Chapter 11
Metallization

Hong Xiao, Ph. D.

hxiao89@hotmail.com

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

Objectives

- Explain device application of metallization
- List three most commonly used metals
- List three different metallization methods
- Describe the sputtering process
- Explain the purpose of high vacuum in metal deposition processes

Metallization

- Definition
- Applications
- PVD vs. CVD
- Methods
- Vacuum
- Metals
- Processes
- Future Trends

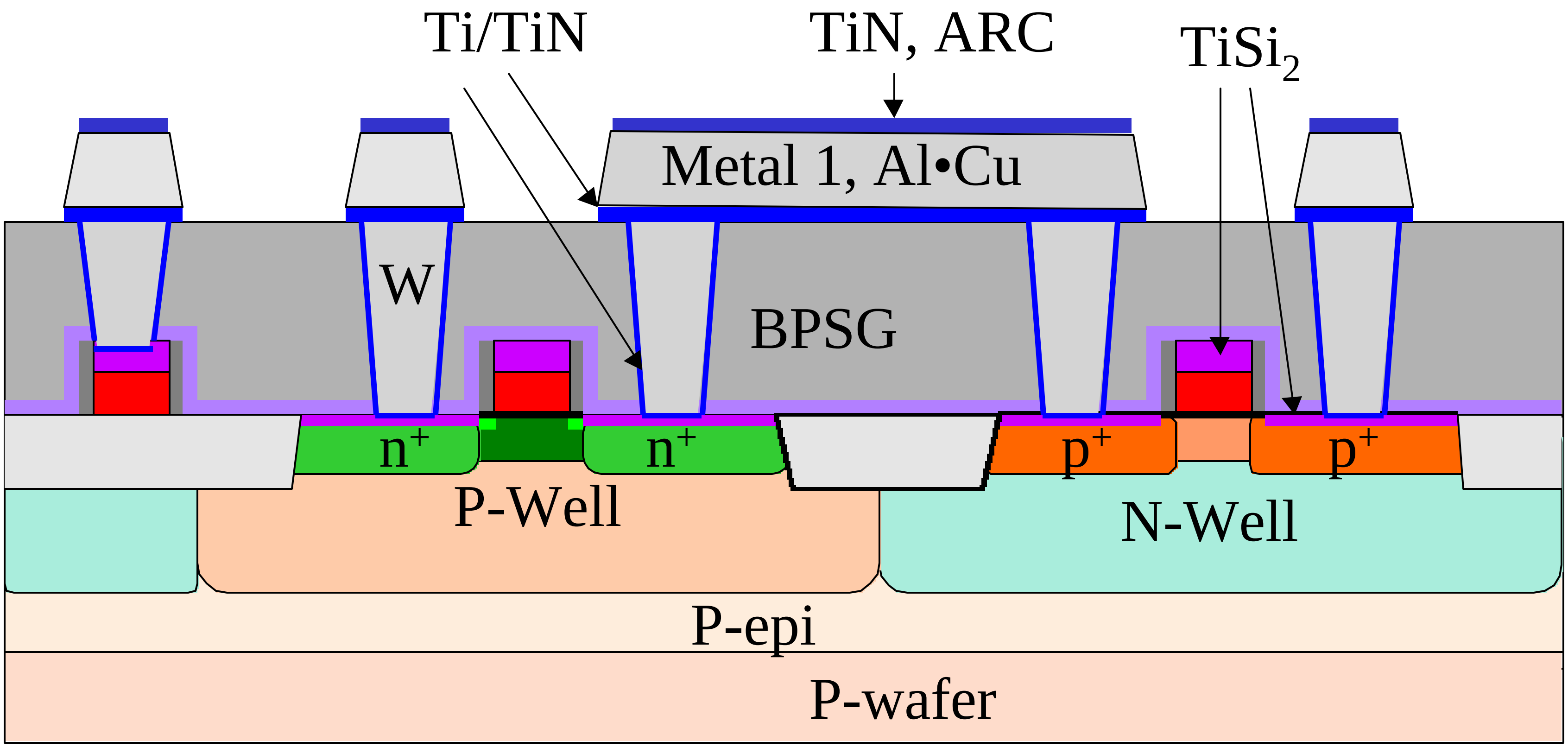
Metallization

- Processes that deposit metal thin film on wafer surface.

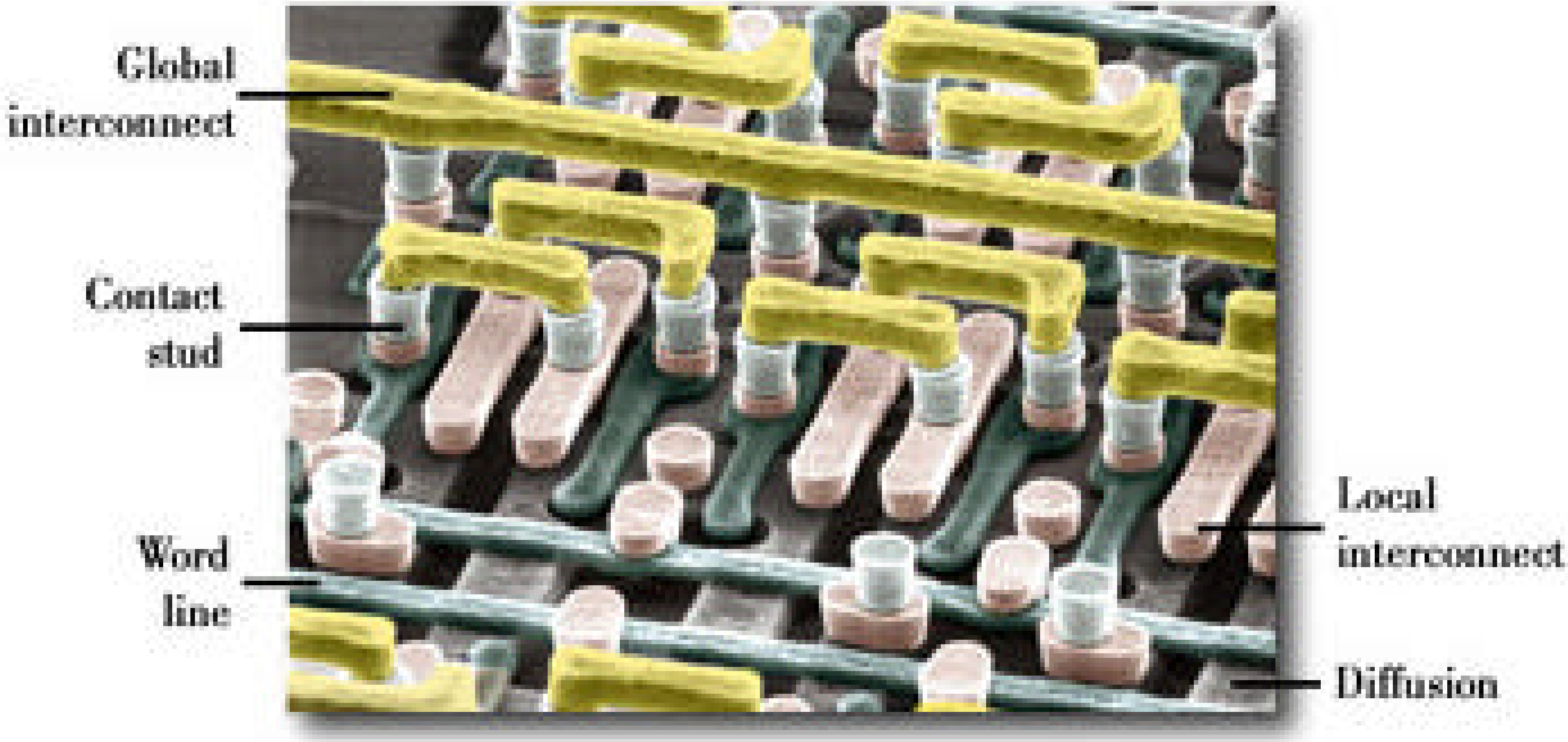
Applications

- Interconnection
- Gate and electrodes
- Micro-mirror
- Fuse

CMOS: Standard Metallization



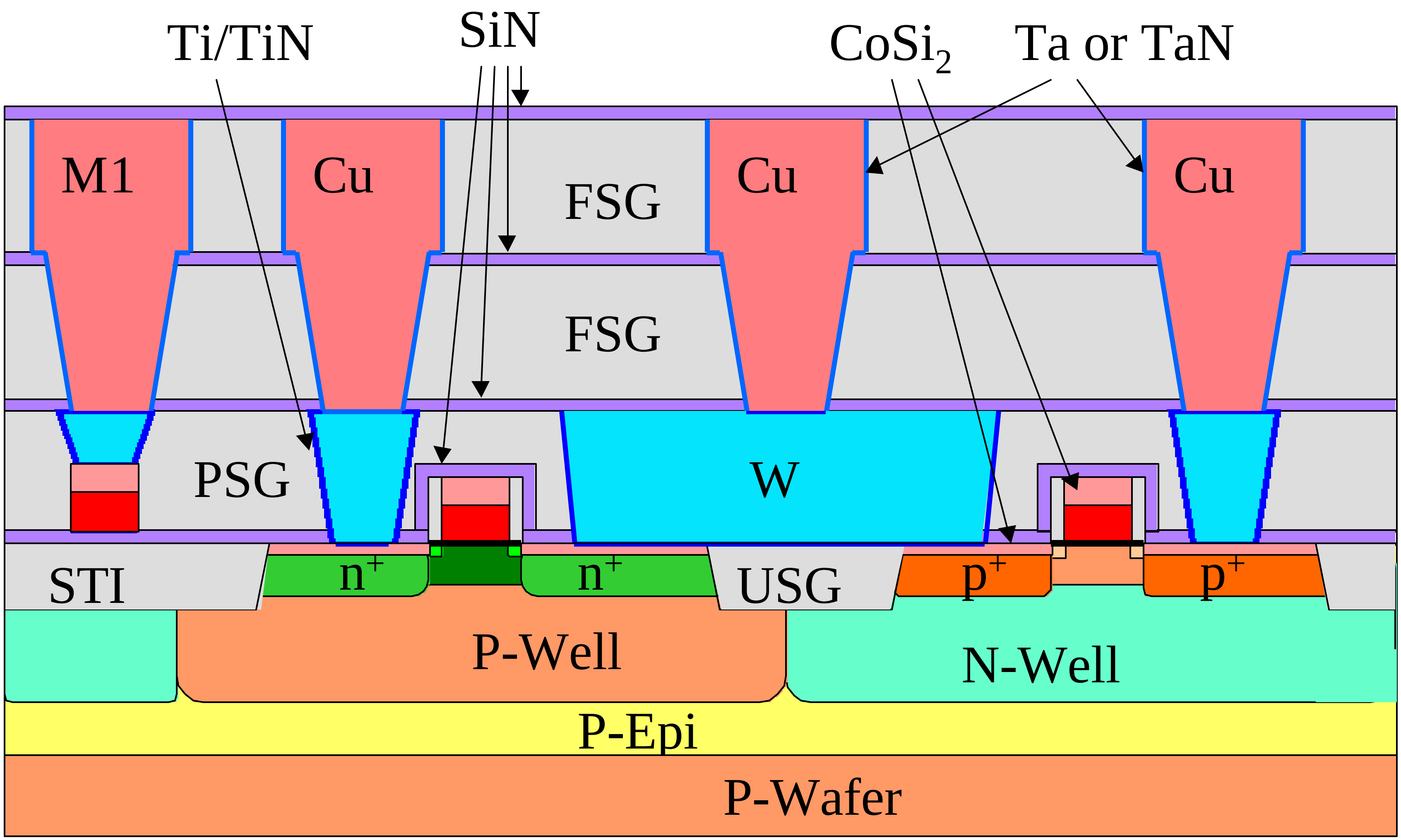
Applications: Interconnection



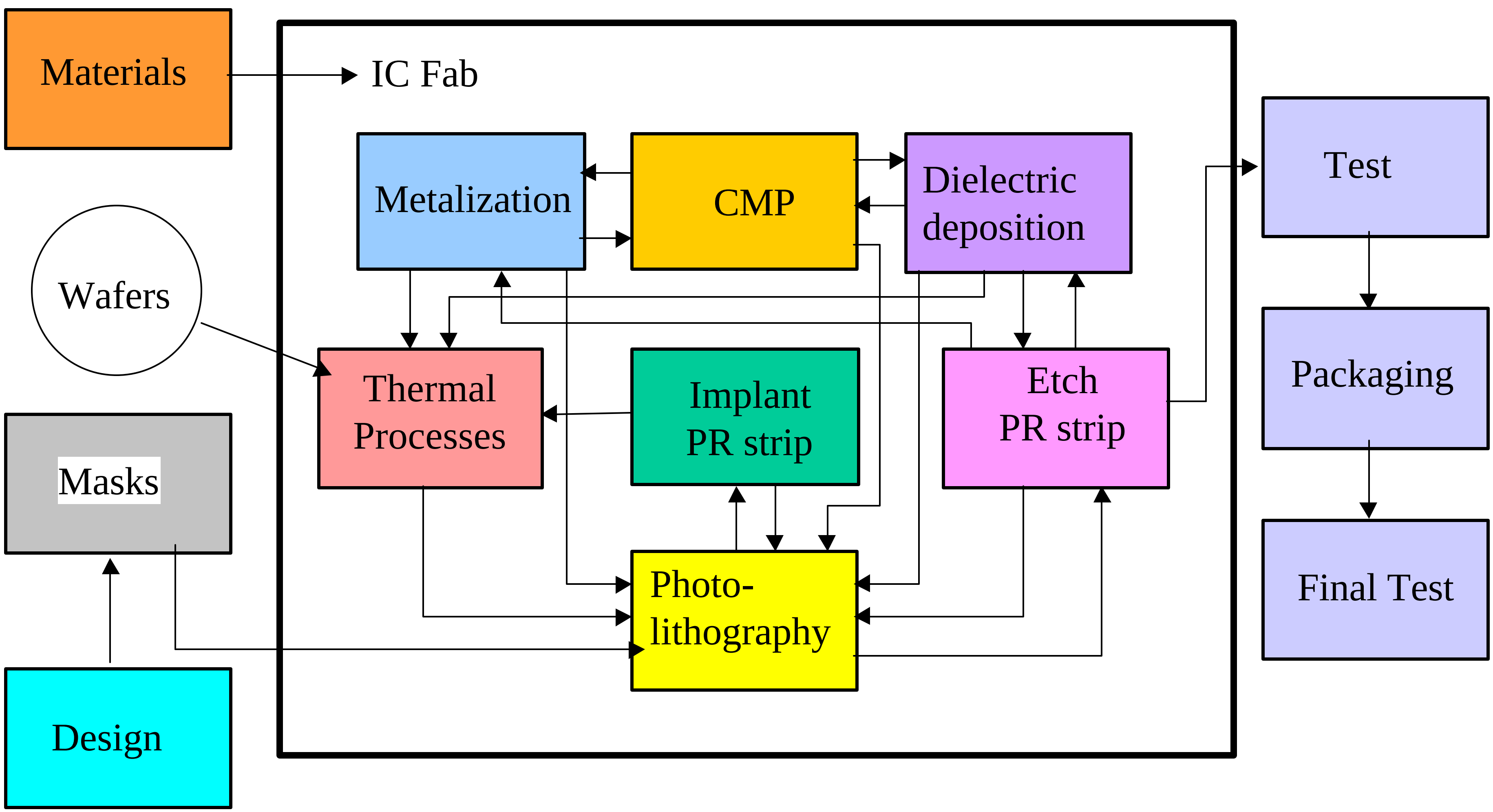
Applications: Interconnection

- Dominate the metallization processes
- Al-Cu alloy is most commonly used
- W plug, technology of 80s and 90s
- Ti, welding layer
- TiN, barrier, adhesion and ARC layers
- The future is --- Cu!

Copper Metallization



Wafer Process Flow



Applications: Gate and Electrode

- Al gate and electrode
- Polysilicon replace Al as gate material
- Silicide
  - WSi_2
  - $TiSi_2$
  - $CoSi_2$, $MoSi_2$, $TaSi_2$, …
- Pt, Au, …as electrode for DRAM capacitors

Q & A

- Can we reduce all dimensions of metal interconnection line at the same ratio?

