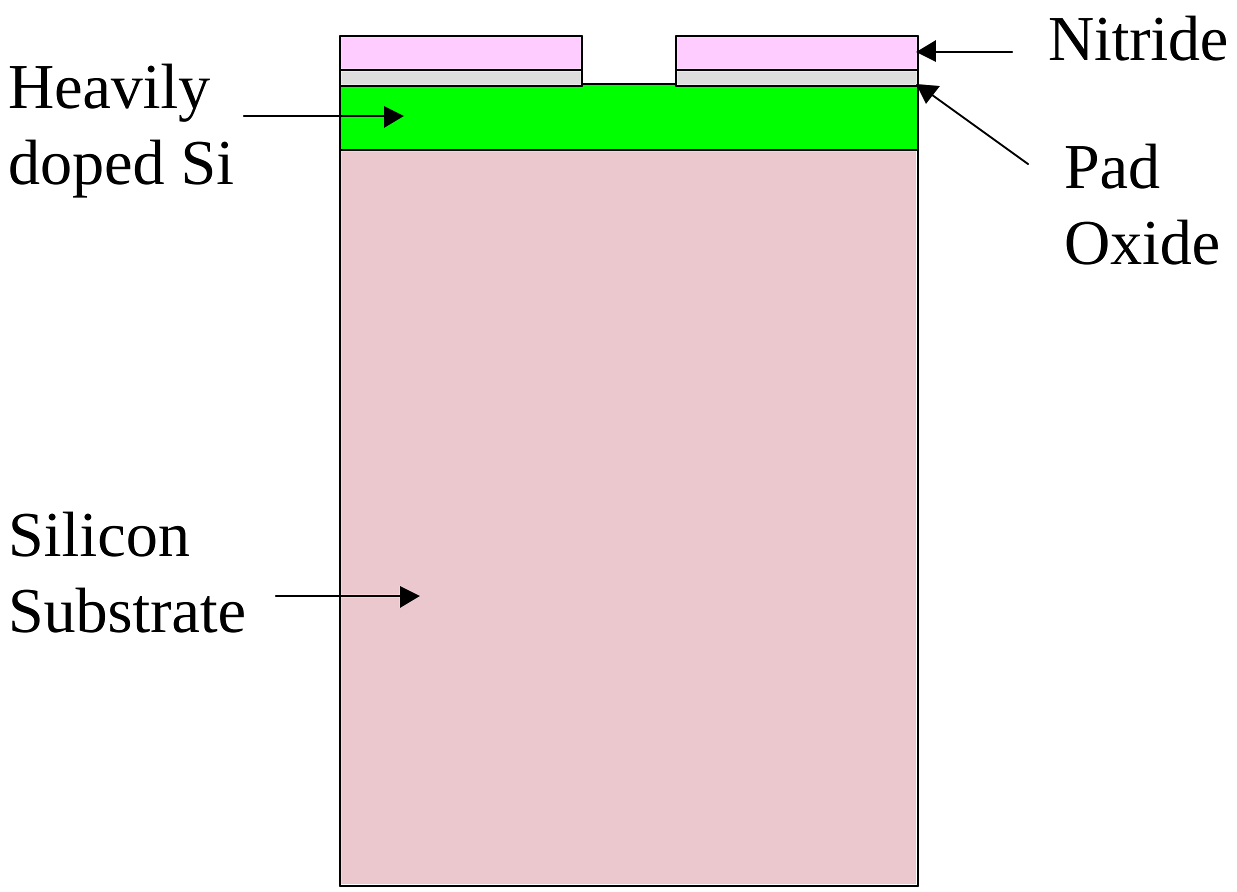
Deep Trench Capacitor



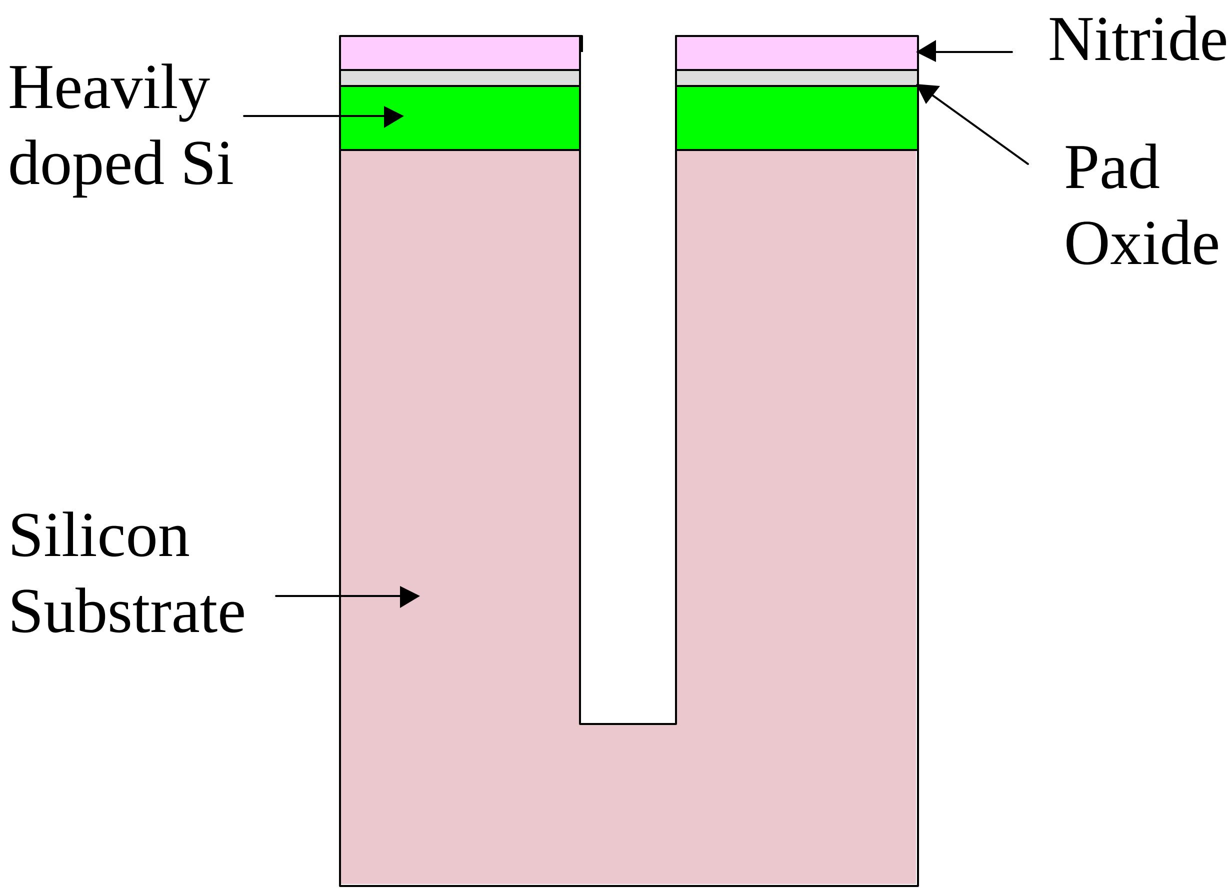
Deep Trench Capacitor



Deep Trench Capacitor



Deep Trench Capacitor



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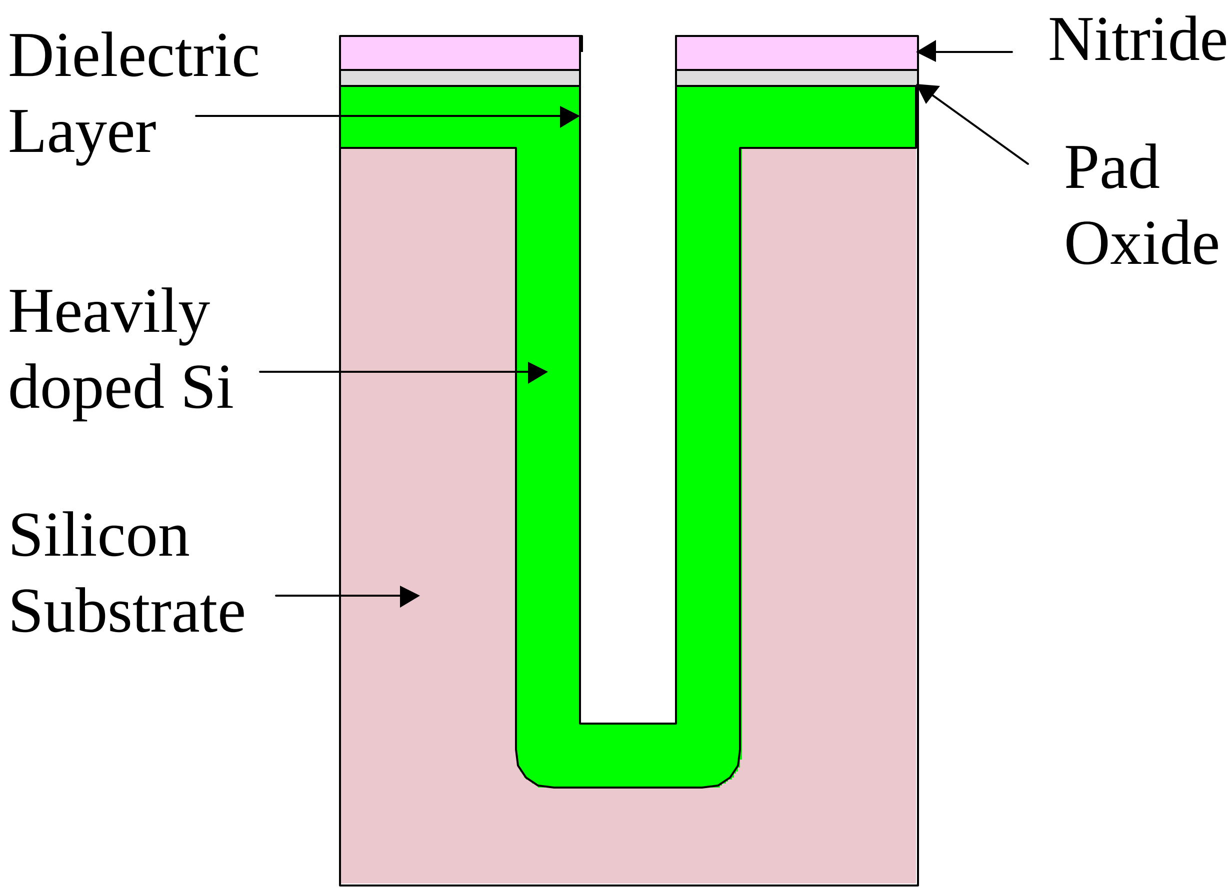

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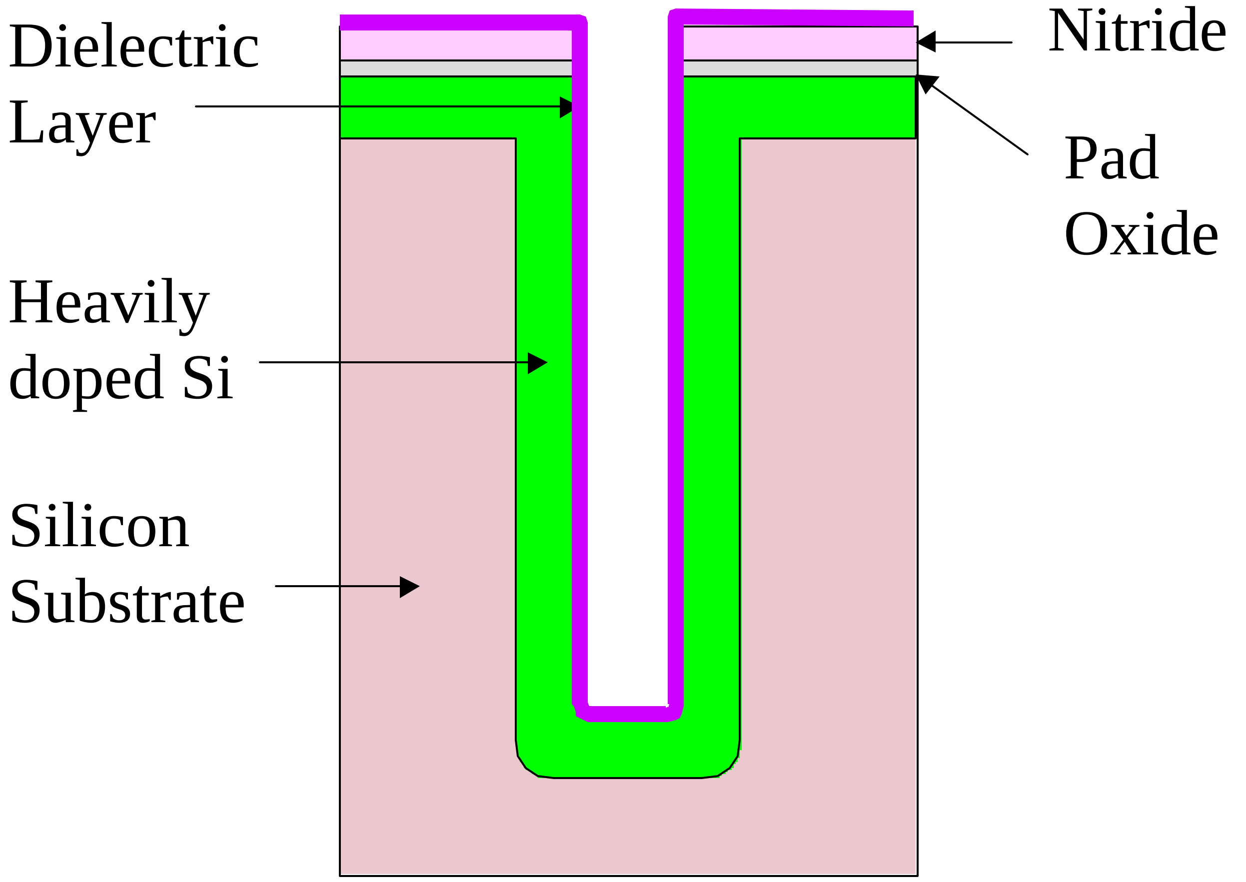

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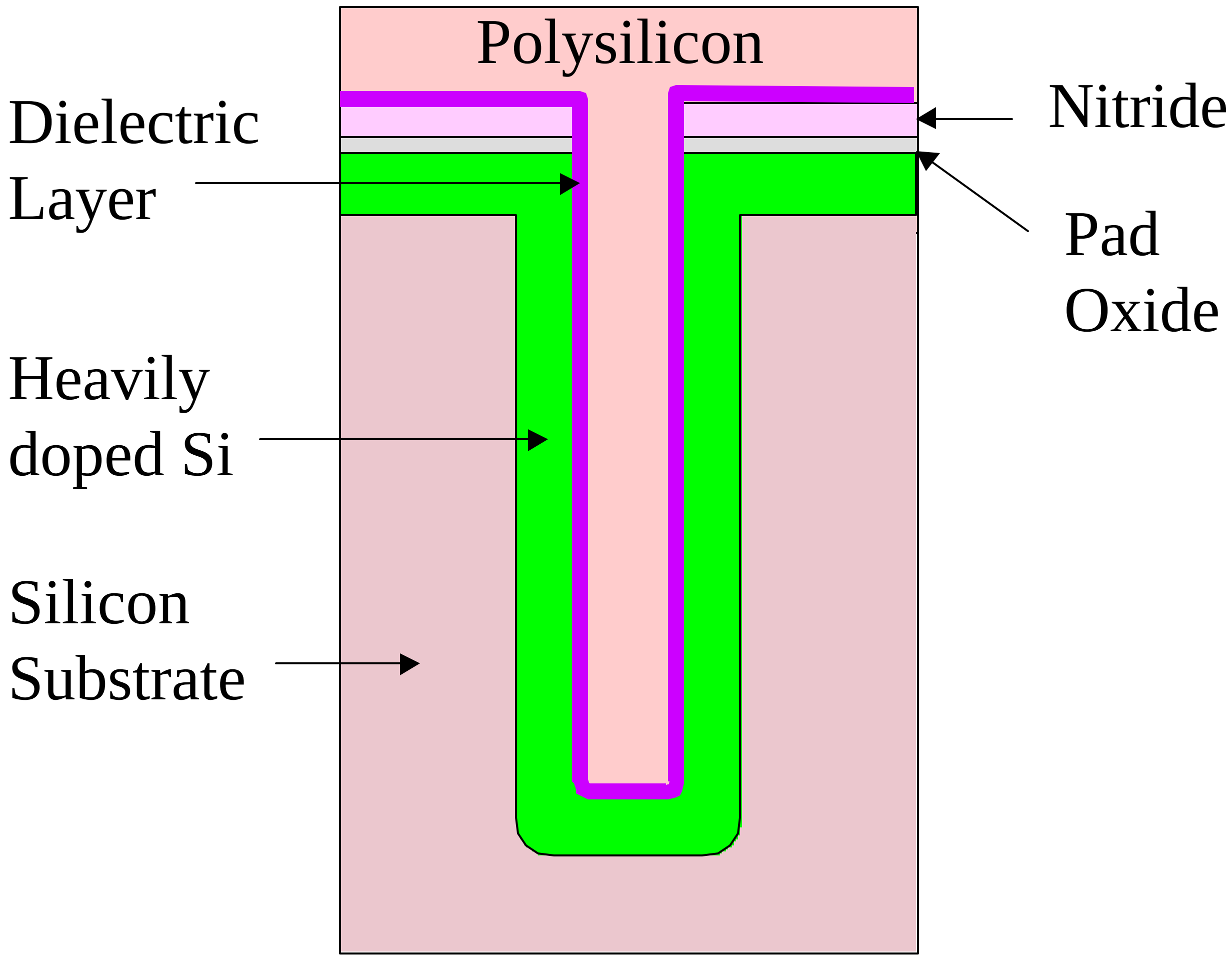

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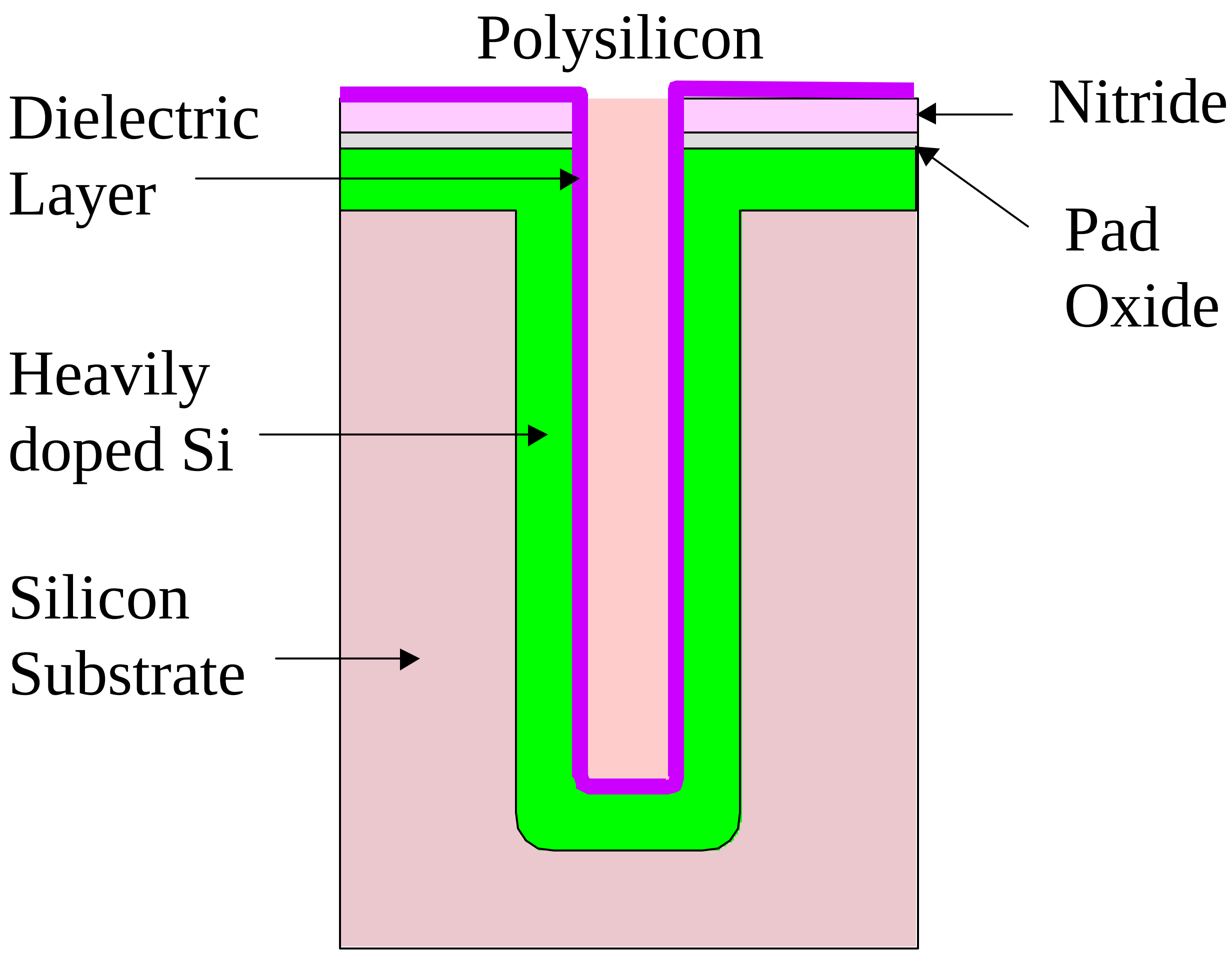

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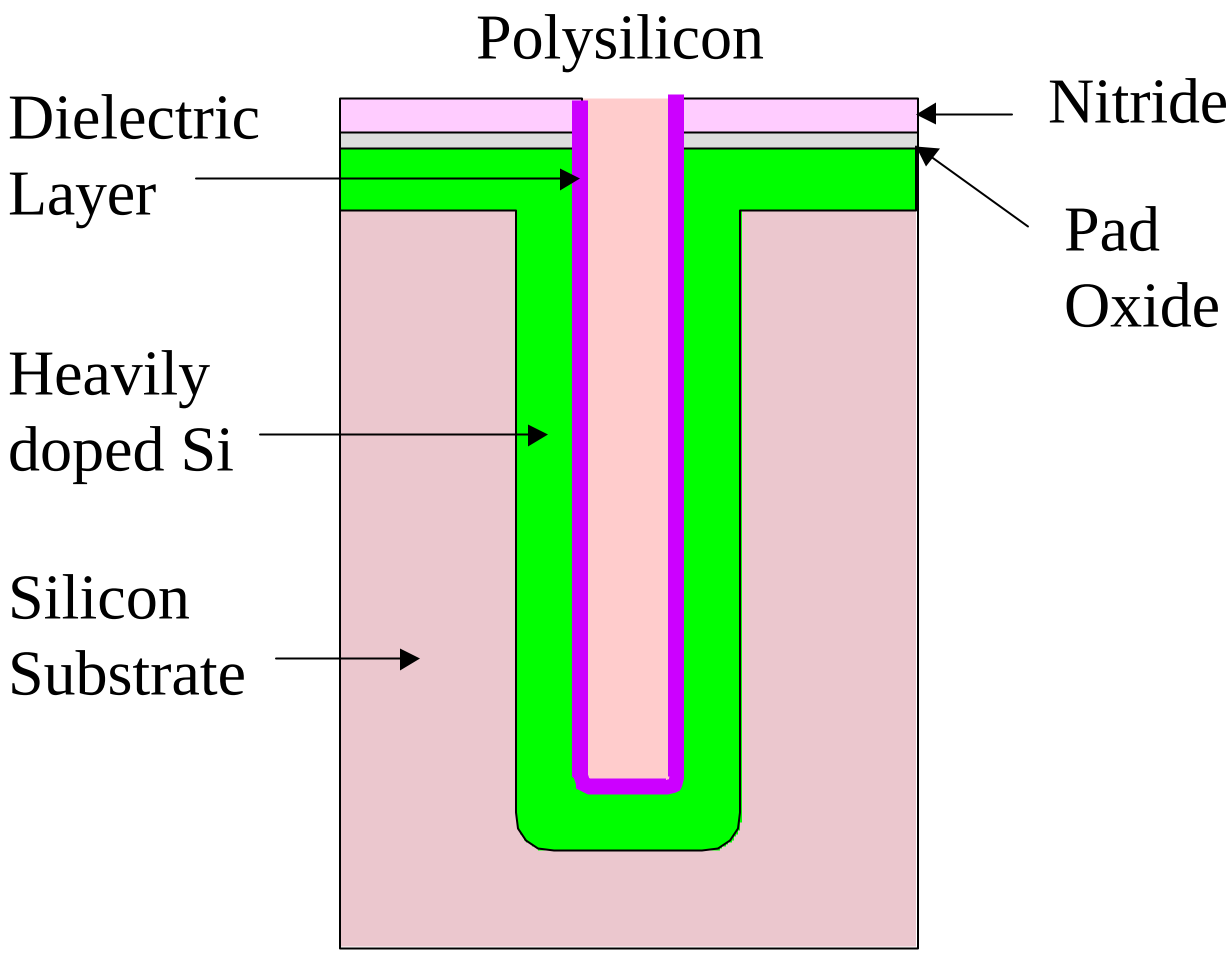

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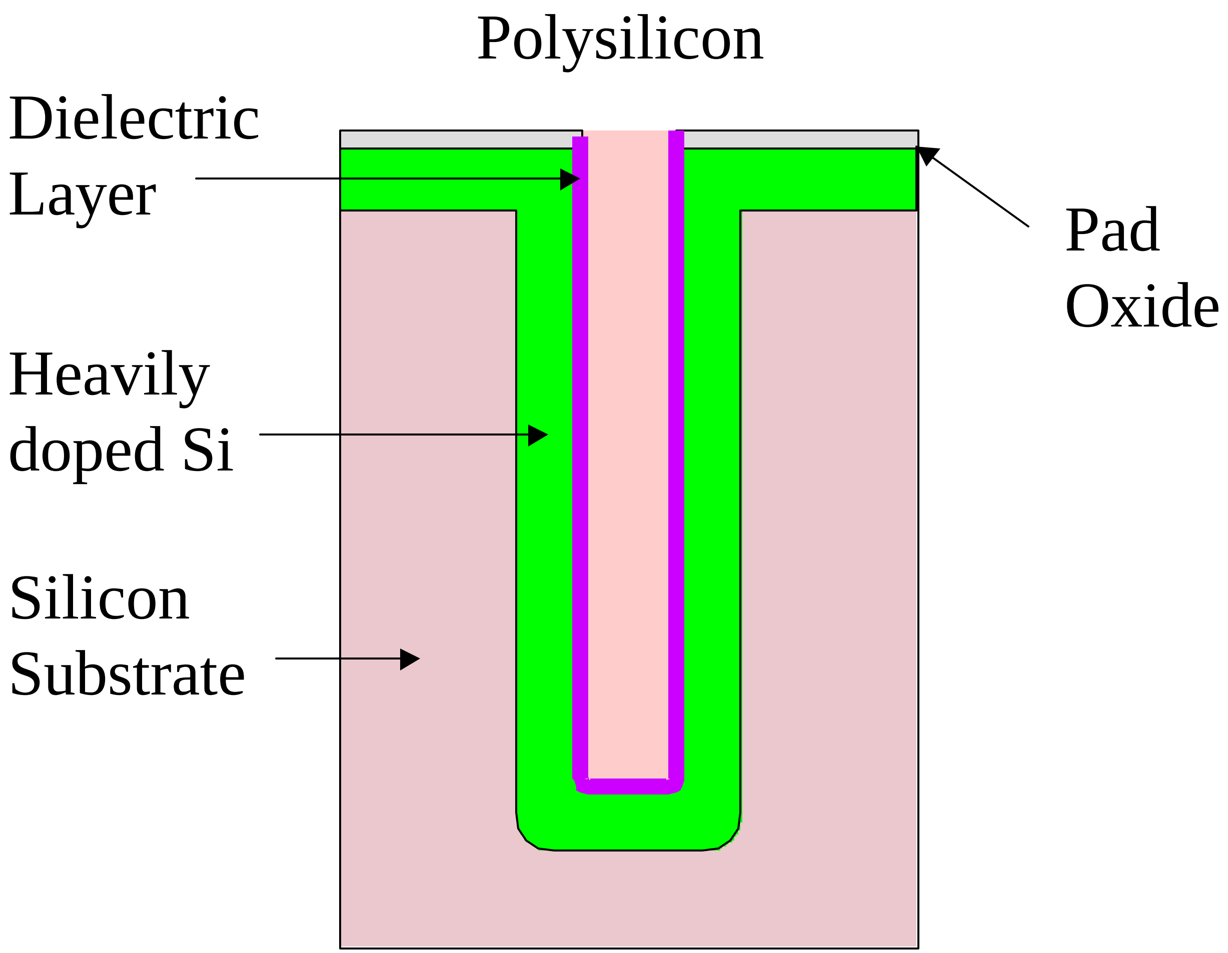
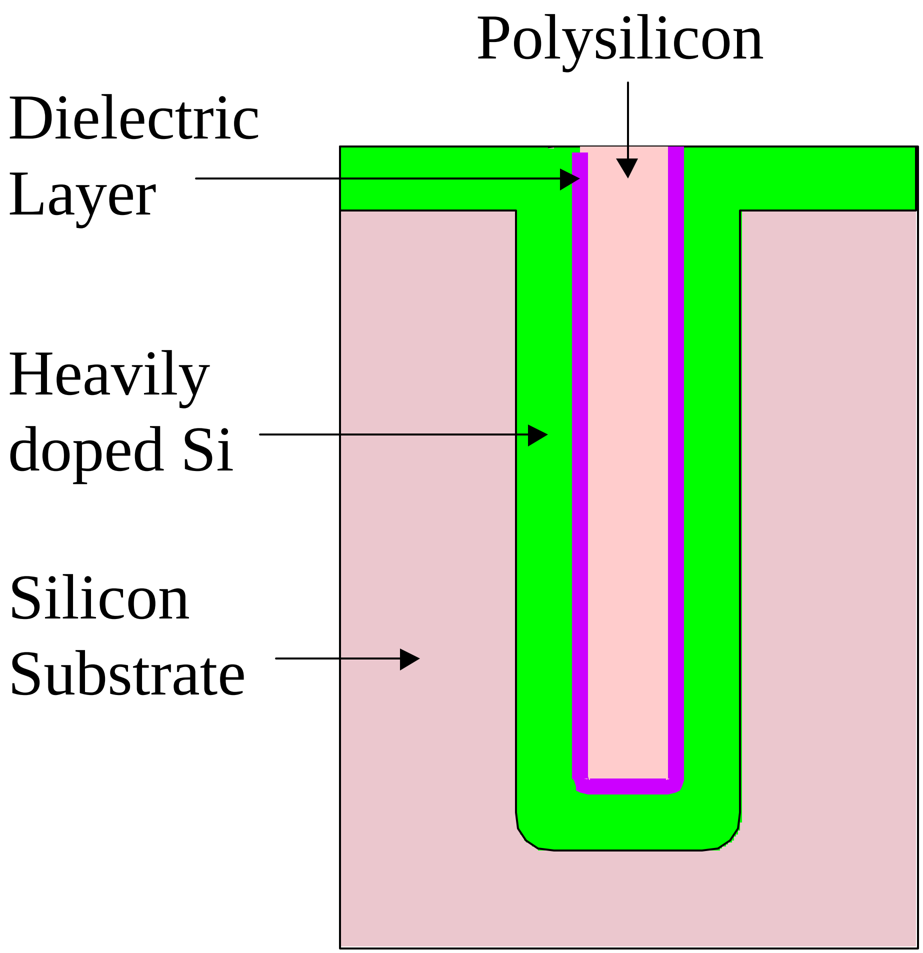


Deep Trench Capacitor



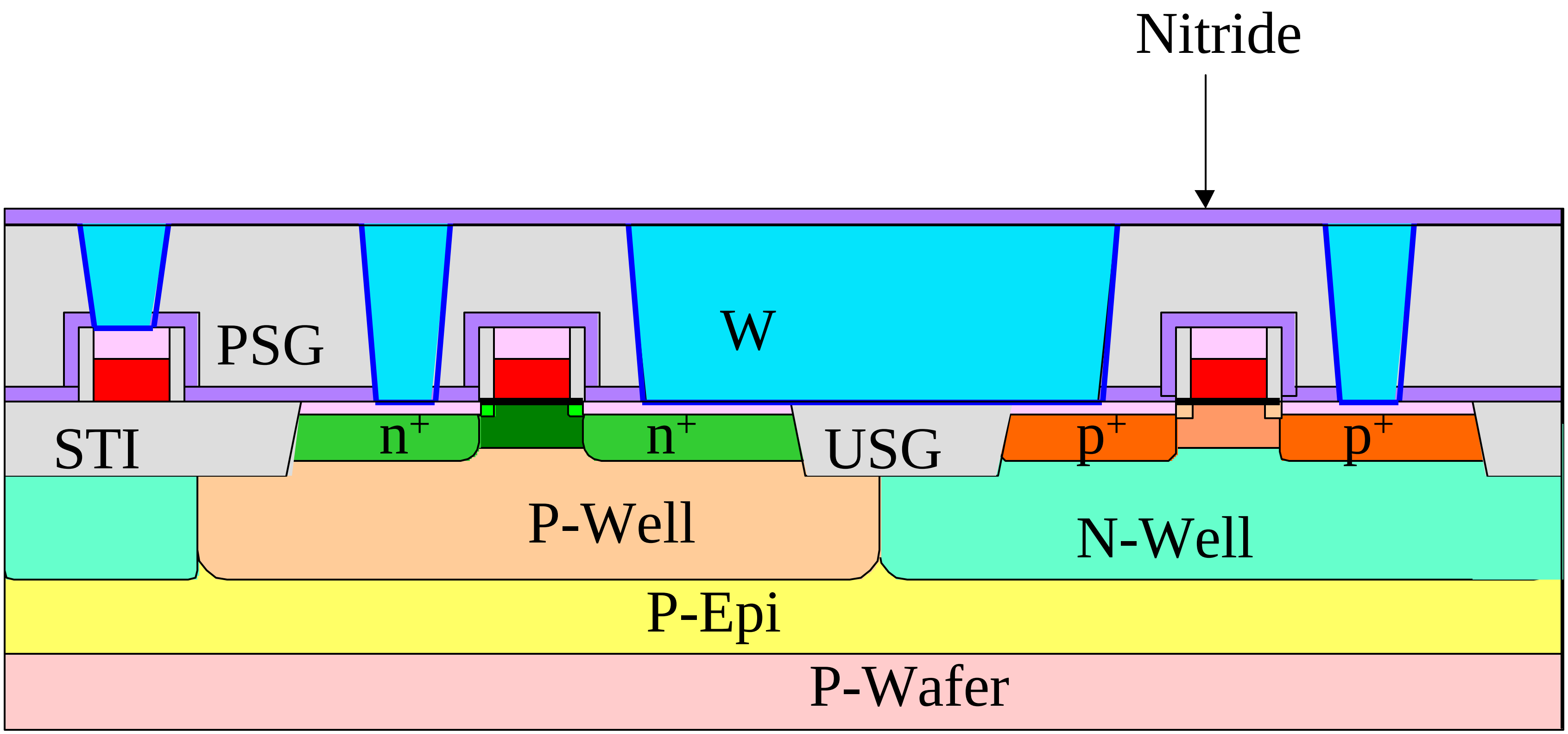
Applications of CMP

- Copper interconnection.
- Copper is very difficult to dry etch,
- Dual damascene: process of choice
- Tungsten plug is a damascene process