- *R=r l/wh*. When we shrink all dimensions (length *l*, width *w*, and height *h*) accordingly to the shrinking of the device feature size, resistance *R* increases,
- Slower circuit and more power consumption

Applications: Micro-mirror

- Digital projection display
- Aluminum-Titanium Alloy
- Small grain, high reflectivity
- “Home Theater”

Applications: Fuse

- For programmable read-only memory (PROM)
- High current generates heat which melt thin Al line and open the circuit
- Polysilicon also being used as fuse materials

Conducting Thin Films

Conducting Thin Films

- Polysilicon
- Silicides
- Aluminum alloy
- Titanium
- Titanium Nitride
- Tungsten
- Copper
- Tantalum

Polysilicon

- Gates and local interconnections
- Replaced aluminum since mid-1970s
- High temperature stability
  - Required for post implantation anneal process
  - Al gate can not use form self-aligned source/drain
- Heavily doped
- LPCVD in furnace

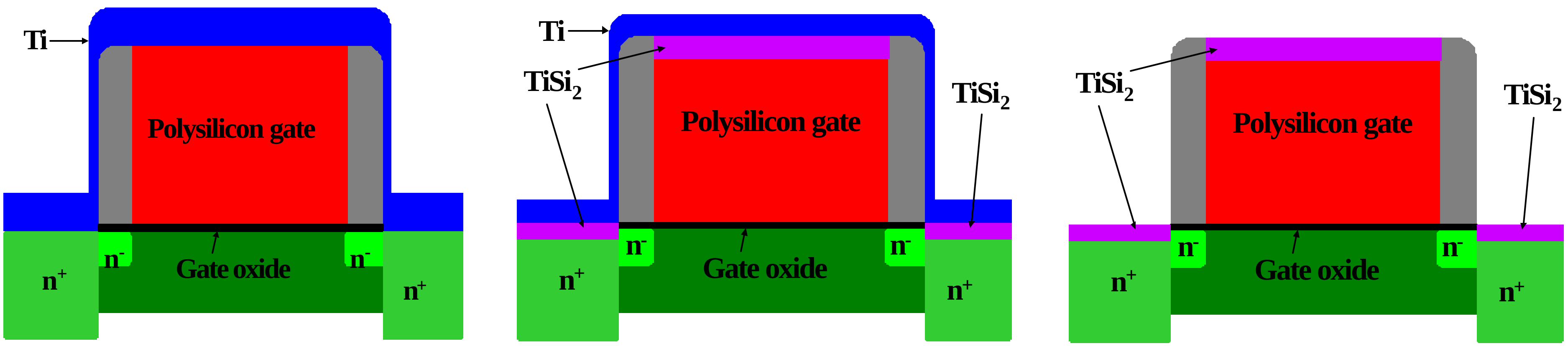
Silicide

- Much lower resistivity than polysilicon
- $TiSi_2$, WSi_2, and $CoSi_2$ are commonly used

Salicide

- $TiSi_2$ and $CoSi_2$
  - Argon sputtering removes the native oxide
  - Ti or Co deposition
  - Annealing process forms silicide
  - Ti or Co don't react with SiO_2, silicide is formed at where silicon contacts with Ti or Co
  - Wet strips unreacted Ti or Co
  - Optional second anneal to increase conductivity

Self-aligned Titanium Silicide Formation



Titanium deposition

Silicide annealing

Titanium wet striping

Tungsten Silicide

- Thermal CVD process
  - WF_6 as the tungsten precursor
  - SiH_4 as the silicon precursor.
- Polycide stack is etched
  - Fluorine chemistry etches WSi_x
  - Chlorine chemistry etches polysilicon
- Photoresist stripping
- RTA increases grain size and conductivity

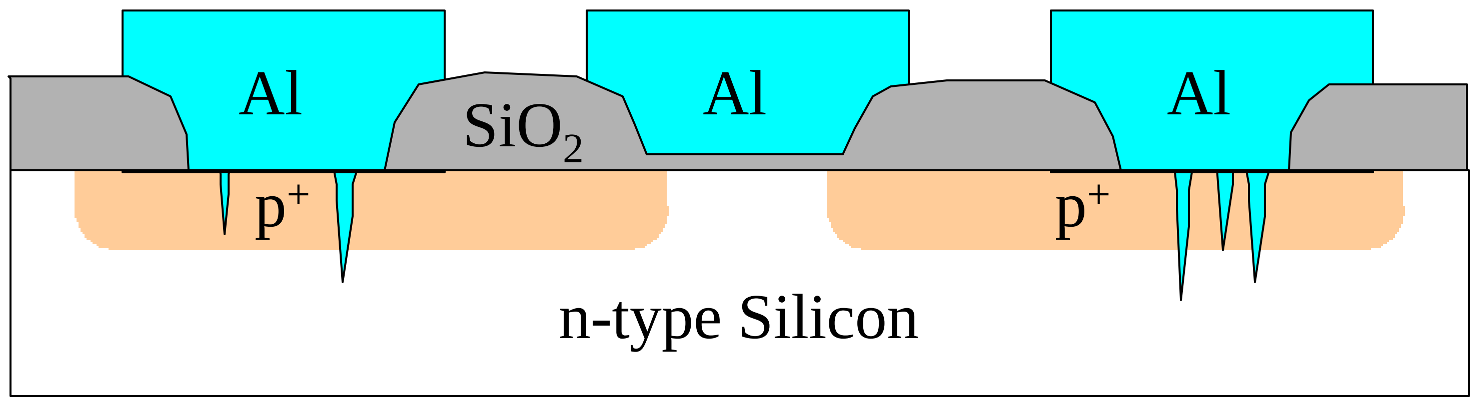
Aluminum

- Most commonly used metal
- The fourth best conducting metal
  - Silver 1.6 μΩ·cm
  - Copper 1.7 μΩ·cm
  - Gold silver 2.2 μΩ·cm
  - Aluminum 2.65 μΩ·cm
- It was used for gate before mid-1970

Aluminum-Silicon Alloy

- Al make direct contact with Si at source/drain
- Si dissolves in Al and Al diffuses into Si
- Junction spike
  - Aluminum spikes punctuate doped junction
  - Short source/drain with the substrate
- ~1% of Si in Al saturates it
- Thermal anneal at 400 °C to form Si-Al alloy at the silicon-aluminum interface

Junction Spike



Electromigration

- Aluminum is a polycrystalline material
- Many mono-crystalline grains
- Current flows through an aluminum line
- Electrons constantly bombards the grains
- Smaller grains will start to move
- This effect is called electromigration

Electromigration

- Electromigration tear the metal line apart
- Higher current density in the remaining line
  - Aggravates the electron bombardment
  - Causes further aluminum grain migration
  - Eventually will break of the metal line
- Affect the IC chip reliability
- Aluminum wires: fire hazard of old houses

Electromigration Prevention

- When a small percent of copper is alloyed with aluminum, electromigration resistance of aluminum significantly improved
- Copper serves as “glue” between the aluminum grains and prevent them from migrating due to the electron bombardment
- Al-Si-Cu alloy was used
- Al-Cu (0.5%) is very commonly

Aluminum Alloy Deposition

- PVD
  - Sputtering
  - Evaporation
    - Thermal
    - Electron beam
- CVD
  - Dimethylaluminum hydride [DMAH, $Al(CH_3)_2H$]
  - Thermal process

PVD vs. CVD

- CVD: Chemical reaction on the surface
- PVD: No chemical reaction on the surface

- CVD: Better step coverage (50% to ~100%) and gap fill capability
- PVD: Poor step coverage (~ 15%) and gap fill capability

PVD vs. CVD

- PVD: higher quality, purer deposited film, higher conductivity, easy to deposit alloys
- CVD: always has impurity in the film, lower conductivity, hard to deposit alloys

Some Facts About Aluminum

Name	Aluminum
Symbol	Al
Atomic number	13
Atomic weight	26.981538
Discoverer	Hans Christian Oersted
Discovered at	Denmark
Discovery date	1825
Origin of name	From the Latin word "alumen" meaning "alum"
Density of solid	2.70 g/cm^3
Molar volume	10.00 cm^3
Velocity of sound	5100 m/sec
Hardness	2.75
Electrical resistivity	2.65 μΩ cm
Reflectivity	71%
Melting point	660 C
Boiling point	2519 C
Thermal conductivity	235 $W\ m^{-1}\ K^{-1}$
Coefficient of linear thermal expansion	23.1 $10^{-6}\ K^{-1}$
Etchants (wet)	H_3PO_4, HNO_4, CH_3COOH
Etchants (dry)	Cl_2, BCl_3
CVD Precursor	$Al(CH_3)_2H$

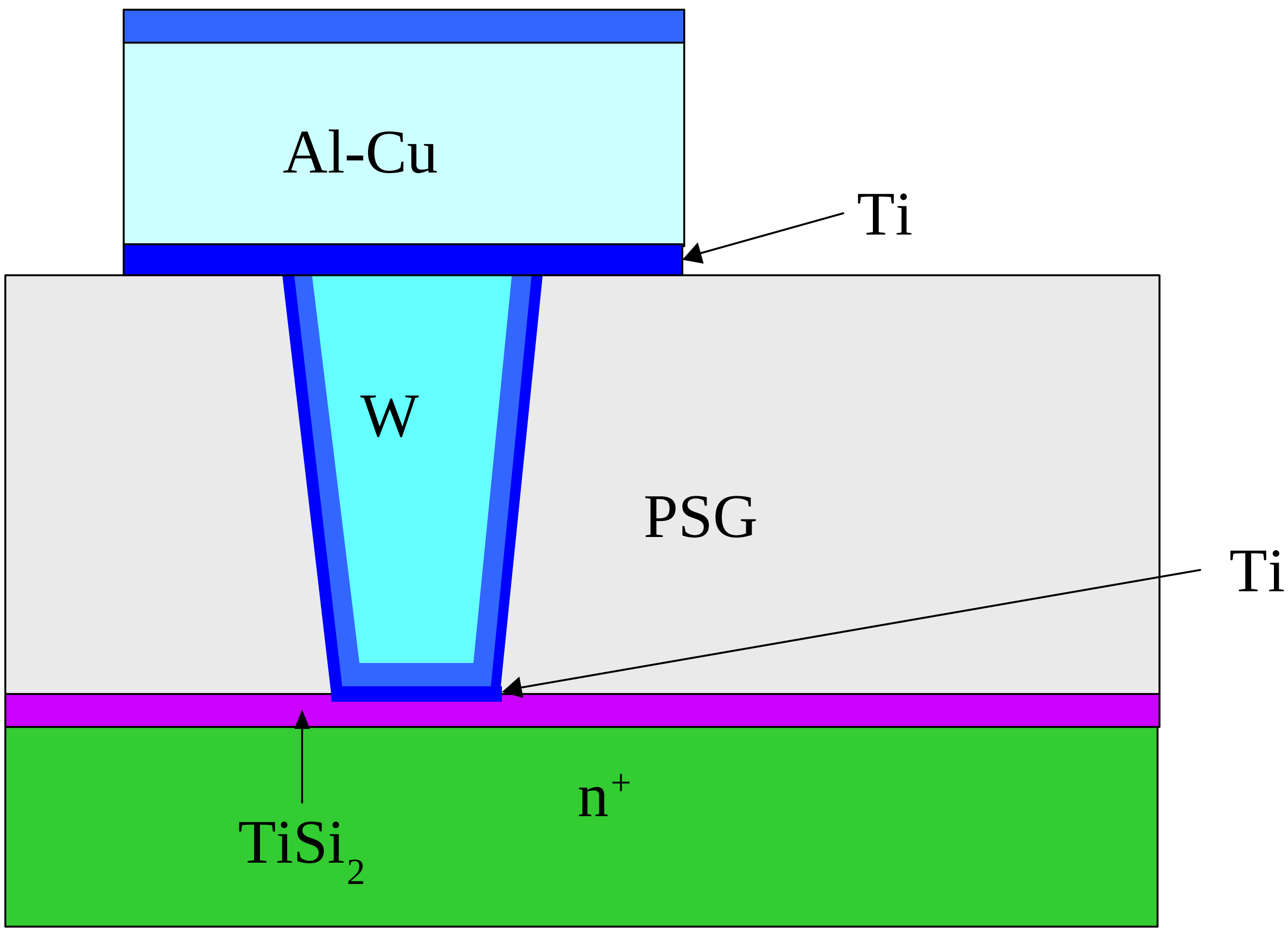
Titanium

- Applications
  - Silicide formation
  - Titanium nitridation
  - Wetting layer
  - Welding layer

Welding Layer

- Reduce contact resistance.
  - Titanium scavenges oxygen atoms
  - Prevent forming high resistivity WO_4 and Al_2O_3.
- Use with TiN as diffusion barrier layer
  - Prevent tungsten from diffusing into substrate
  -

Applications of Titanium



Some Face About Titanium

Name	Titanium
Symbol	Ti
Atomic number	22
Atomic weight	47.867
Discoverer	William Gregor
Discovered at	England
Discovery date	1791
Origin of name	Named after the "Titans", (the sons of the Earth goddess in Greek mythology)
Density of solid	4.507 g/cm^3
Molar volume	10.64 cm^3
Velocity of sound	4140 m/sec
Hardness	6.0
Electrical resistivity	40 $\mu\Omega$ cm
Melting point	1668 C
Boiling point	3287 C
Thermal conductivity	22 $W\ m^{-1}\ K^{-1}$
Coefficient of linear thermal expansion	8.6 $10^{-6}\ K^{-1}$
Etchants (wet)	H_2O_2, H_2SO_4
Etchants (dry)	Cl_2, NF_3
CVD Precursor	$TiCl_4$

Titanium Nitride

- Barrier layer
  - prevents tungsten diffusion
- Adhesion layer
  - help tungsten to stick on silicon oxide surface
- Anti-reflection coating (ARC)
  - reduce reflection and improve photolithography resolution in metal patterning process
  - prevent hillock and control electromigration
- Both PVD and CVD

Titanium Nitride PVD

- Barrier layer, adhesion layer and ARC
- Reactive sputtering a Ti target with Ar and N_2
  - N_2 molecules dissociate in plasma
  - Nitrogen free radials (N)
  - N reacts with Ti and form TiN layer on Ti surface
  - Ar ions sputter TiN off and deposit them on the wafer surface

Titanium Nitride CVD

- Barrier layer and adhesion layer
- Better step coverage than PVD
- Metal organic process (MOCVD)
  - ~350 °C
  - TDMAT, $Ti[N(CH_3)_2]_4$
  - Via application

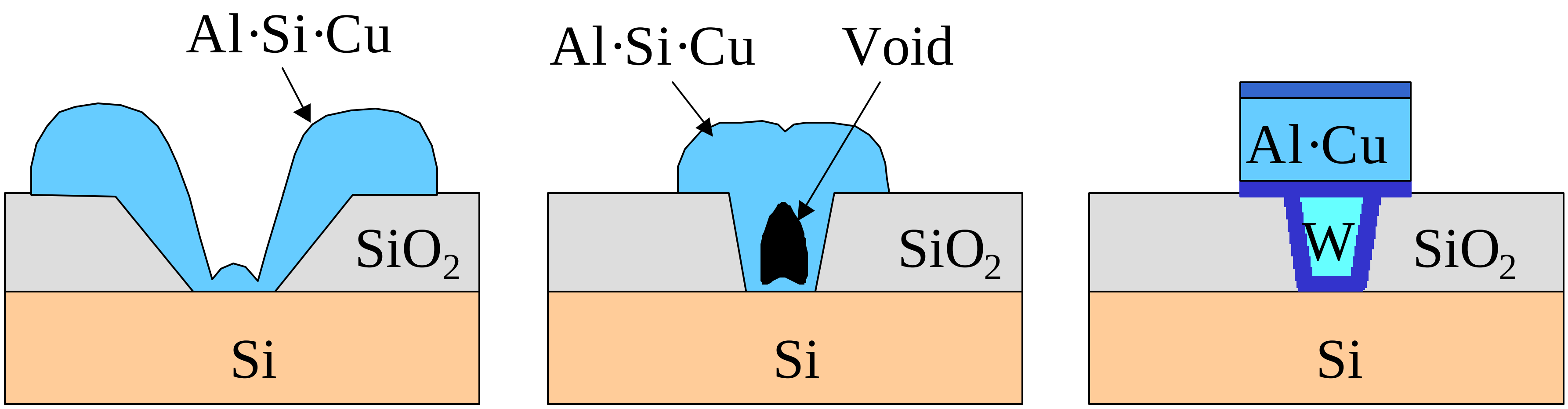
Titanium Nitridation

- Titanium PVD
- Nitridation of titanium surface with ammonia
- Rapid thermal process

Tungsten

- Metal plug in contact and via holes
- contact holes become smaller and narrower
- PVD Al alloy: bad step coverage and void
- CVD W: excellent step coverage and gap fill
- higher resistivity: 8.0 to 12 $\mu\Omega\cdot$cm compare to PVD Al alloy (2.9 to 3.3 $\mu\Omega\cdot$cm)
- only used for local interconnections and plugs

Evolution of Contact Processes



Widely tapered contact hole, PVD metal fill

Narrow contact hole, void with PVD metal fill

Narrow contact hole, WCVD for tungsten plug

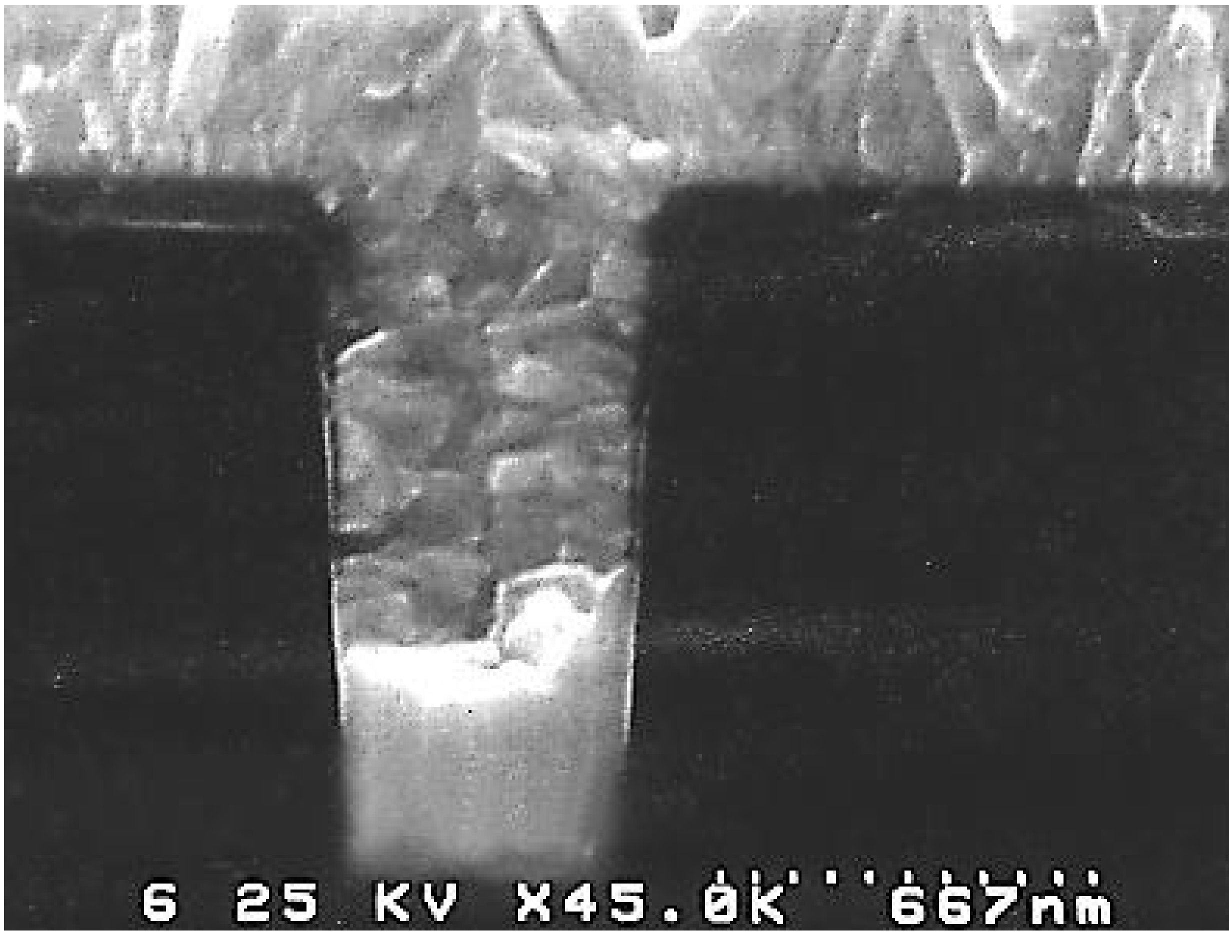
Tungsten CVD

- WF_6 as the tungsten precursor
- React with SiH_4 to form nucleation layer
- React with H_2 for bulk tungsten deposition
- Needed a TiN layer to adhere on oxide

Some Facts About Tungsten

Name Symbol	Tungsten W
Atomic number Atomic weight	74 183.84
Discoverer	Fausto and Juan Jose de Elhuyar
Discovered at	Spain
Discovery date	1783
Origin of name	From the Swedish words "tung sten" meaning "heavy stone". W comes from "wolfram", named after the tungsten mineral wolframite.
Density of solid	19.25 g/cm^3
Molar volume	9.47 cm^3
Velocity of sound	5174 m/sec
Hardness	7.5
Reflectivity	62%
Electrical resistivity	5 $\mu\Omega\cdot$cm
Melting point	3422 °C
Boiling point	5555 °C
Thermal conductivity Coefficient of linear thermal expansion Etchants (wet)	170 W m^{-1} K^{-1} 4.5×10^{-6} K^{-1} KH_2PO_4, KOH, and $K_3Fe(CN)_6$; boiling H_2O
Etchants (dry) CVD Precursor	SF_6, NF_3, CF_4, etc. WF_6

W Plug and TiN/Ti Barrier/Adhesion Layer



Copper

- Low resistivity (1.7 μΩ·cm),
  - lower power consumption and higher IC speed
- High electromigration resistance
  - better reliability
- Poor adhesion with silicon dioxide
- Highly diffusive, heavy metal contamination
- Very hard to dry etch
  - copper-halogen have very low volatility

Copper Deposition

- PVD of seed layer
- ECP or CVD bulk layer
- Thermal anneal after bulk copper deposition
  - increase the grain size
  - improving conductivity

Some Facts About Copper

Name	Copper
Symbol	Cu
Atomic number	29
Atomic weight	63.546
Discoverer Discovered at	Copper had been used by human being since ancient time, long before any written history.
Discovery date	
Origin of name	From the Latin word "cuprum" meaning the island of "Cyprus"
Density of solid	8.92 g/cm^3
Molar volume	7.11 cm^3
Velocity of sound Hardness Reflectivity	3570 m/sec 3.0 90%
Electrical resistivity	1.7 μΩ·cm
Melting point	1084.77 °C
Boiling point	5555 °C
Thermal conductivity	400 W m^{-1} K^{-1}
Coefficient of linear thermal expansion	16.5×10^{-6} K^{-1}
Etchants (wet)	HNO_4, HCl, H_2SO_4
Etchants (dry)	Cl_2, needs low pressure and high temperature
CVD Precursor	(hfac)Cu(tmvs)

Tantalum

- Barrier layer
- Prevent copper diffusion
- Sputtering deposition

Some Facts About Tantalum

Name	Tantalum
Symbol	Ta
Atomic number Atomic weight	73 180.9479
Discoverer	Anders Ekeberg
Discovered at	Sweden
Discovery date	1802
Origin of name	From the Greek word "Tantalos" meaning "father of Niobe" due it close relation to niobium in the Periodic Table
Density of solid	16.654g/cm^3
Molar volume	7.11 cm^3
Velocity of sound	3400 m/sec
Hardness	3.0
Reflectivity	90%
Electrical resistivity	12.45μΩ·cm
Melting point	2996 °C
Boiling point	5425°C
Thermal conductivity	57.5 W m^{-1} K^{-1}
Coefficient of linear thermal expansion	6.3×10^{-6} K^{-1}

Cobalt

- Mainly used for cobalt silicide ($CoSi_2$).
- Normally deposited with a sputtering process

Cobalt Silicide

- Titanium silicide grain size: ~ 0.2 μm
- Can't be used for 0.18 mm gate
- Cobalt silicide will be used
- Salicide process

Cobalt Silicide: Process

- Pre-deposition argon sputtering clean
- Cobalt sputtering deposition
- First anneal, 600 °C

$$Co + Si \rightarrow CoSi$$

- Strip Unreacted cobalt
- Second anneal, 700 °C

$$Co + Si \rightarrow CoSi_2$$

Some Facts About Cobalt

Name	Tantalum
Symbol	Co
Atomic number	27
Atomic weight	180.9479
Discoverer	Georg Brandt
Discovered at	Sweden
Discovery date	1735
Origin of name	From the German word "kobald" meaning "goblin" or evil spirit
Density of solid	8.900 g/cm^3
Molar volume	6.67 cm^3
Velocity of sound	4720 m/sec
Hardness	6.5
Reflectivity	67%
Electrical resistivity	13 $\mu\Omega\cdot$cm
Melting point	1768 K or 1495 °C
Boiling point	3200 K or 2927 °C
Thermal conductivity	100 W m^{-1} K^{-1}
Coefficient of linear thermal expansion	13.0×10^{-6} K^{-1}

Metal Thin Film Characteristics

Metal Thin Film Measurements

- Thickness.
- Stress
- Reflectivity
- Sheet resistance

Metal Thin Film Thickness

- TEM and SEM
- Profilometer
- 4-point probe
- XRF
- Acoustic measurement

TEM and SEM

- Cross section
- TEM: very thin film, few hundred Å
- SEM: film over thousand Å

Q & A

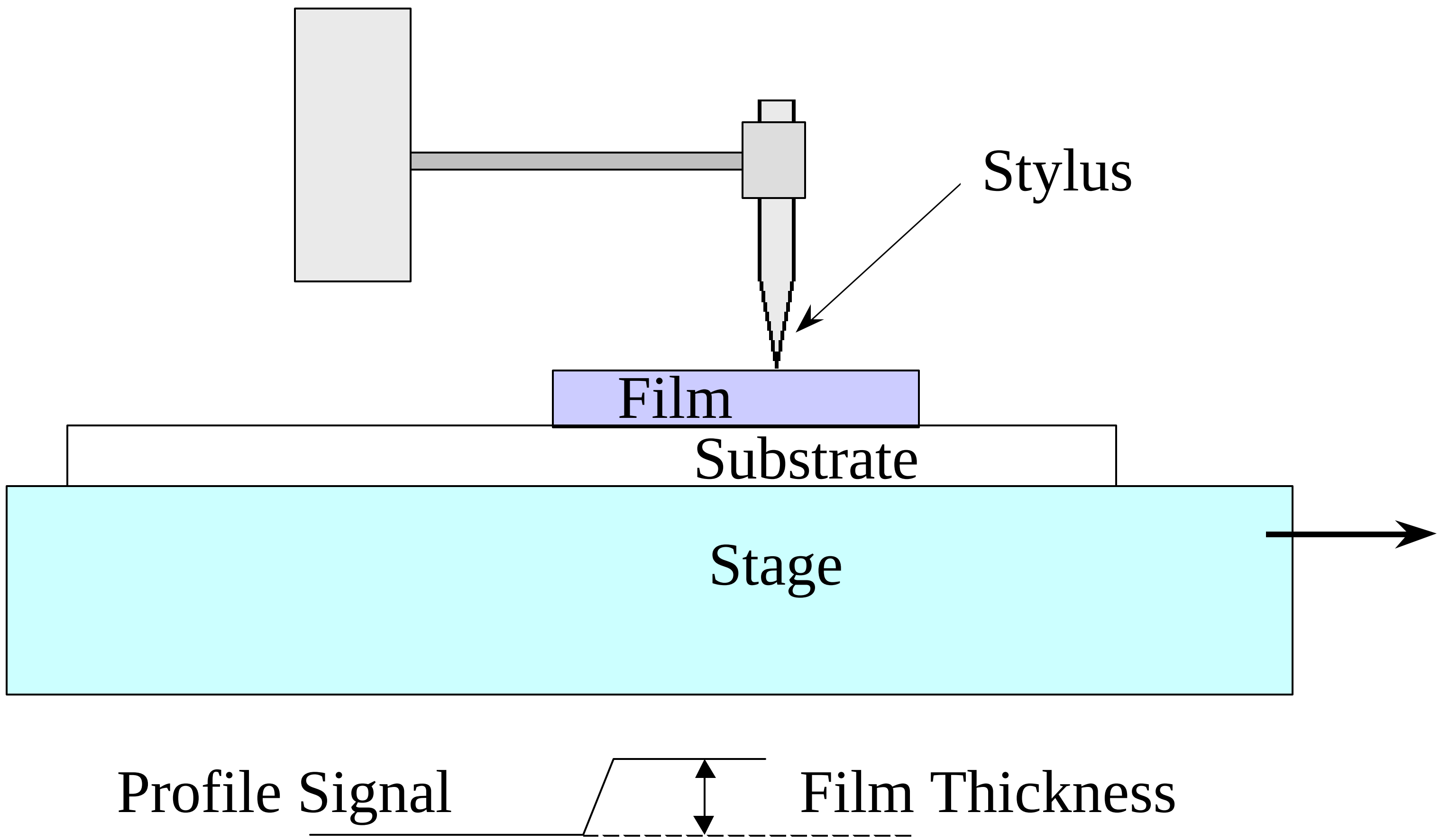
- Why is SEM photo is always in black and white?

- Intensity of the secondary electron emission
  - strong or weak signals
  - photo image: bright and dim, black and white
- SEM photo can be painted after it has been analyzed

Profilometer

- Thicker film (> 1000 Å),
- Patterned etch process prior to measurement
- Stylus probe senses and records microscopic surface profile

Schematic of Stylus Profilometer



Four-point Probe

- Measure sheet resistance
- Commonly used to monitor the metal film thickness by assuming the resistivity of the metal film is a constant all over the wafer surface

Acoustic Measurement

- New technique
- Directly measure opaque thin film thickness
- Non-contact process, can be used for production wafer

Acoustic Measurement

- Laser shots on thin film surface
- Photo-detector measures reflected intensity
- 0.1 ps laser pulse heat the spot up 5 to 10 °C
- Thermal expansion causes a sound wave
- It propagates in the film and reflects at the interface of the different materials
- The echo causes reflectivity change when it reaches the thin film surface.

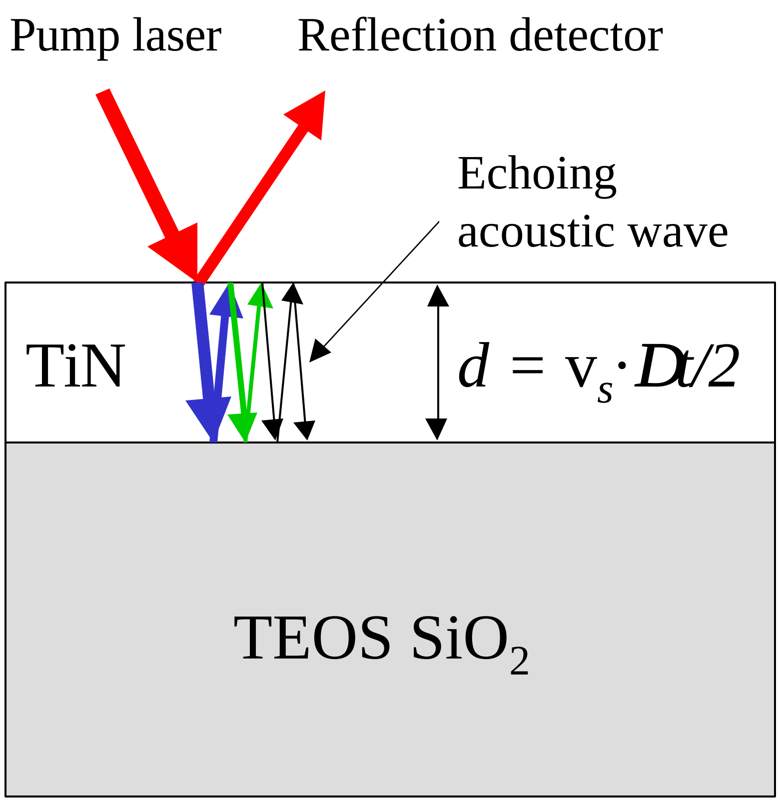
Acoustic Measurement

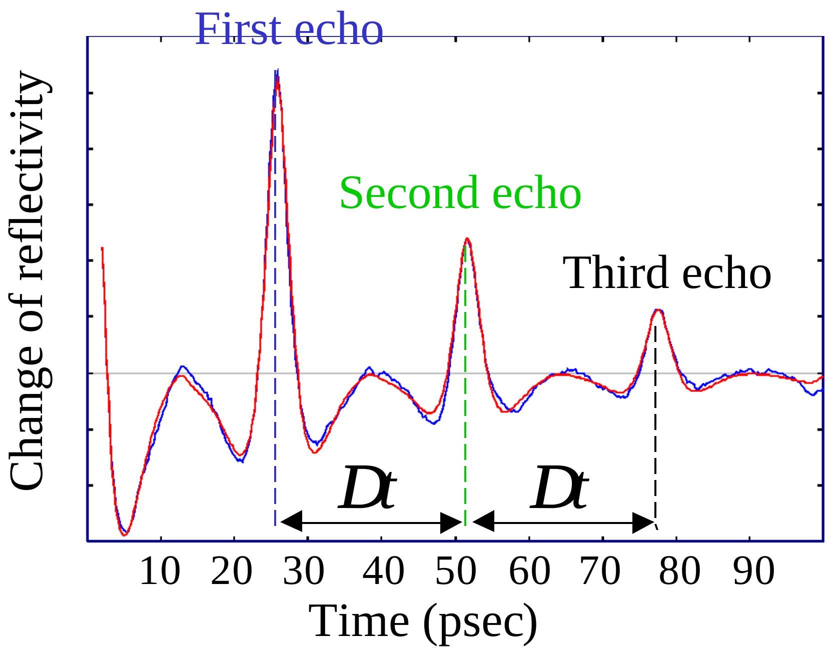
- Acoustic wave echoes back and forth in film
- The film thickness can be calculated by

$$d = V_s \, Dt/2$$

- V_s is speed of sound and *Dt* is time between reflectivity peaks
- The decay rate the echo is related to the film density.
- Multi-layer film thickness