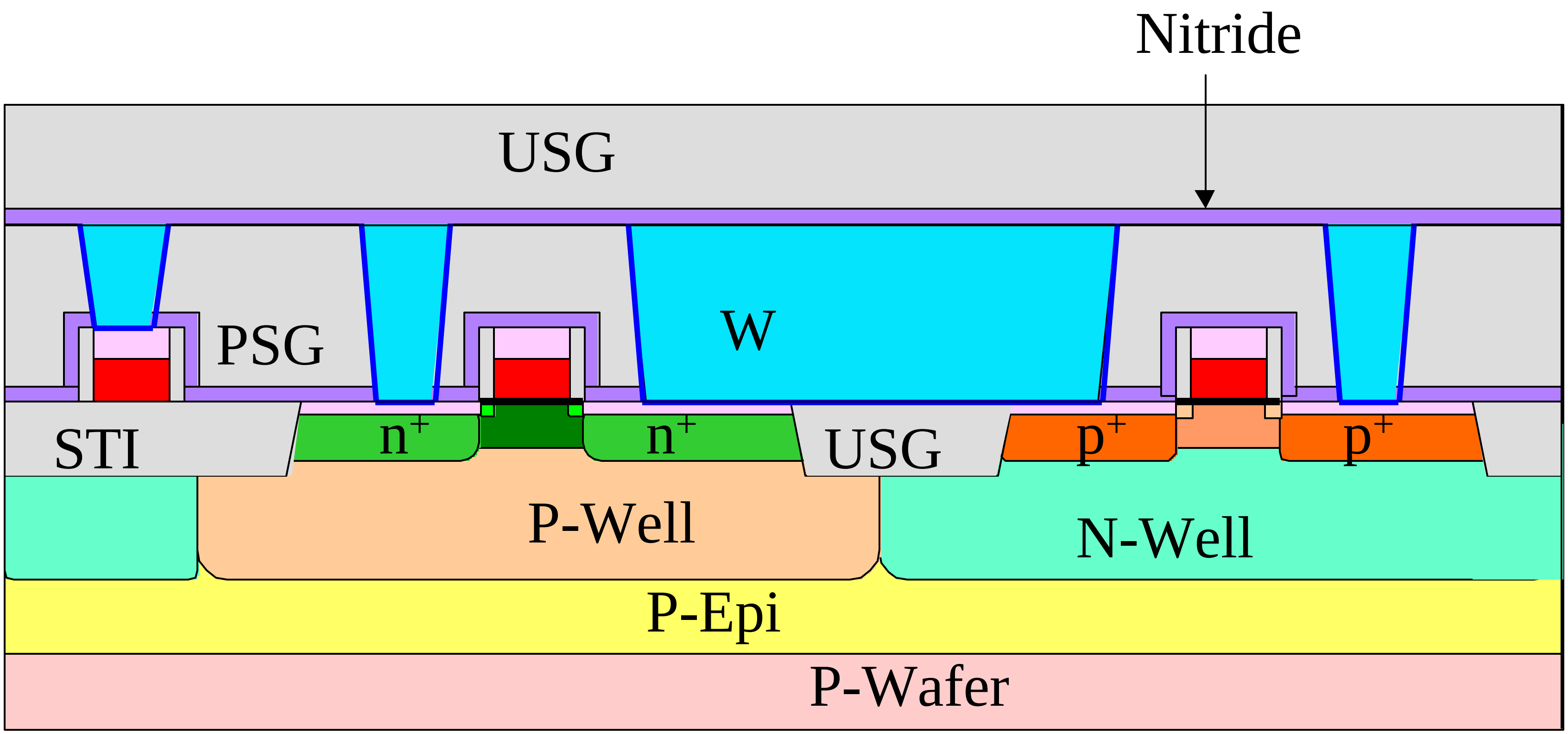
Applications of CMP

- It uses two dielectric etch processes,
  - one via etch and one trench etch
- Metal layers are deposition into via holes and trenches.
- A metal CMP process removes copper and tantalum barrier layer
- Leave copper lines and plugs imbedded inside the dielectric layer