Acoustic Method Measurement





TiN Thickness

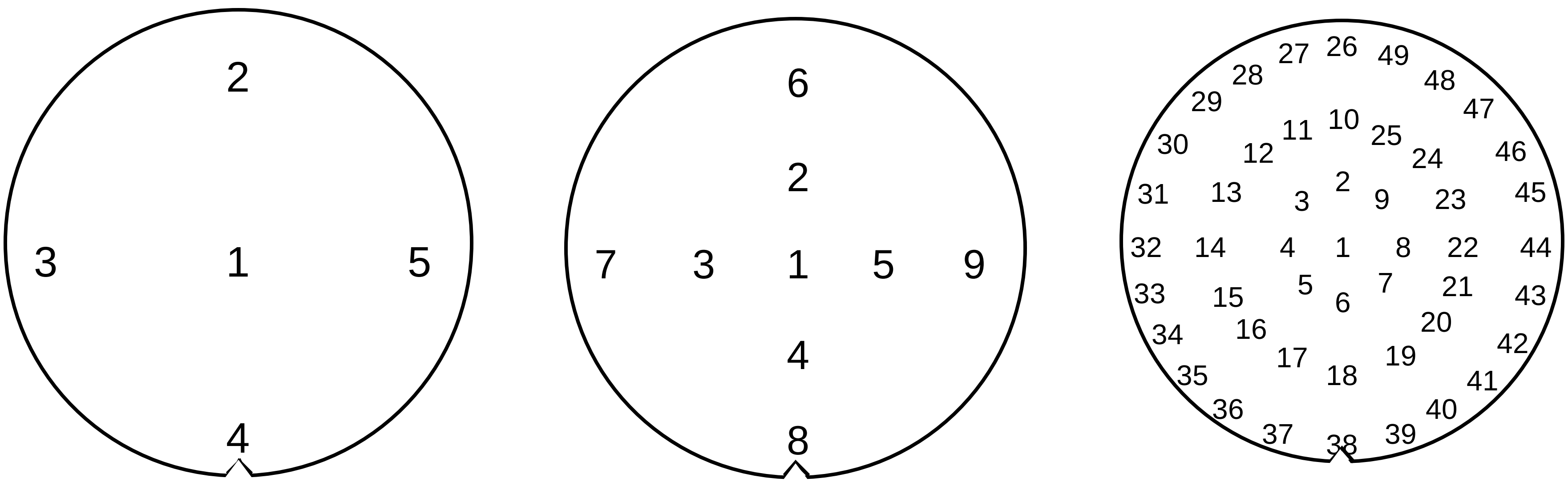
- $d = V_s \cdot Dt/2$
- Sound velocity in TiN film $V_s = 95$ Å / ps
- Dt » 25.8 ps

- $d = 1225$ Å

Uniformity

- The uniformity, in fact it is non-uniformity, of the thickness, sheet resistance, and reflectivity are routinely measured during the process development and for the process maintenance.
- It can be calculated by measuring at multiple locations on a wafer

Mapping Patterns for Uniformity Measurement



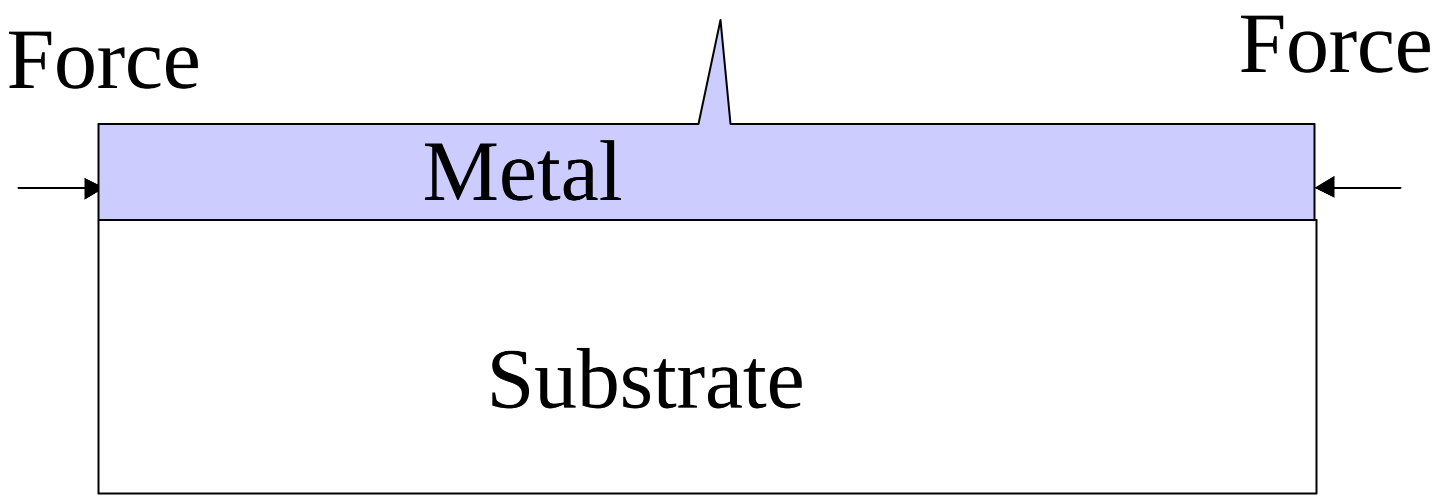
Uniformity

- Most commonly used non-uniformity definition: 49-point, 3σ standard deviation
- Clearly define non-uniformity
  - For the same set of data, different definitions causes different results
- 5-point and 9-point are commonly used in production

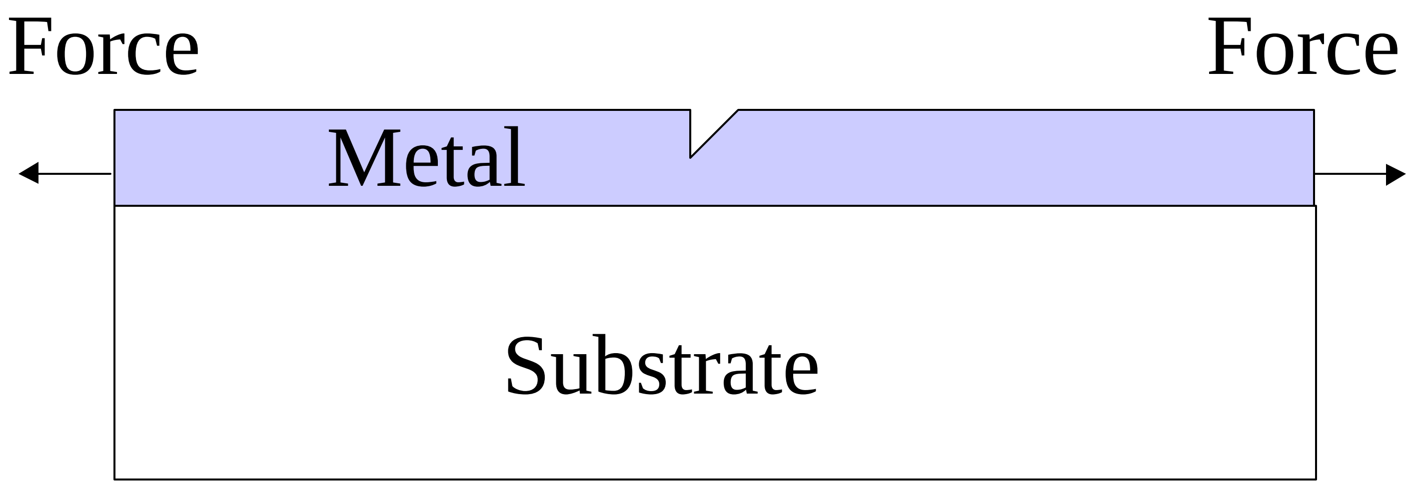
Stress

- Caused by mismatching between film and substrate
- Compressive and tensile
- High compressive stress causes hillocks
  - short metal wires between different layers
- High tensile stress causes cracks or peels

Compressive Stress Causes Hillock



Tensile Stress Causes Crack



Favorable Stress

- Aluminum has higher thermal expansion rate than silicon

  $\alpha_{Al} = 23.6\times10^{-6}\ K^{-1}$, $\alpha_{Si} = 2.6\times10^{-6}\ K^{-1}$
- It favor tensile stress at room temperature
- Stress becomes less tensile when wafer is heated up later
  - metal annealing (~ 450 °C)
  - dielectric deposition (~ 400 °C)

Q & A

- Why does silicon oxide film favor compressive stress at room temperature?

- Silicon oxide has lower thermal expansion rate ($\alpha_{SiO2} = 0.5\times10^{-6}\ K^{-1}$) than the silicon
- If it has tensile stress at room temperature, it will become more tensile when the wafer is heated up in later processes

Reflectivity

- Reflectivity change indicates drift of process
- A function of film grain size and surface smoothness
- Larger grain size film has lower reflectivity
- Smoother metal surface has higher reflectivity
- Easy, quick and non-destructive
- Frequently performed in semiconductor fabs

Sheet Resistance

- 4-point probe
- Widely used to determine film thickness
- Assuming resistivity is the same on wafer
- Faster and cheaper than the profilometer, SEM, and acoustic measurement

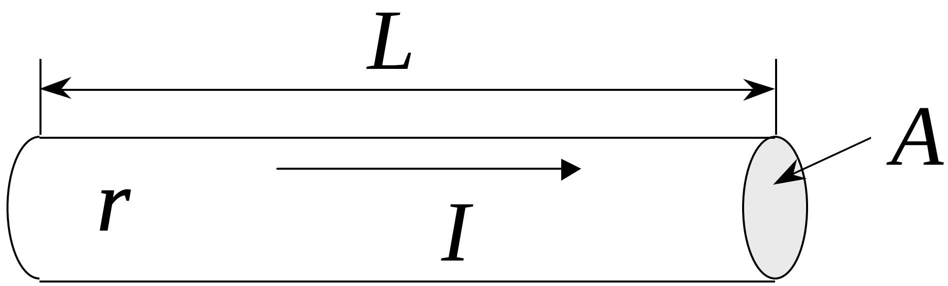
Sheet Resistance

- Sheet resistance (R_s) is a defined parameter

$$R_s = r/t$$

- By measuring R_s, one can calculate film resistivity (ρ) if film thickness t is known, or film thickness if its resistivity is known

Resistance of a Metal Line

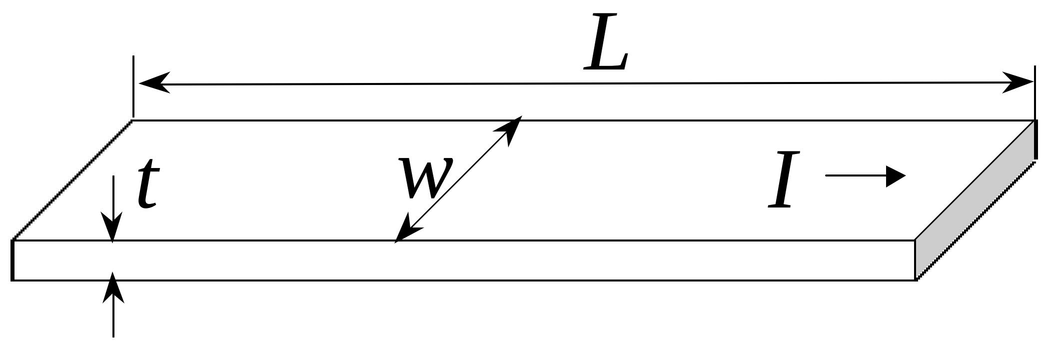


$$R = r \frac{L}{A}$$

R = Resistance, ρ = Resistivity

L = Length, *A* = Area of line cross-section

Sheet Resistance Concepts



Apply current I and measure voltage V,

Resistance: $R = V/I = \rho L/(wt)$

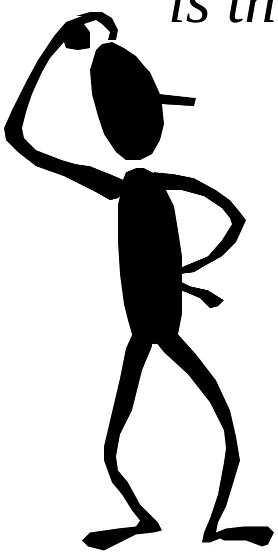
For a square sheet, $L = w$, so $R = \rho/t = R_s$

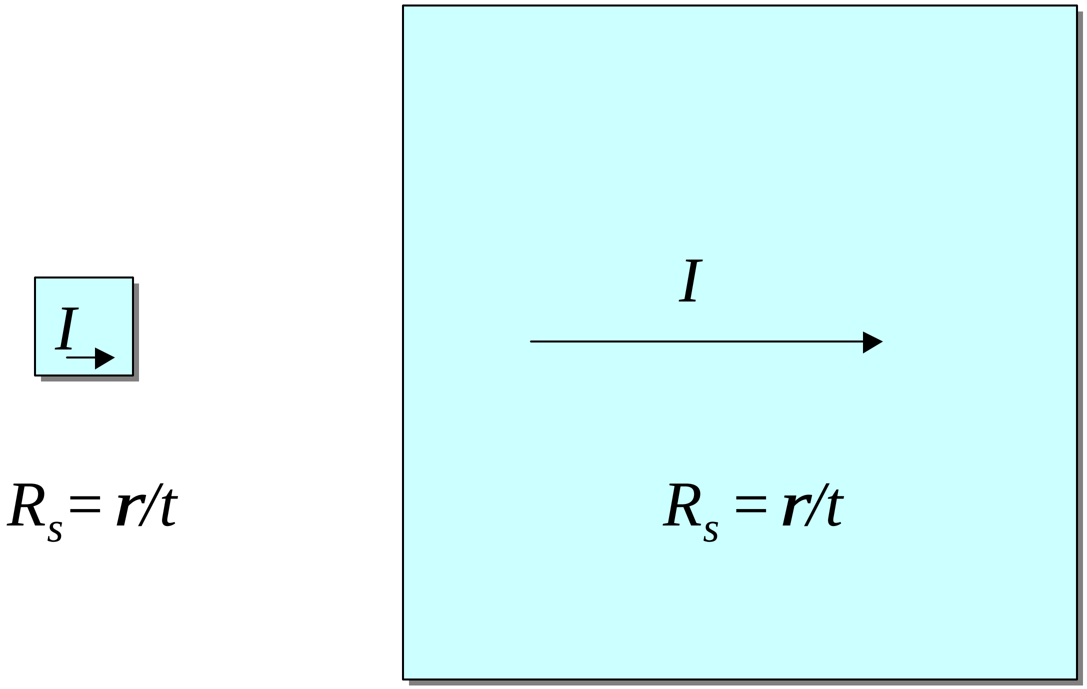
Unit of R_s: ohms per square (Ω/□)

Sheet Resistance

Sheet Resistance

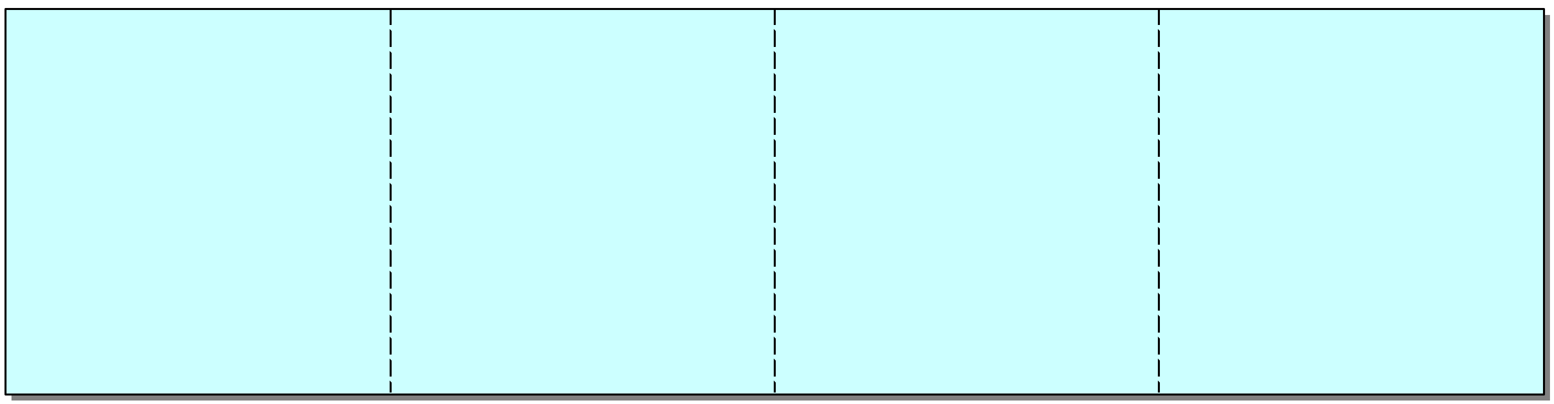
Are you sure their resistance is the same?



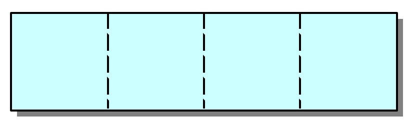


Sheet Resistance

For this two conducting lines patterned from the same metal thin film with the same length-to-width ratios, are their line resistance the same?



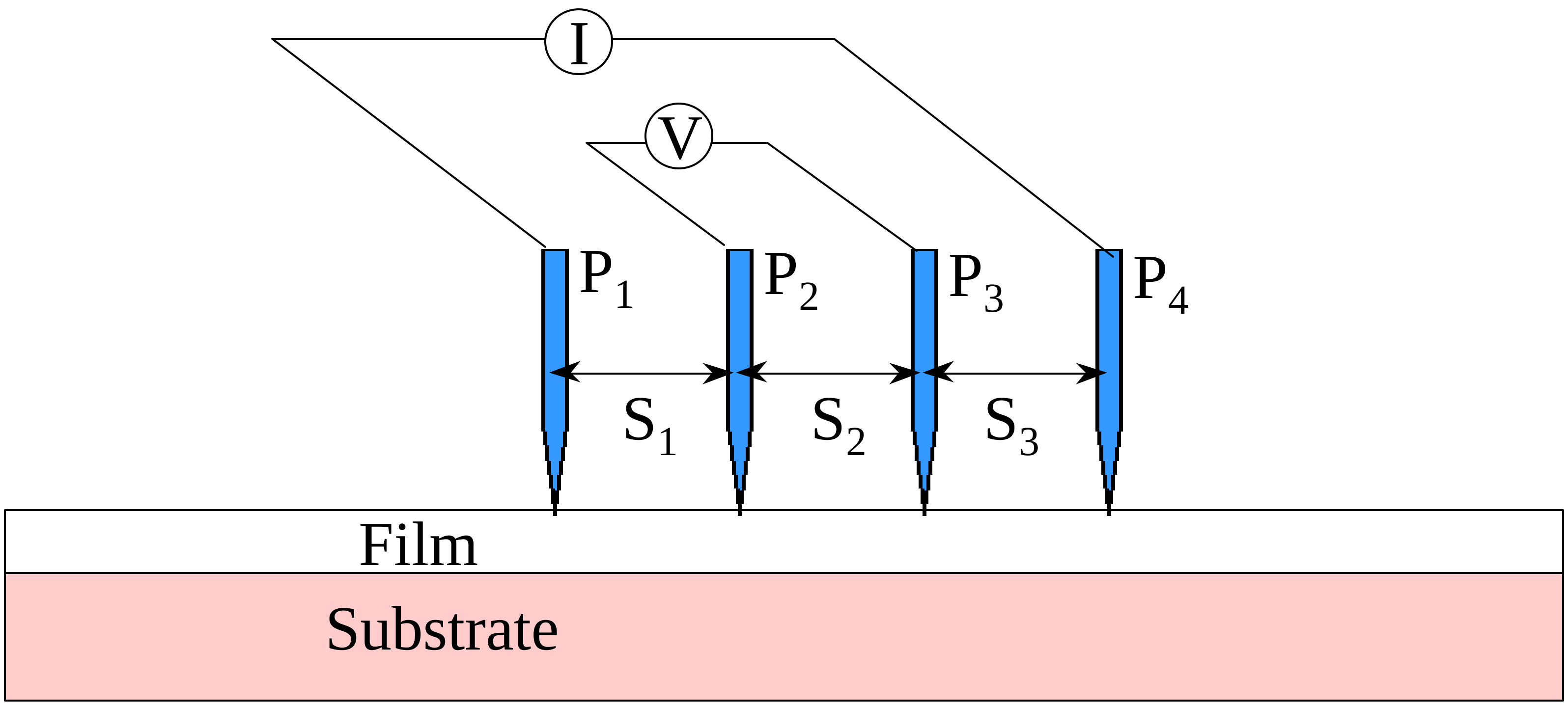
Yes.



Four-point Probe

- Commonly used tool for sheet resistance
- A current is applied between two pins and voltage is measured between other two pins
  - If current *I* is between P_1 and P_4, $\boldsymbol{R_s = 4.53\ V/I}$, *V* is voltage between P_2 and P_3
  - If current *I* is between P_1 and P_3, $\boldsymbol{R_s = 5.75\ V/I}$, *V* is voltage between R_2 and R_4
- Both configurations are used in measurement

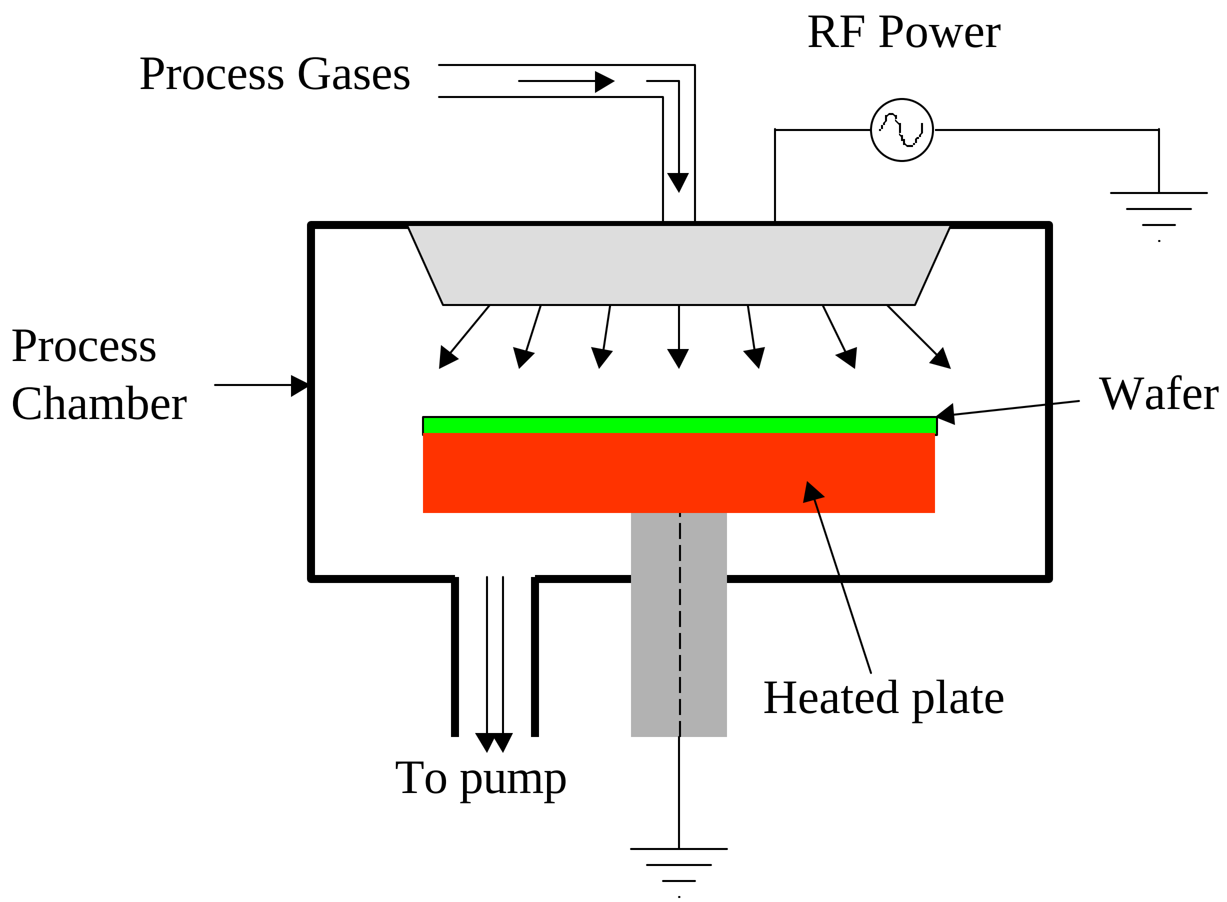
Four-Point Probe Measurement



Metal CVD

- Widely used to deposit metal
- Good step coverage and gap fill capability
  - can fill tiny contact holes to make connections between metal layers.
- Poorer quality and higher resistivity than PVD metal thin films.
  - Used for plugs and local interconnections
  - Not applied for global interconnections

Metal CVD Chamber



Metal CVD

- W, WSi_x, Ti, and TiN
- Thermal process, heat provides free energy needed for the chemical reaction
- RF system is used for plasma dry clean of the process chamber

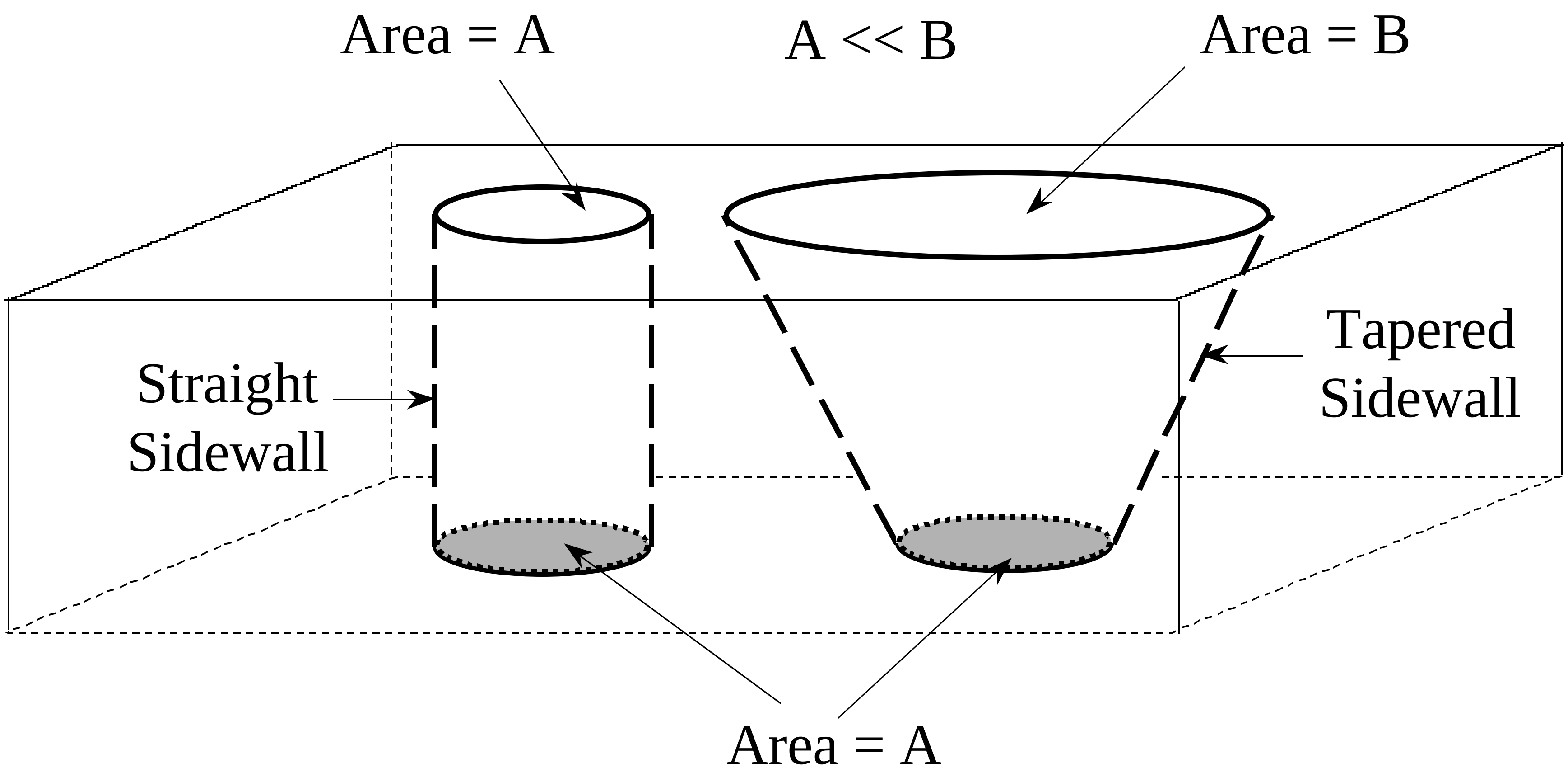
Metal CVD Process Steps

- Wafer into the chamber
- Slip valve closes
- Set up pressure and temperature, with secondary process gas(es)
- All process gases flow in, start deposition
- Termination of the main process gas. Secondary process gas(es) remain on
- Termination of all process gases
- Purge chamber with nitrogen
- Slip valve opens and robot pull wafer out

Metal CVD Chamber Clean Steps

- Chamber pumps down
- Set up pressure and temperature
- RF turns on. Start plasma and clean process
- RF turns off. Chamber is purged
- Set up pressure and temperature, with secondary process gas(es)
- Flows main process gas to deposit the seasoning layer
- Terminate the main process gas
- Terminate all process gases
- Purge chamber with nitrogen
- Chamber is ready for the next deposition

Vertical and Tapered Contact Holes



Tungsten CVD Basics

Tungsten source gas: tungsten hexafluoride (WF_6)

Additional reactant: hydrogen (H_2)

Temperature: 400 - 475 °C

Step Coverage is 100 %

Typical W CVD Process

- Wafer transferred to chamber
- Pressure and gas flows (H_2, SiH_4) established
- Nucleation takes place (silane reduction of WF_6)
- Pressure and gas flows changed for bulk deposit
- Bulk deposit takes place (H_2 reduction of WF_6)
- Chamber pumped and purged
- Wafer transferred out of chamber