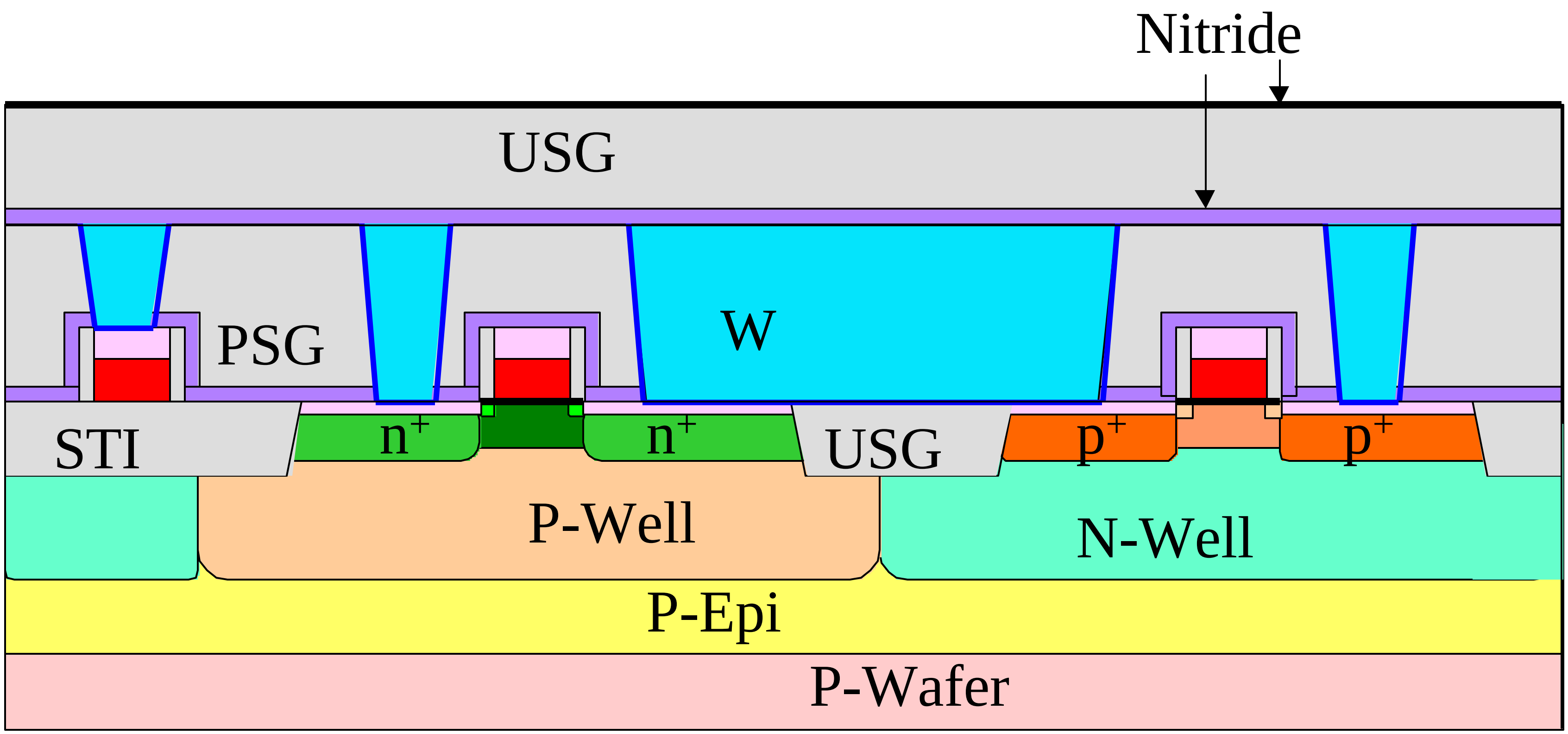
PECVD Nitride



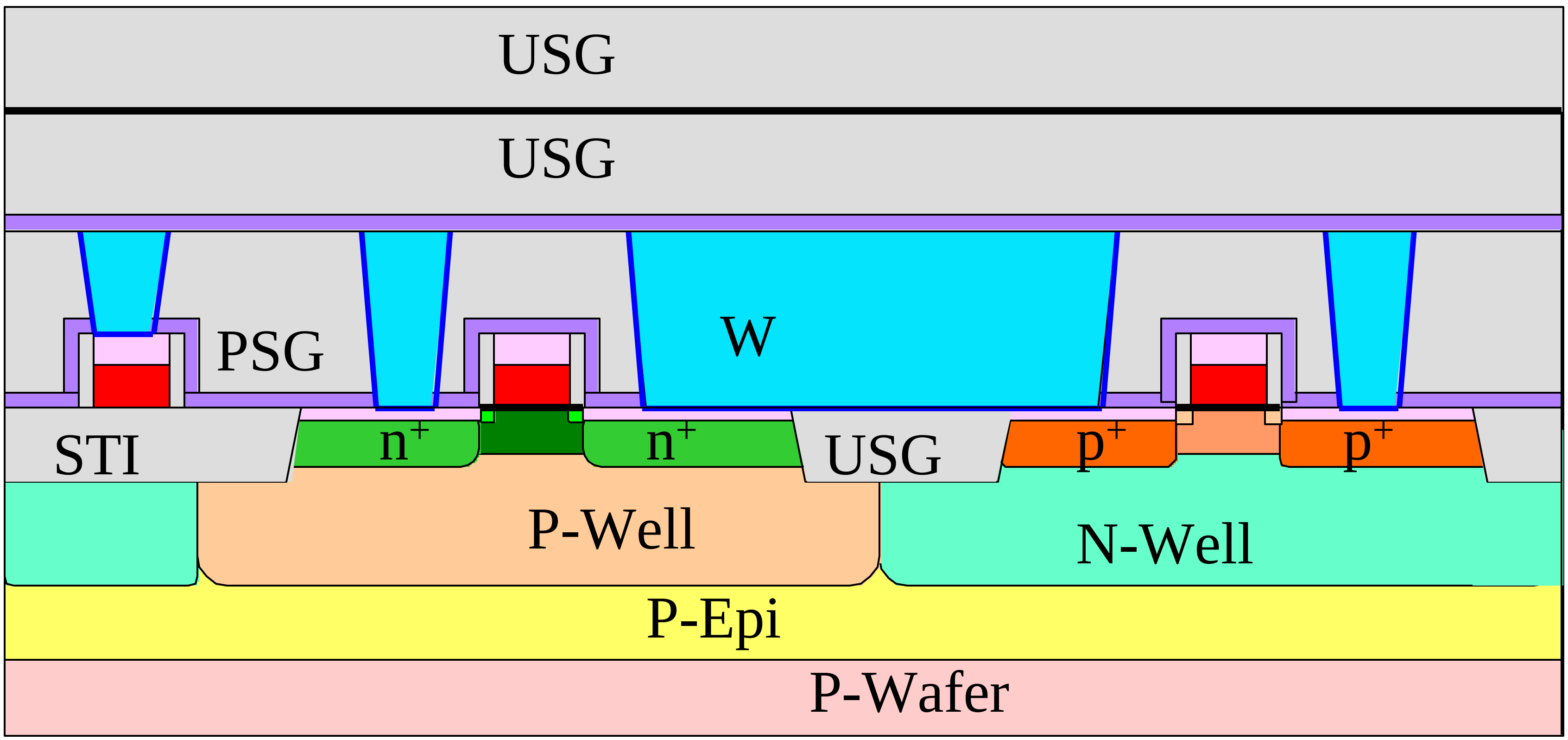
PECVD USG



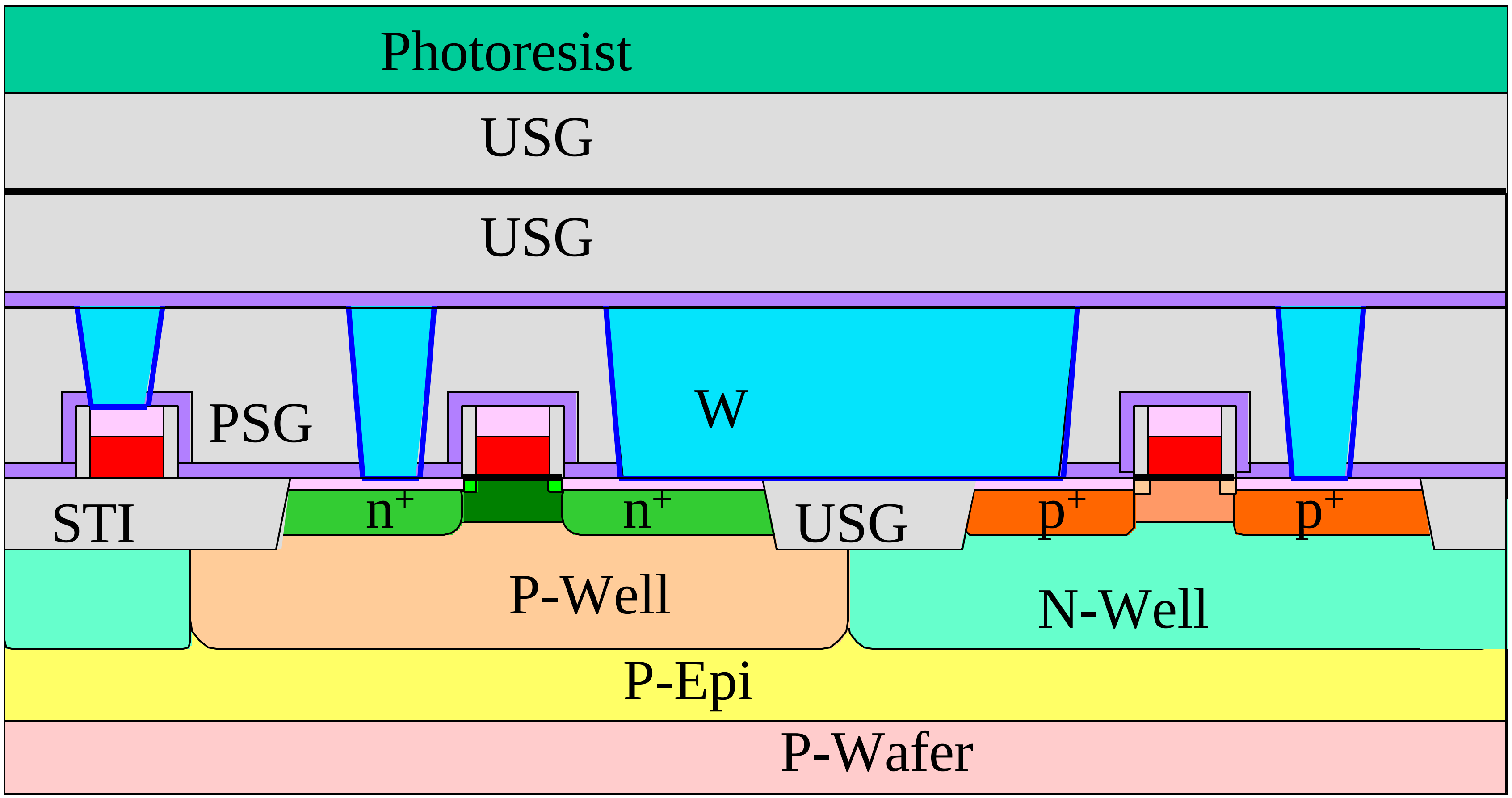
PECVD Etch Stop Nitride



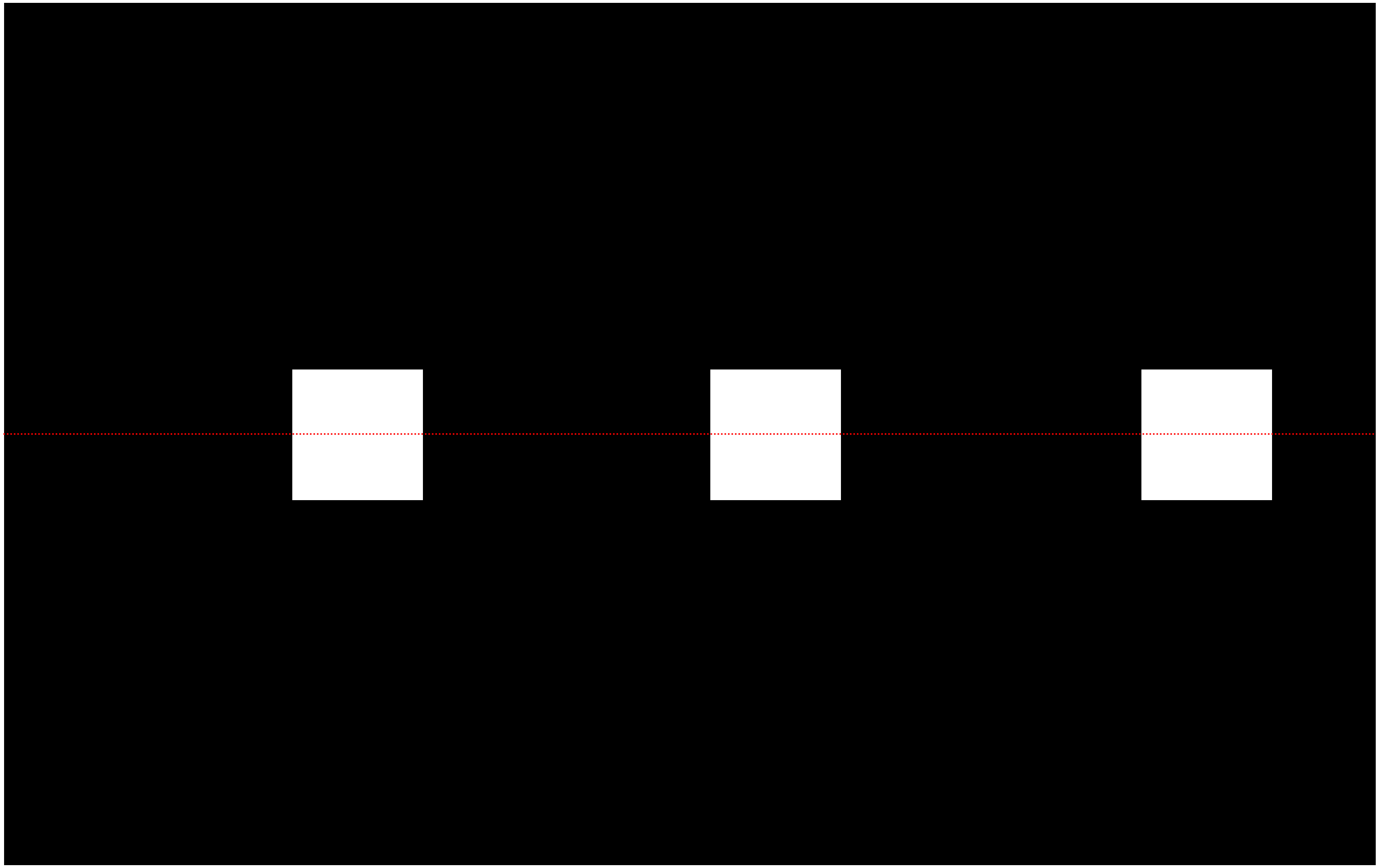
PECVD USG



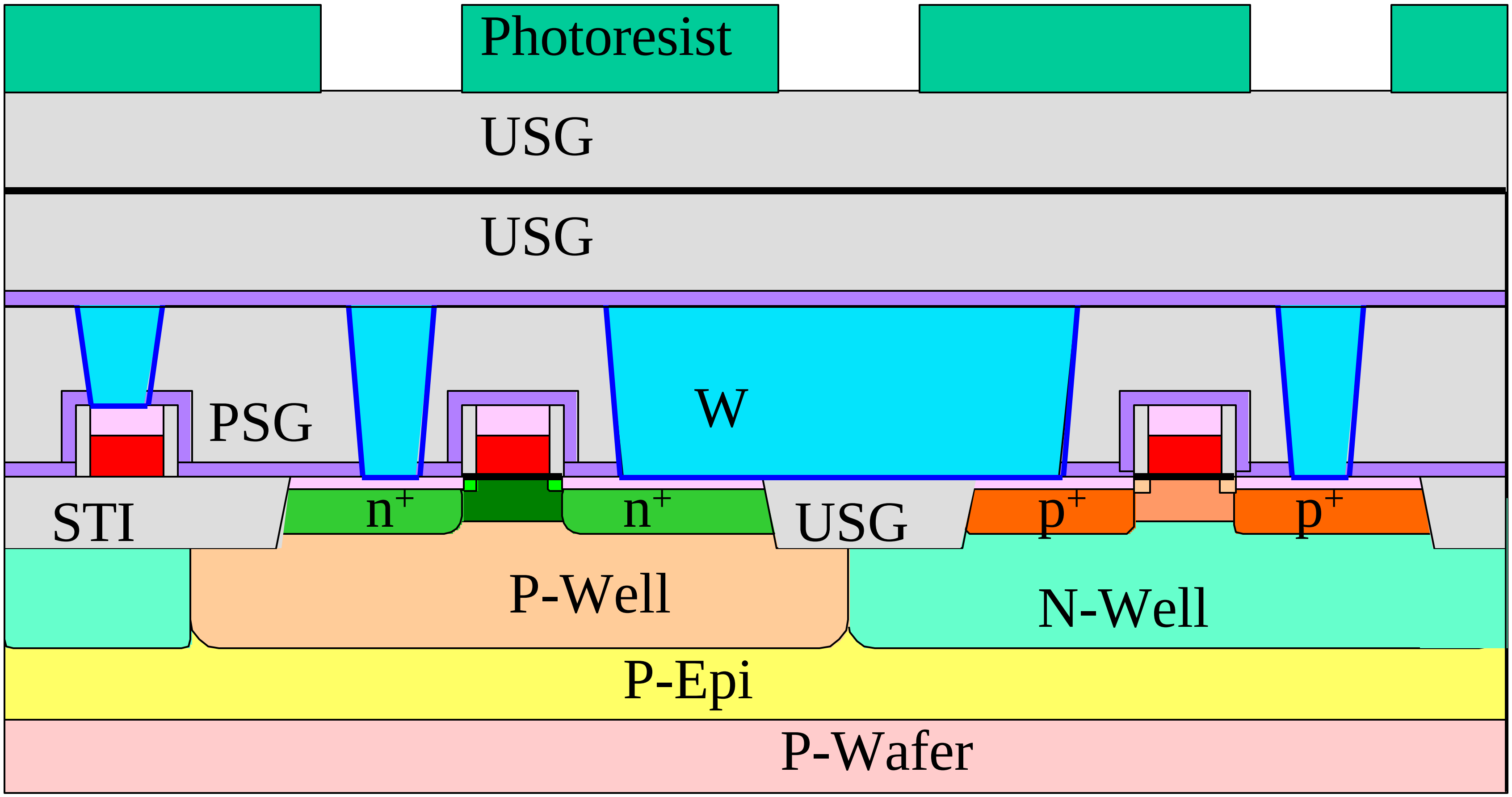
Photoresist Coating



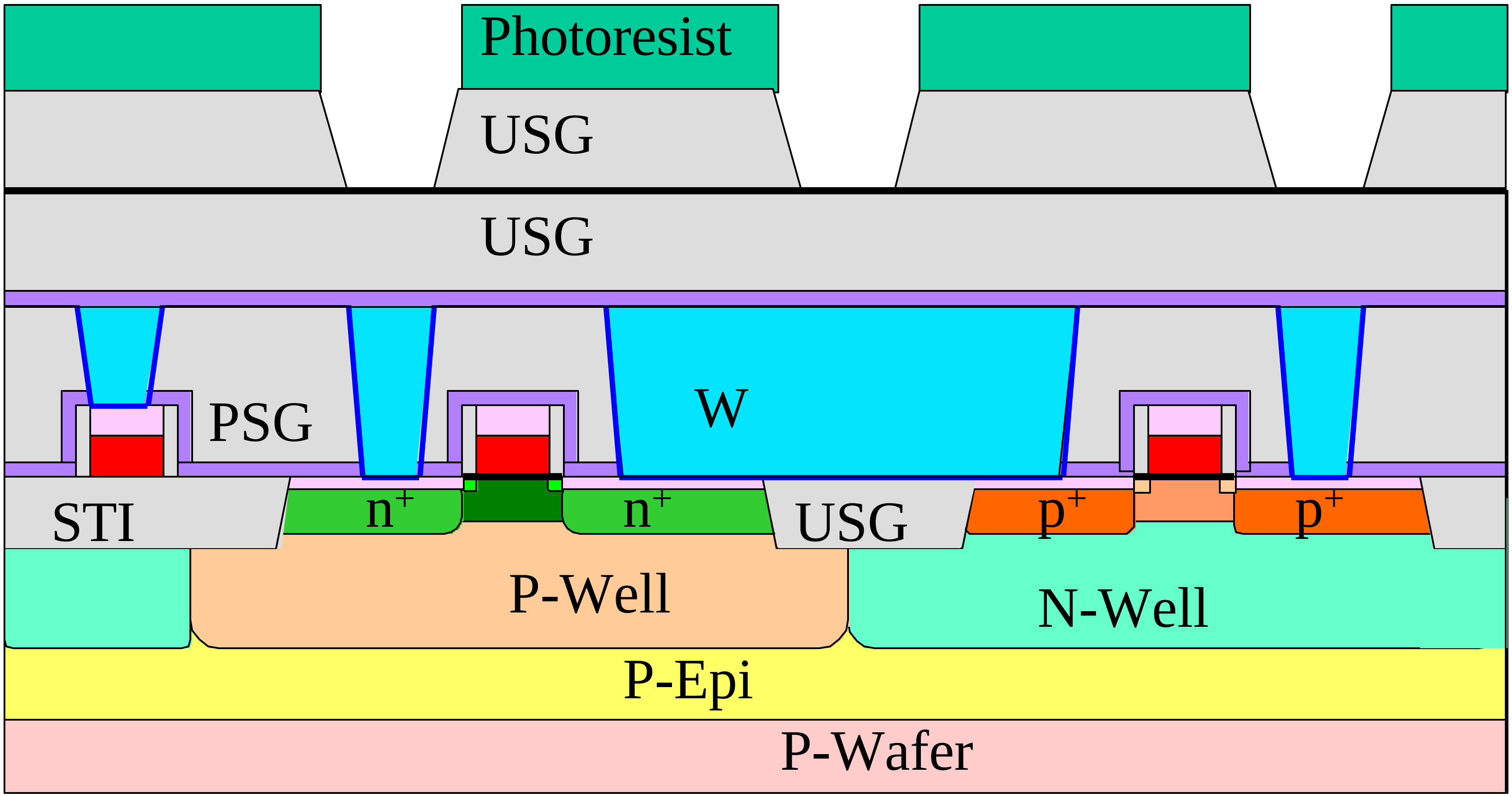
Via 1 Mask



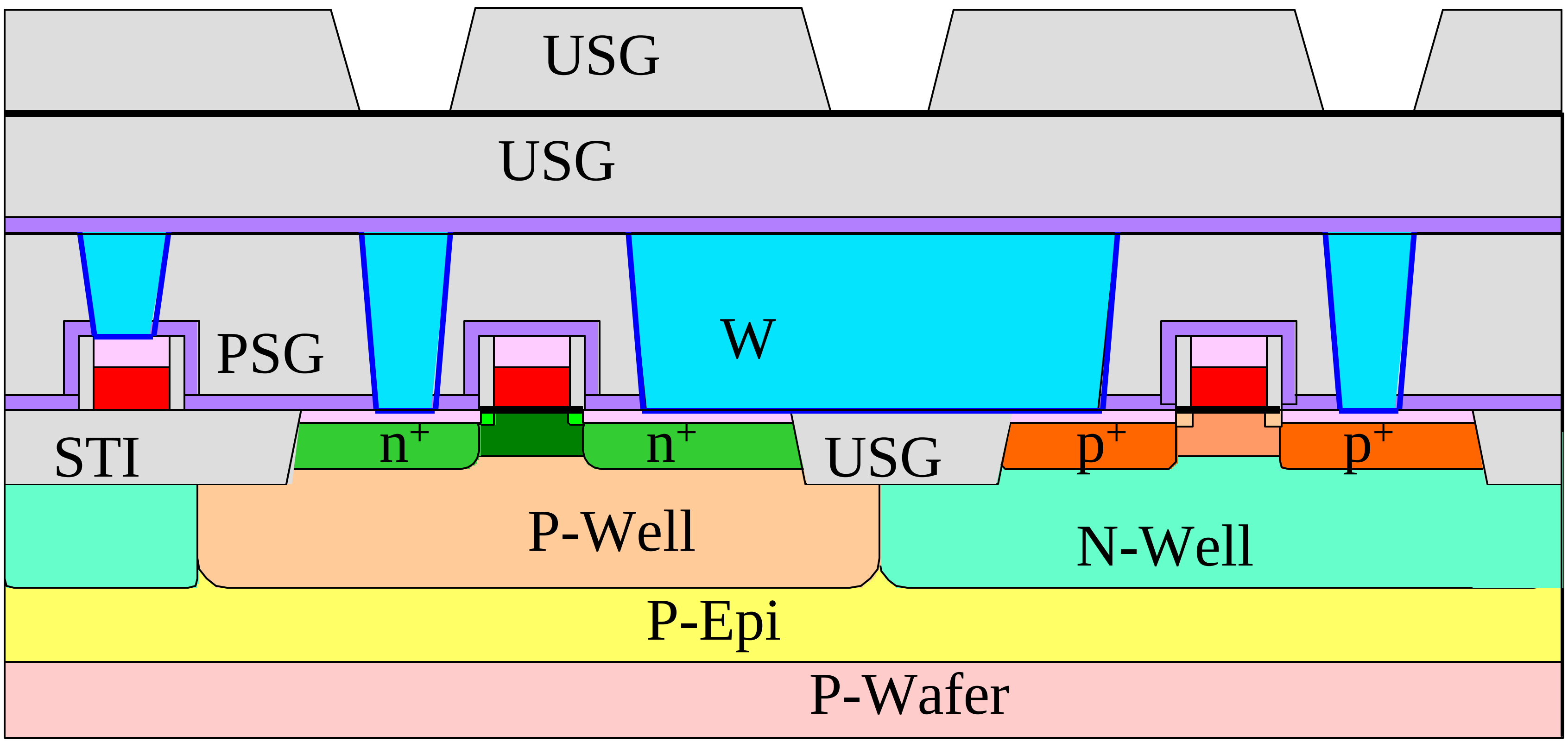
Via 1 Mask Exposure and Development



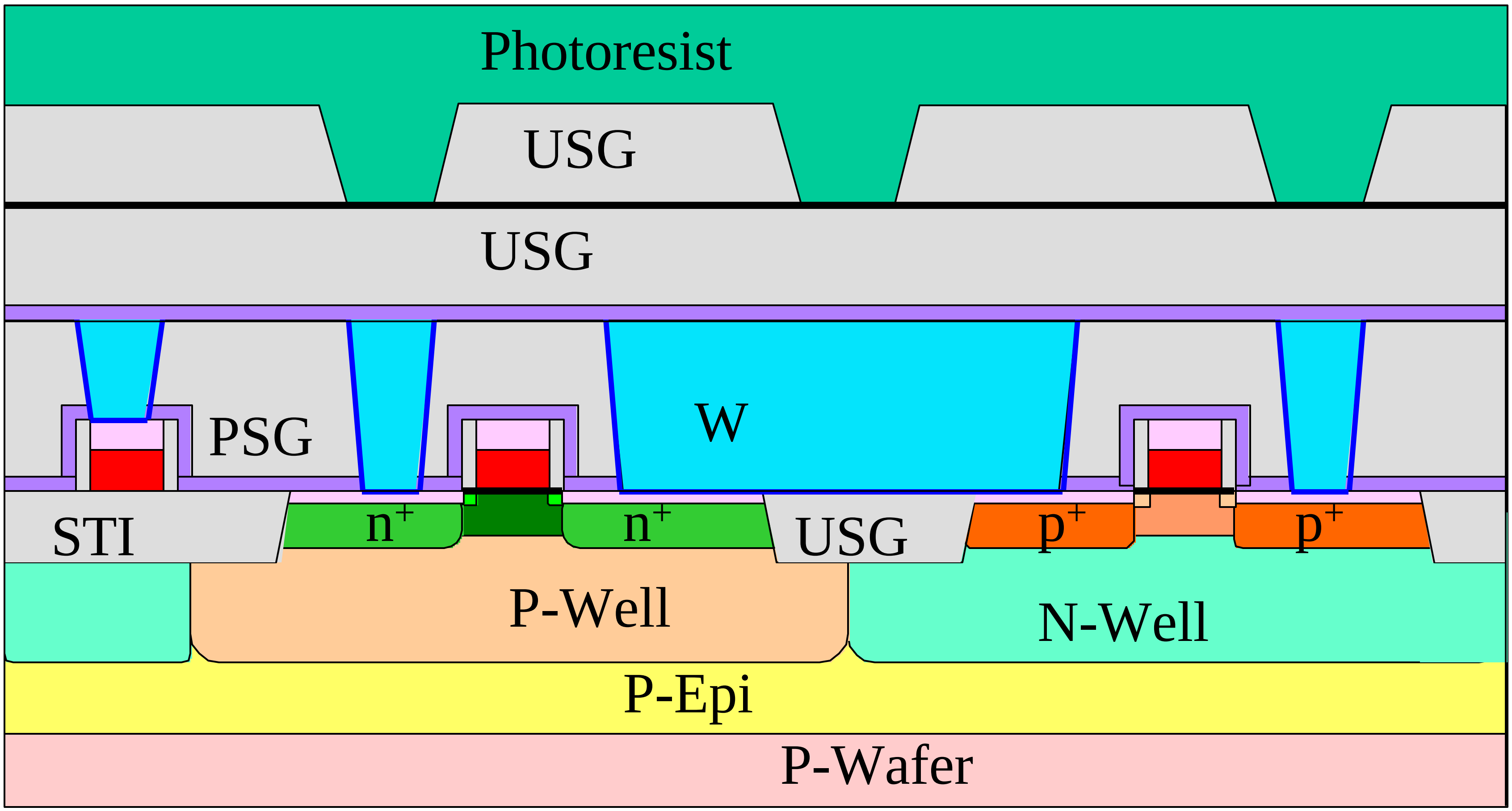
Etch USG, Stop on Nitride



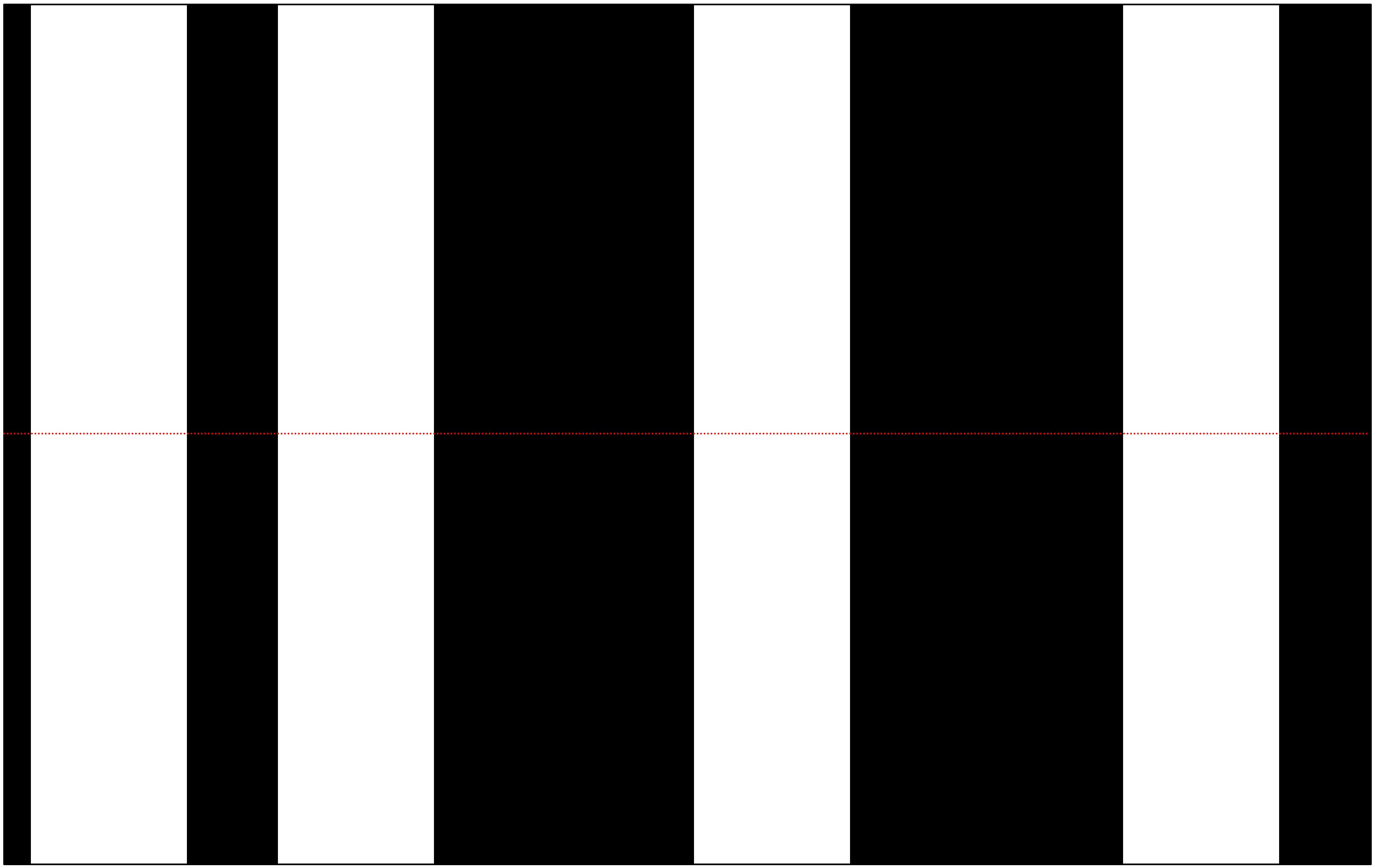
Strip Photoresist



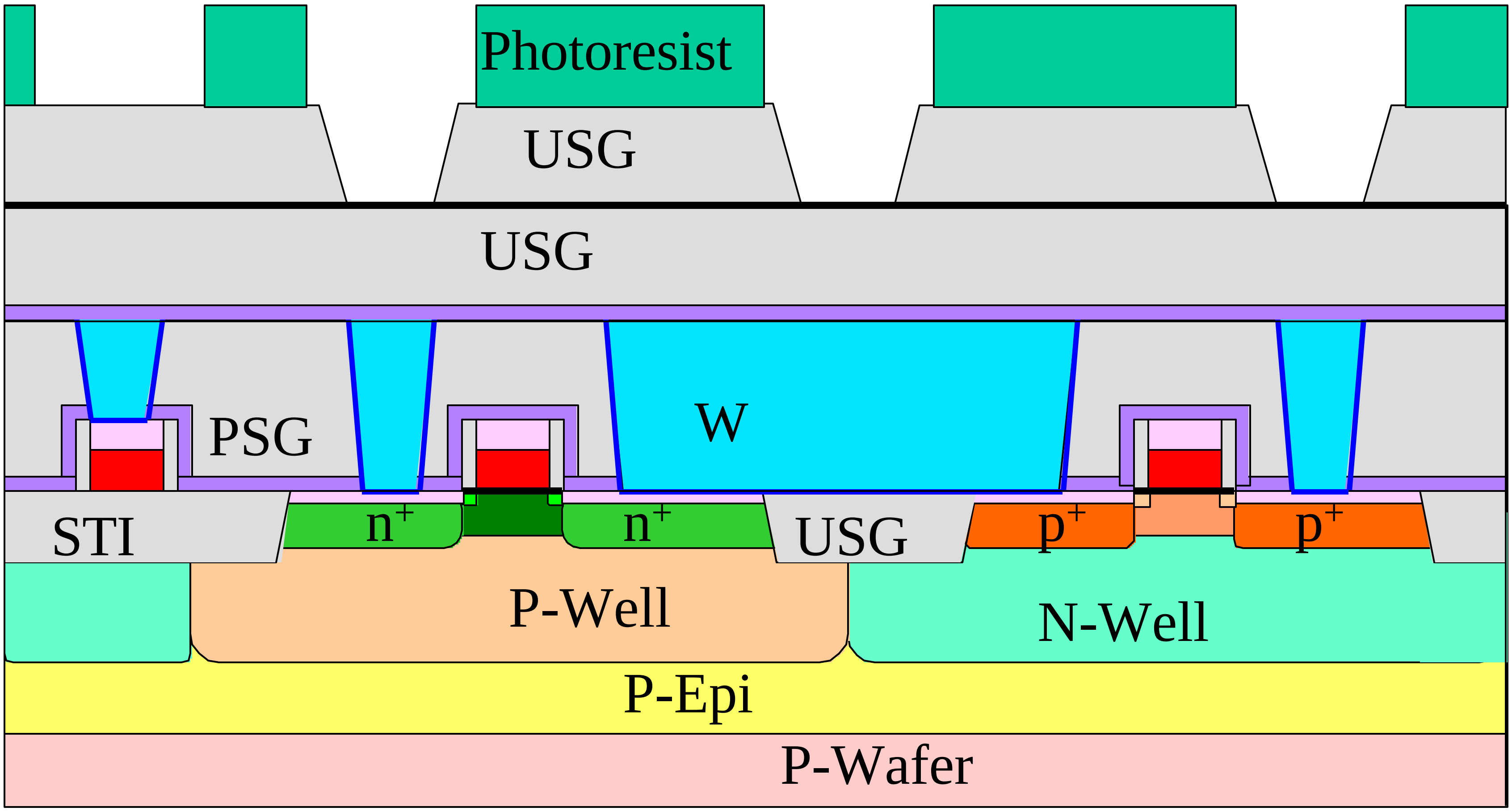
Photoresist Coating



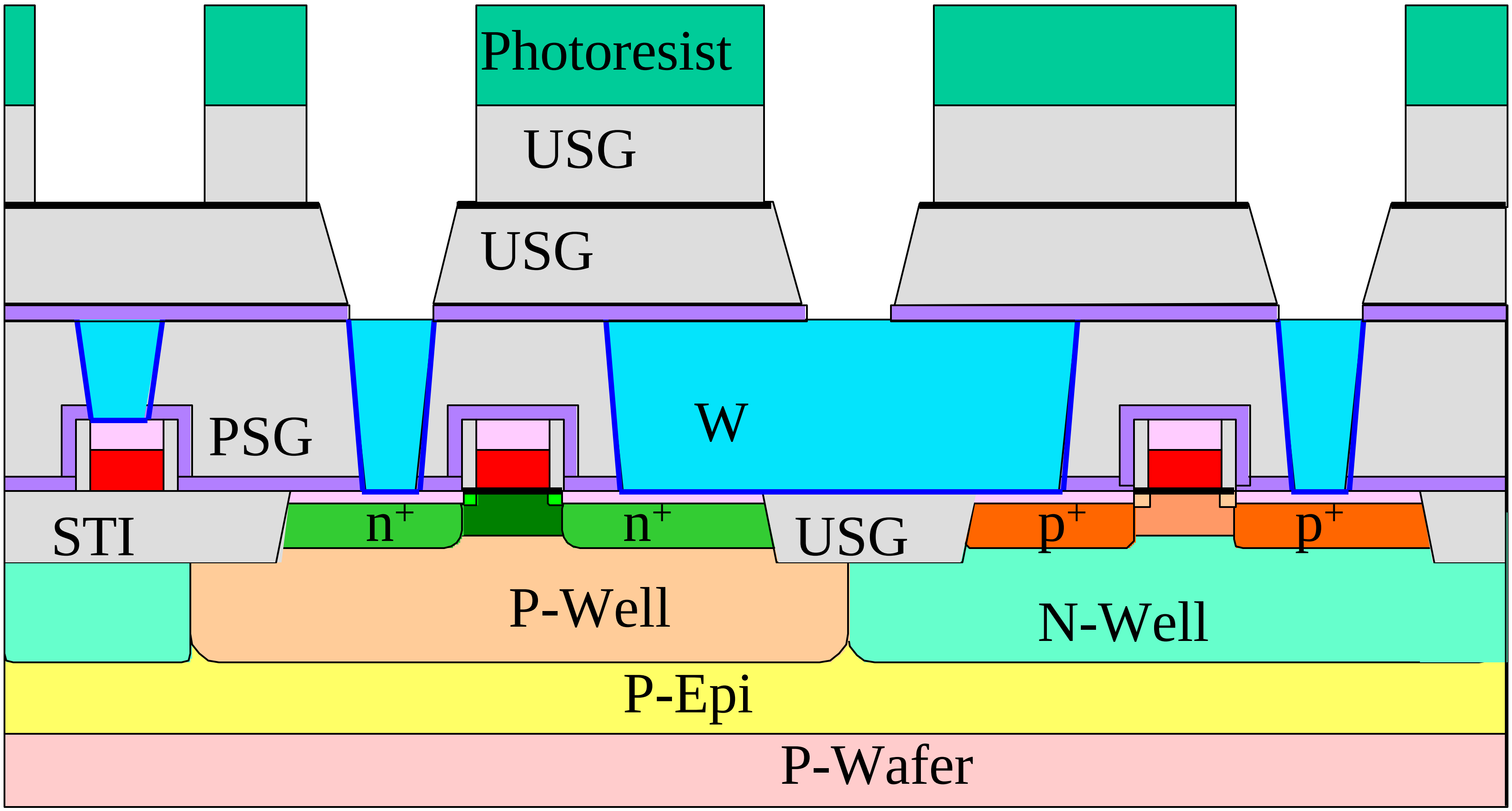
Metal 1 Mask



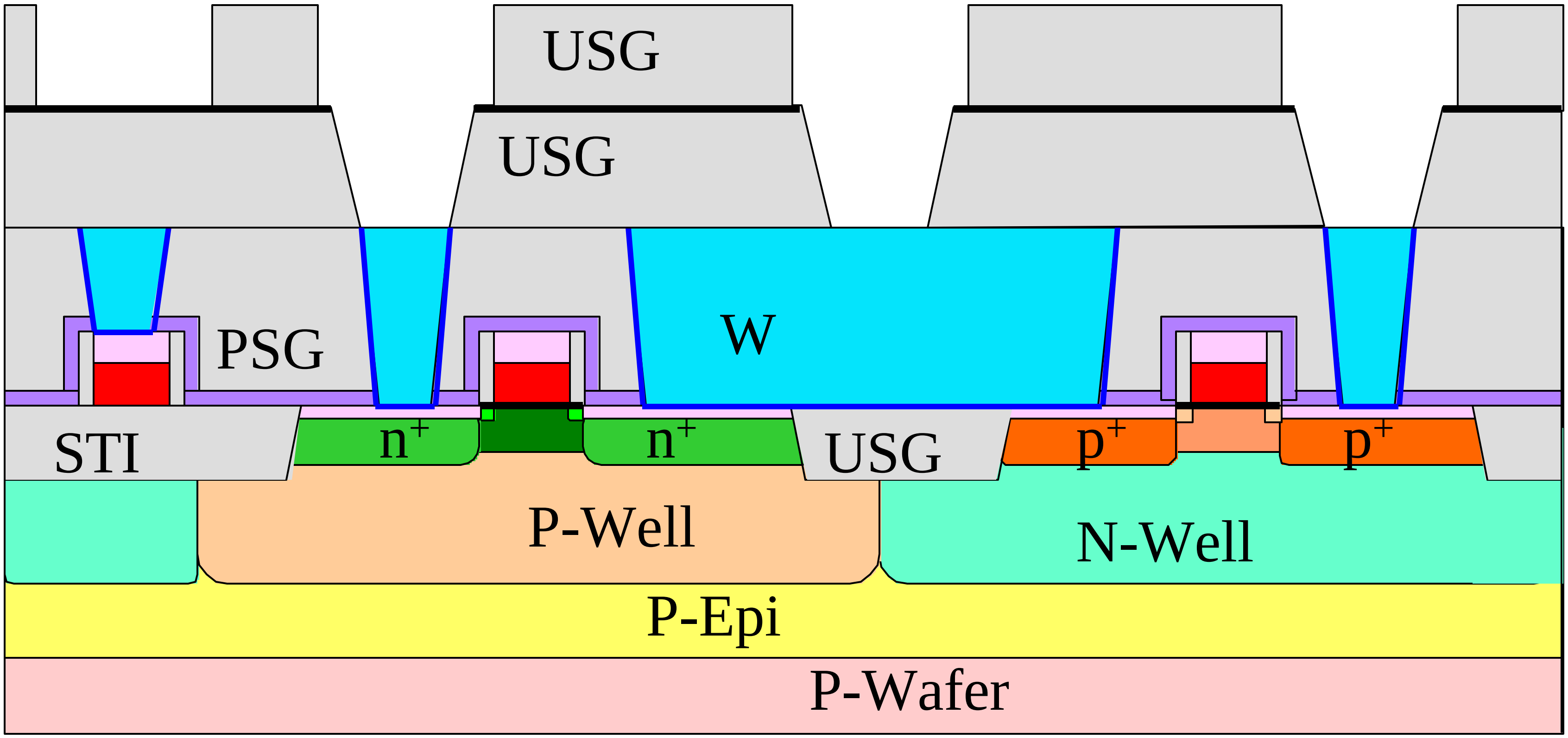
Metal 1 Mask Exposure and Development



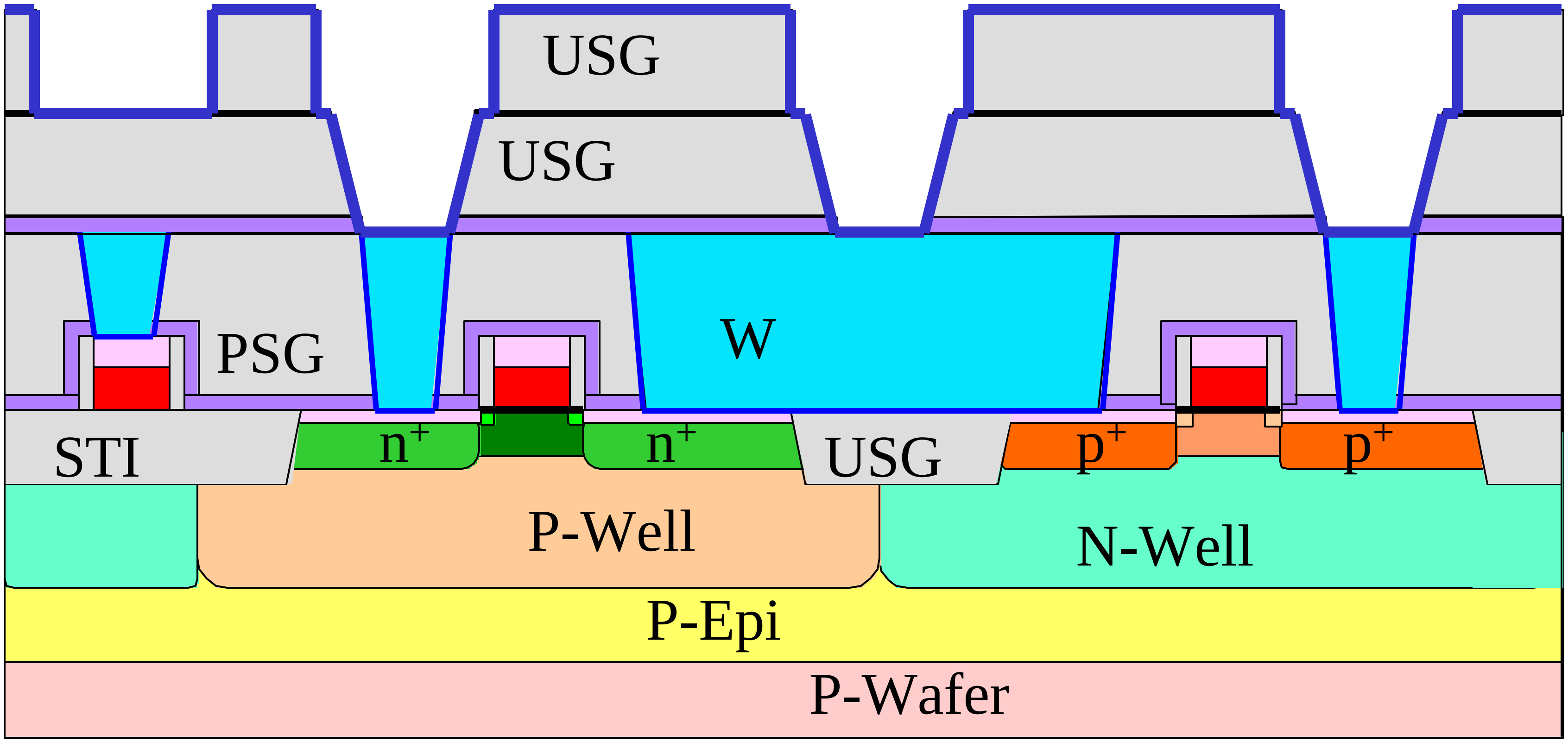
Etch USG and Nitride



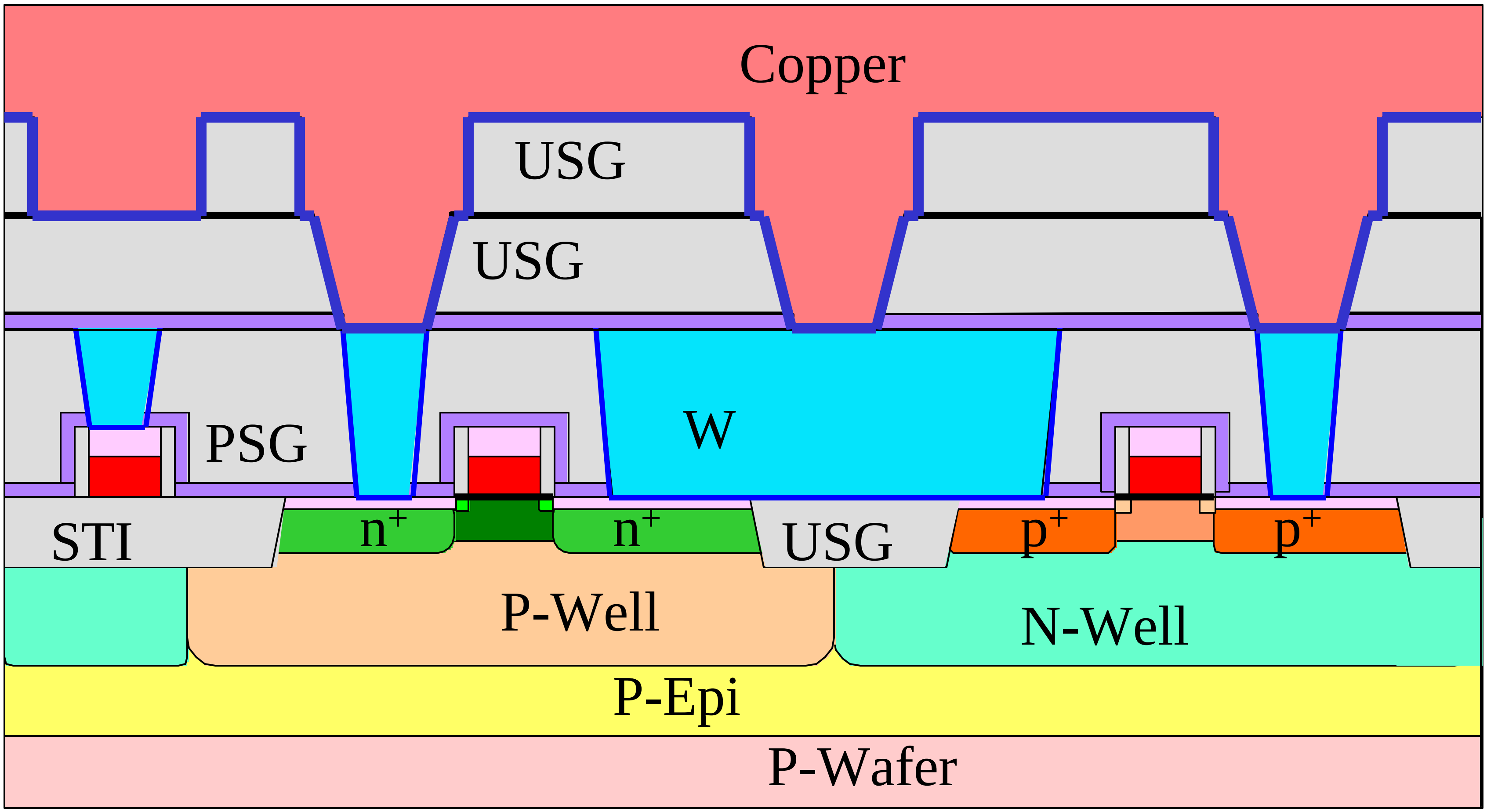
Strip Photoresist



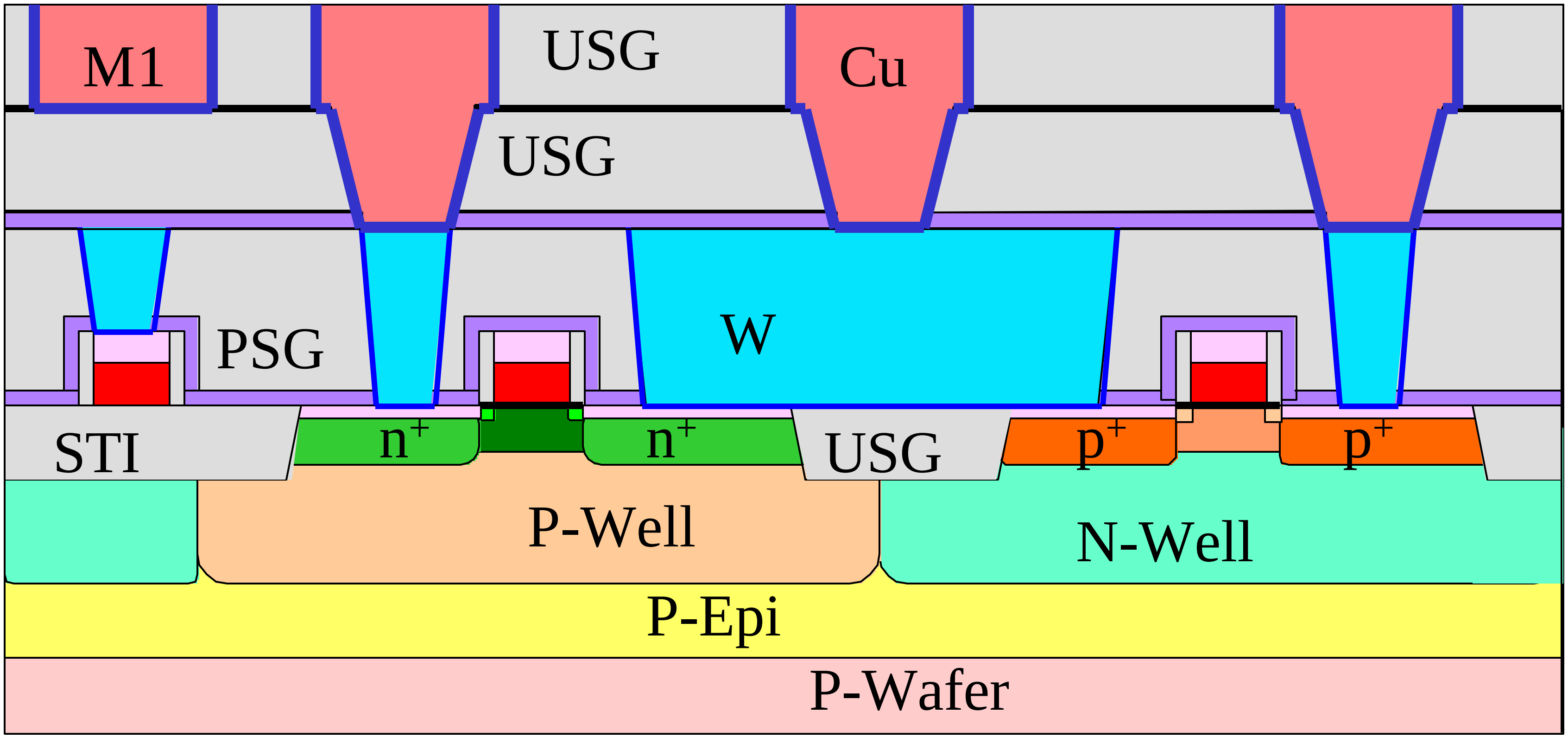
Deposit Tantalum Barrier Layer



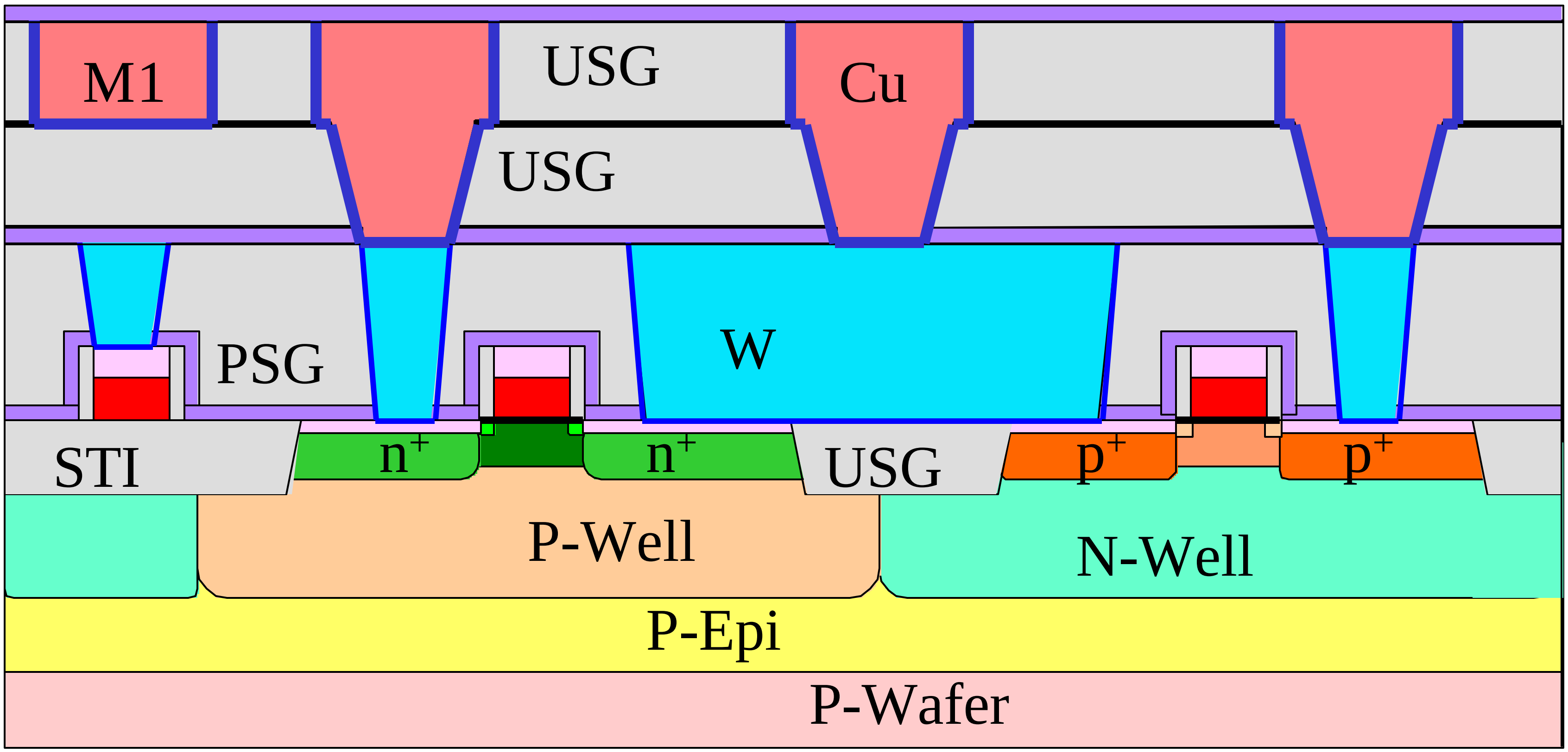
Deposit Copper



CMP Copper and Tantalum



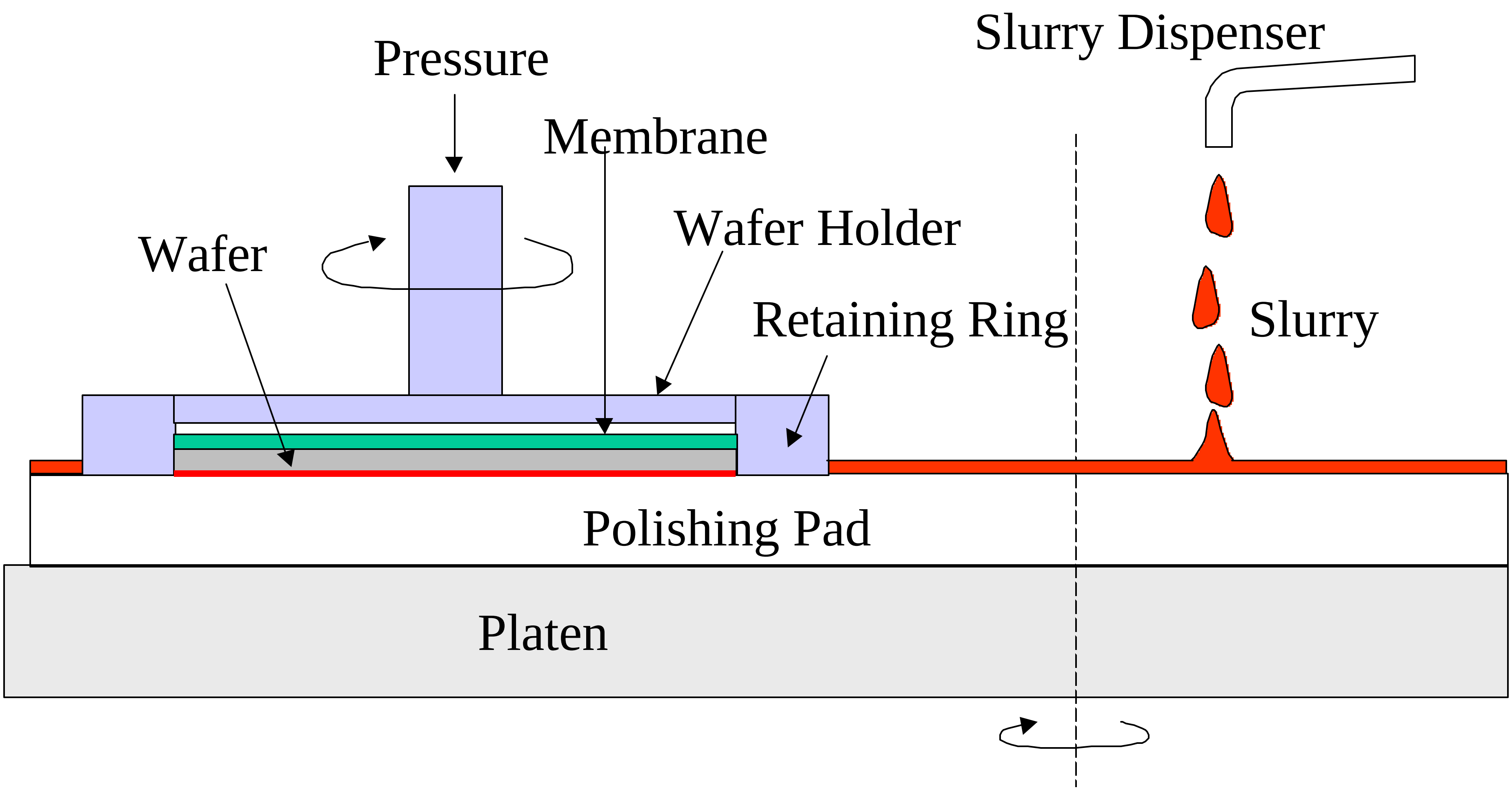
PECVD Seal Nitride



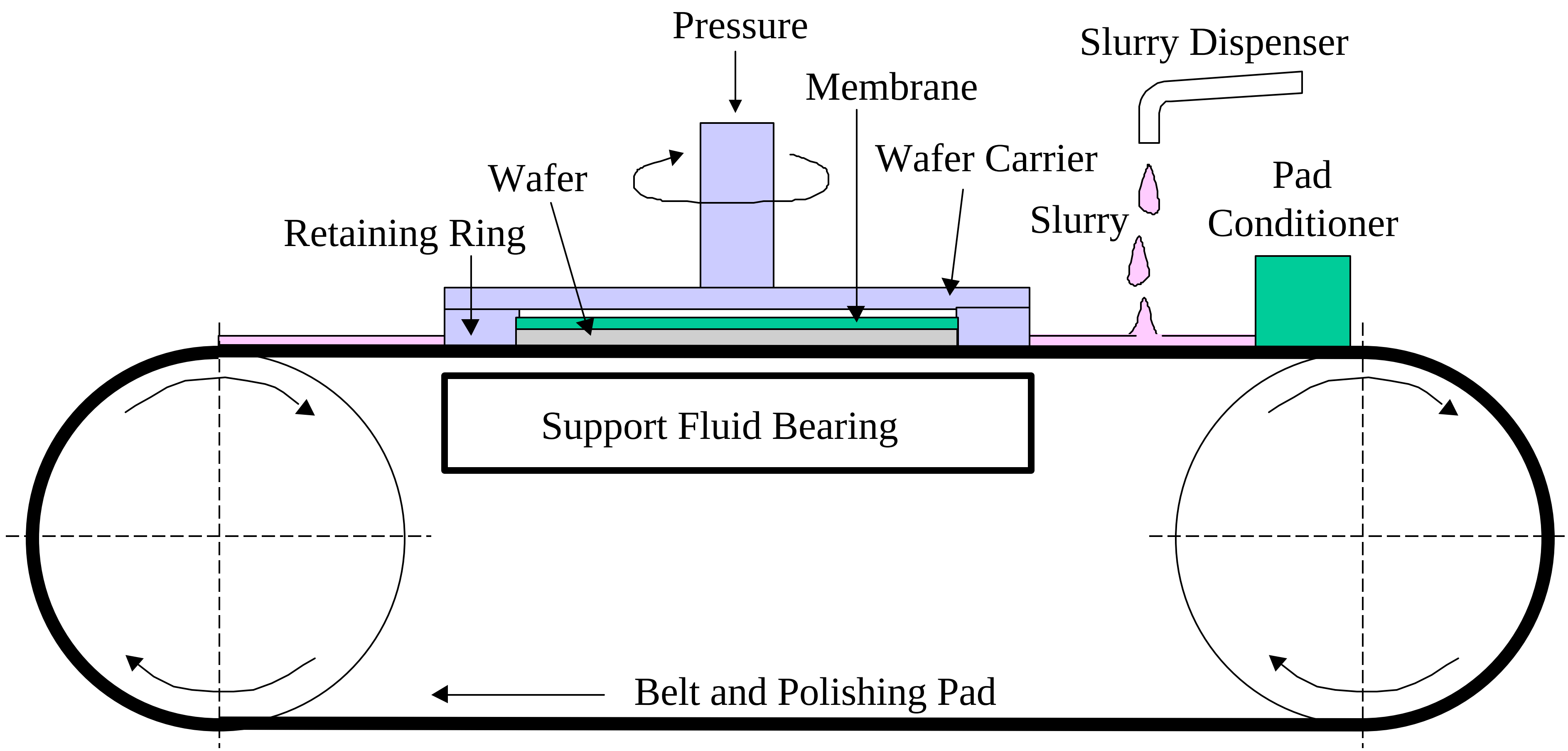
CMP Hardware

- Polishing pad
- Wafer carrier
- Slurry dispenser

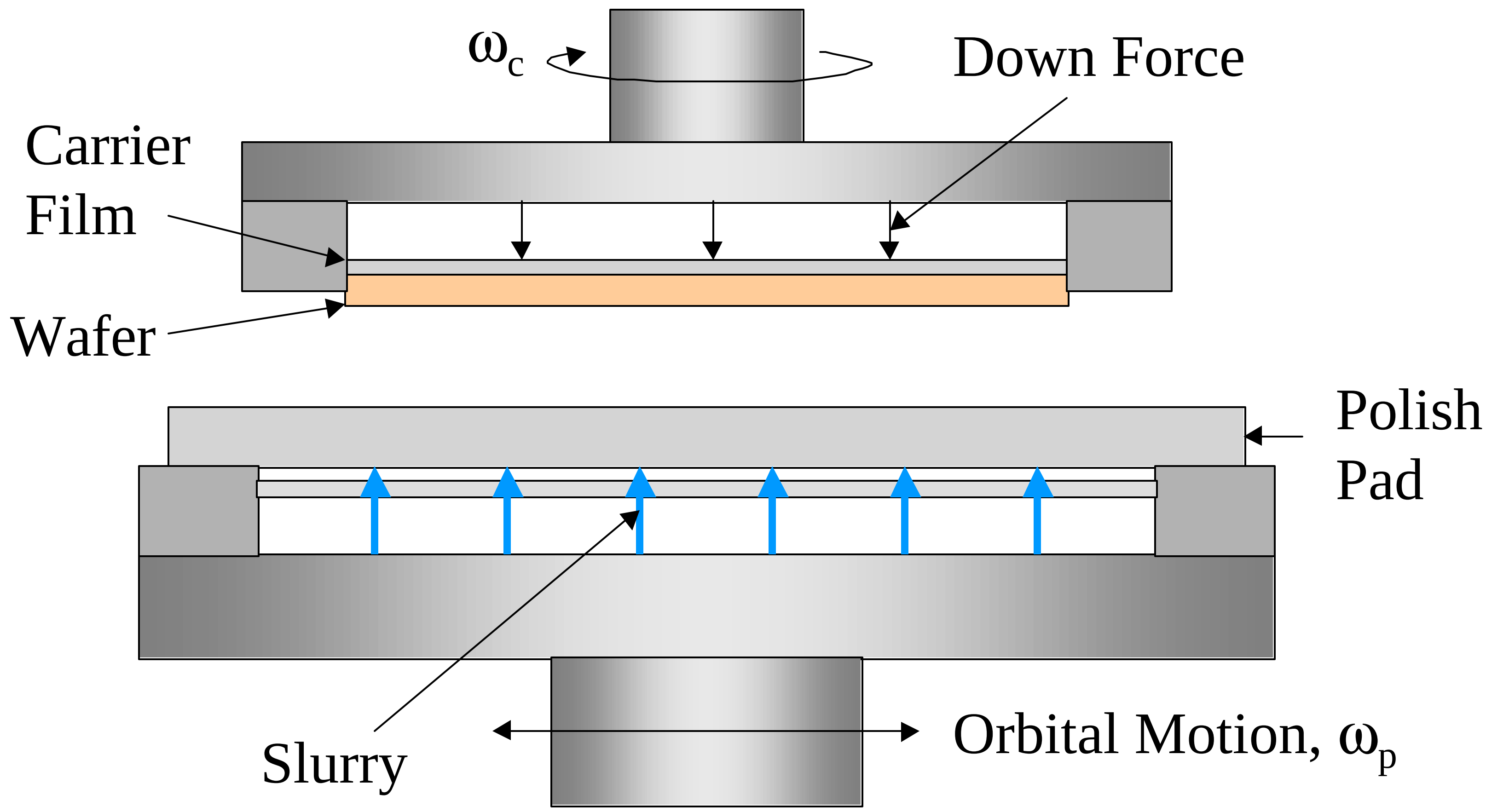
Chemical Mechanical Polishing



Linear Polishing System



Orbital Polishing



Polishing Pad

- Porous, flexible polymer material
  - cast, sliced polyurethane or urethane coated polyester felt
- Pad directly affects quality of CMP process
- Pad materials: durable, reproducible, compressible at process temperature
- Process requirement: high topography selectivity to achieve surface planarization

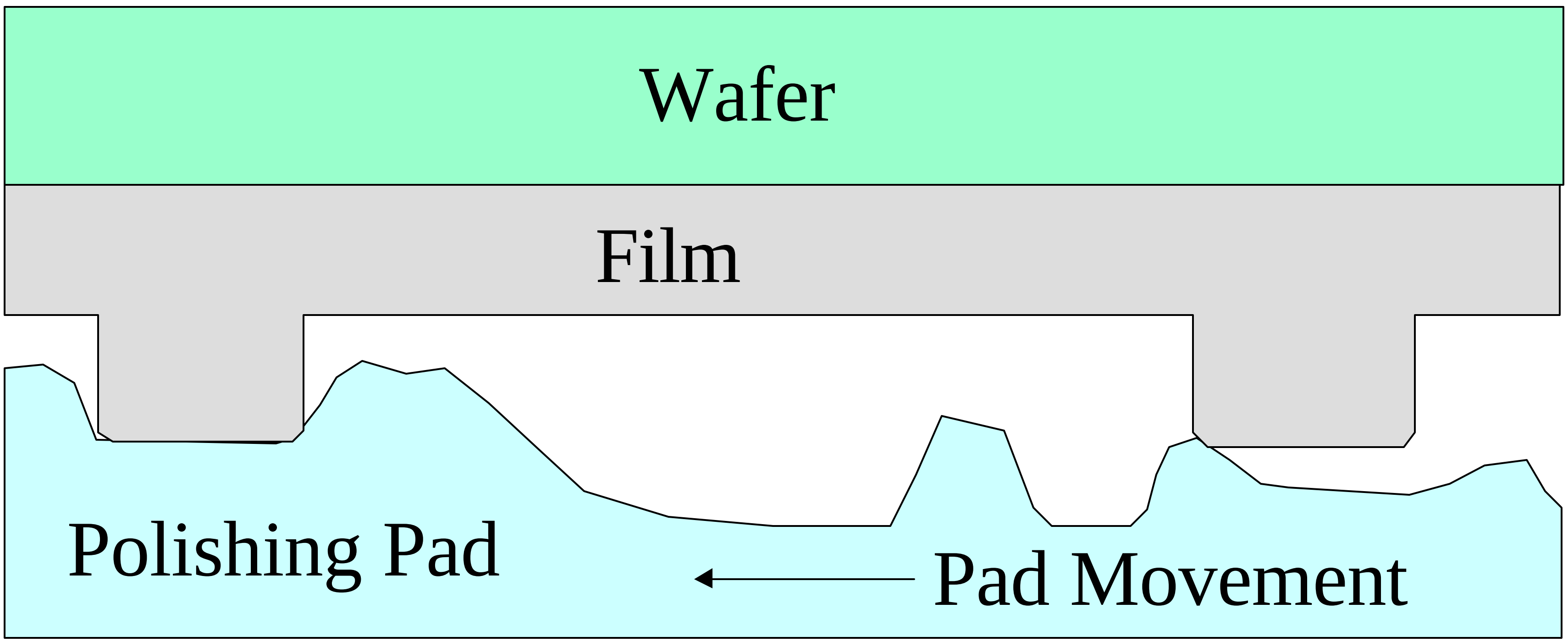
Polishing Pad Hardness

- Harder polishing pad: higher removal rate and better within die (WID) uniformity
- Softer pad: better within wafer (WIW) uniformity.
- Hard pads easier to cause scratches.
- The hardness is controlled by pad chemical compositions or by cellular structure.