W CVD Reactions

Nucleation on silicon

$$2\ WF_6 + 3\ Si \rightarrow 2\ W\ (s) + 3\ SiF_4$$

Nucleation on glue layer

$$2\ WF_6 + 3\ SiH_4 \rightarrow 2\ W\ (s) + 3\ SiF_4 + 6\ H_2$$

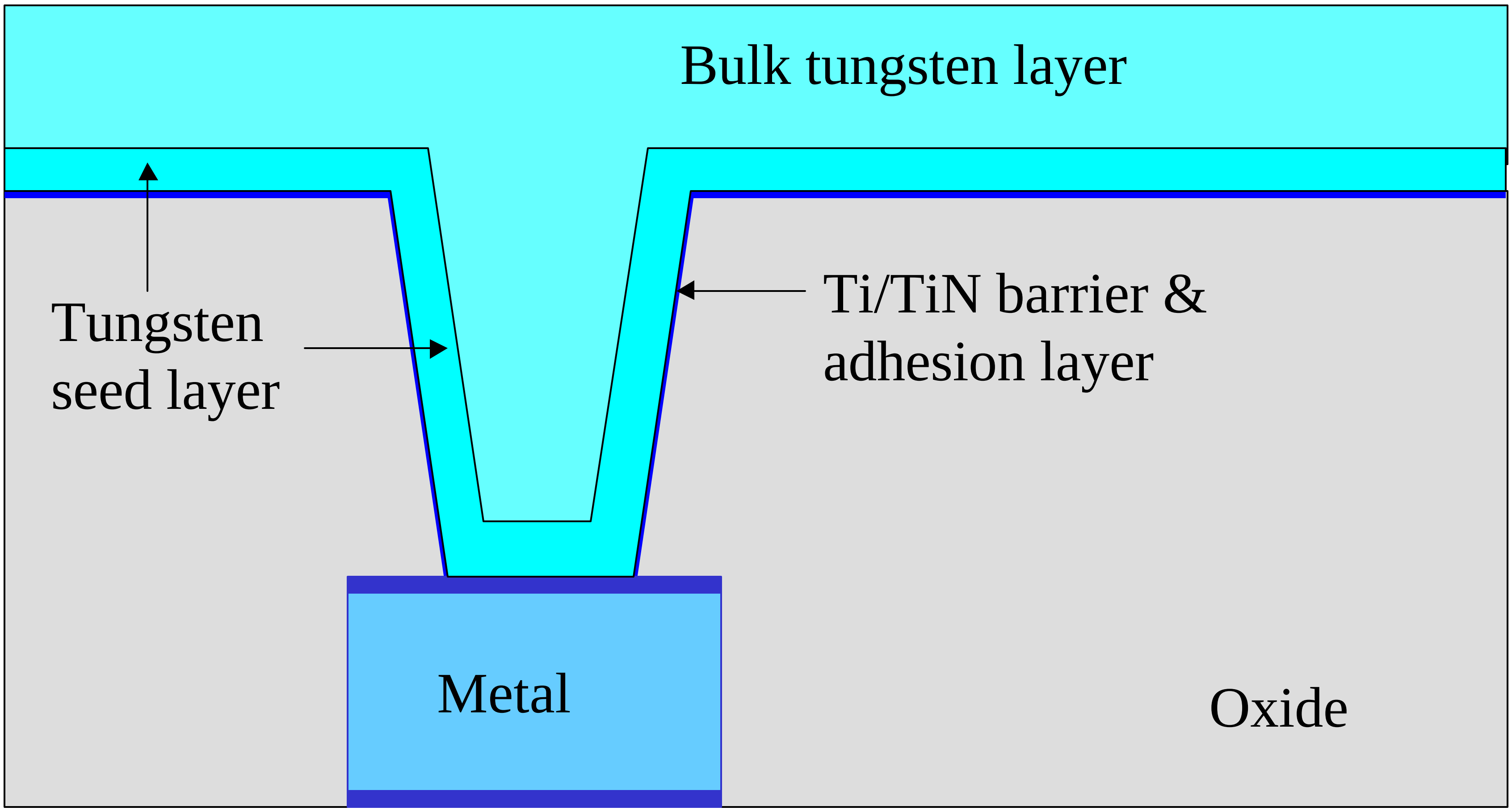
Bulk deposit

$$WF_6 + 3\ H_2 \rightarrow W\ (s) + 6\ HF$$

WF_6 reaction with moisture

$$WF_6 + 3\ H_2O \rightarrow WO_3 + 6\ HF$$

Tungsten Seed and Bulk Layers



Tungsten Silicide

- CVD and RTP
- WF_6 and SiH_4 as CVD source gases
- Anneal after gate etch
- Less popular than TiS_2 due to higher resistivity

Tungsten Silicide

- Sate and local interconnection applications
- Silicon sources: SiH_4 and SiH_2Cl_2 (DCS)
- Tungsten precursor is WF_6
- SiH_4/WF_6: lower temperature, ~ 400 °C,
- DCS/WF_6: higher temperature, ~ 575 °C

Tungsten Silicide: CVD

$$WF_6 + 2\ SiH_4 \xrightarrow{300\ to\ 400\ °C} WSi_2 + 6\ HF + H_2$$

- Wider process window, more matured process

$$WF_6 + 3.5\ SiH_2Cl_2 \xrightarrow{500\ to\ 600\ °C} WSi_2 + 1.5\ SiF_4 + 7\ HCl$$

- Better step coverage
- Less fluorine integration

Silane-Based WSi_x

$$WF_6 + 2\ SiH_4 \rightarrow WSi_2(s) + 6\ HF + H_2$$

- Very similar to the nucleation step of the tungsten CVD process.
- Different flow rate ratio of SiH_4/WF_6
  - lower than 3:1, tungsten deposition
  - larger than 10:1 tungsten silicide deposition

DCS-Based WSi_x

$$2\ WF_6 + 7\ SiH_2Cl_2 \rightarrow 2\ WSi_2 + 3\ SiF_4 + 14\ HCl$$

- Requires higher deposition temperature,
- Higher deposition rate
- Better step coverage
- Lower fluorine concentration
- Less tensile stress
  - less film peeling and cracking

Titanium CVD

- High temperature (~ 600 °C)
- CVD Ti can react with Si to form $TiSi_2$ simultaneously during the Ti deposition

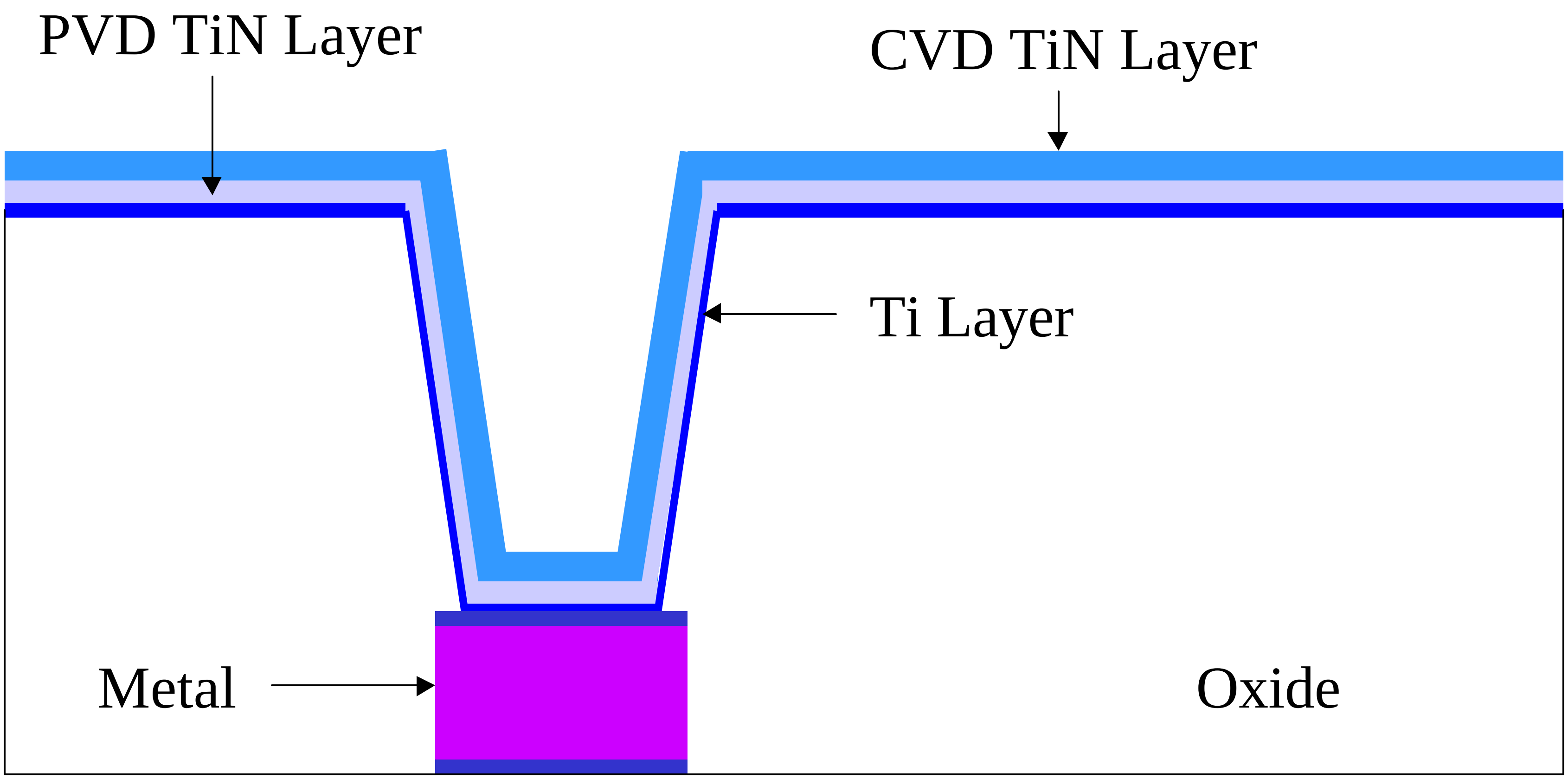
$$TiCl_4 + 2\ H_2 \rightarrow Ti + 4\ HCl$$

$$Ti + Si \rightarrow TiSi_2$$

Titanium Nitride CVD

- Barrier/glue layer for the tungsten plug
- Better sidewall step coverage
- A thin layer of (~200 Å) usually is applied for the contact/via holes after PVD Ti and TiN deposition

CVD PVD and CVD TiN Layers



CVD TiN

- Inorganic chemistry: $TiCl_4$ and NH_3 at 400 to 700 °C:

$$6TiCl_4 + 8\ NH_3 \rightarrow 6\ TiN + 24\ HCl + N_2$$

- MOCVD at 350 °C and 300 mTorr:

$$Ti[N(CH_3)_2]_4 \rightarrow TiN + \text{organics}$$

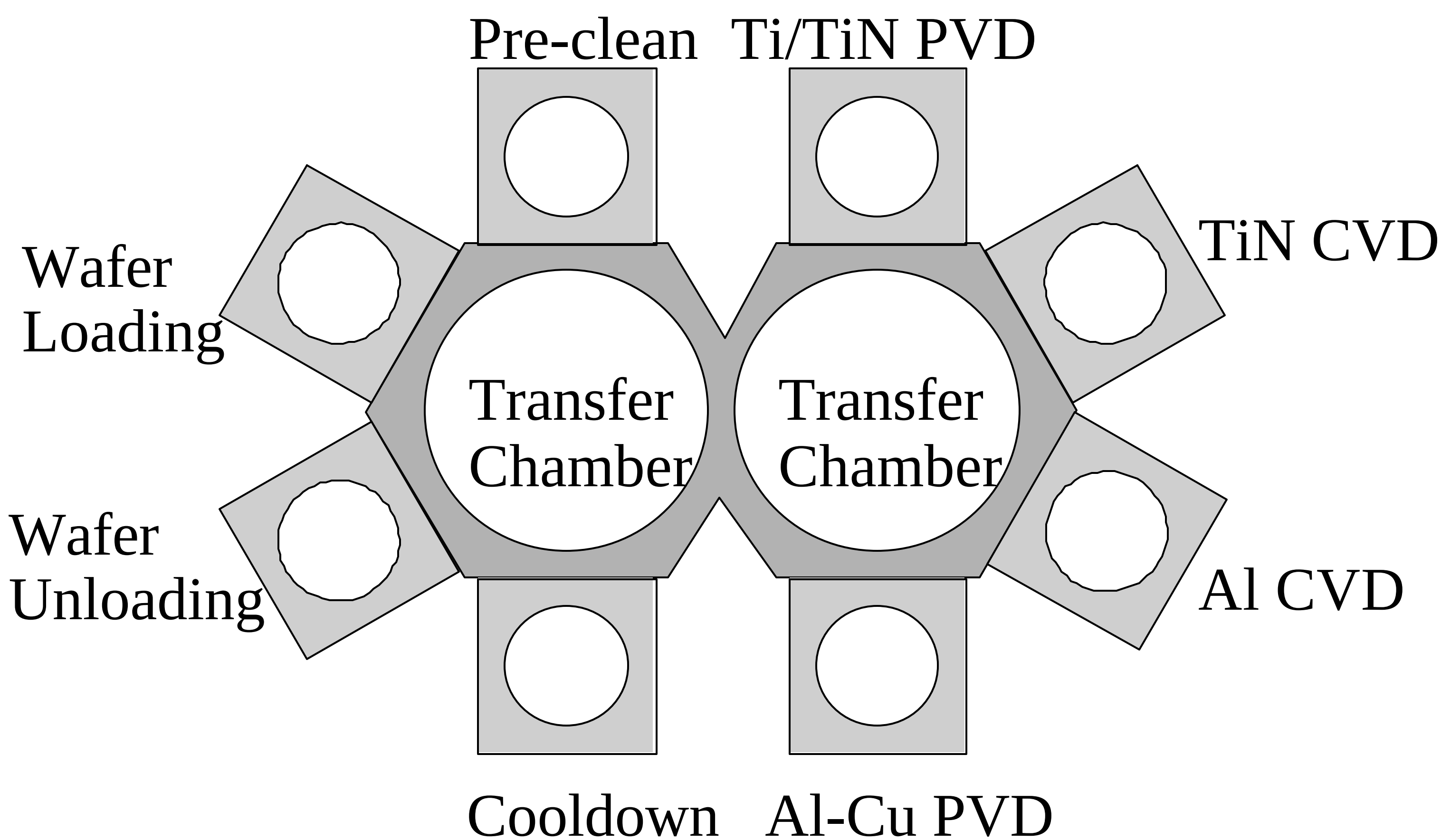
CVD Aluminum

- R&D to replace tungsten plug
- Dimethylaluminum hydride (DMAH), $Al(CH_3)_2H$
- At about 350 °C, DMAH dissociates and deposits aluminum

$$Al(CH_3)_2H \rightarrow Al + \text{volatile organics}$$

- Difficult to incorporate ~1% Cu needed for electromigration resistance

Cluster Tool, Aluminum CVD/PVD



Aluminum CVD/PVD

- Ti/TiN barrier/glue layer deposition
- Al CVD via fill, Al alloy PVD, TiN PVD
  - No need for W and W etch back

- Not a matured technology
- Hard to compete with copper metallization

Physical Vapor Deposition

PVD

- Vaporizing solid materials
- Heating or sputtering
- Condensing vapor on the substrate surface
- Very important part of metallization

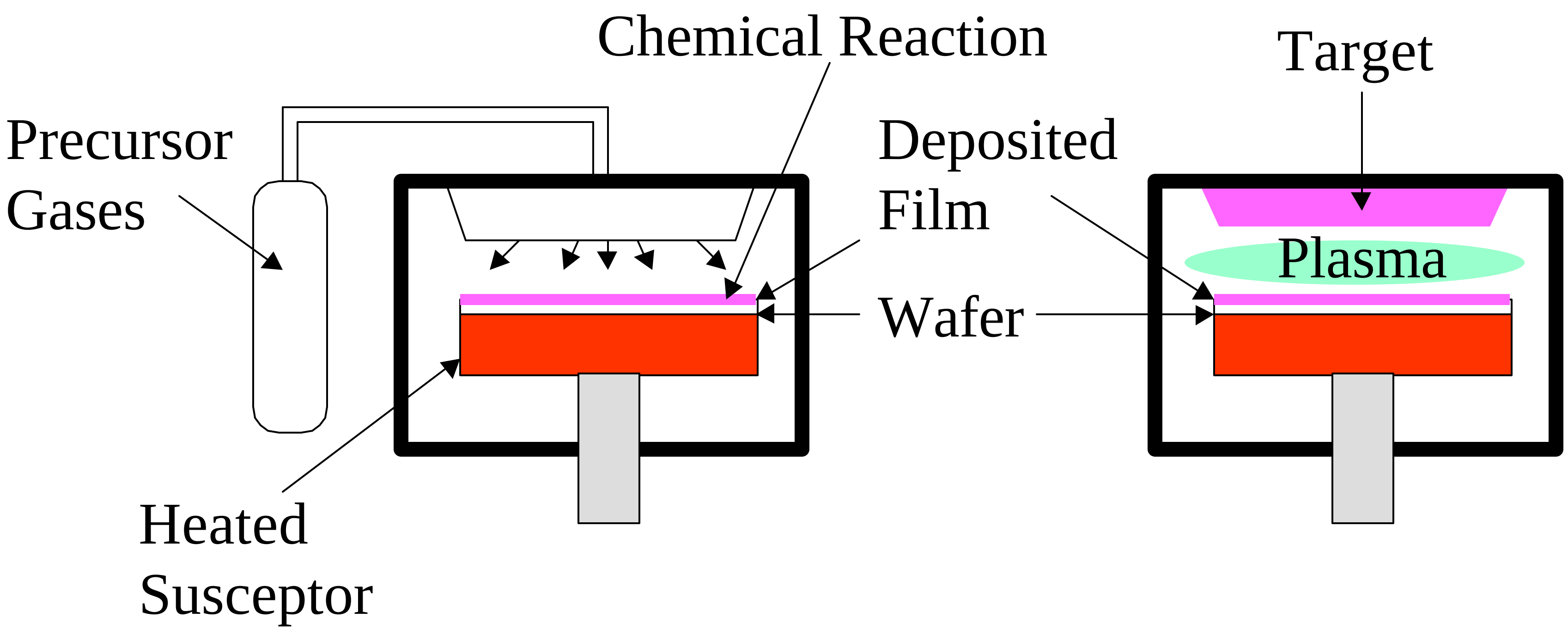
PVD vs. CVD

• PVD	Start with P
• CVD	Start with C

PVD vs. CVD: Sources

• PVD	Solid materials
• CVD	Gases or vapors

CVD vs. PVD



Chemical Reaction
Target
Precursor Gases
Deposited Film
Plasma
Wafer
Heated Susceptor