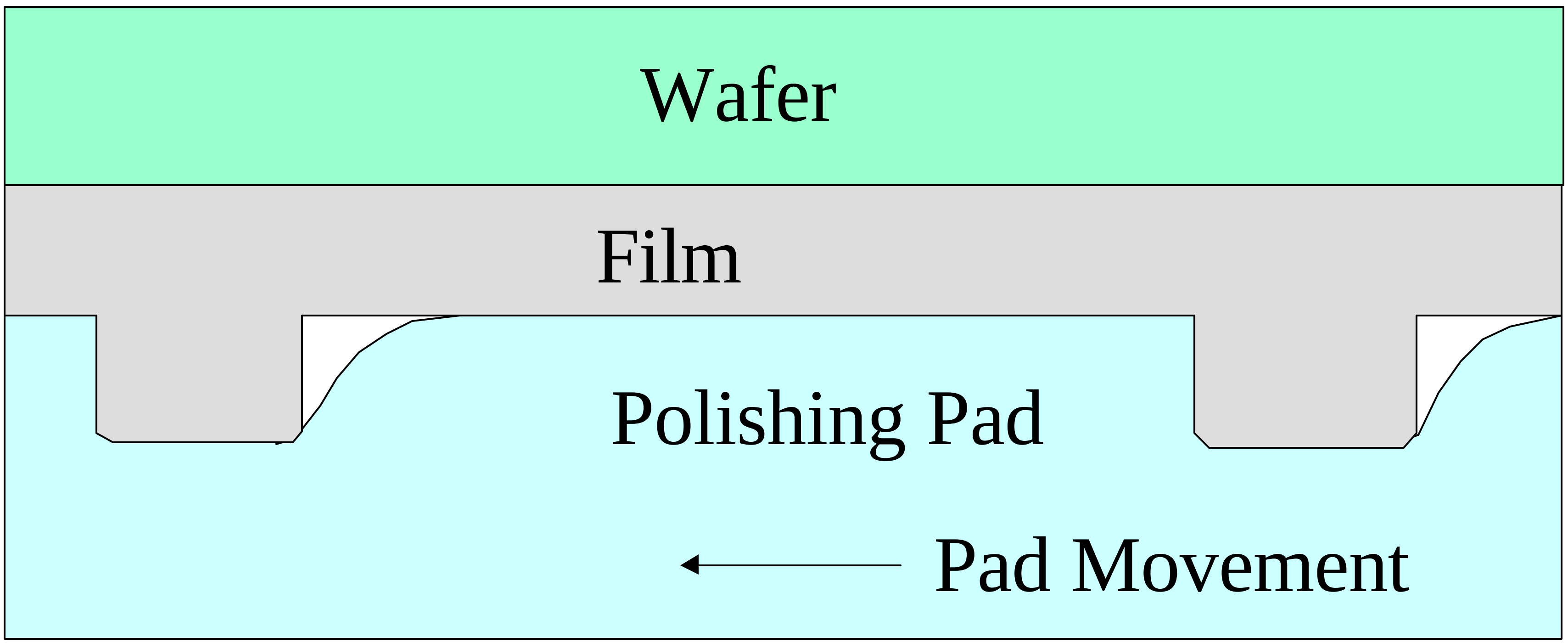
Polishing Pad

- Cells absorb polishing slurry
- Filler improve mechanical properties
- Polishing pad surface roughness determines the conformality range.
  - Smoother pad has poorer topographical selectivity less planarization effect.
  - Rougher pad has longer conformality range and better planarization polishing result

Hard Rough Pad



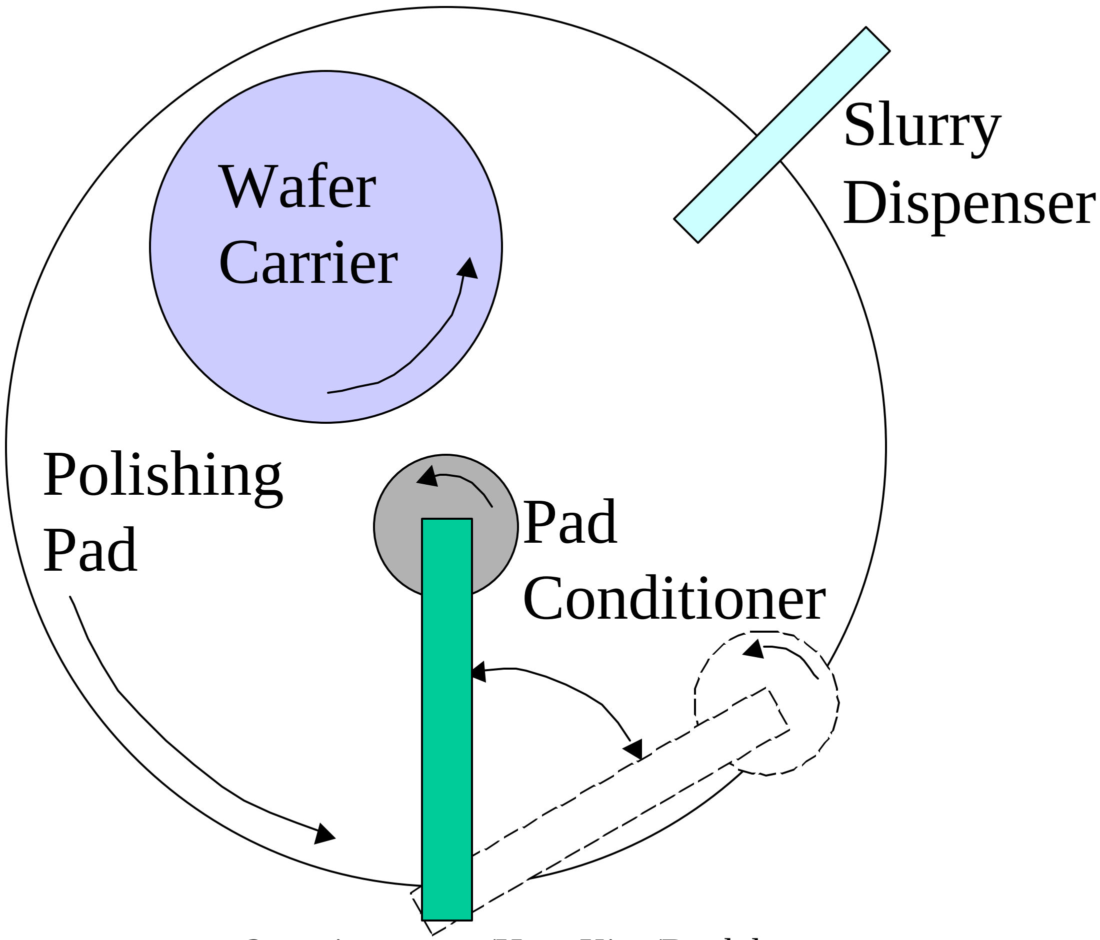
Soft Smooth Pad



Pad Conditioning

- Pad becomes smoother due to the polishing
- Need to recreate rough pad surface
- In-situ pad conditioner for each pad
- The conditioner resurfaces the pad
- Removes the used slurry
- Supplies the surface with fresh slurry

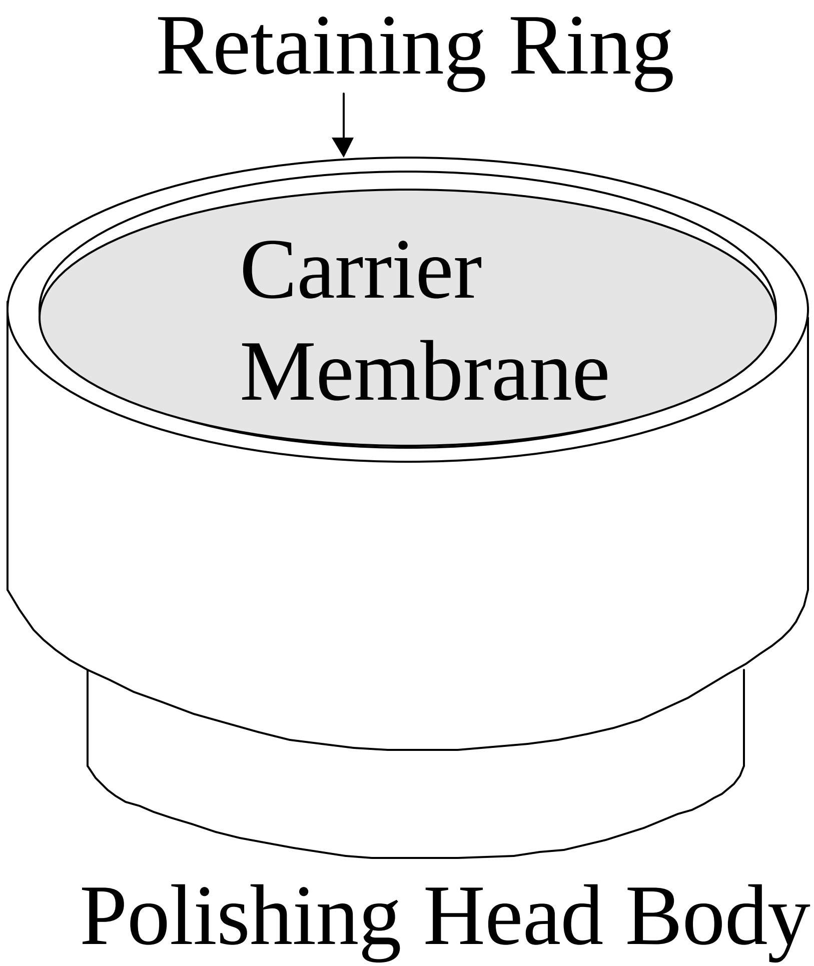
Polishing Pad and Pad Conditioner



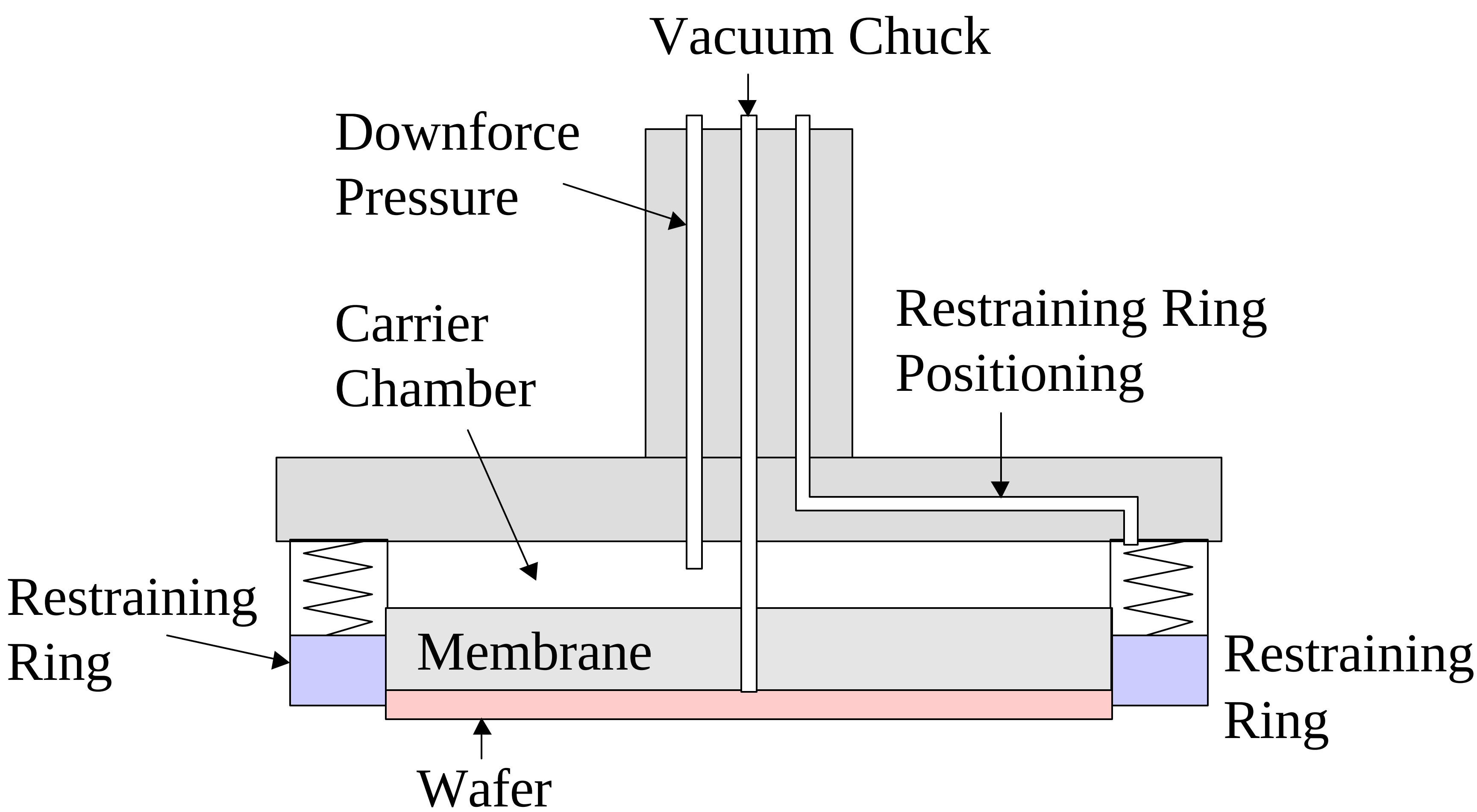
Polishing Head

- Polishing head is also called wafer carrier
- It consists of a polishing head body
- Retaining ring
- Carrier membrane
- Down force driving system

Polishing Head



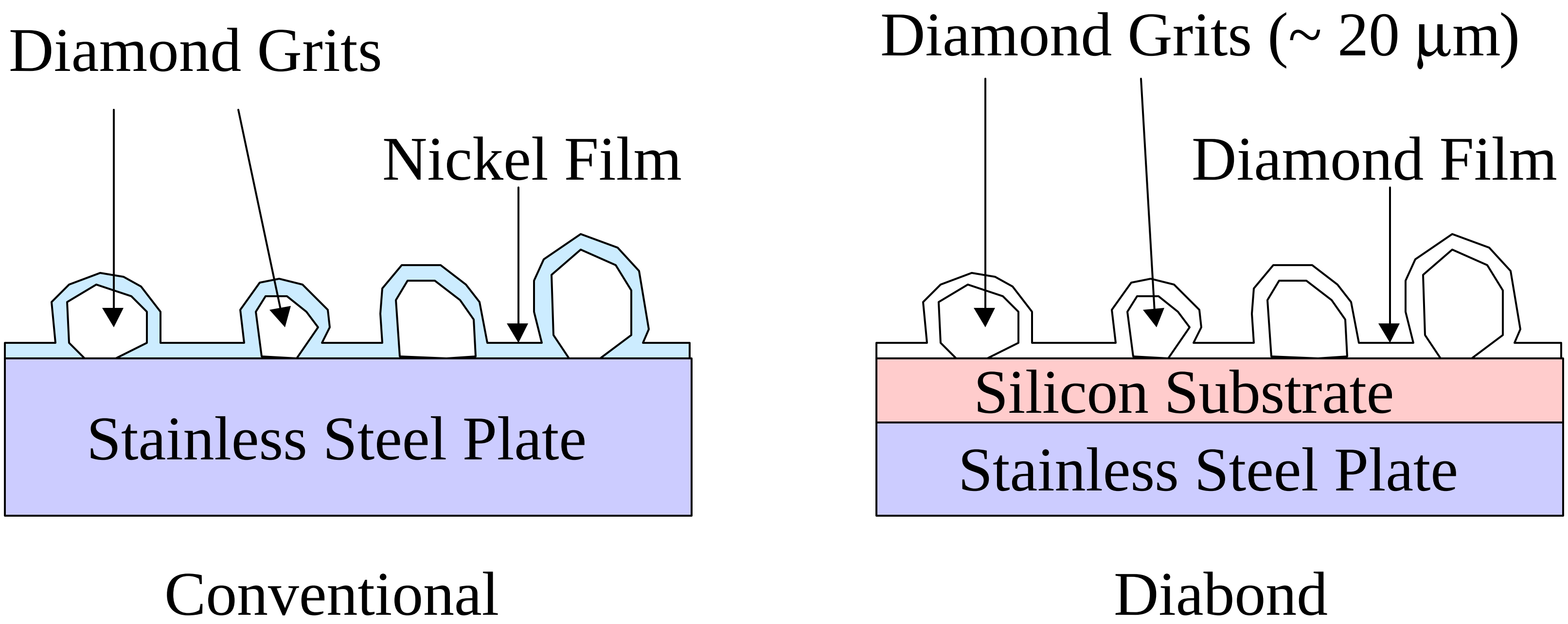
Schematic of Polishing Head



Pad Conditioner

- Sweeps across the pad to increase surface roughness required by planarization and removes the used slurry
- Conditioner is a stainless steel plate coated with nickel-plated diamond grits
- Diabond CMP conditioner: stainless steel plate coated with CVD diamond film plated diamond grids

Surface of CMP Conditioners



CMP Slurries

- Chemicals in the slurry react with surface materials, form chemical compounds that can be removed by abrasive particles
- Particulate in slurry mechanically abrade the wafer surface and remove materials
- Additives in CMP slurries help to achieve desired polishing results

CMP Slurries

- CMP slurries work just like toothpaste
- Chemicals kill gems, remove tartar, and form protection layer on the teeth
- Particles abrade away unwanted coating from tooth surface during tooth brushing

CMP Slurries

- Water-based chemicals with abrasive particles and chemical additives
- Different polishing processes require different slurries
- Slurry can impact removal rate, selectivity, planarity and uniformity
- Slurries always are engineered and formulated for a specific application.

CMP Slurries

- 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

pH Values

Neutral

↓

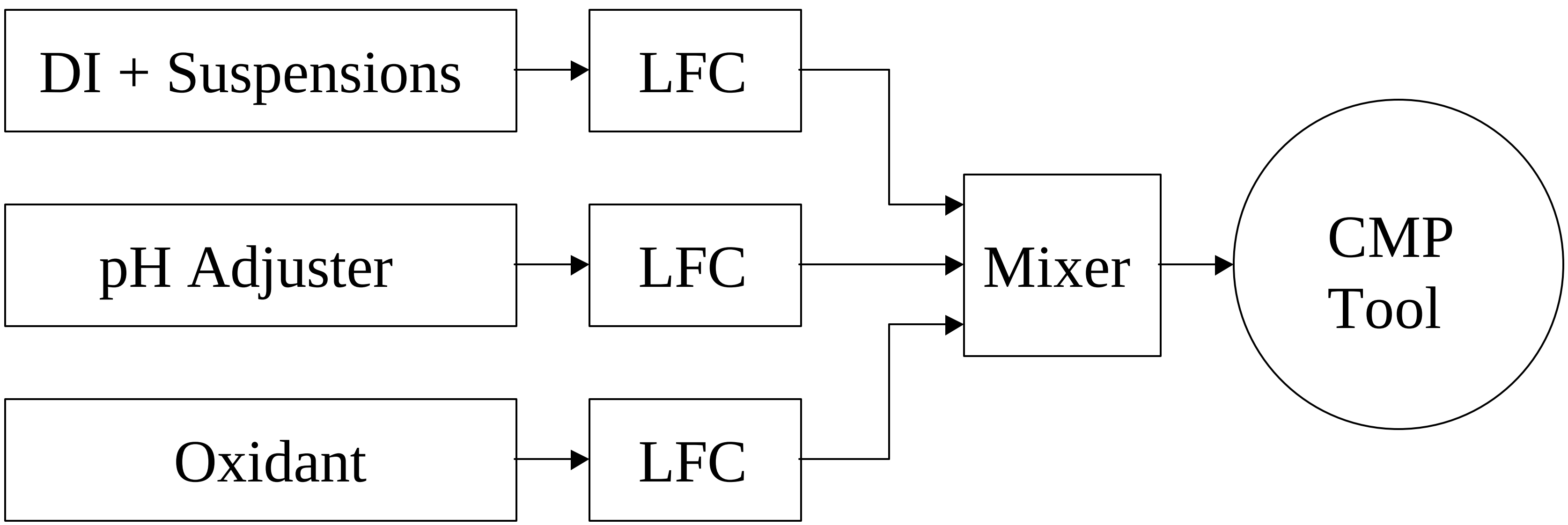
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

More Acidic ← pH → More Basic

Slurry Delivery

- Slurry components are stored separately
  - DI water with particulate
  - additives for pH control
  - oxidants for metal oxidation
- Flow to a mixer to mix at required ratio

Slurry Flow



LFC: liquid flow controller

Oxide Slurry

- Based on experience of optical industry, which polish silicate glass to make lenses and mirrors for a long time
- Oxide slurry is a colloidal suspension of fine fumed silica (SiO_2) particles in water
- KOH is used to adjust the pH at 10 to 12
- NH_4OH can also be used

Oxide Slurry

- Abrasives: fumed silica particles
- Normally contain ~ 10% solids
- Shelf lifetime of up to 1 year with proper temperature control

Fumed Silica

- Fumed silica particles are formed in a vapor phase hydrolysis of $SiCl_4$ in a hydrogen-oxygen flame

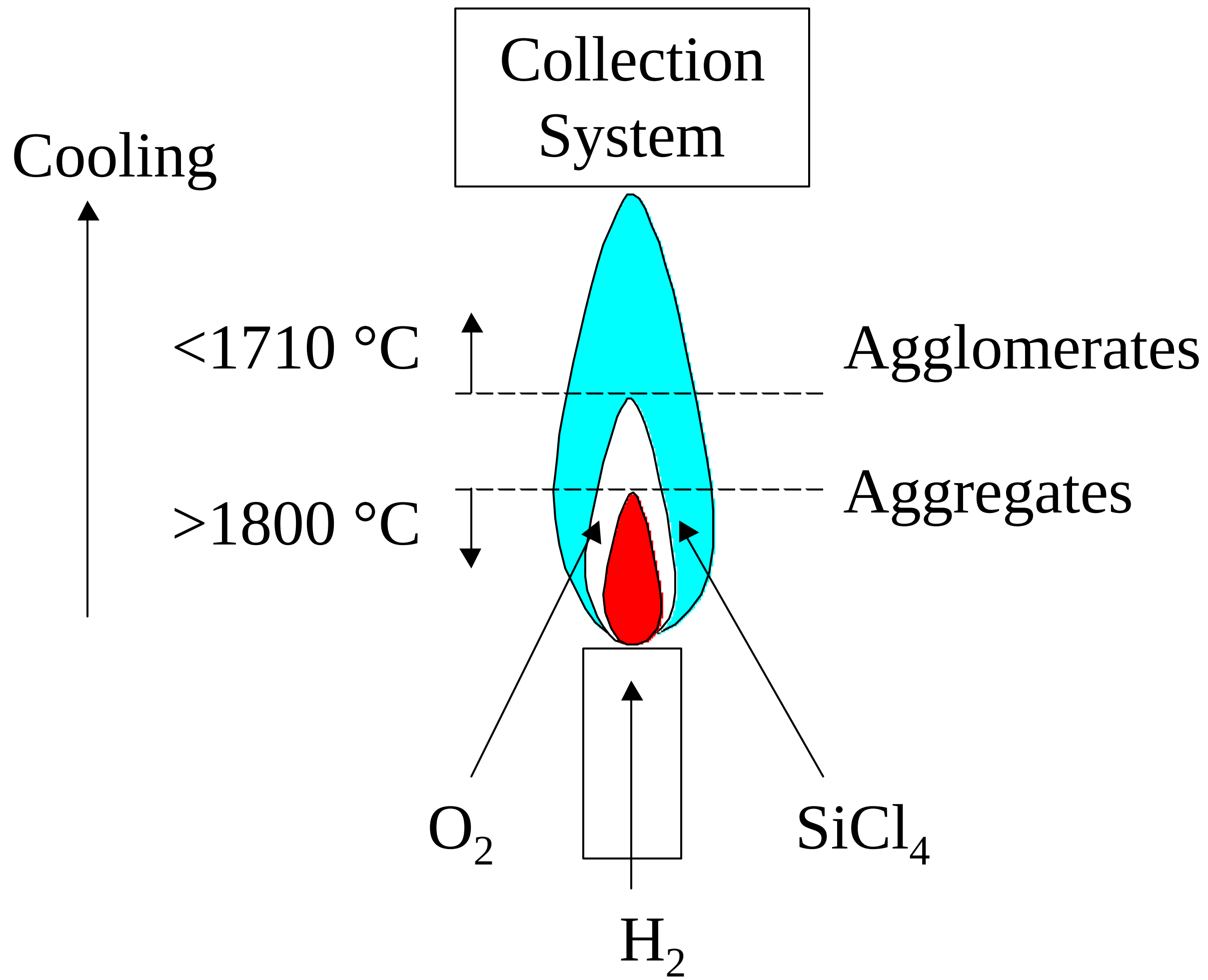
$$2\,H_2 + O_2 \rightarrow 2\,H_2O$$

$$SiCl_4 + 2\,H_2O \rightarrow SiO_2 + 4HCl\uparrow$$

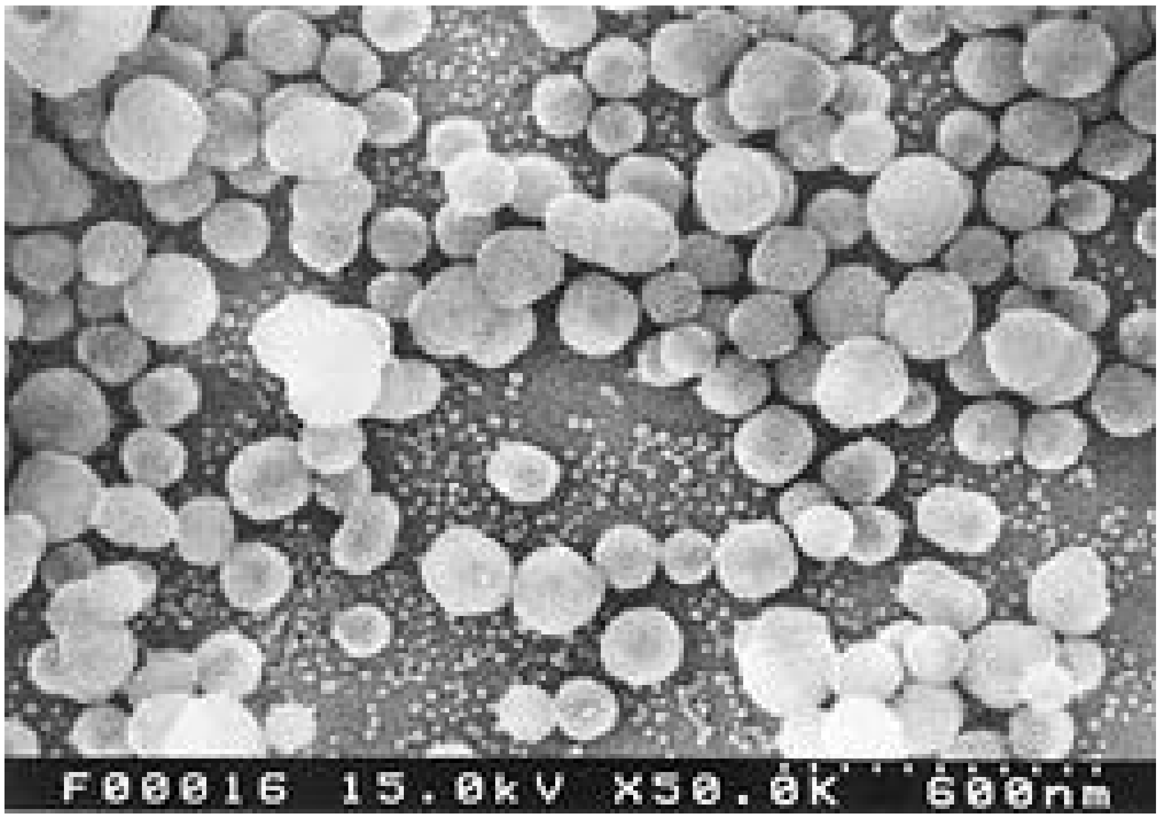
- Overall reaction

$$SiCl_4 + 2\,H_2 + O_2 \rightarrow SiO_2 + 4HCl\uparrow$$

Fumed Silica Particle Formation



Fumed Silica Particles



Courtesy of Fujimi Corporation

Metal Polishing Slurry

- Metal CMP process is similar to the metal wet etch process
  - Oxidant reacts with metal to form oxide
  - Metal oxide is removed
  - Repeat metal oxidation and oxide removal

Metal Polishing Slurry

- The metal CMP slurries usually are pH-adjusted suspensions of alumina (Al_2O_3)
- The slurry pH controls the two competing metal removal mechanisms
  - metal corrosive wet etching
  - metal oxidation passivation

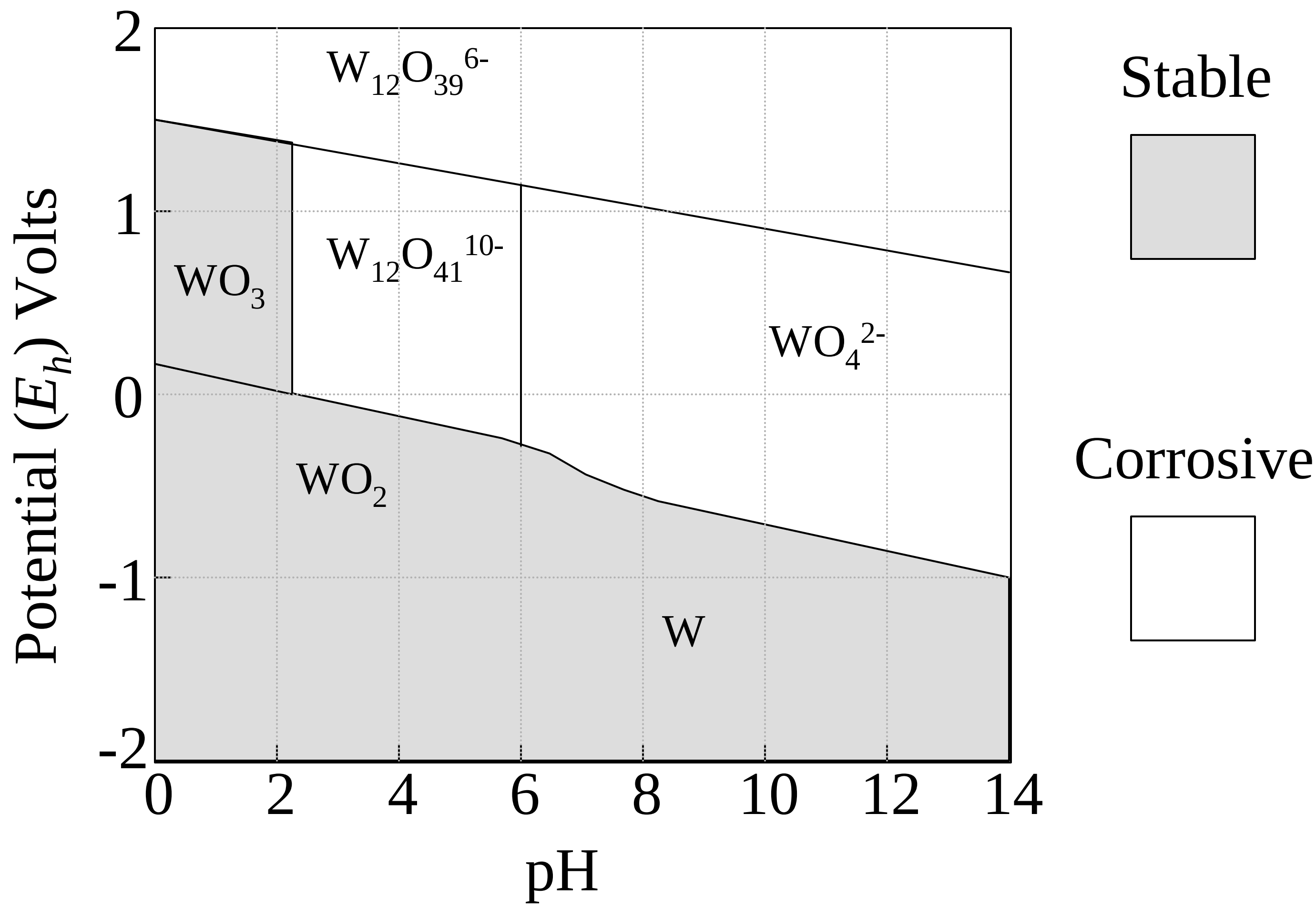
Metal Polishing Slurry

- Different metal oxides have different solubility
- If oxide is soluble, wet etch will dominate
  - Not favored: isotropic with no topographic selectivity
- If oxide is insoluble, it blocks further oxidation
  - Particles mechanically abrade oxide layer
  - Repeating metal oxidation and oxide abrasion
  - favorable: high surface topographic selectivity
- The pH value controls oxidation process

Tungsten Slurry

- Pourbaix diagram
- When pH < 2, tungsten is in passivation regime
- Tungsten can form passivation oxide WO_3 with pH lower than 4 in the presence of an oxidant
  - Oxidants: potassium ferricyanid ($K_3Fe(CN)_6$), ferric nitrade ($Fe(NO_3)_3$), and H_2O_2
- For a higher pH, the soluble $W_{12}O_{41}^{10-}$, WO_4^{2-}, and $W_{12}O_{39}^{6-}$ ions can be formed, cause wet etch

Pourbaix Diagram for Tungsten



Tungsten Slurry

- Adjusting slurry pH allows low wet etch rates and chemical-mechanical polish removal
- Tungsten slurries normally are quite acidic with pH level from 4 to 2.
- Tungsten slurries have lower solid contents and much shorter shelf lifetime.
- Tungsten slurries require mechanical agitation prior to and during delivery to the CMP tools

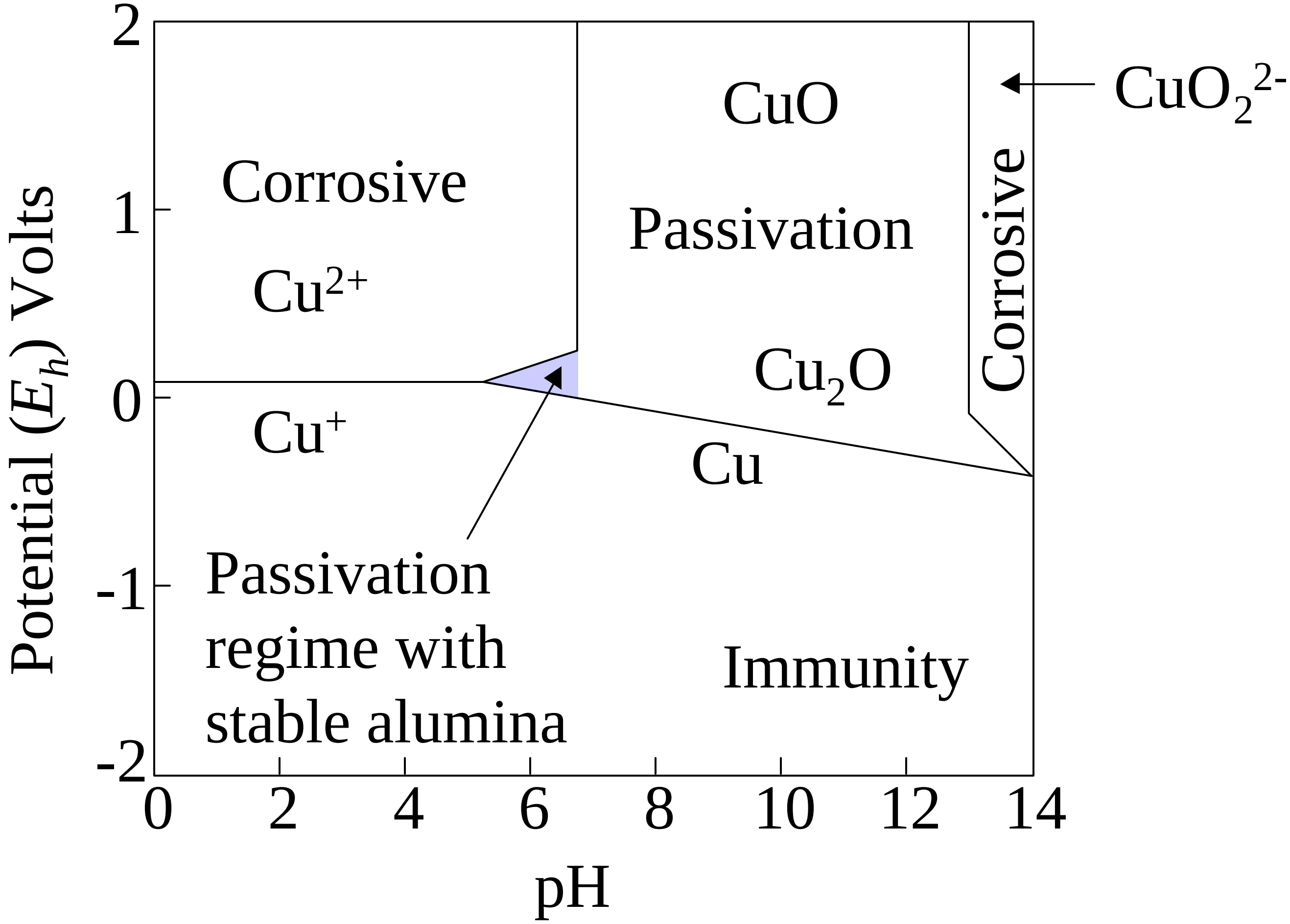
Aluminum Slurry

- Water-based acidic solutions
- H_2O_2 as oxidant,
- Alumina as abrasives.
- Limited shelf lifetime
- H_2O_2 molecule is unstable
- Aluminum CMP is not popularly used
  - Hard to compete with copper metallization

Copper Slurry

- Acidic solutions
- Oxidants: hydrogen peroxide (H_2O_2), ethanol (HOC_2H_5) with nitric acid (HNO_4), ammonium hydroxide (NH_4OH) with potassium ferri- and ferro-cyanide, or nitric acid with benzotriazole
- Alumina as abrasives

Pourbaix Diagram for Copper



Copper Slurry

- Need colloidally stable slurry to achieve consistent polishing process results
- A colloidally stable alumina suspension can be achieved at pH just below 7.
- Only a small window for copper slurries to achieve both electrochemical passivation and colloidally stable suspension of aqueous alumina particles

CMP Basics

- Removal rate
- Uniformity
- Selectivity
- Defects

Removal Rate

- Mechanical removal rate *R* was found by Preston
- The Preston equation can be expressed as

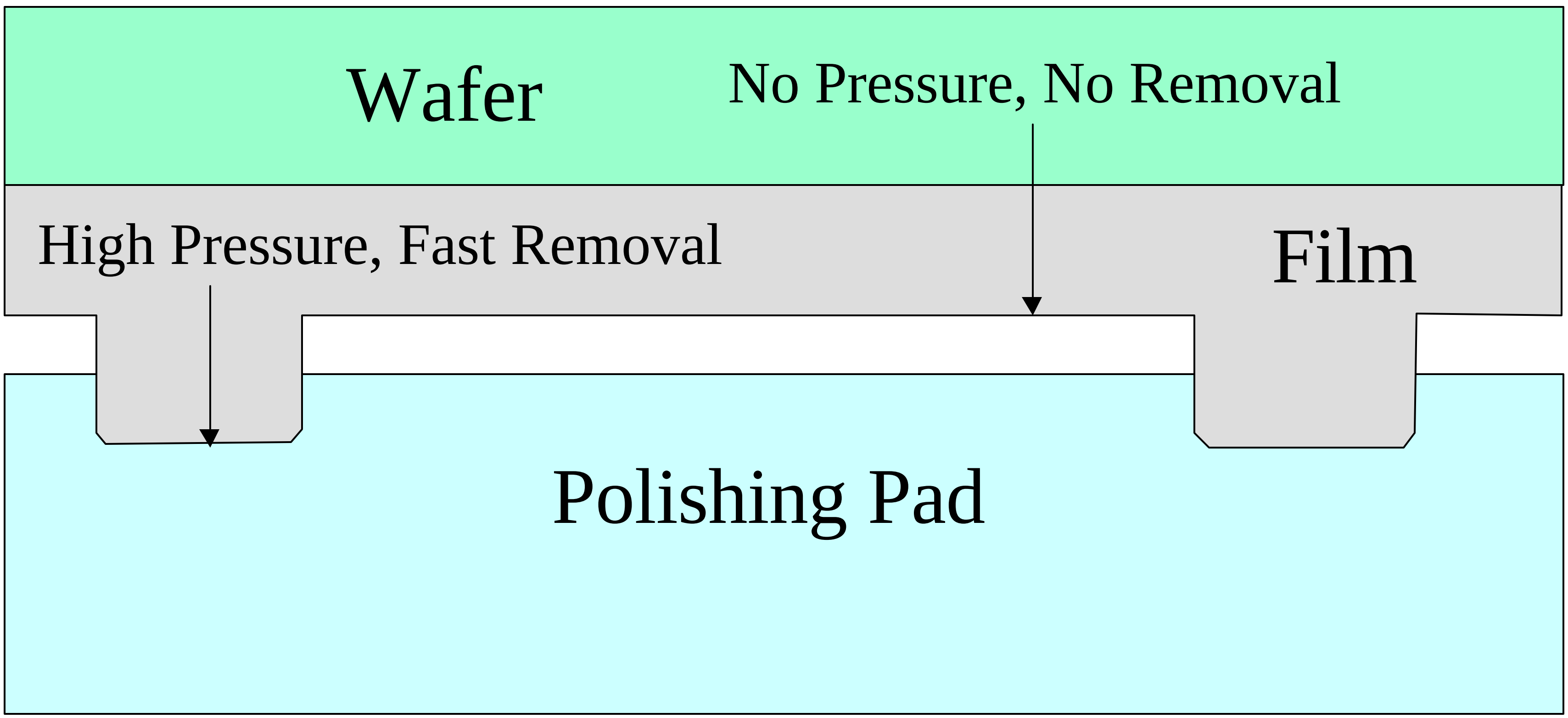
$$R = K_p \cdot p \cdot D\mathrm{v}$$

- *p* is the polishing pressure
- K_p is the Preston coefficient
- *D*v is relative velocity of wafer and pad

Removal Rate

- Preston equation works very well for the bulk film polishing processes
- The protruding portions on a rough surface have higher polishing pressure
- Removal rate of protruding parts is higher
- This helps to remove surface topography and planarize the surface

Protruding Parts with Higher Pressure



Removal Rate

- Thickness difference before and after CMP divided by CMP time
- Multiple measurement for uniformity
- Test wafer, blanket film
- Daily tool qualification

Uniformity

- Usually 49-point, 3σ standard deviation as the definition of the uniformity for the CMP process qualifications
- Changes of the film thickness before and after CMP process is monitored
- For the production wafers, uniformity after CMP process is monitored
- Normally use 9 or 13 points measurement

Uniformity

- Both WIW and WTW uniformity can be affected by the polish pad condition, down force pressure distribution, relative speed, restraining ring positioning, and the shape of the wafers.
- By using harder pad and lower pressure a good global uniformity can be achieved
- Lower pressure, lower removal rate, affect throughput

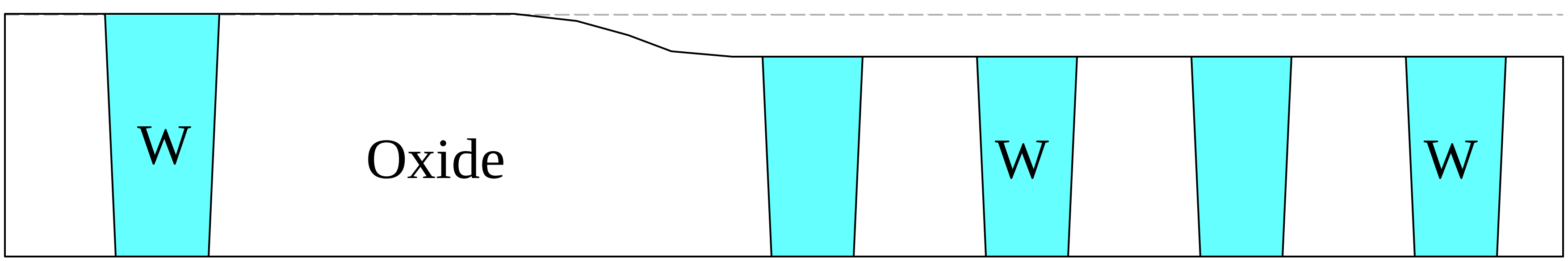
Selectivity

- 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
- Because only polish oxide, selectivity is not important in PMD and IMD CMP processes

Selectivity

- For tungsten CMP process, selectivity to oxide and titanium nitride is very important.
- Usually tungsten to TEOS oxide selectivity is very high, from 50 to 200
- Slurry chemistry, oxidant
- Selectivity is also related to the pattern density
- higher pattern density, lower removal selectivity
  - lead to erosion of the tungsten and oxide film

Erosion Caused by High Pattern Density



IC Layout and Erosion

- IC design layout can directly affect the erosion problems
- By designing opening area less than 30% of the chip surface, it can help to solve the erosion problem

Defects

- CMP removes defects and improves yield
- Introduce some new defects
  - scratches, residual slurry, particles, erosion, and dishing.
- Large foreign particles and hard polish pad can cause scratches
  - Tungsten fill the scratches in oxide surface cause short circuit and reduce the IC yield.

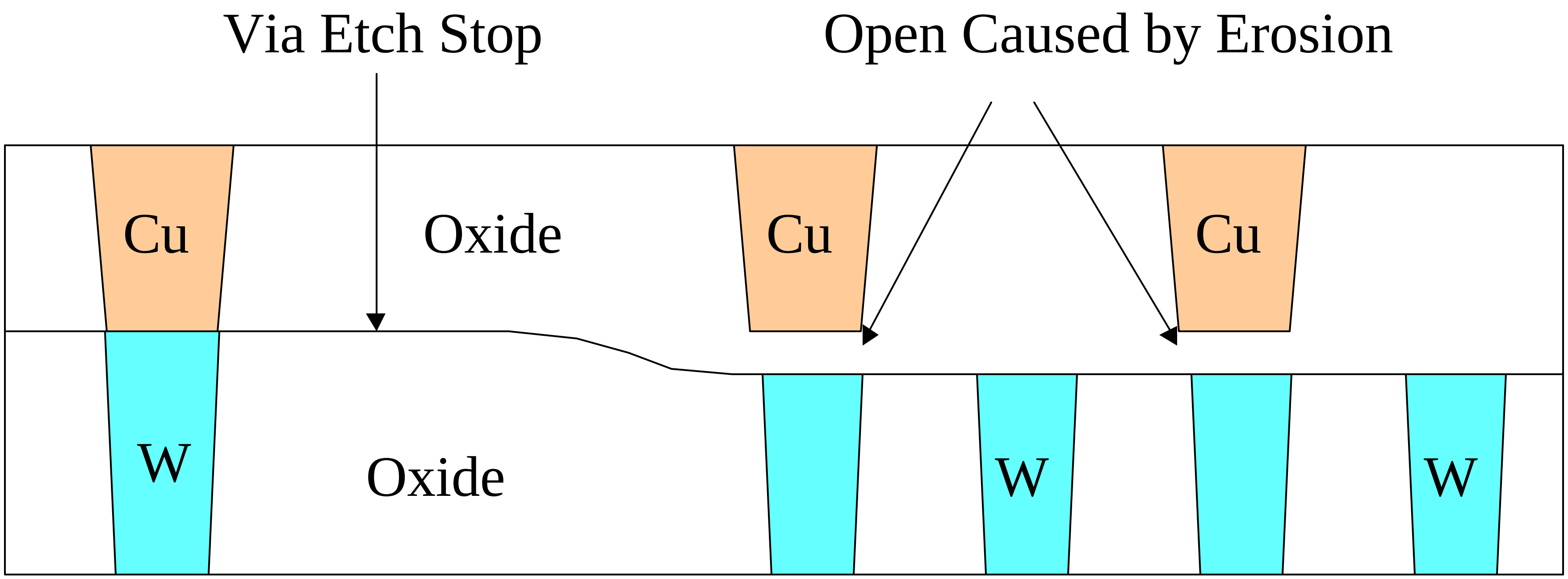
Defects

- Improper down force pressure, worn pad, inadequate pad conditioning, particle surface attraction, and slurry drying
- Slurry residue on the wafer surface and cause contamination
- Post-CMP clean is very important to remove slurry residue and improve process yield

Erosion

- Increases depth of via holes
- Incomplete via hole etch
- Open loop between the different layers in the next dual damascene interconnection

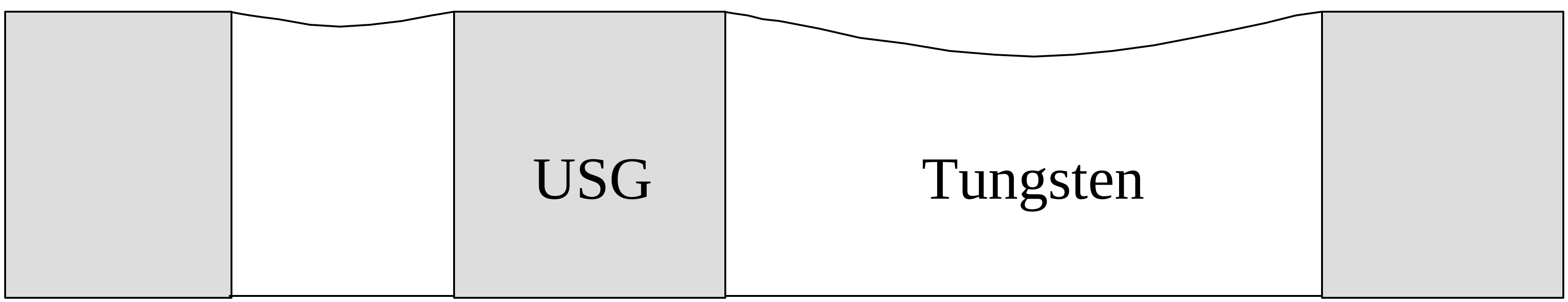
Circuit Opening Caused by Erosion



Dishing Effect

- Usually happens at a larger opening area
  - large metal pads
  - STI oxide in the trenches.
- More materials are removed from the center
- Cross-section view looks like a dish

Dishing Effect



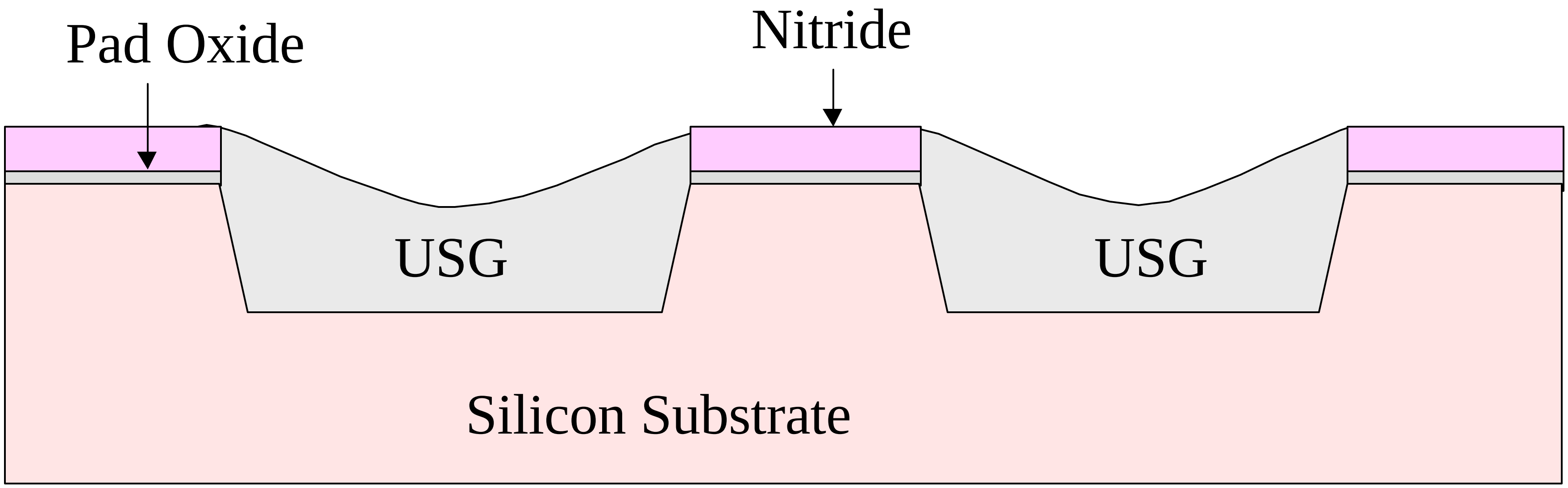
Dishing/Erosion and Selectivity

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

Dishing/Erosion and Selectivity

- Oxide CMP with high selectivity of oxide to nitride can cause oxide dishing during the oxide overpolishing step of the oxide CMP in the STI formation

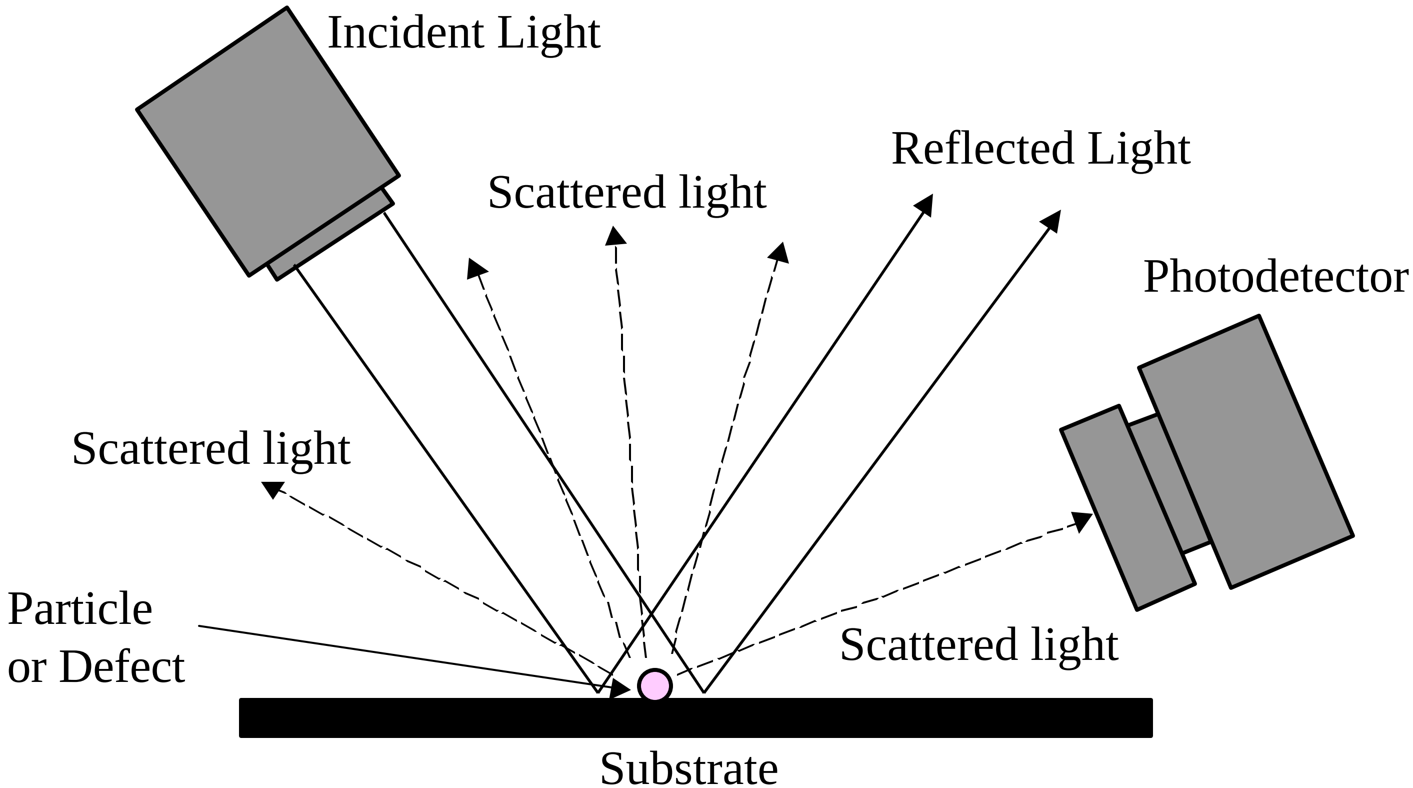
Dishing Effect of STI USG



Particles and Defects

- Particles and defects cause irregular topography on wafer surface
- Scattering incident light
- Monitor particles and defects by detecting the scattered light

Particle Detection By Light Scattering



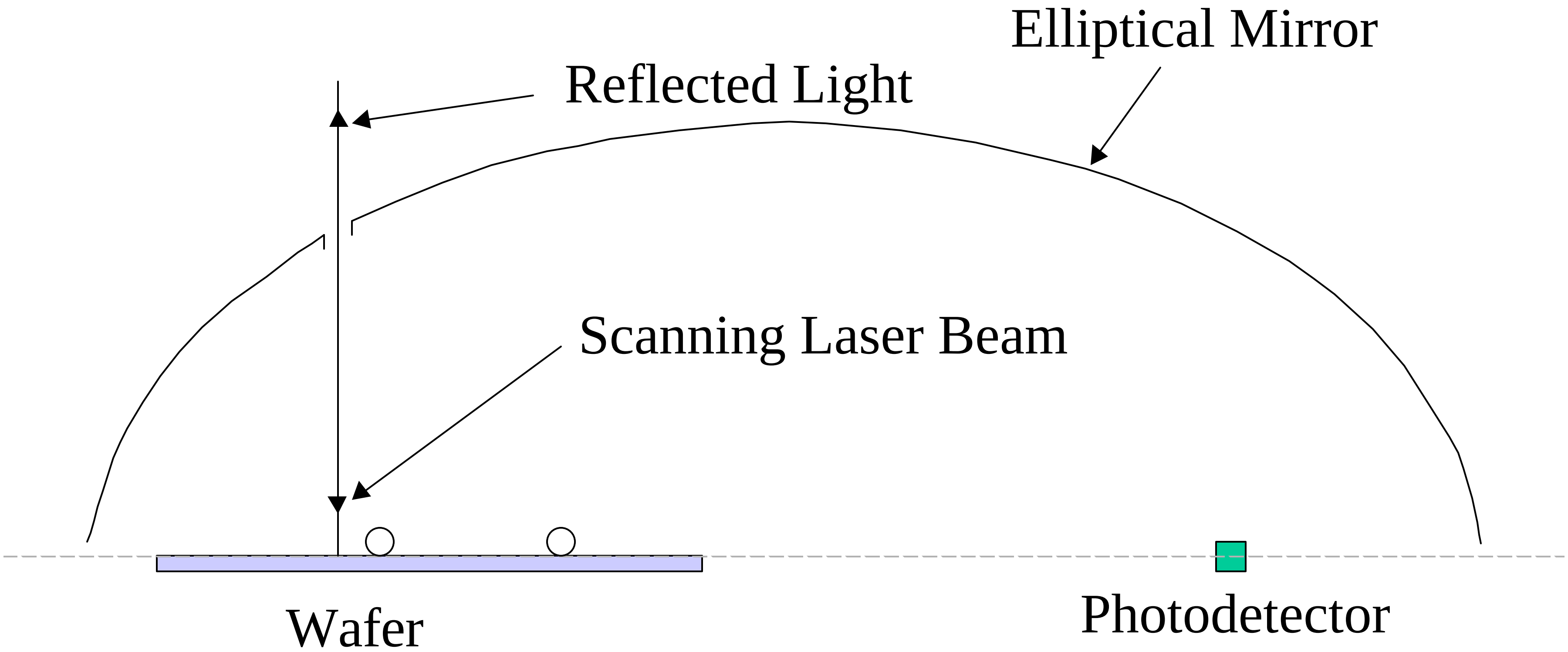
Particle Measurement

- Intensity of the scattered light is very weak
- Elliptical mirror is used to collect the light
- Elliptical curve has two focuses
- Light from one focus reflects to another focus

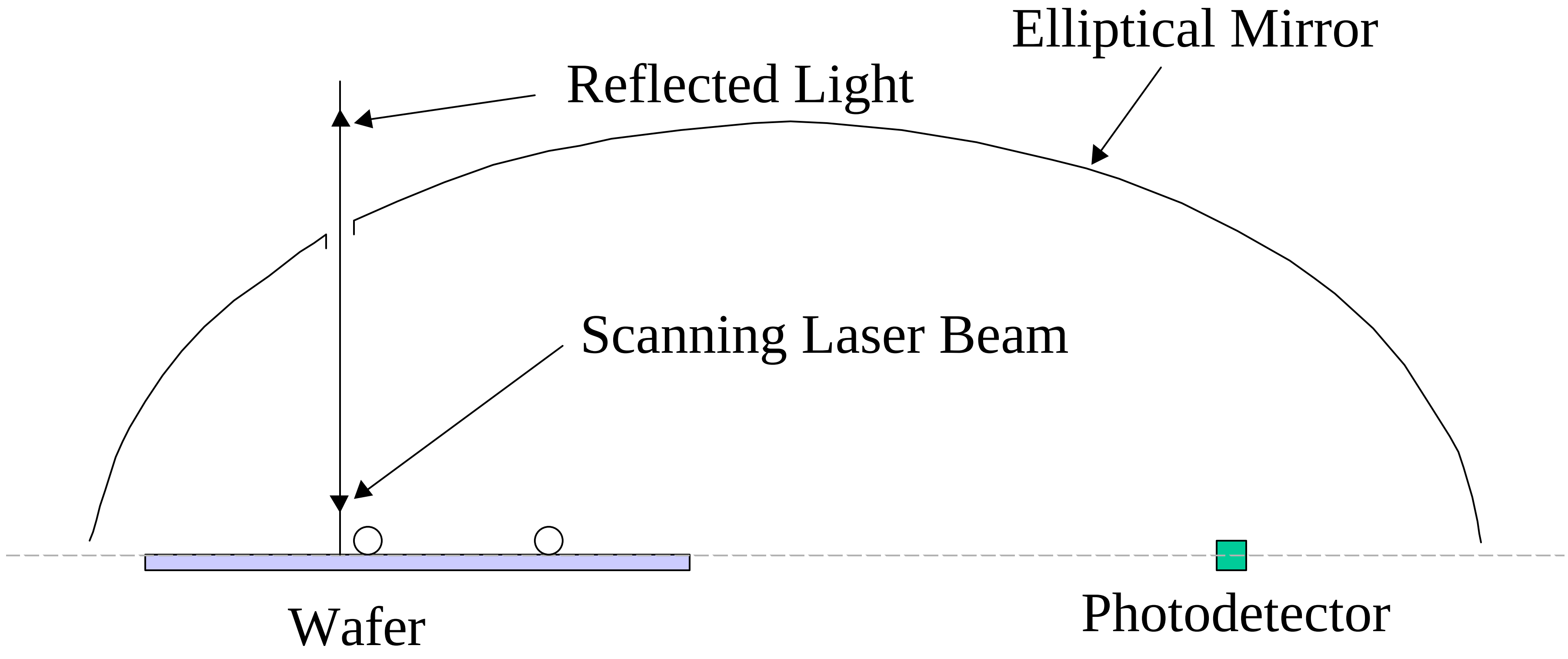
Particle Measurement

- Laser beam scans wafer surface vertically at one focus of elliptical mirror and a photo-detector is placed at another focus
- Moving wafer, and collecting scattered light to detect tiny particles and defects
- Mapping particle/defect locations on the wafer surface