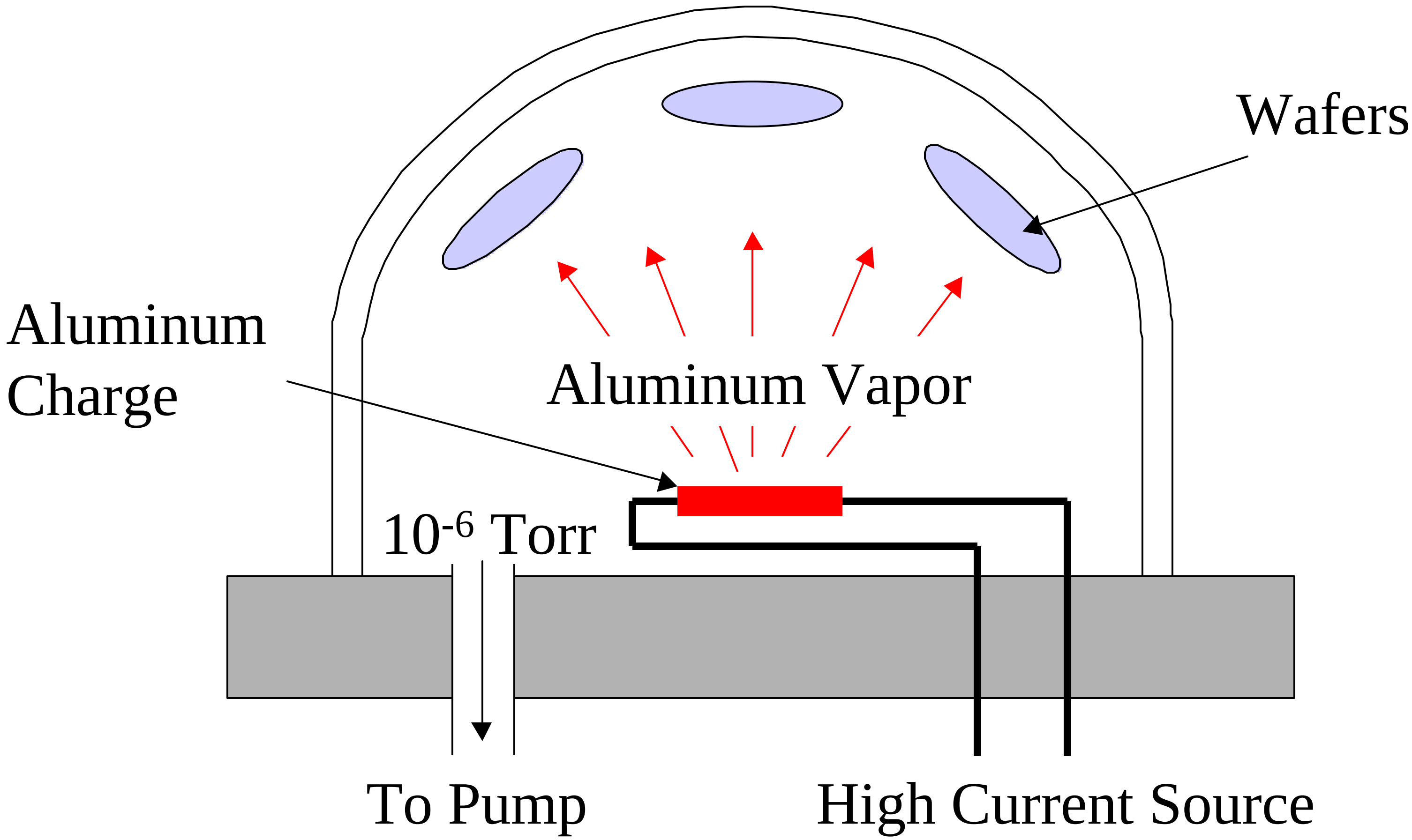
PVD Methods

- Evaporation
- Sputtering

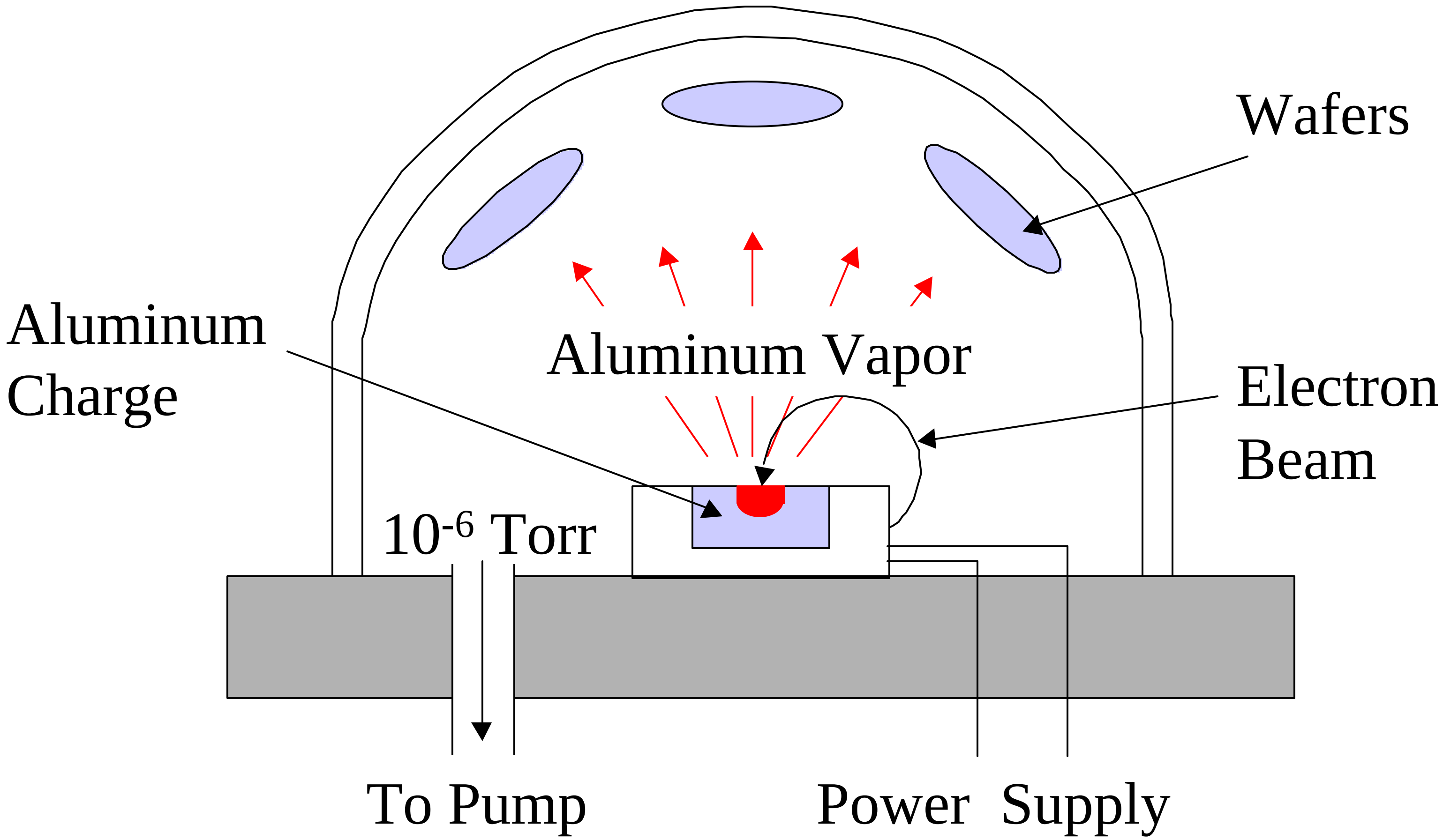
PVD Methods: Evaporation

- Filaments
- Flash hot plate
- Electron beam

Thermal Evaporator



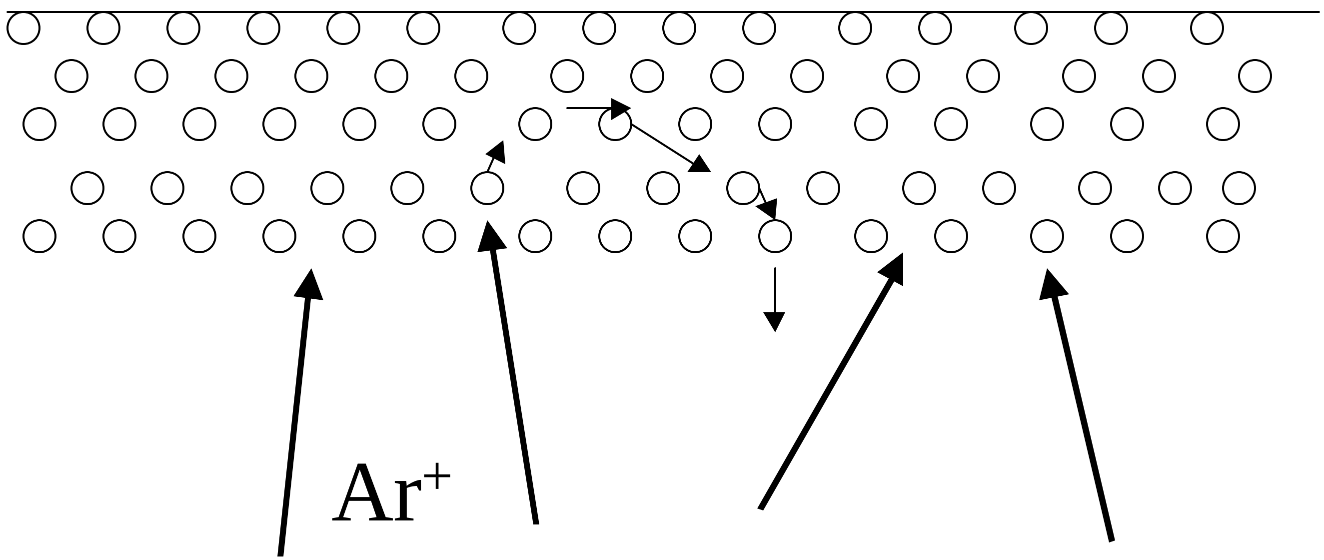
Electron Beam Evaporator



PVD Methods: Sputtering

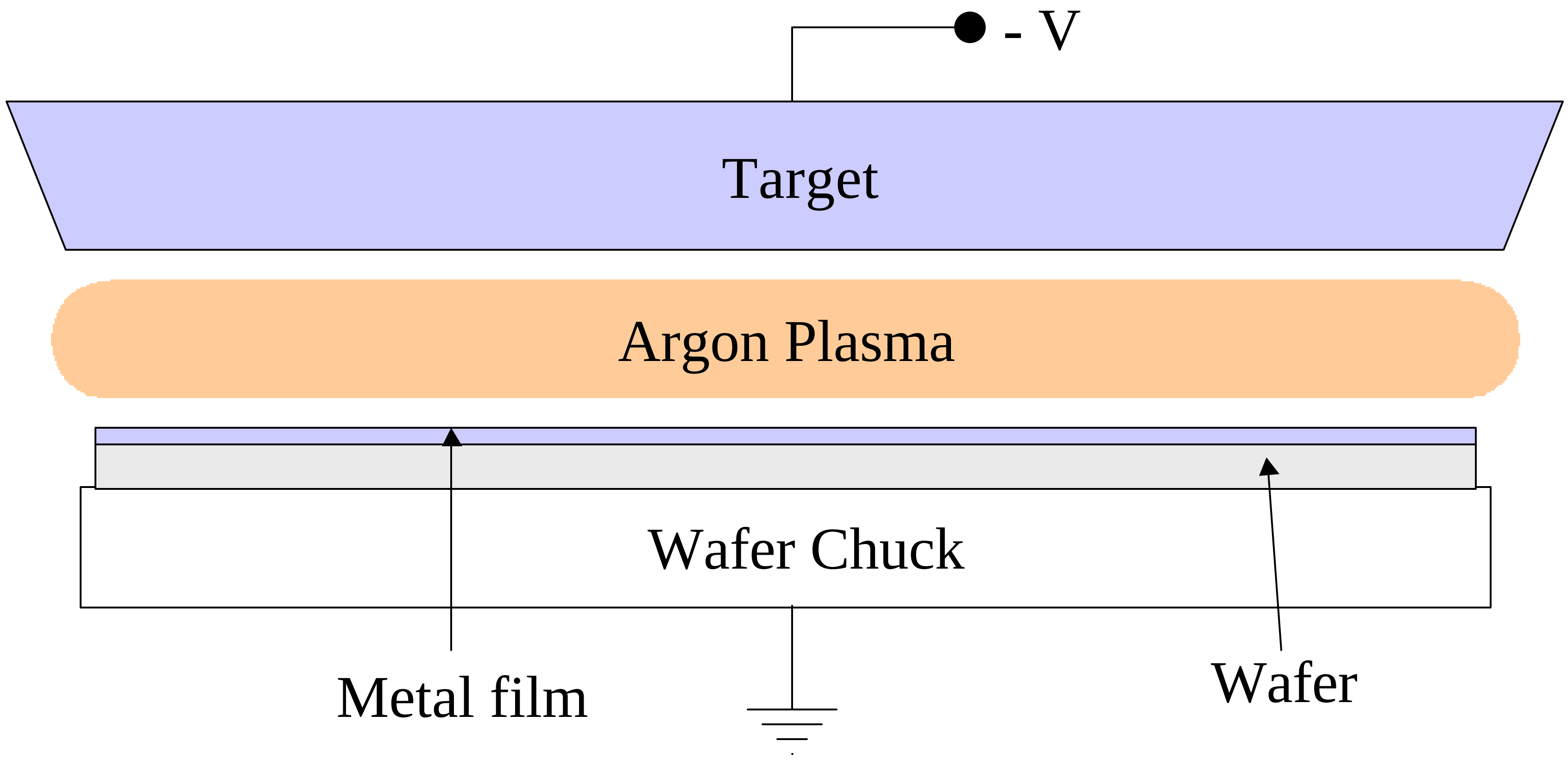
- DC Diode
- RF Diode
- **Magnetron**

Sputtering

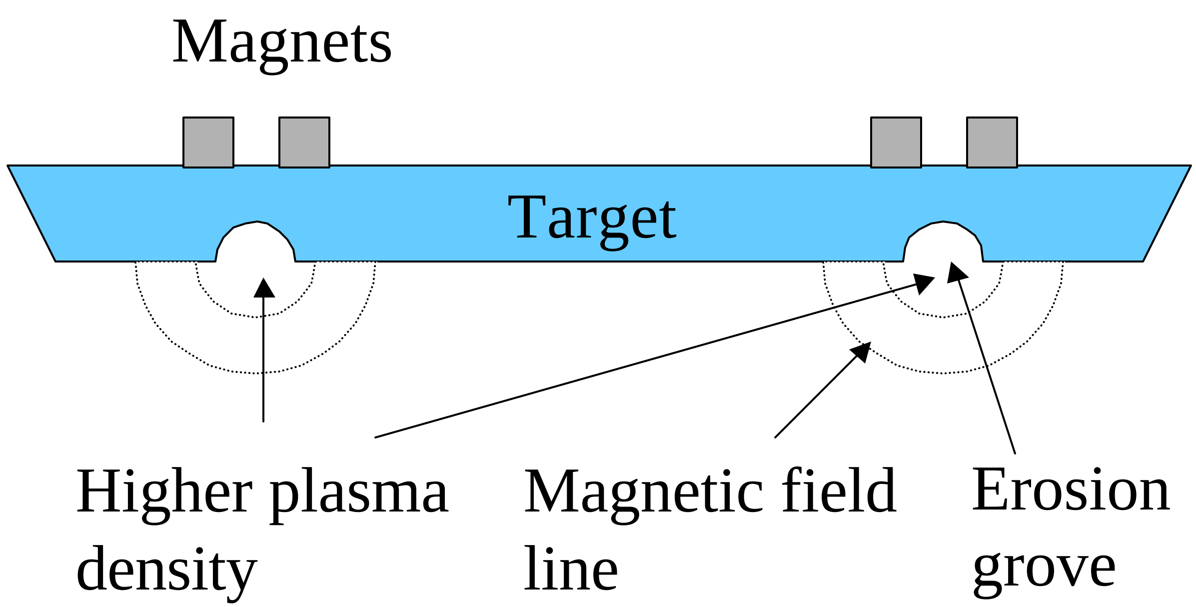


Momentum transfer will dislodge surface atoms off

DC Diode Sputtering



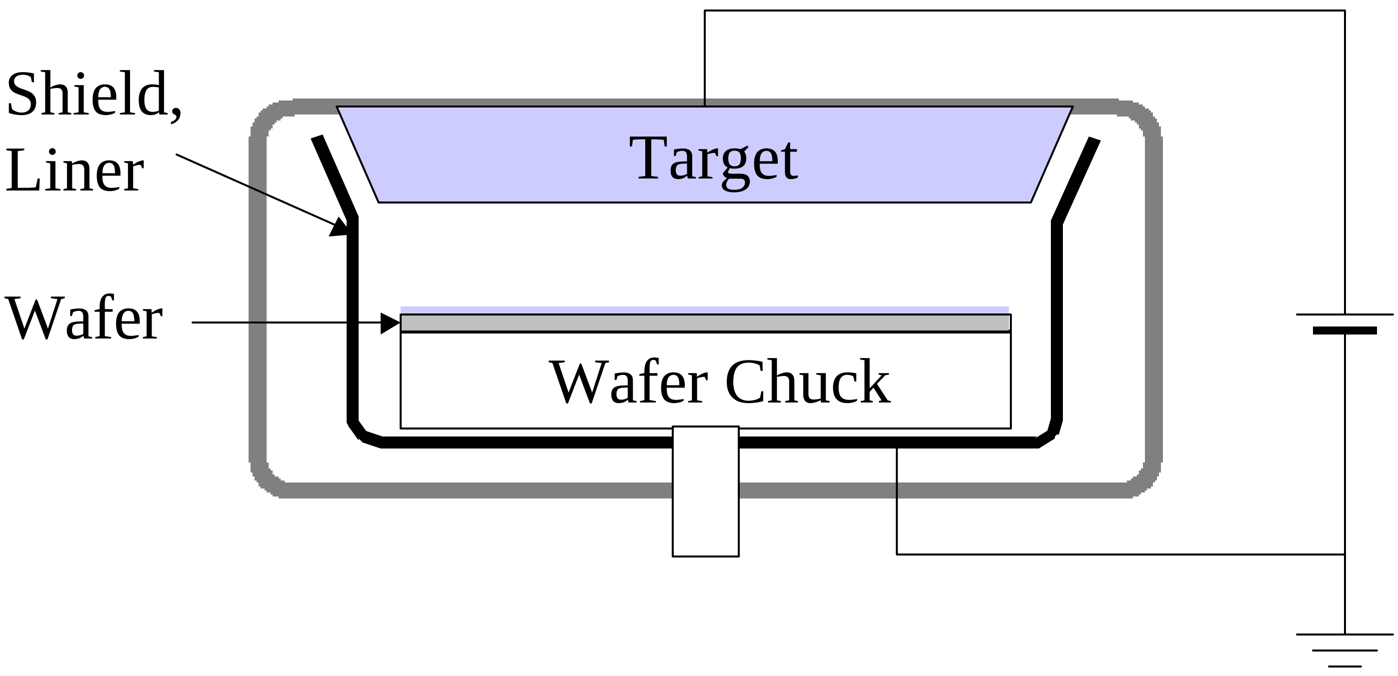
Schematic of Magnetron Sputtering



Magnetron Sputtering

- Most widely used PVD system
- More sputter from grove
- Better uniformity cross wafer

PVD Chamber with Shield



Applications of Argon

- Sputtering deposition
- Sputtering etch
  - pre-clean to remove native oxide before metal deposition
  - Taper opening for dielectric gap fill
- Patterned etch
  - dielectric to enhance bombardment and damaging effect

Properties of Argon

- Inert
- Relatively heavy
- Abundance
  - about 1% in atmosphere
  - low cost

Some Facts About Argon

Name	Argon
Symbol	Ar
Atomic number	18
Atomic weight	39.948
Discoverer	Sir William Ramsay, Lord Rayleigh
Discovered at	Scotland
Discovery date	1894
Origin of name	From the Greek word "argos" meaning "inactive"
Molar volume	22.56 cm^3
Speed of sound	319 m /sec
Refractive index	1.000281
Electrical resistivity	N/A
Melting point Boiling point	-189.2 °C -185.7 °C
Thermal conductivity	0.01772 W m^{-1} K^{-1}

Sputtering vs. Evaporator

Sputtering

- Purer film
- Better uniformity
- Single wafer, better process control
- Larger size wafer

Evaporator

- More impurities
- Batch process
- Cheaper tool

PVD Vacuum Requirement

- Residue gases on the vacuum chamber wall