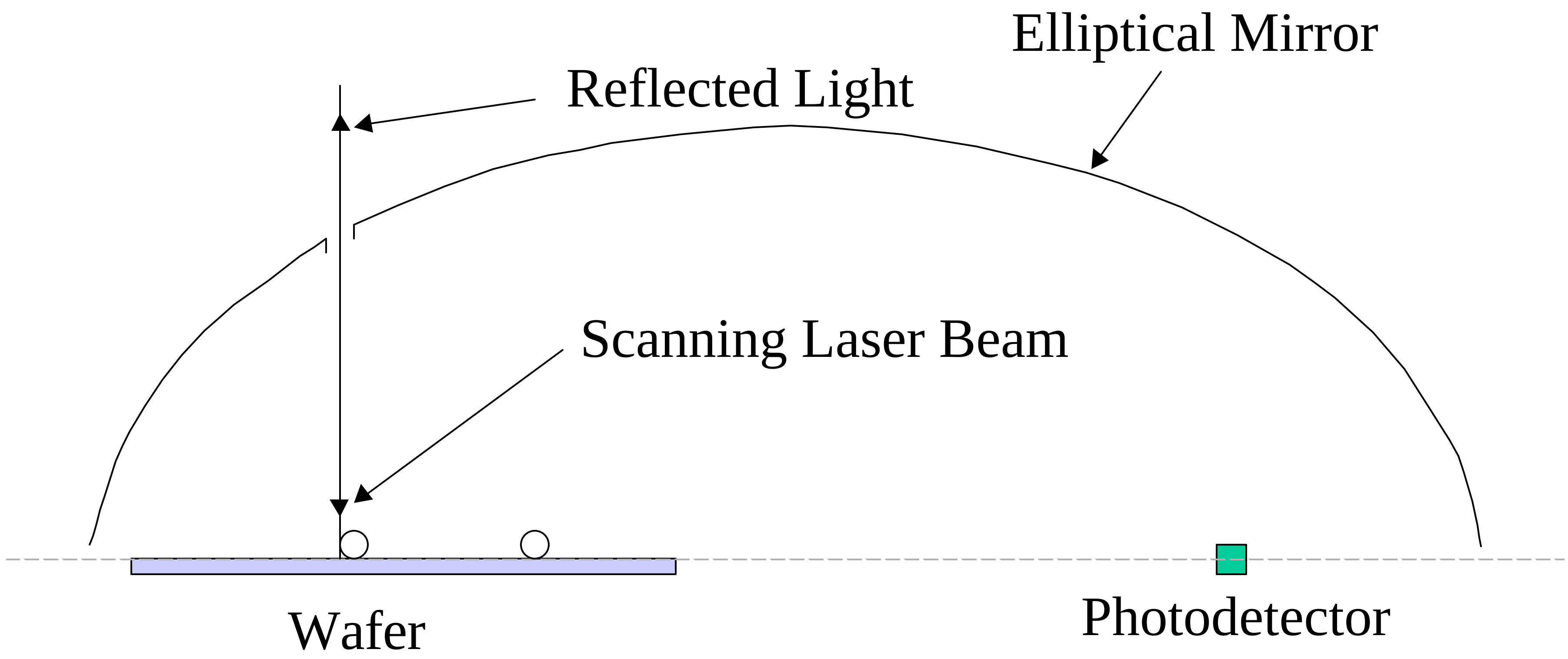
Laser Scan


Elliptical Mirror
Reflected Light
Scanning Laser Beam
Wafer
Photodetector

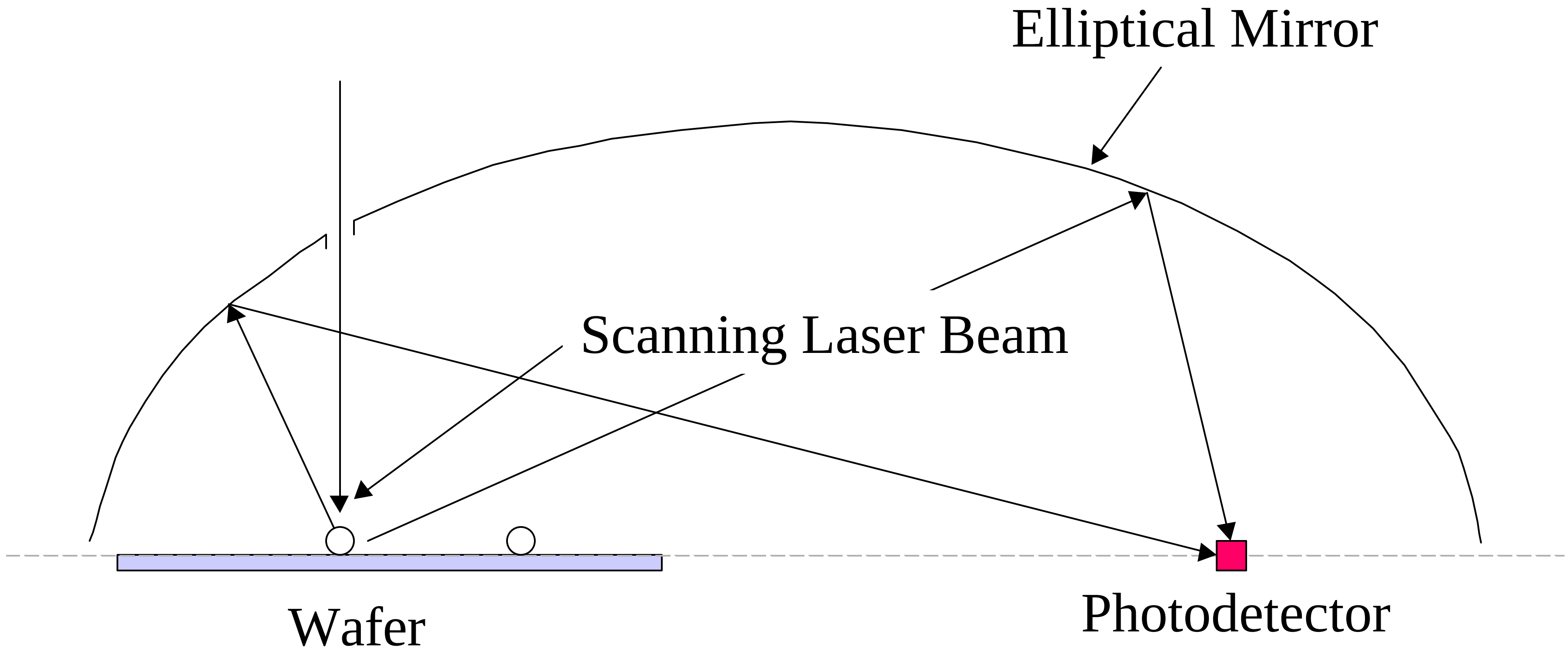
Particle Measurement



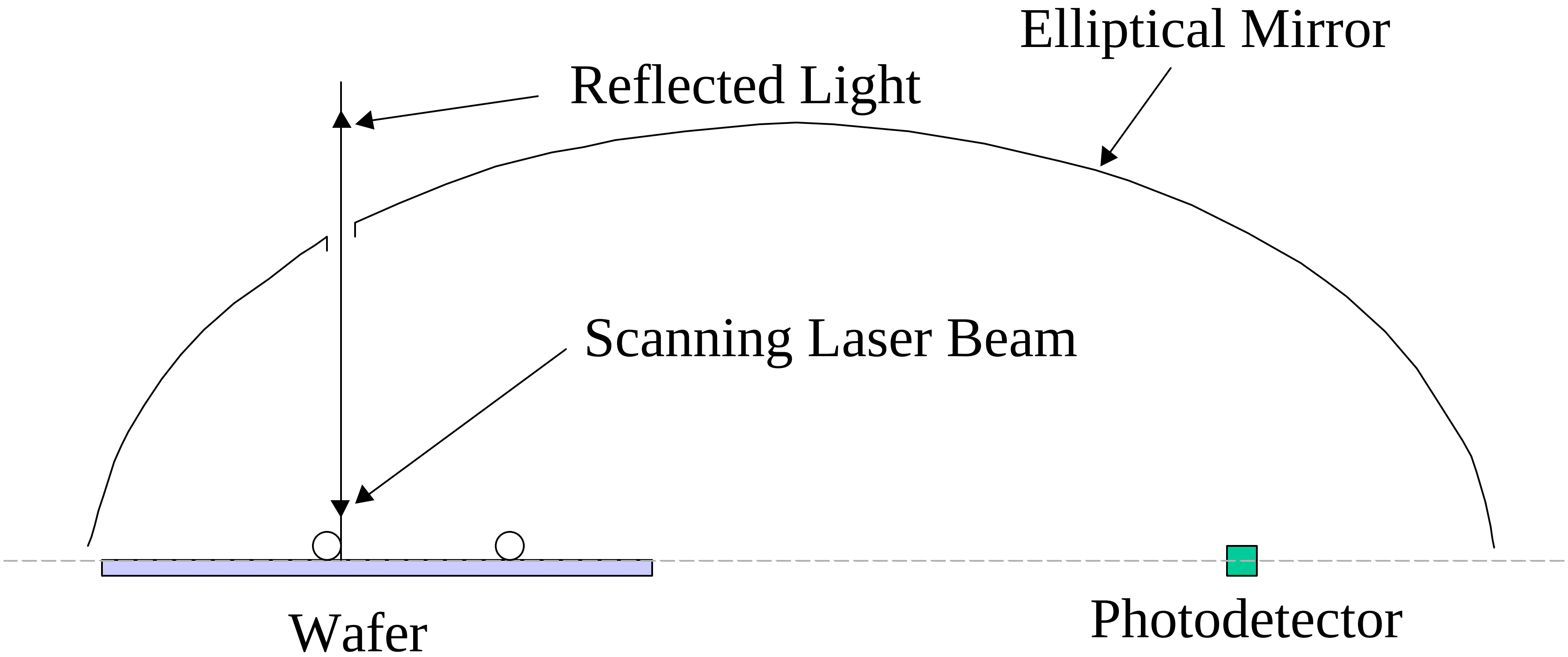
Particle Measurement



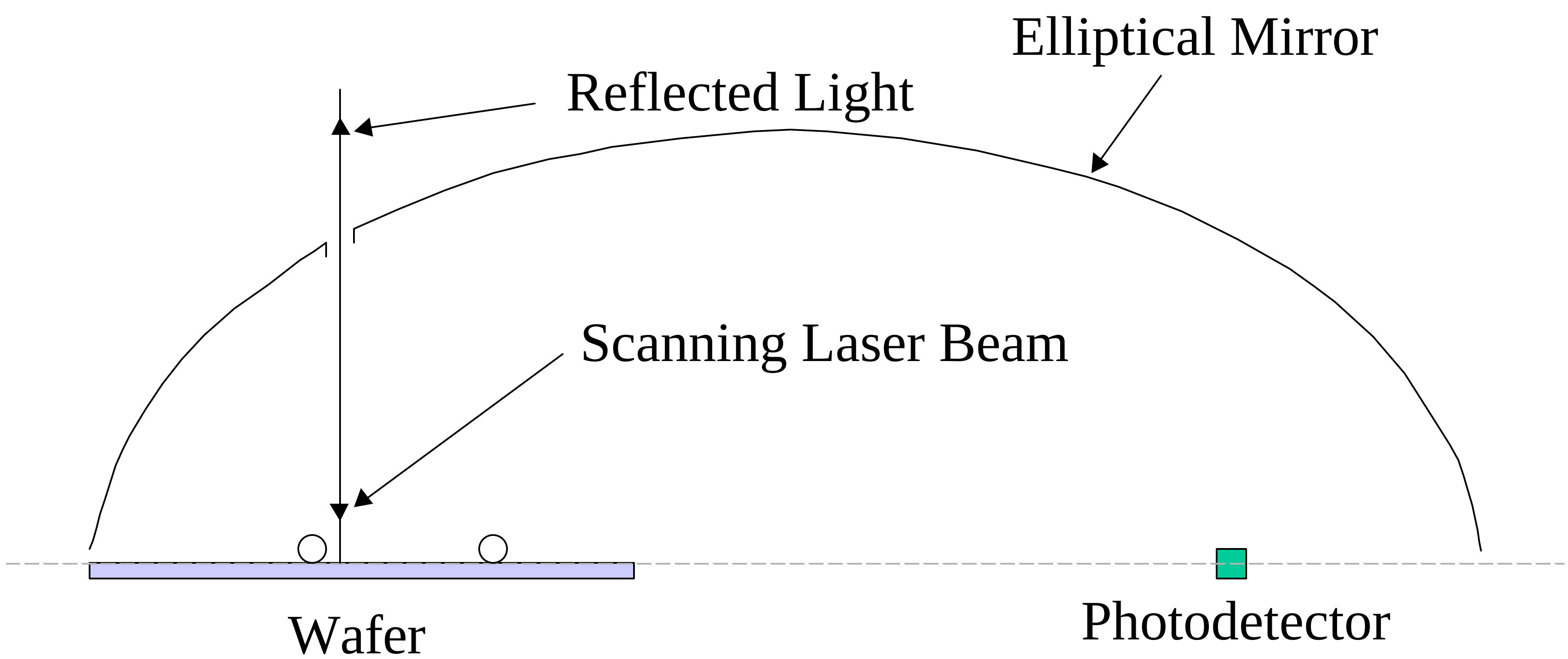
Particle Measurement: Particle 1



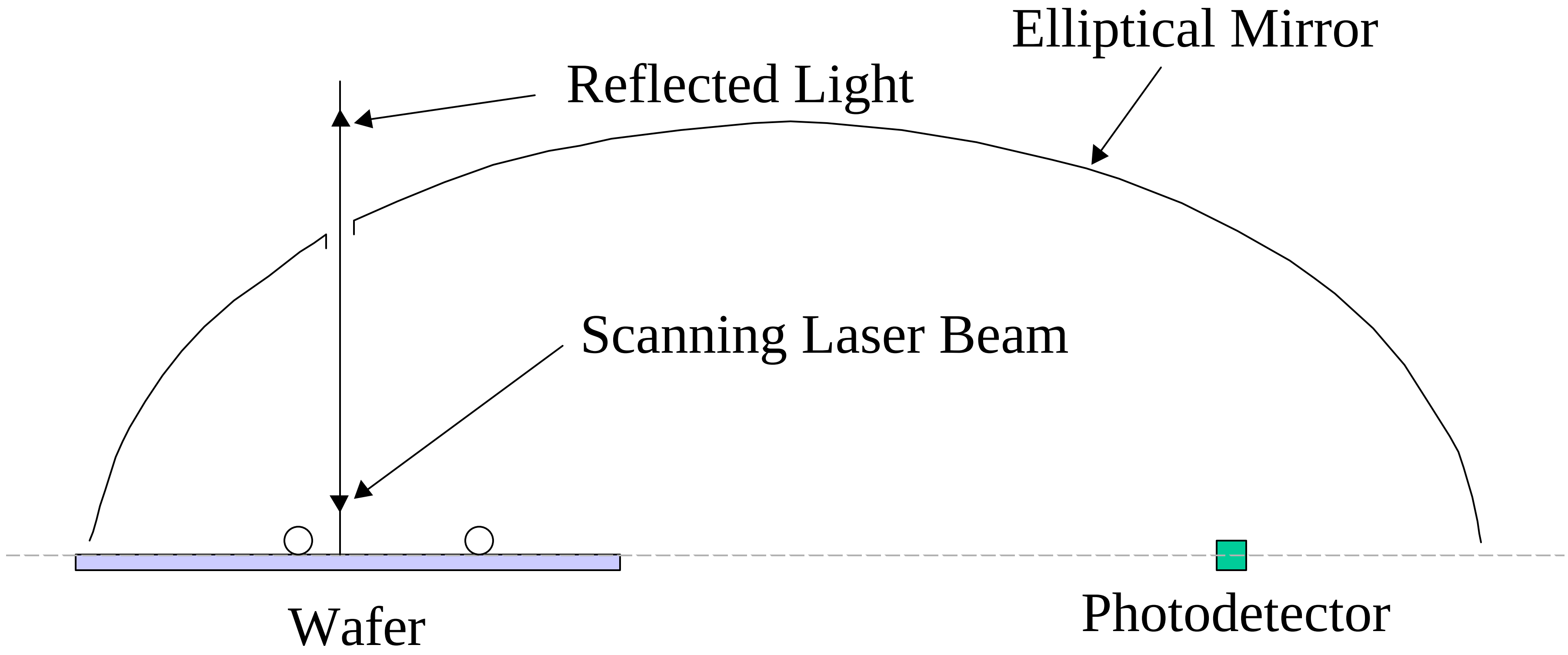
Particle Measurement



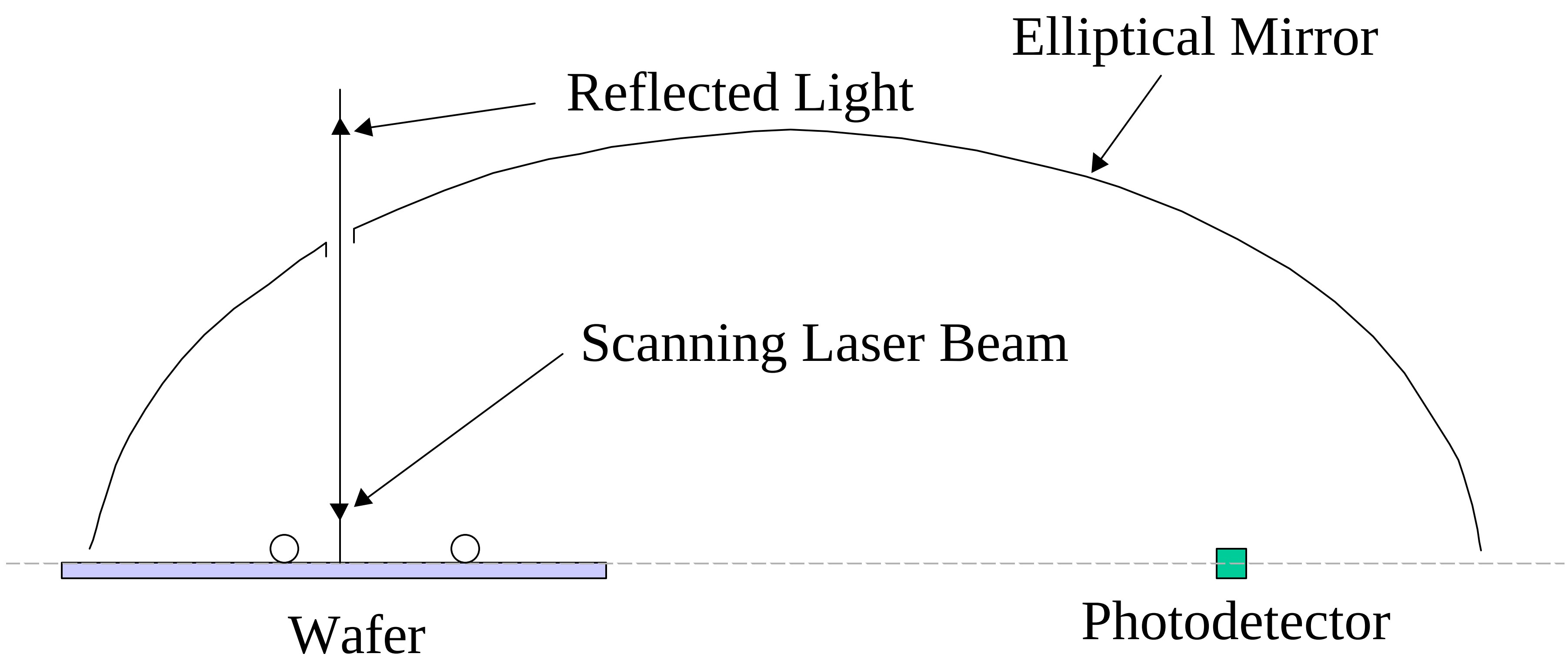
Particle Measurement



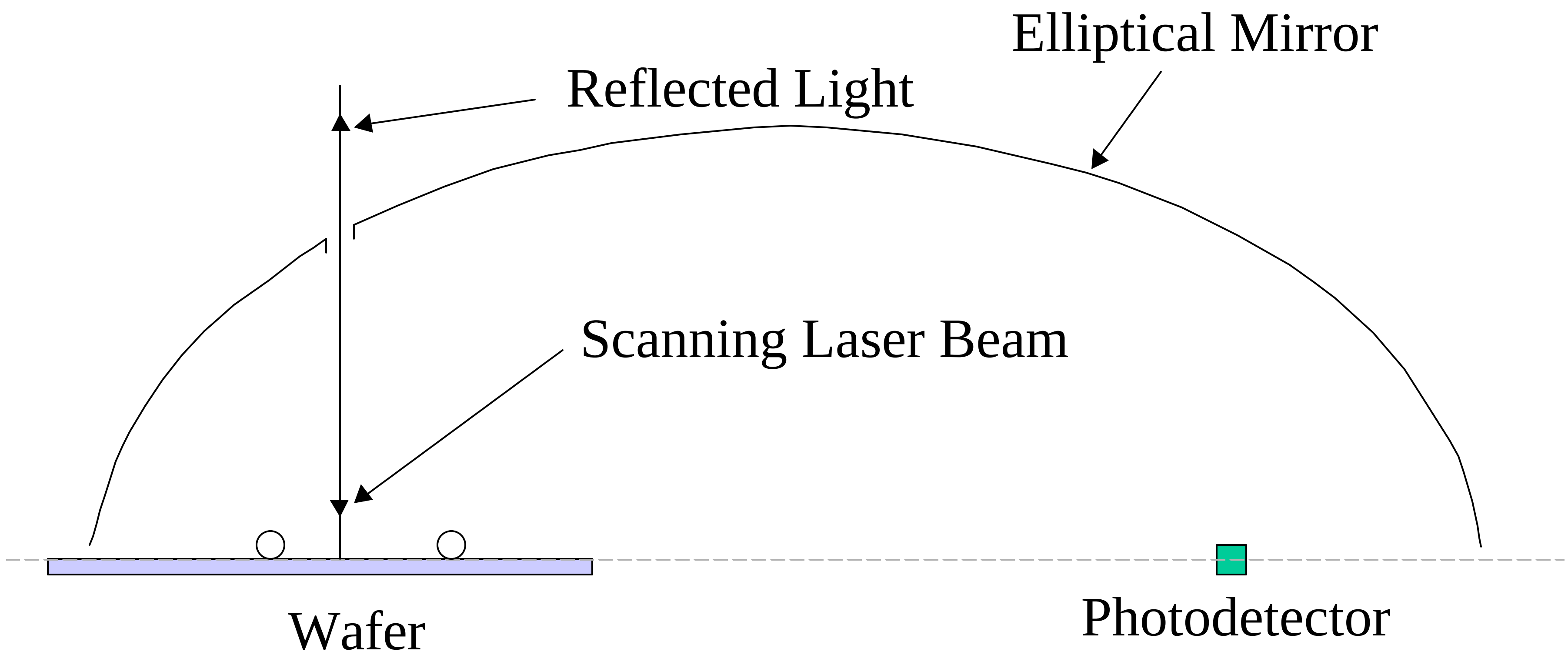
Particle Measurement



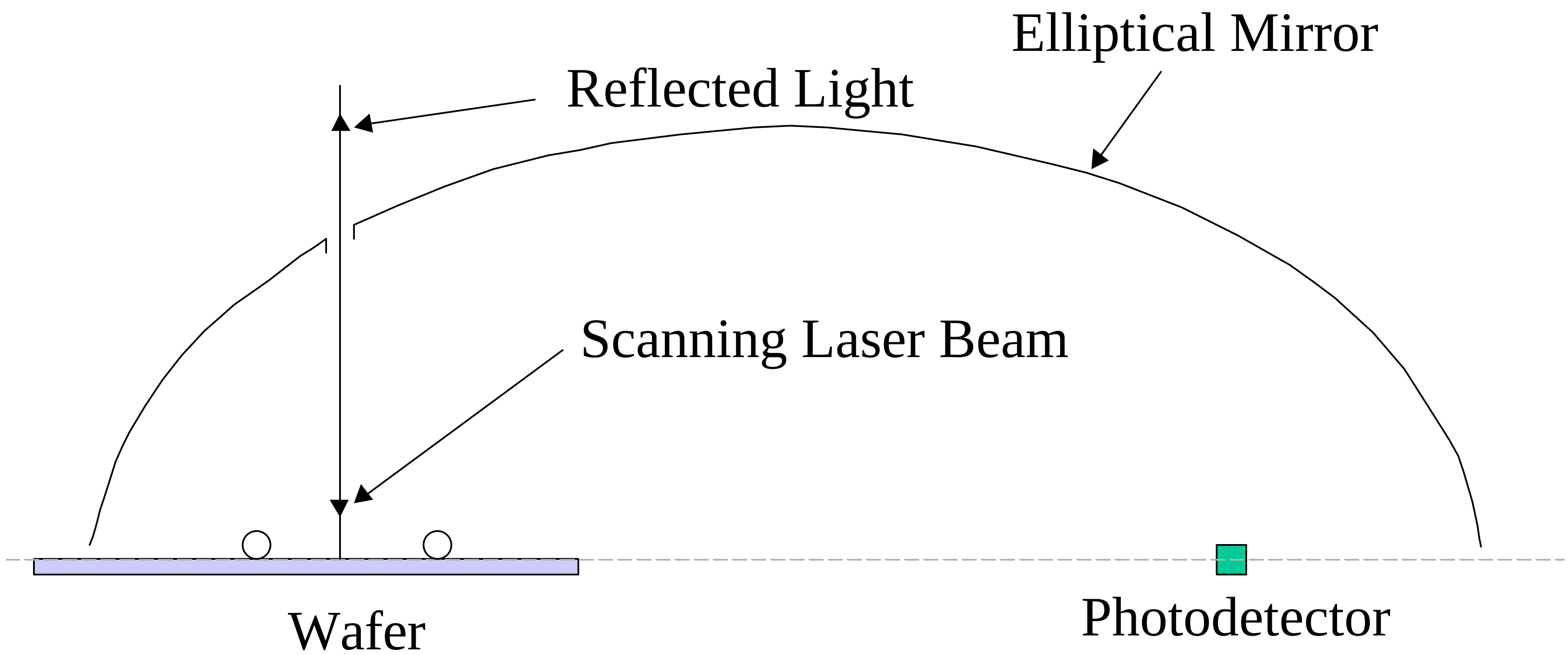
Particle Measurement



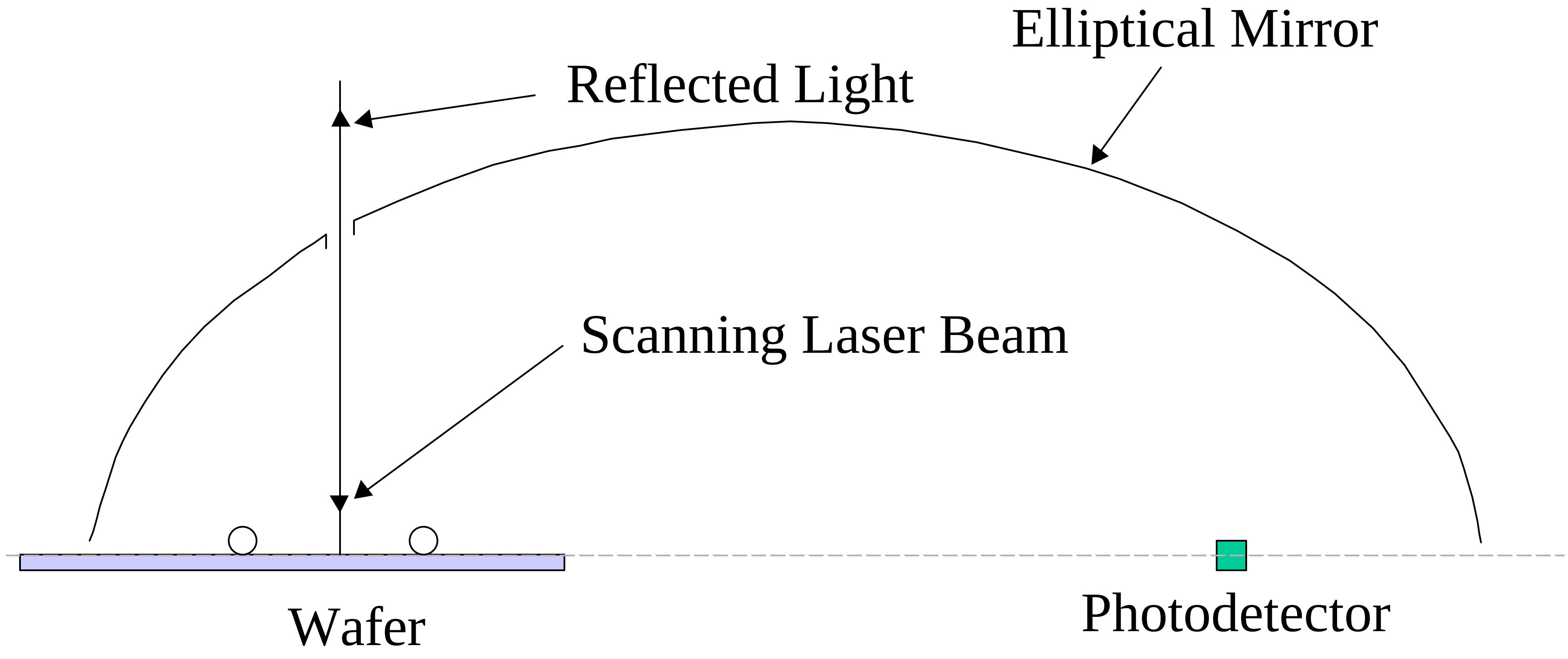
Particle Measurement



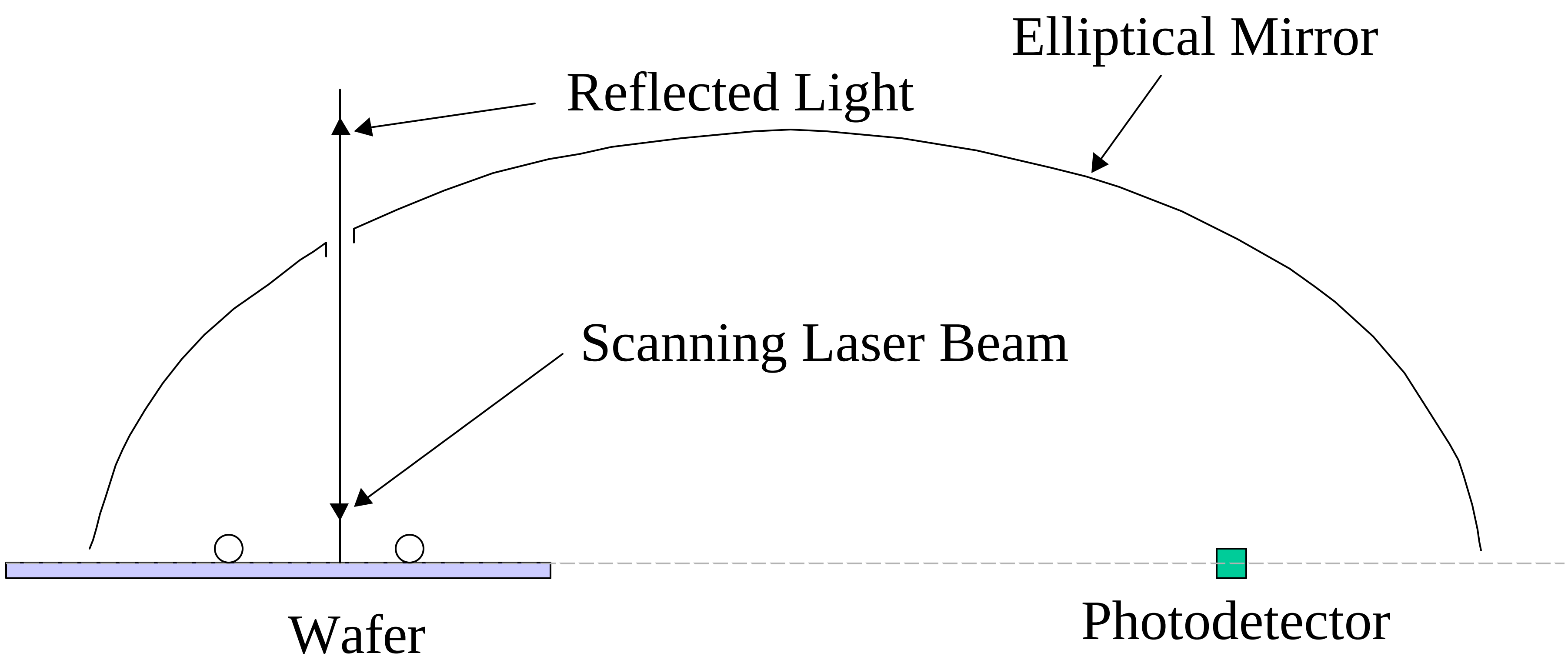
Particle Measurement



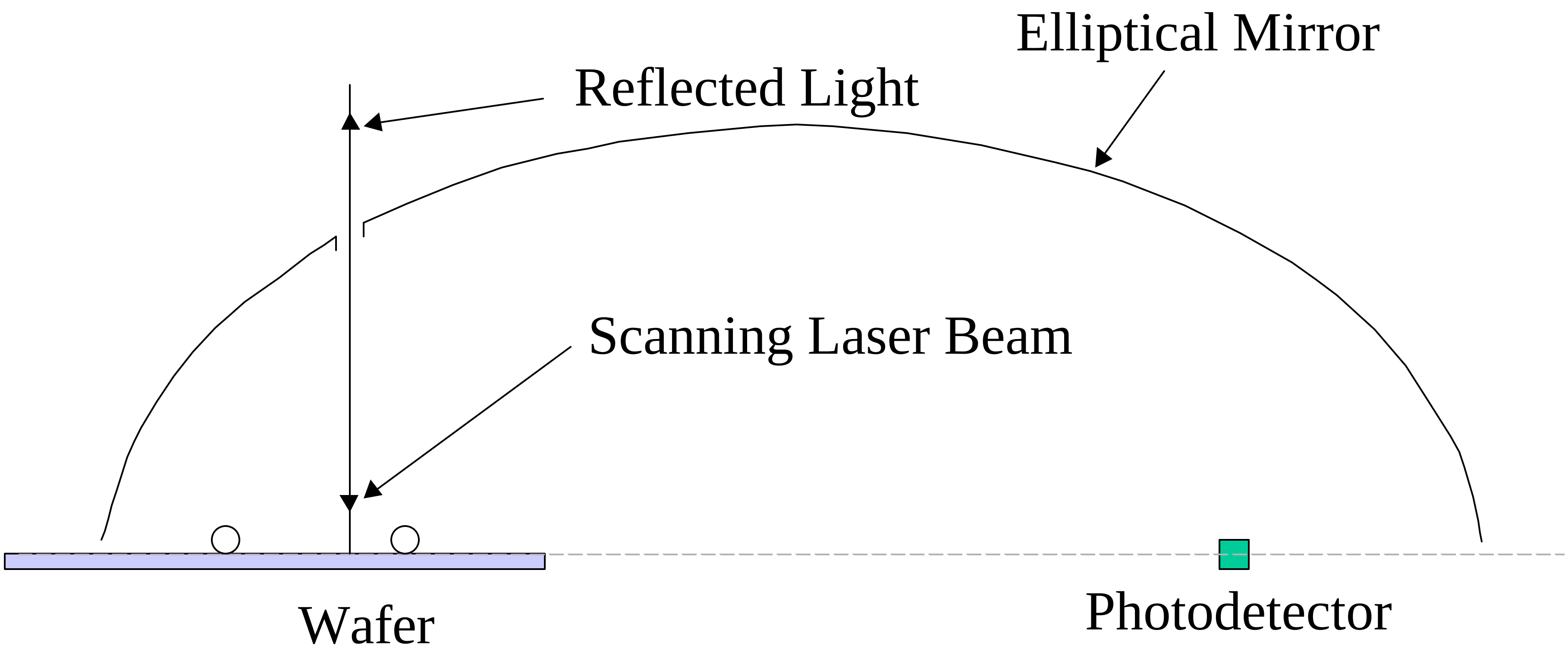
Particle Measurement



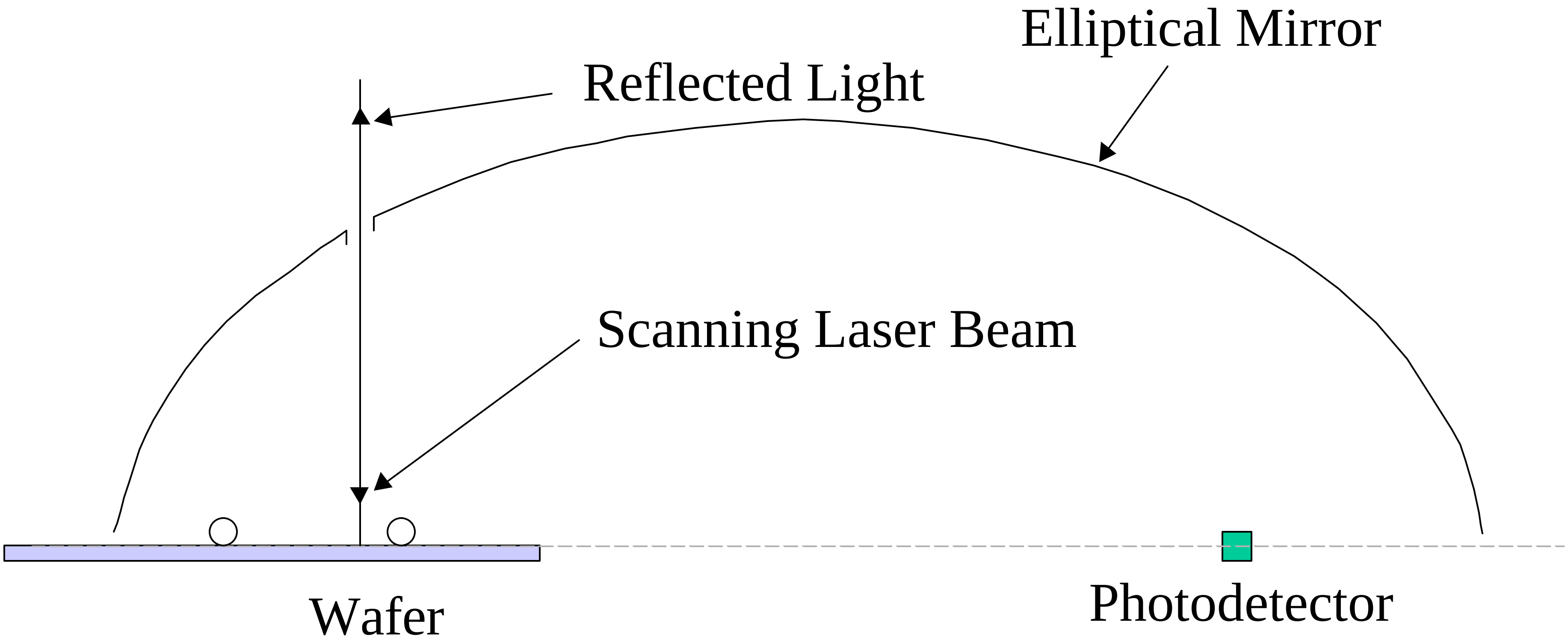
Particle Measurement



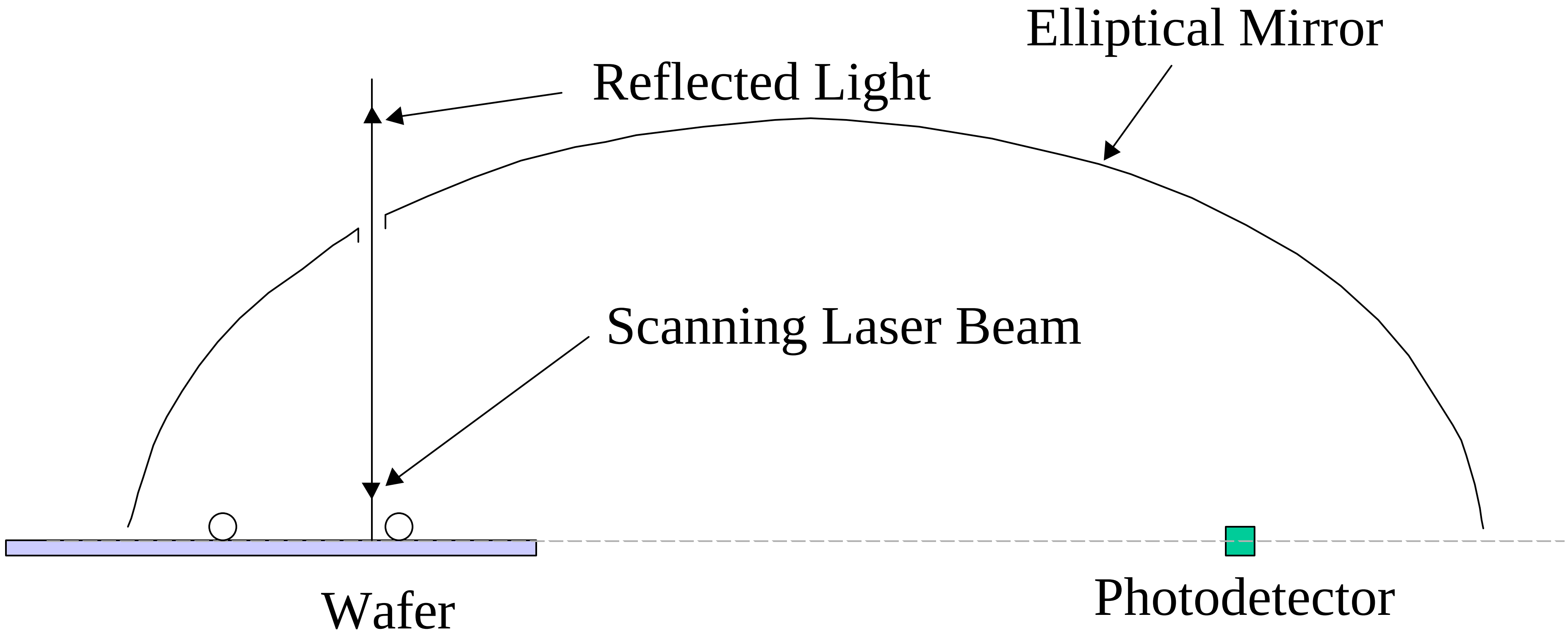
Particle Measurement



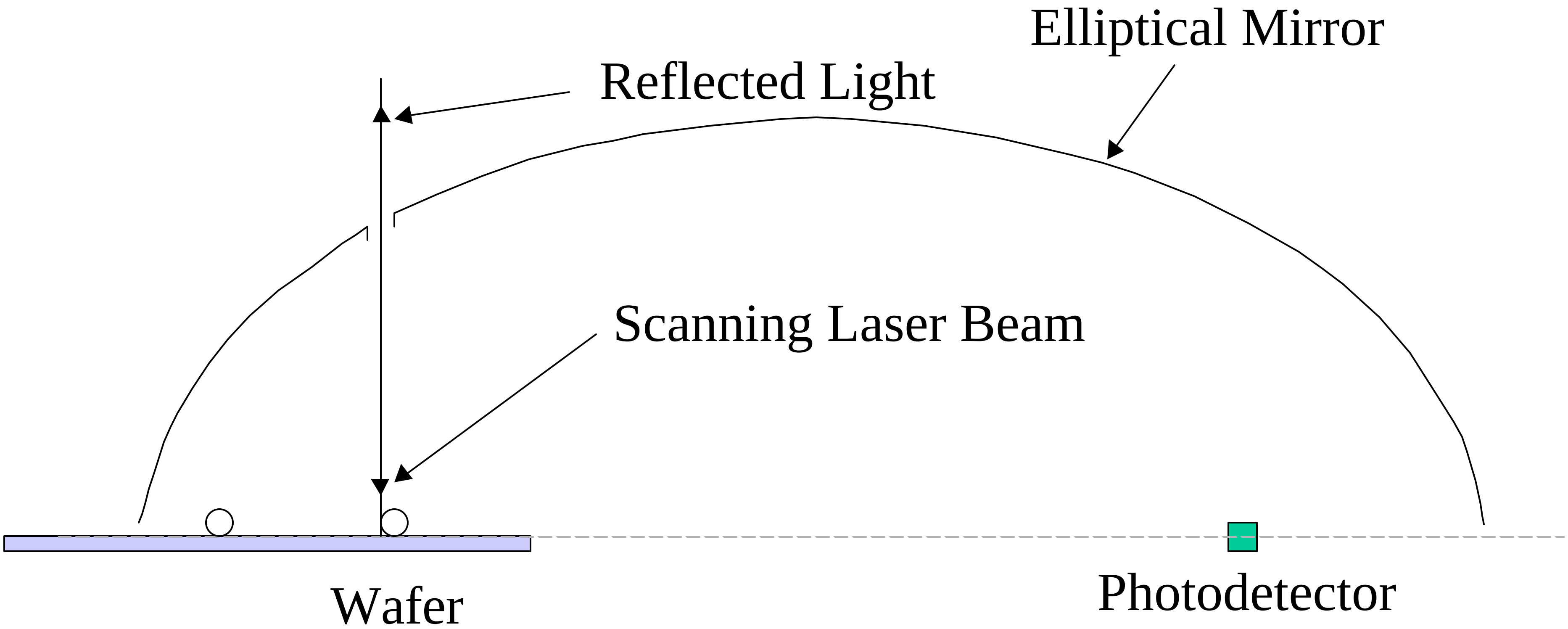
Particle Measurement



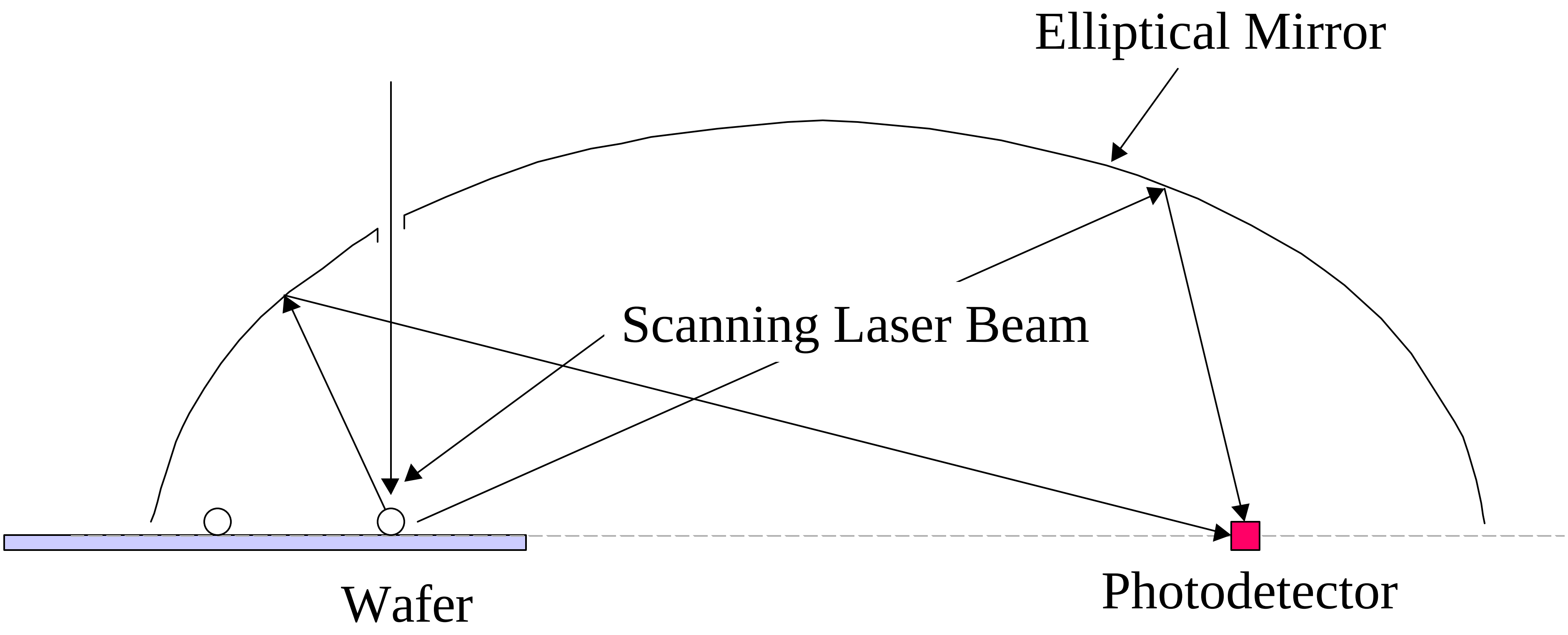
Particle Measurement



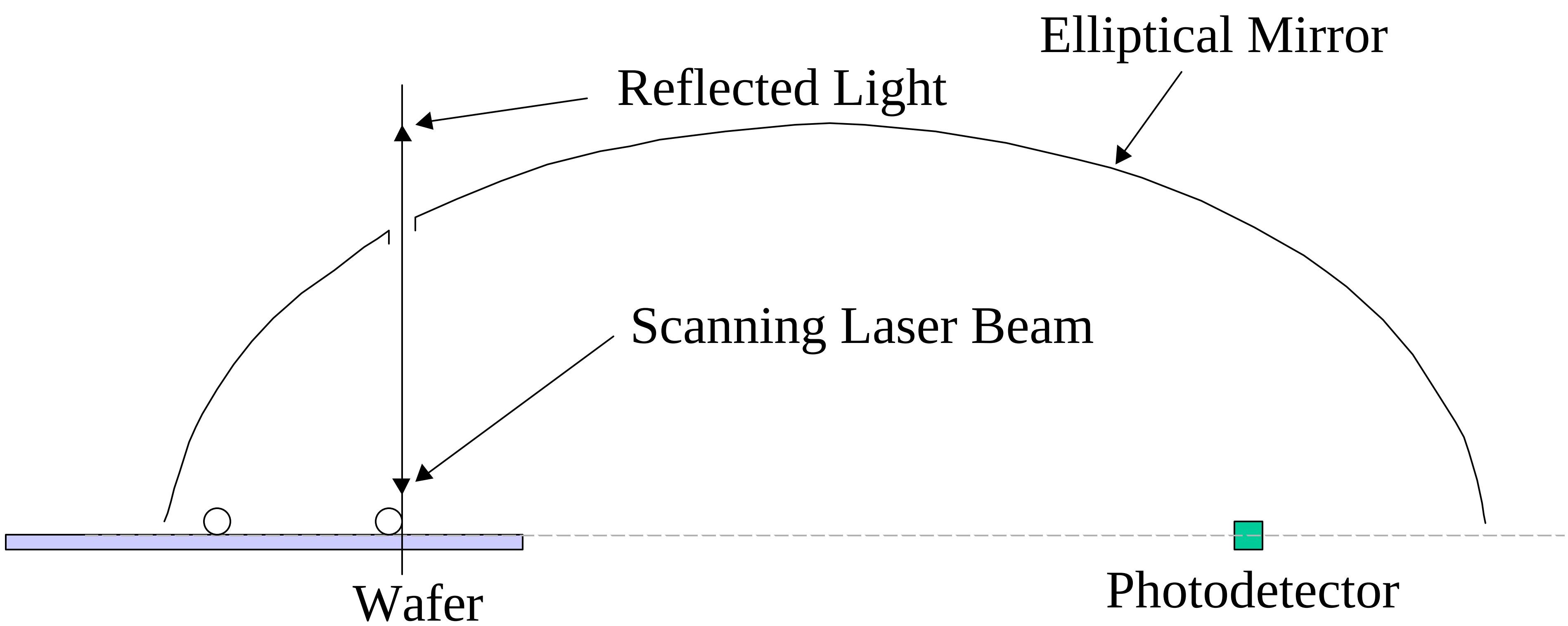
Particle Measurement



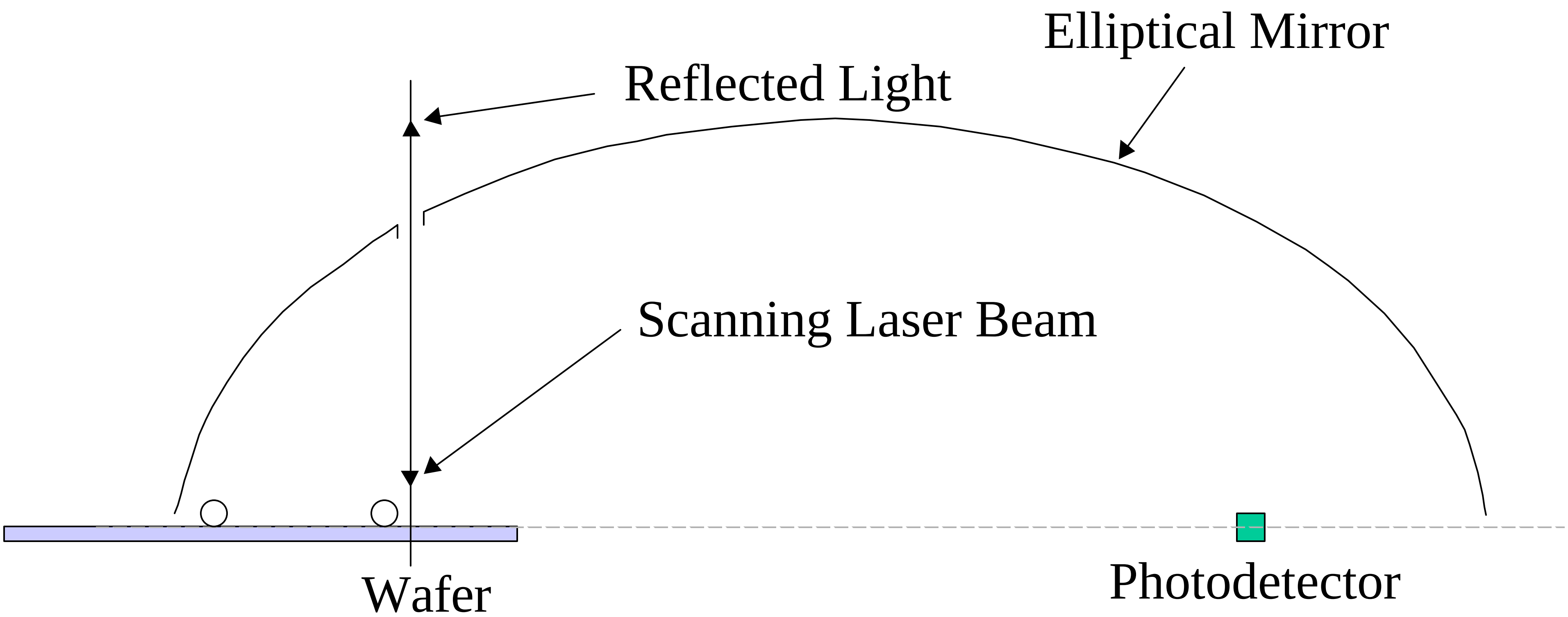
Particle Measurement, Particle 2



Particle Measurement



Particle Measurement



CMP Processes

- Oxide removal mechanism
- Metal removal mechanisms
- Endpoint methods

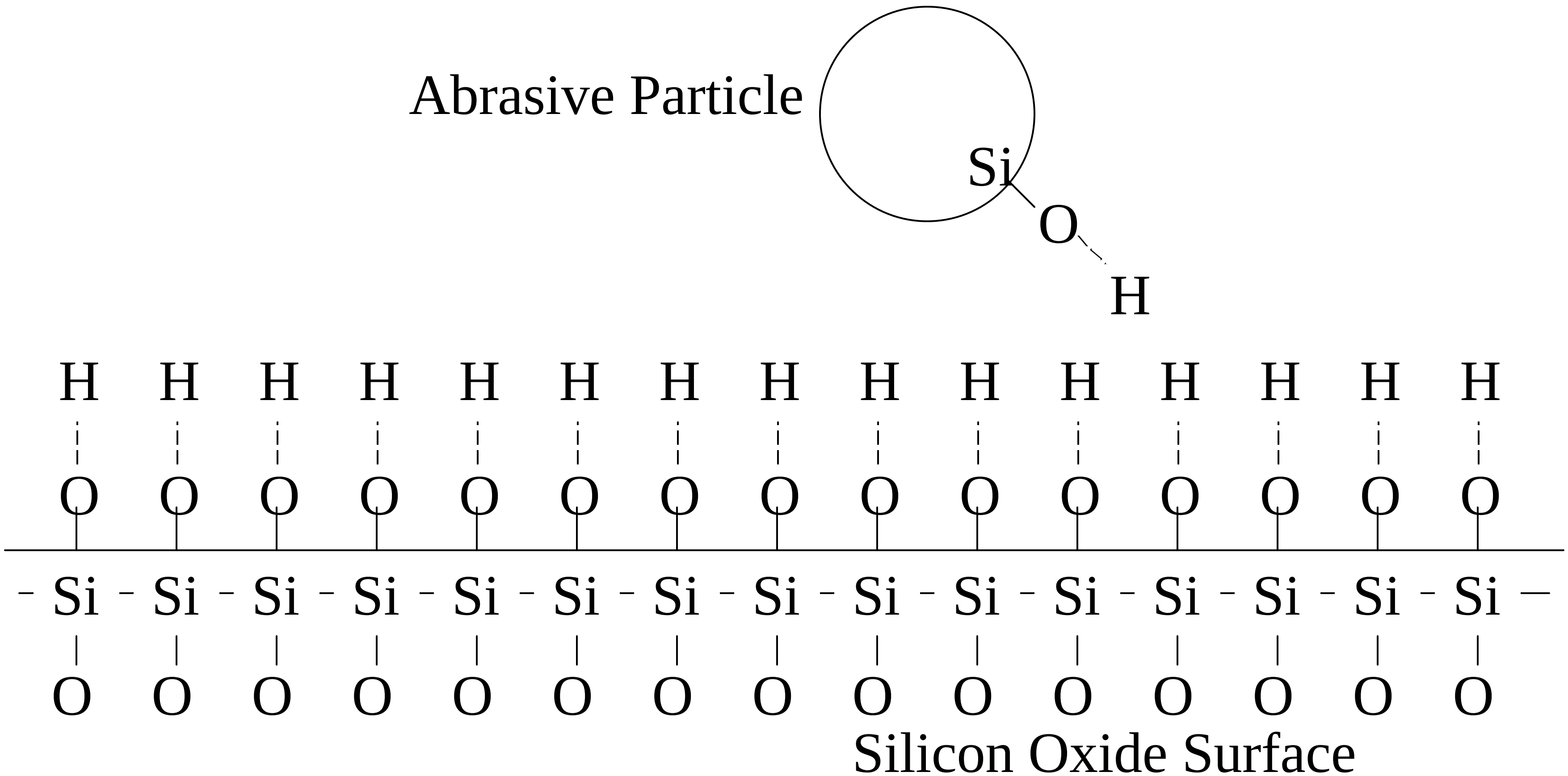
Oxide CMP

- Early development in the mid-1980s in IBM
- Combined knowledge and experience of glass polishing and silicon wafer polishing

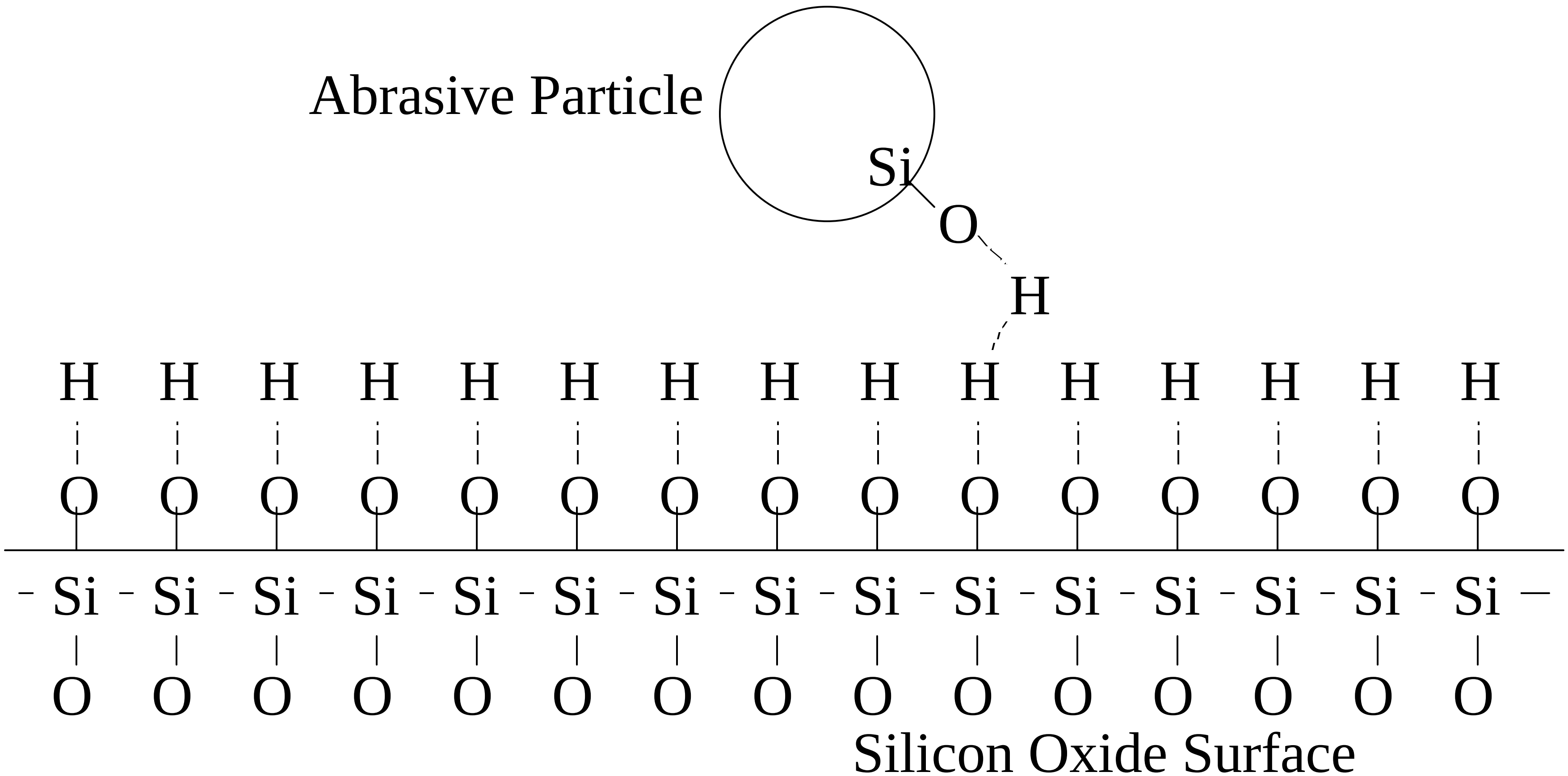
Oxide CMP

- Hydroxyls on both film and silica surfaces
- Form hydrogen bonds of silica and surface
- Form molecular bonds of silica and surface
- Mechanical removal of the particles bonded with wafer surface
- Tear away atoms or molecule from film on wafer surface

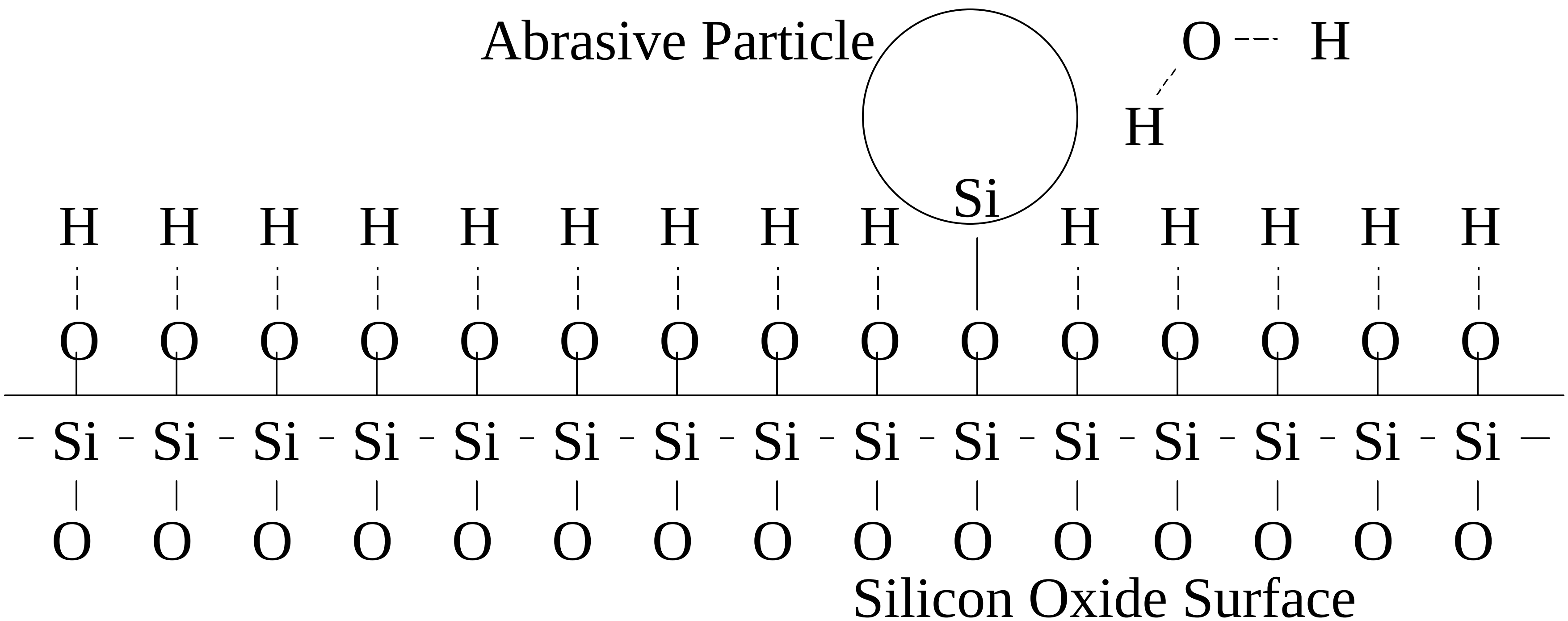
Oxide CMP


Abrasive Particle
Si
O
H
H H H H H H H H H H H H H H H
O O O O O O O O O O O O O O O
Si Si Si Si Si Si Si Si Si Si Si Si Si Si Si
O O O O O O O O O O O O O O O
Silicon Oxide Surface

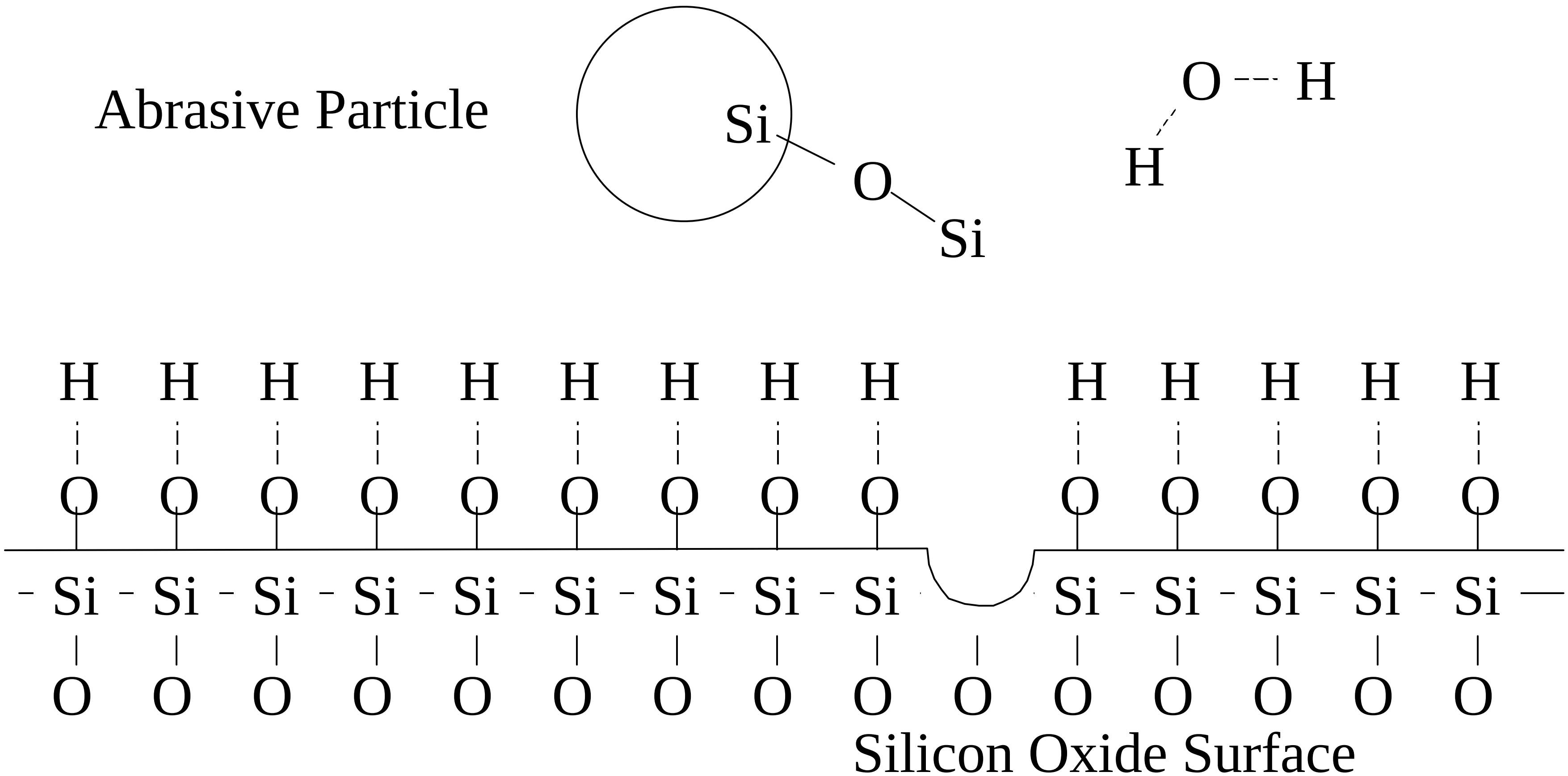
Oxide CMP, Hydrogen Bond



Oxide CMP, Molecule Bond



Oxide CMP, Removal of Oxide

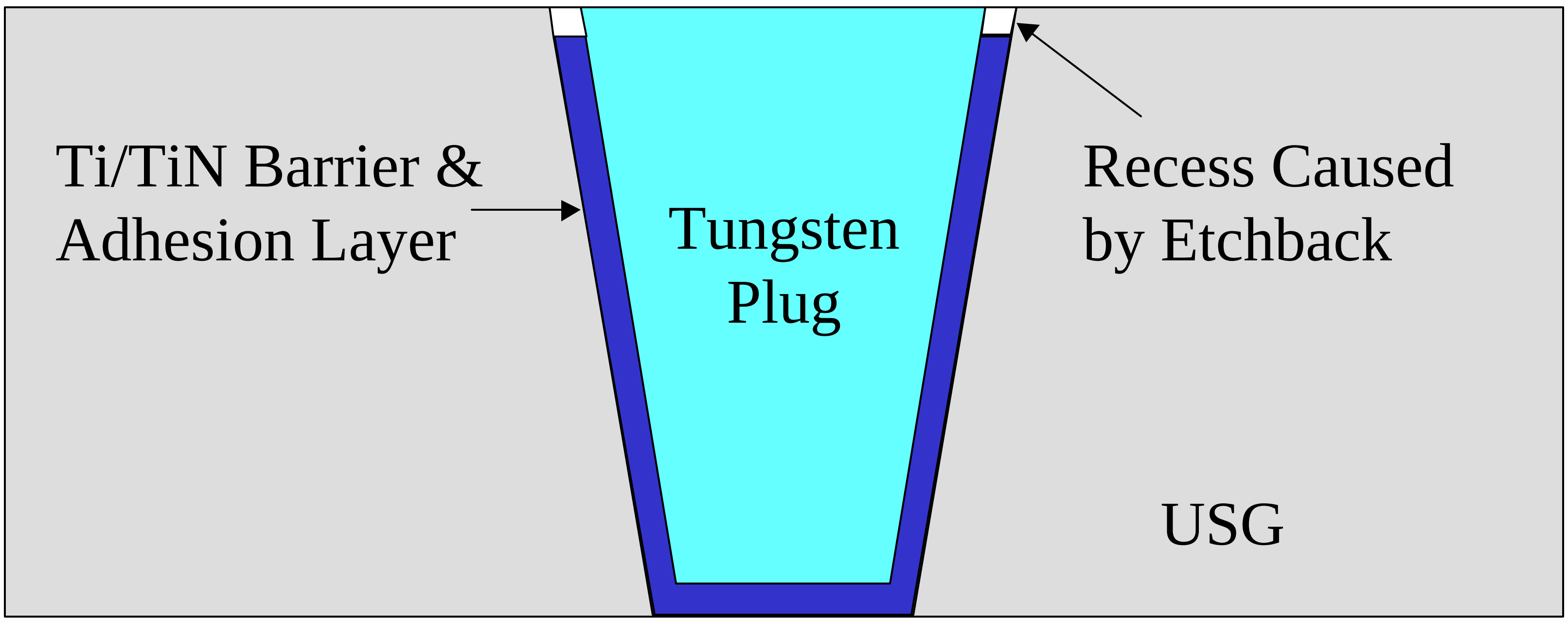


Tungsten CMP

- Form plugs to connect metal lines between different layers
- Tungsten etch back and Tungsten CMP
  – Fluorine based tungsten RIE etchback
    - In-situ with tungsten CVD process in a cluster tool
    - Recessing of the Ti/TiN barrier/adhesion layer due to the aggressive fluorine chemical etch of Ti/TiN and affects the chip yield

  – Tungsten CMP: winner for higher yield

Recess of Ti/TiN due to W Etchback



Tungsten CMP

- Two completing removal mechanisms
- Wet etch: a pure chemical process
  - Unfavorable
- Passivation oxidation and oxide abrading: chemical and mechanical process
  - Favorable
- Controlled by pH value of slurry

Tungsten CMP

- Potassium ferricyanide, $K_3Fe(CN)_6$, is used as both etchant and oxidant
- The wet etch chemistry can be expressed

$$W + 6Fe(CN)_6^{-3} + 4H_2O \rightarrow WO_4^{-2} + 6Fe(CN)_6^{-4} + 8H^+$$

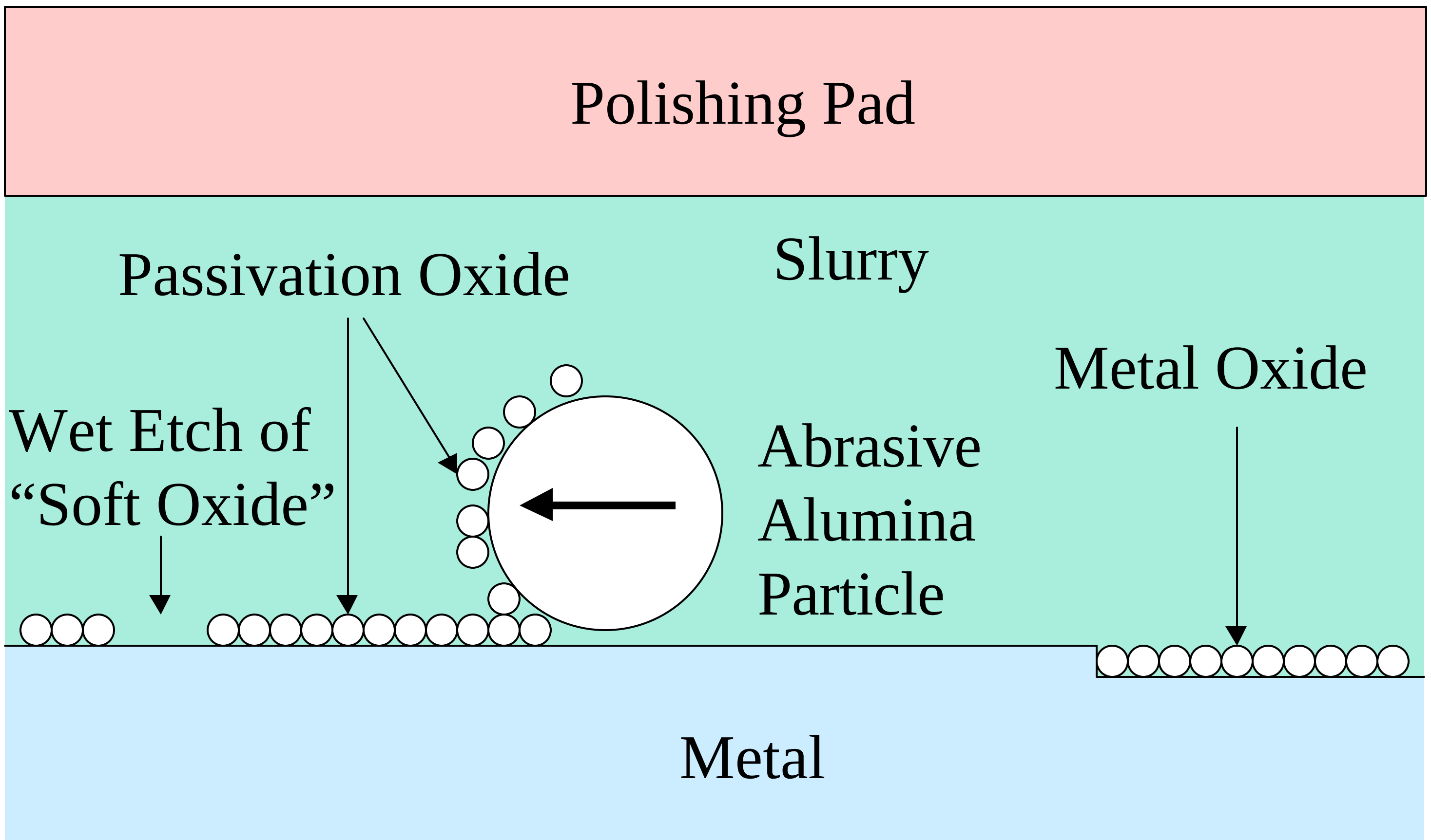
- The competing passivation oxidation reaction

$$W + 6Fe(CN)_6^{-3} + 3H_2O \rightarrow WO_3 + 6Fe(CN)_6^{-3} + 6H^+$$

Tungsten CMP

- Normally tungsten CMP uses two step process
- The first step remove bulk W with slurry pH < 4,
- The second step remove TiN/Ti stacked barrier/adhesion layer with slurry pH > 9

Metal CMP Process



Copper CMP

- Difficult to plasma etch copper
  - Lack of volatile inorganic copper compounds
- Copper CMP key process in copper metallization process
- H_2O_2, or HNO_4 can be used as oxidant
- Alumina particulate is used for abrasion

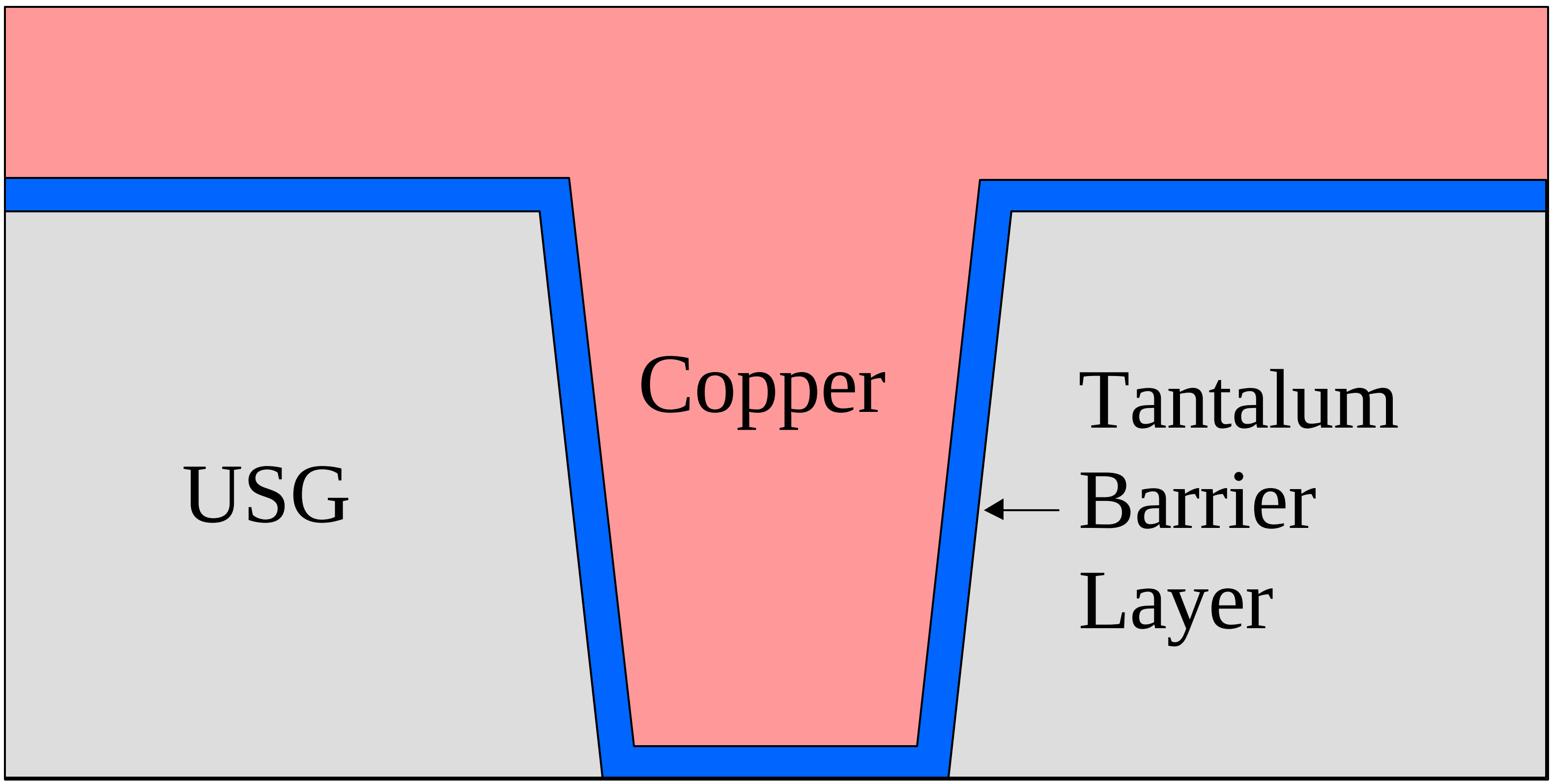
Copper CMP

- CuO_2 is porous and can't form a passivation layer to stop further copper oxidation
- Additive is needed to enhance passivation
- NH_3 is one of additives used in slurry
- Other additives such as NH_4OH, ethanol or benzotriazole can also be used as complexing agents to reduce wet etch effect

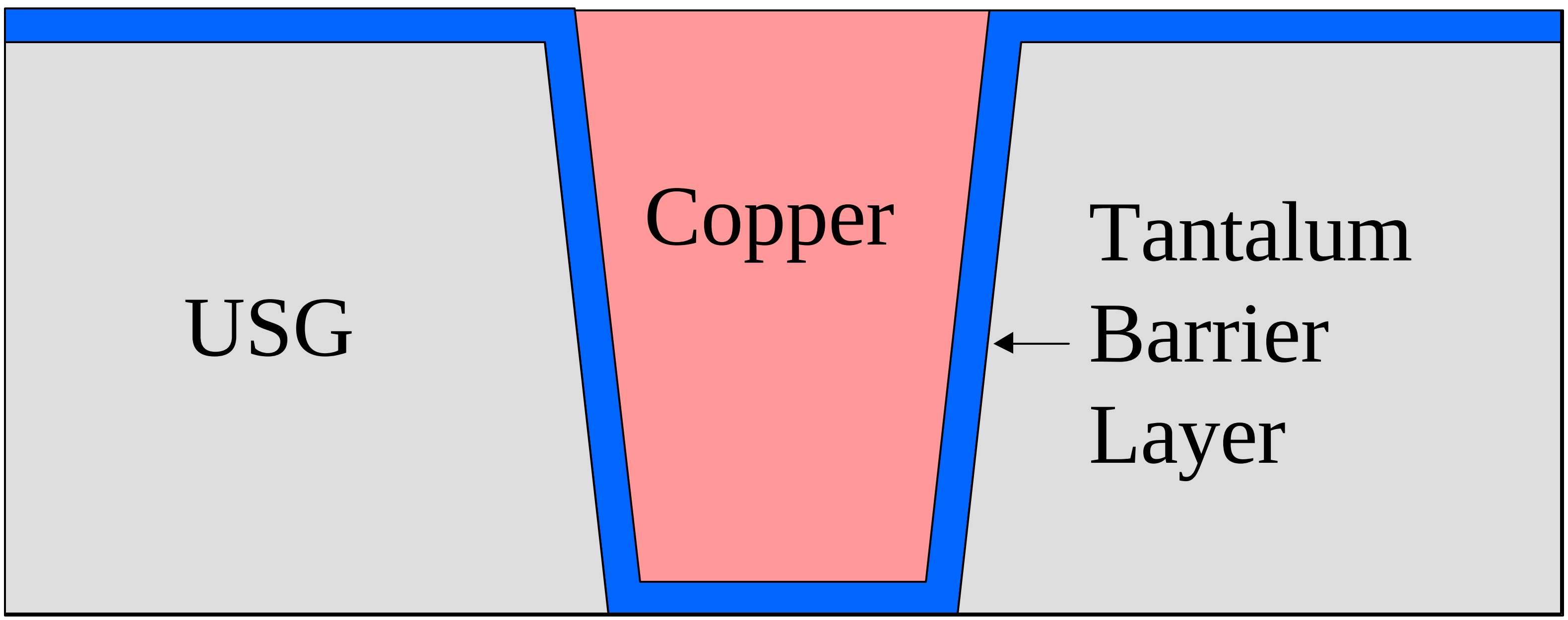
Copper CMP

- Dual-damascene copper metallization
- 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

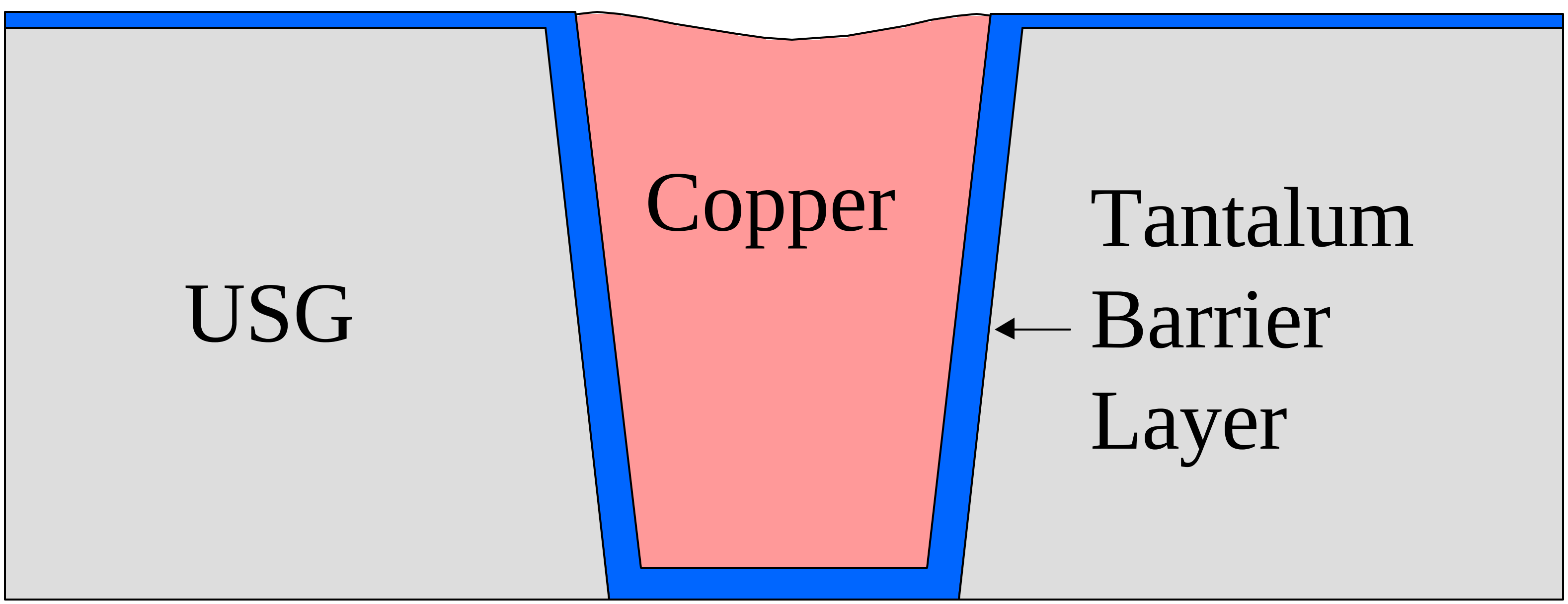
Copper Deposition



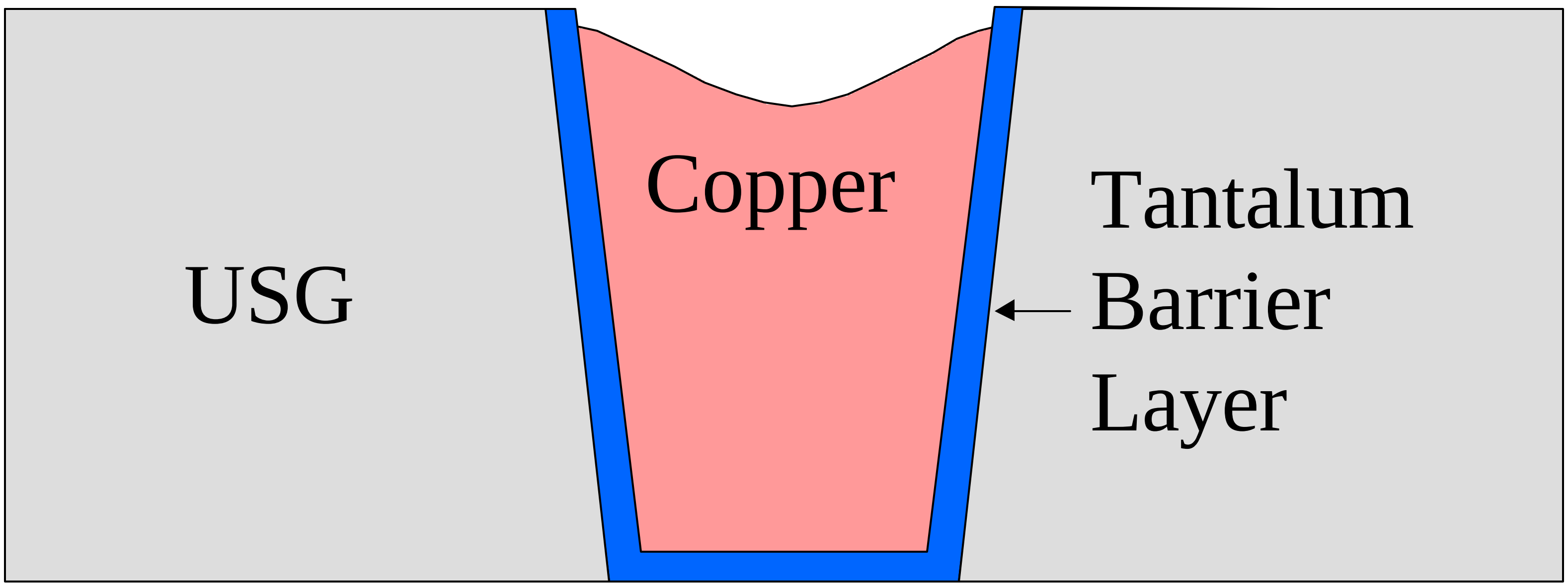
Copper CMP



Over Polish to Remove Tantalun



Copper Dishing and Recessing



Copper CMP

- Two-slurry polishing
- The first slurry remove bulk copper layer
- The second slurry remove Ta barrier layer
- The two-slurry CMP process reduces
  - Copper recessing and dishing
  - Oxide erosion
- Multiple polishing platens greatly simplifies multi-slurry CMP processing

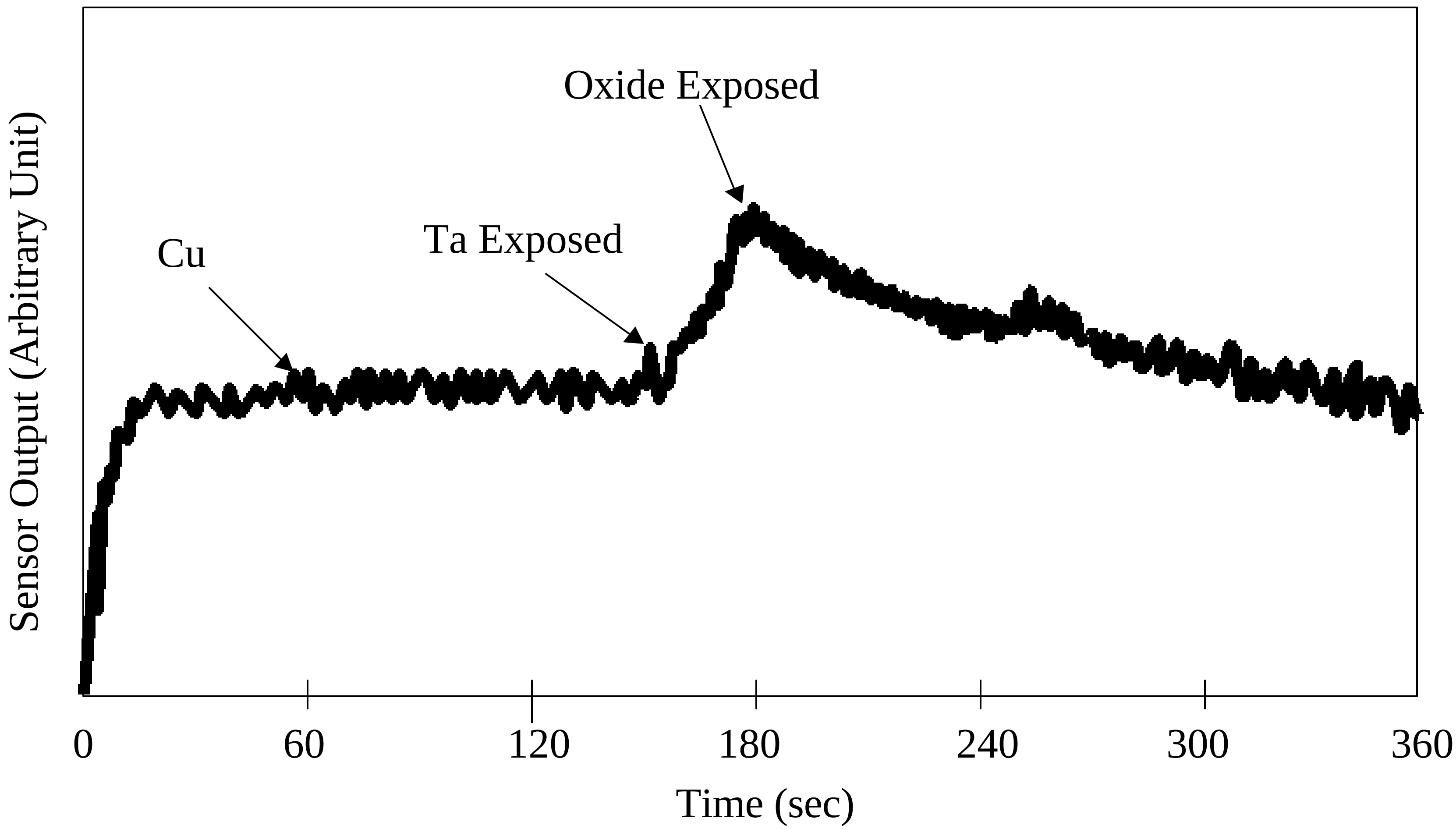
CMP Endpoint Detection

- Monitoring the motor current
- Optical measurement

Motor Current CMP Endpoint

- When CMP process closing to end, polish pad start to contact and polish underneath layer
- Friction force start to change
- Current of the polish head rotary motor will change to keep constant pad rotation rate
- Monitoring the change of motor current can find endpoint of the CMP process

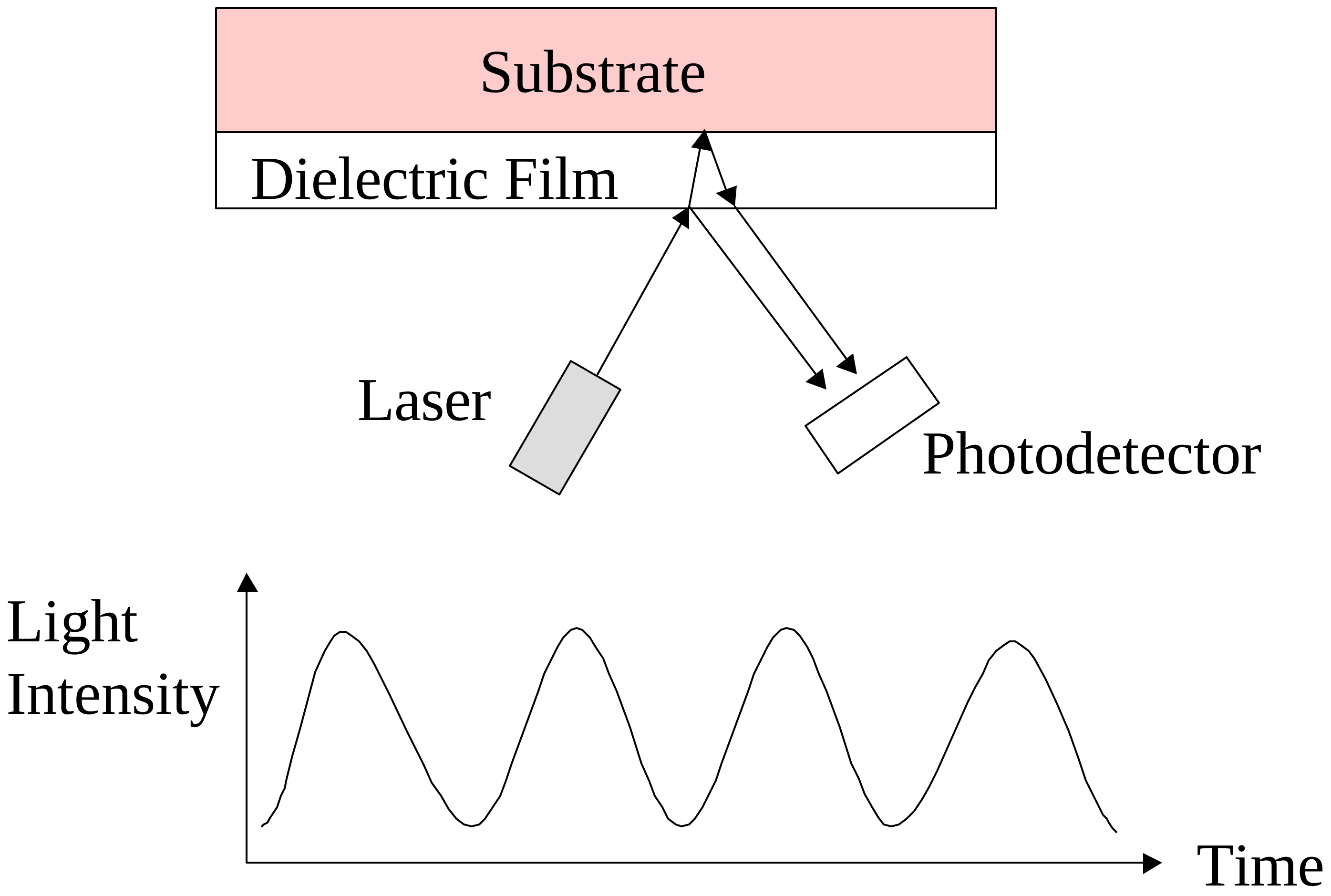
Motor Current During Copper CMP



Optical Endpoint: Dielectric

- Endpoint by either thickness measurement
- Reflected lights interfere with each other
- Constructive and destructive interference
- Change of the film thickness causes the periodically changes of interference state
- Dielectric film thickness change can be monitored by the change of reflection light

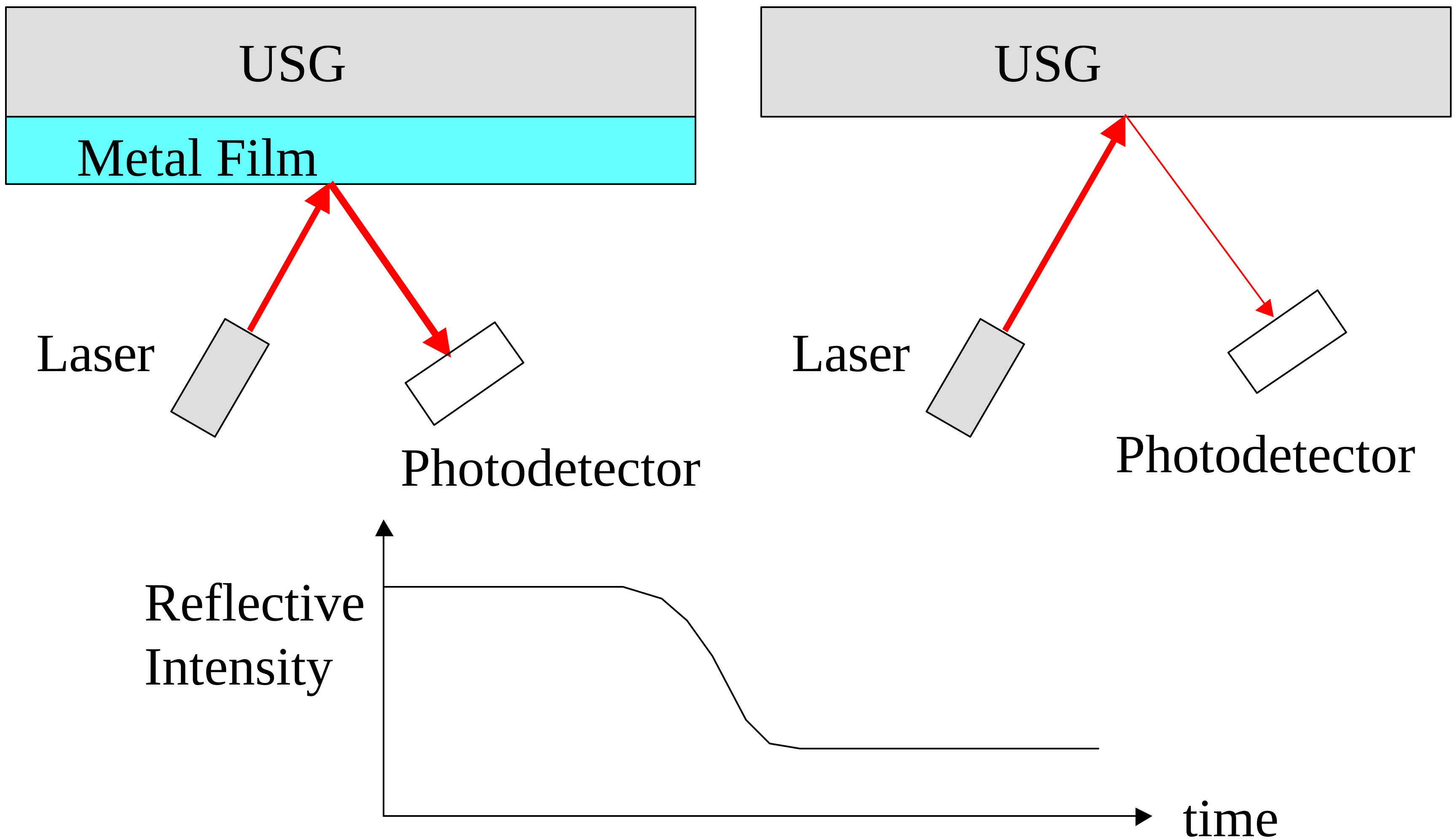
Endpoint of Dielectric CMP



Optical Endpoint: Metal

- The change of reflectivity can be used for metal CMP process endpoint
- Usually metal surface has high reflectivity
- Reflectivity significantly reduces when metal film is removed
- Trigger endpoint

Endpoint of Metal CMP



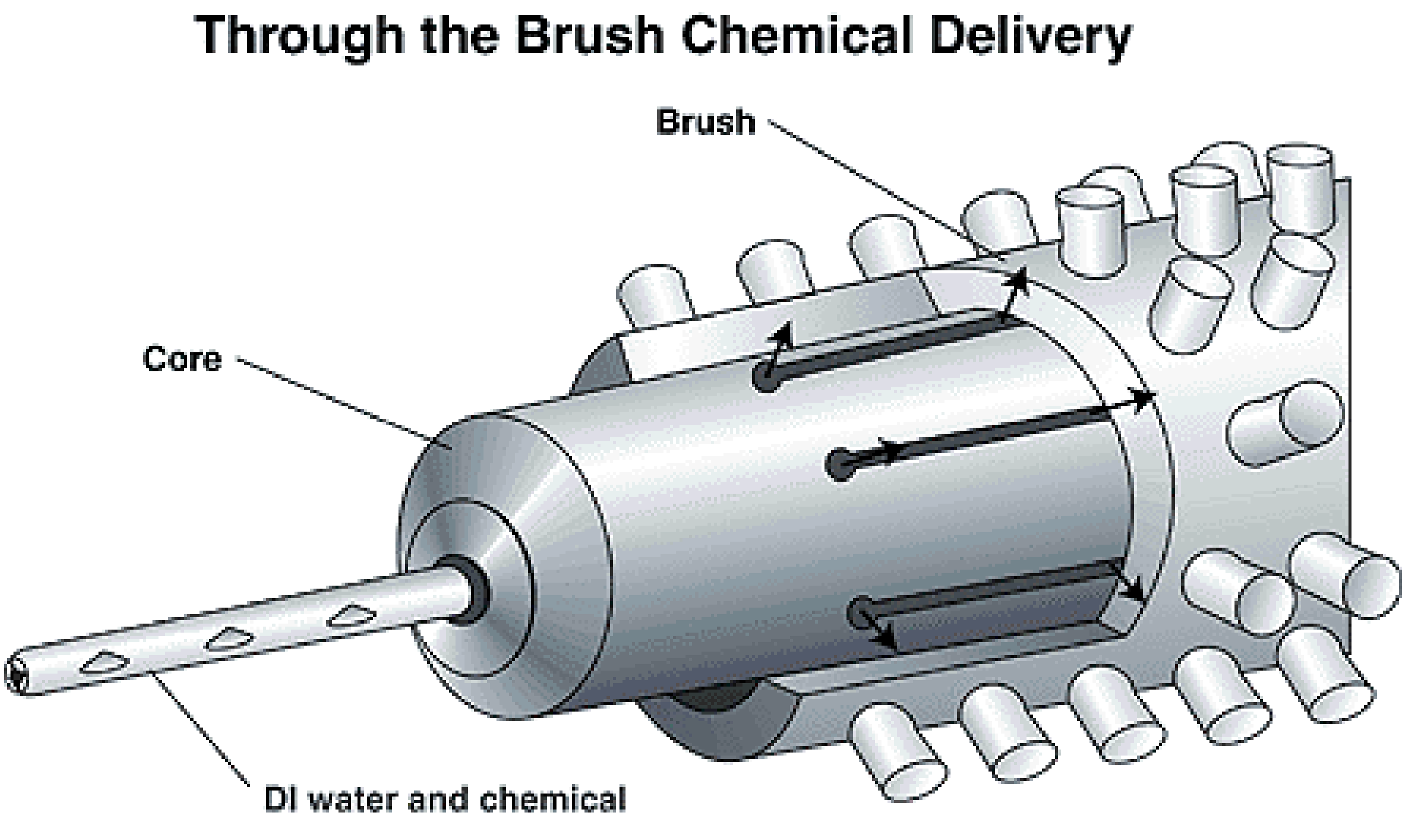
Post CMP Clean

- Post-CMP cleaning need remove both particles and other chemical contaminants
- Otherwise, defect generation and low yield
- Mechanical scrubbing cleaners with DI water
- Larger DI water volume, higher brush pressure high cleaning efficiency
- Three basic steps: clean, rinse, and dry

Post CMP Clean

- Usually brush is made of porous polymers, allows chemicals to penetrate through it and deliver to wafer surface
- Double-sided scrubbers are used in the post-CMP clean process

Brush System



Post CMP Clean

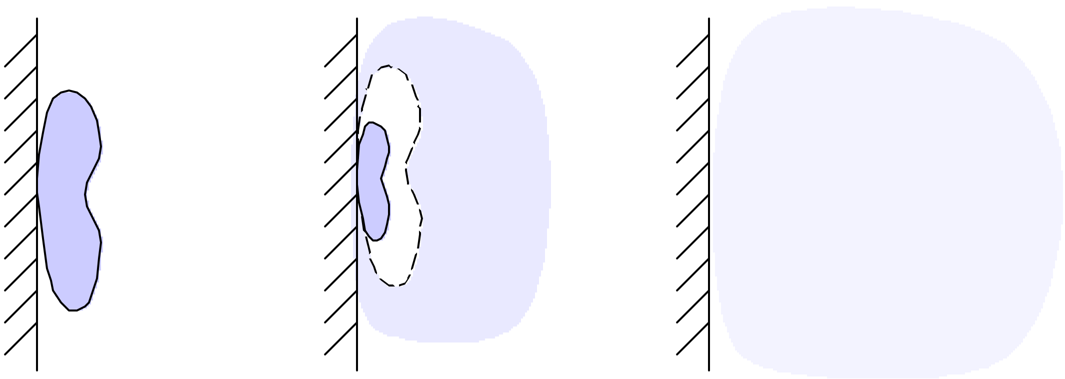
- Slurry particles can chemically bond to atoms on wafer surface if slurry dried
- Chemical additives, such as NH_4OH, HF or surfactants is needed to remove bonded particles by weakening or breaking the bonds
- Additives also help particles diffuse away from the surface

Post CMP Clean

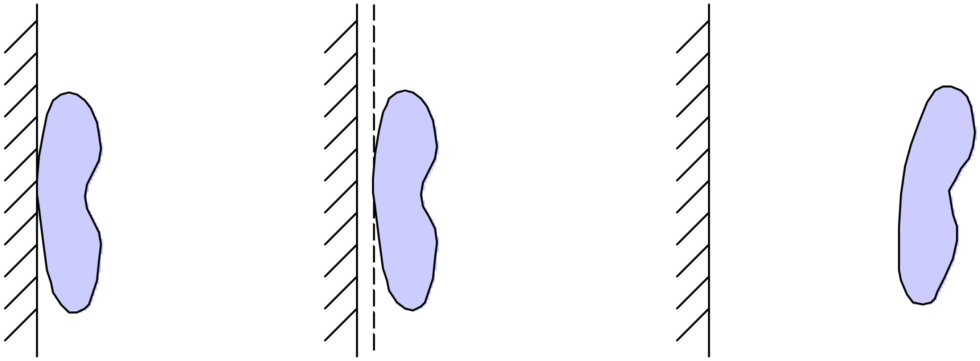
- Chemical solution is also used to adjust the wafer and particle surface charges so that electrostatic repulsion keeps particles from re-deposition on the surface
- Acidic solutions can be used to oxidize and dissolve organic or metal particles

Particle Removal Mechanisms

Acidic Solution: Oxidation and Dissolution



Alkaline Solution: Surface Etch and Electrostatic Repulsion



Post Oxide CMP Clean

- Silica particles adhere to or embedded in oxide surface
- Usually an alkaline chemical, NH_4OH, is used for post oxide CMP clean
- The alkaline solution charges both silica particles and oxide surface negatively
- Electrostatic force expels particles from the surface

Post Oxide CMP Clean

- HF is used to remove particles with strong molecule bonds with surface,
- Breaking the bonds, dissolving silica particles and some oxide surface
- Megasonics (MHz ultrasound wave) is commonly used to release shock waves that help dislodge the particles
- DI water rinse

Post Tungsten CMP Clean

- Tungsten slurries are much harder to remove than oxide slurries.
- DI wafer with NH_4OH is commonly used
- $Fe(NO_3)_3$ as the oxidant results in high Fe^{3+} ion concentration in the solution.
- The Fe^{3+} ion interacts with OH^- to form $Fe(OH)_3$ particulate that grow to 1 micron

Post Tungsten CMP Clean

- The $Fe(OH)_3$ particles can cause high surface defect density and contaminates the brush
- Commonly called *brush loading*
- The defect caused by $Fe(OH)_3$ particles can be reduced by using 100:1 HF clean
- DI water rinse

Wafer Drying

- Residue-free drying process
- Physically removal, without water evaporation
  - Evaporation drying cause contamination by leaving dissolved chemicals in DI water behind
- Most commonly used technique: spin-drying
  - Centrifugal force drives water out the wafer
- Ultra-clean dry air or nitrogen flow remove water from wafer center

Wafer Drying

- Vapor drying
  - Ultra-pure solvent with high vapor pressure
  - Most commonly used: isopropyl alcohol (C_3H_8O, IPA)
  - Displace water from the wafer surface

Dry-in Dry-out CMP

- Integrated CMP and post-CMP clean systems
- Allow so-called "dry-in dry-out" process
- CMP, post-CMP clean, and wafer drying processes in one sequence
- Improve process through put and yield

Process Issues

- CMP process is a relatively new process
- Very limited process details are available
- The main concerns for CMP processes
  - Polishing rate, planarization capability, within die uniformity, within wafer uniformity, wafer to wafer uniformity, removal selectivity, defects and contamination control

Process Issues: Polish Rate

- Polish rate affected by
  - Downforce pressure
  - Pad hardness
  - Pad condition
  - Applied slurry
  - Rotation speed

Process Issues: Planarization

- Planarization capability is mainly determined by the stiffness and surface condition of the polish pad.

Process Issues: Uniformity

- Uniformity affected by
  - Polish pad condition,
  - Down force pressure,
  - Relative speed of the wafer to the polish pad,
  - Curvature of wafers, which is related to film stress
- Downforce pressure distribution is the most important knob to control the CMP uniformity

Process Issues: Removal Selectivity

- Mainly controlled by the slurry chemistry
- Also related to the pattern density
  - determined by the design layout.

Process Issues: Defects

- There are many different kinds of defects, which relate with many different process parameters

Process Issues: Contamination Control

- Contamination Control:
  - Isolate CMP bay from other processing areas
  - Restrict movement between CMP bay and other area
- Dedicate copper CMP tools
  - Avoid copper contamination of the silicon wafer
  - Copper contamination can cause unstable performance of MOSFETs and ruin the IC chips

Process Issues: Contamination Control

- IF slurry has spilled, it is very important to **immediately** wash and clean it thoroughly
- Dried slurry leaves huge amount of tiny particles, which is easy to airborne can become a source of particle contamination.

Future Trends

- More widely used copper CMP
- Copper and low-κ dielectric interconnection
  - low-κ dielectric CMP
  - Copper and barrier layer CMP processes with high selectivity to low-κ dielectric
- DRAM applications: CMP processes involve with polysilicon and high-κ dielectric

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

Summary

- 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

Summary

- The important factors of CMP processes:
  - Polish rate, planarization capability, selectivity, uniformities, defects and contamination controls
- Polish rate affects by: downforce pressure, pad stiffness, pad surface condition, relative speed between pad and wafer, and slurry type.
- CMP uniformity affects by down force pressure distribution, pad stiffness, and pad condition

Summary

- 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/abrade

Summary

- Endpoint detections
  - Optical
    - Thickness measurement for dielectric film
    - Reflectivity measurement for metal film
  - Motor current
- Post-CMP clean reduce defects and improve yield