  - H_2O, …
- Water can react with Al to form Al_2O_3
- Affects conductivity of interconnections
- Only way to get rid of H_2O: reach ultra high vacuum, 10^{-9} Torr

PVD Vacuum Requirement

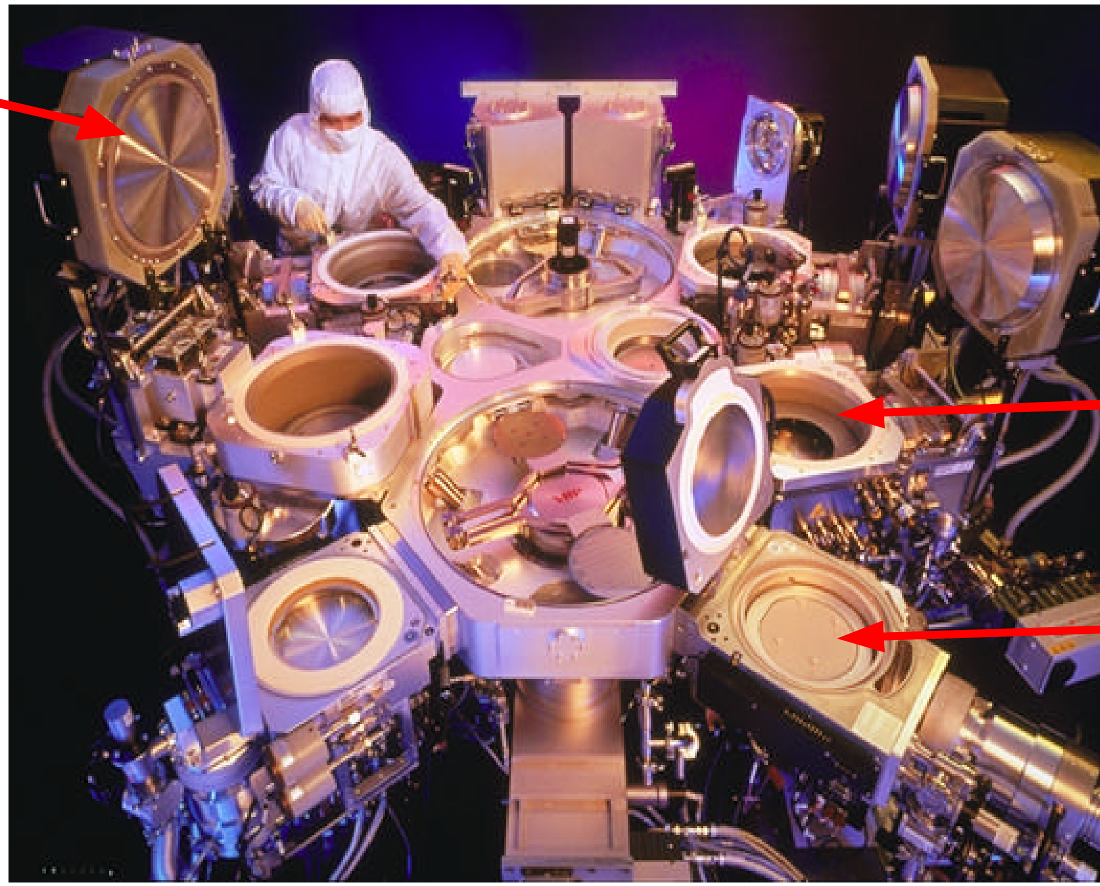
- Cluster tool
- Staged vacuum
- Loading station: 10^{-6} Torr
- Transfer chamber: 10^{-7} to 10^{-8} Torr
- Deposition chamber: 10^{-9} Torr

PVD Vacuum: Pumps

- Wet pump (oil diffusion pump): atm to 10^{-3} Torr, phasing out from fabs.
- Rough pump: atm to 10^{-5} Torr
- Turbo pump: 10^{-2} to 10^{-7} Torr
- Cryo pump: to 10^{-10} Torr
- Ion pump: to 10^{-11} Torr

Endura® PVD System

PVD Target



PVD Chamber

CVD Chamber

Contact/Via Process

- Degas
- Pre-clean
- Ti PVD
- TiN PVD
- TiN CVD
- N_2-H_2 plasma treatment
- W CVD

Aluminum Interconnection Process

- Degas
- Pre-clean
- Ti PVD
- Al-Cu PVD
- TiN PVD

Copper Interconnection Process

- Degas
- Pre-clean
- Ta PVD
- Cu seed PVD

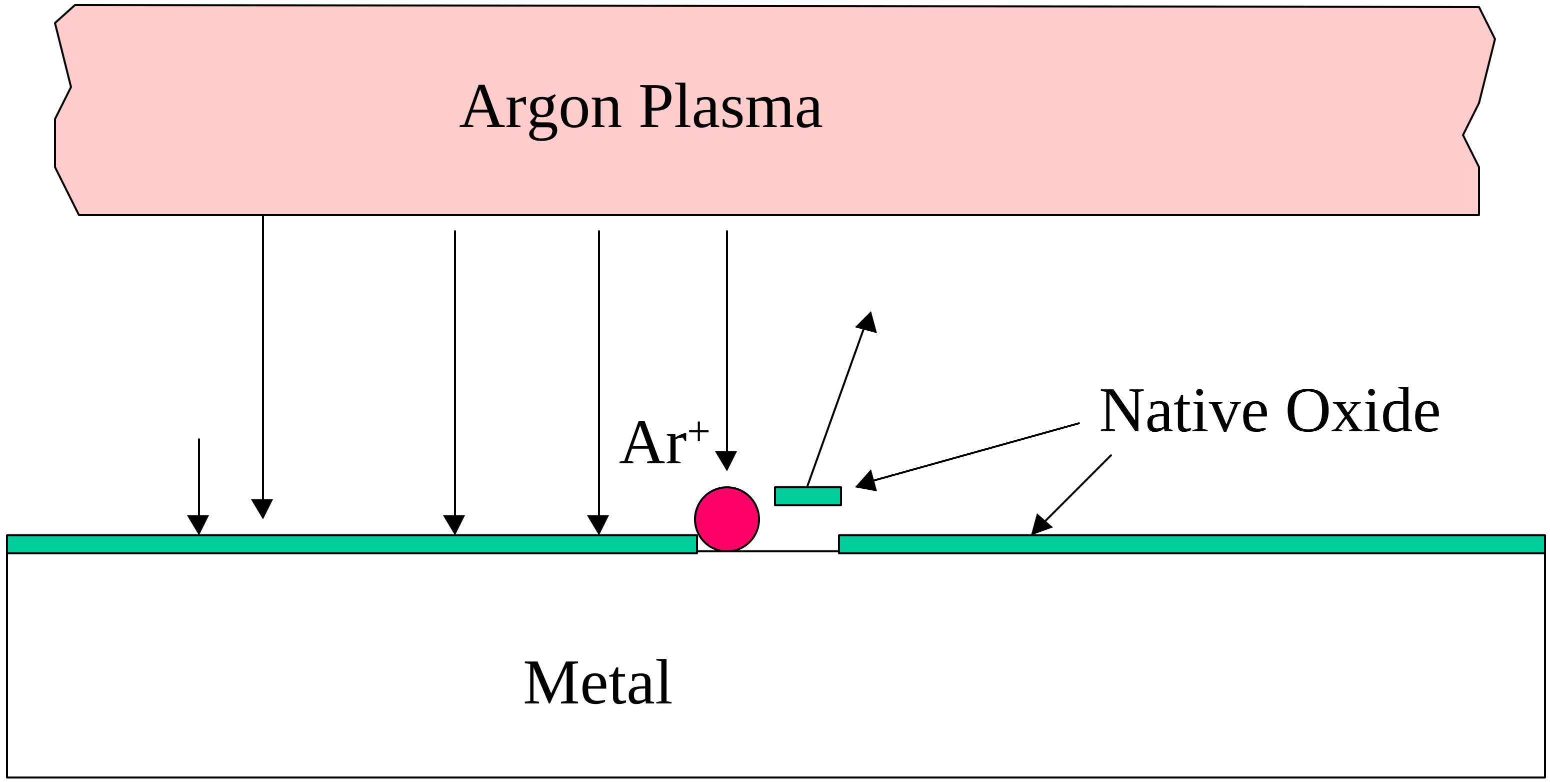
Degas

- Heat wafer to drive away gases and moisture on wafer surface
- Outgassing can cause contamination and high resistivity of deposited metal film

Pre-clean

- Remove the native oxide
- Reduce the contact resistance
- Sputtering with argon ions
- RF plasma

Pre-clean Process



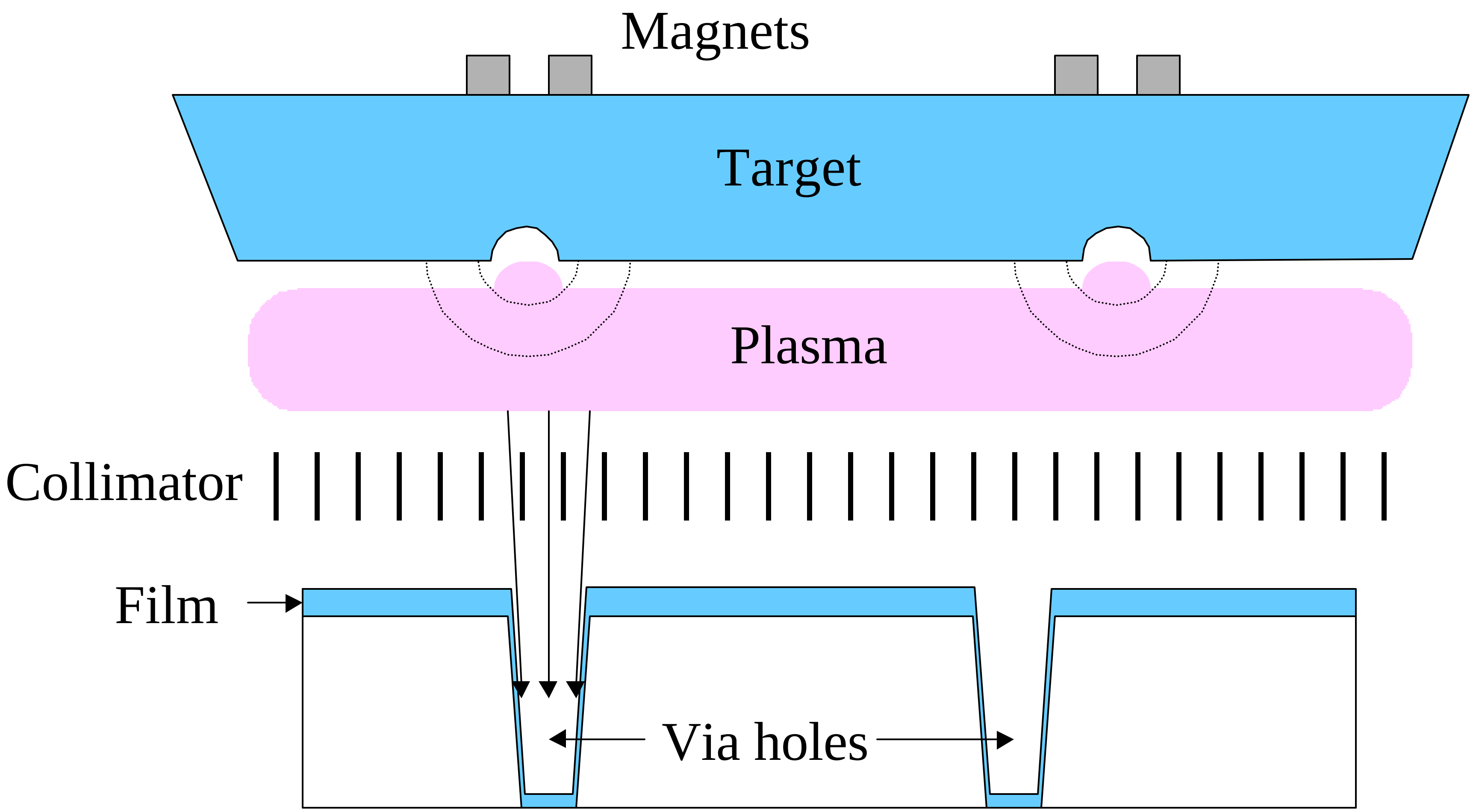
Titanium PVD

- Reduce contact resistance
- Larger grain size with low resistivity
- Wafer normally is heated to about 350 °C during the deposition process to
- Improve the surface mobility
- Improve step coverage

Collimated Sputtering

- Used for Ti and TiN deposition
- Collimator allows metal atoms or molecules to move mainly in vertical direction
- Reach the bottom of narrow contact/via holes
- Improves bottom step coverage

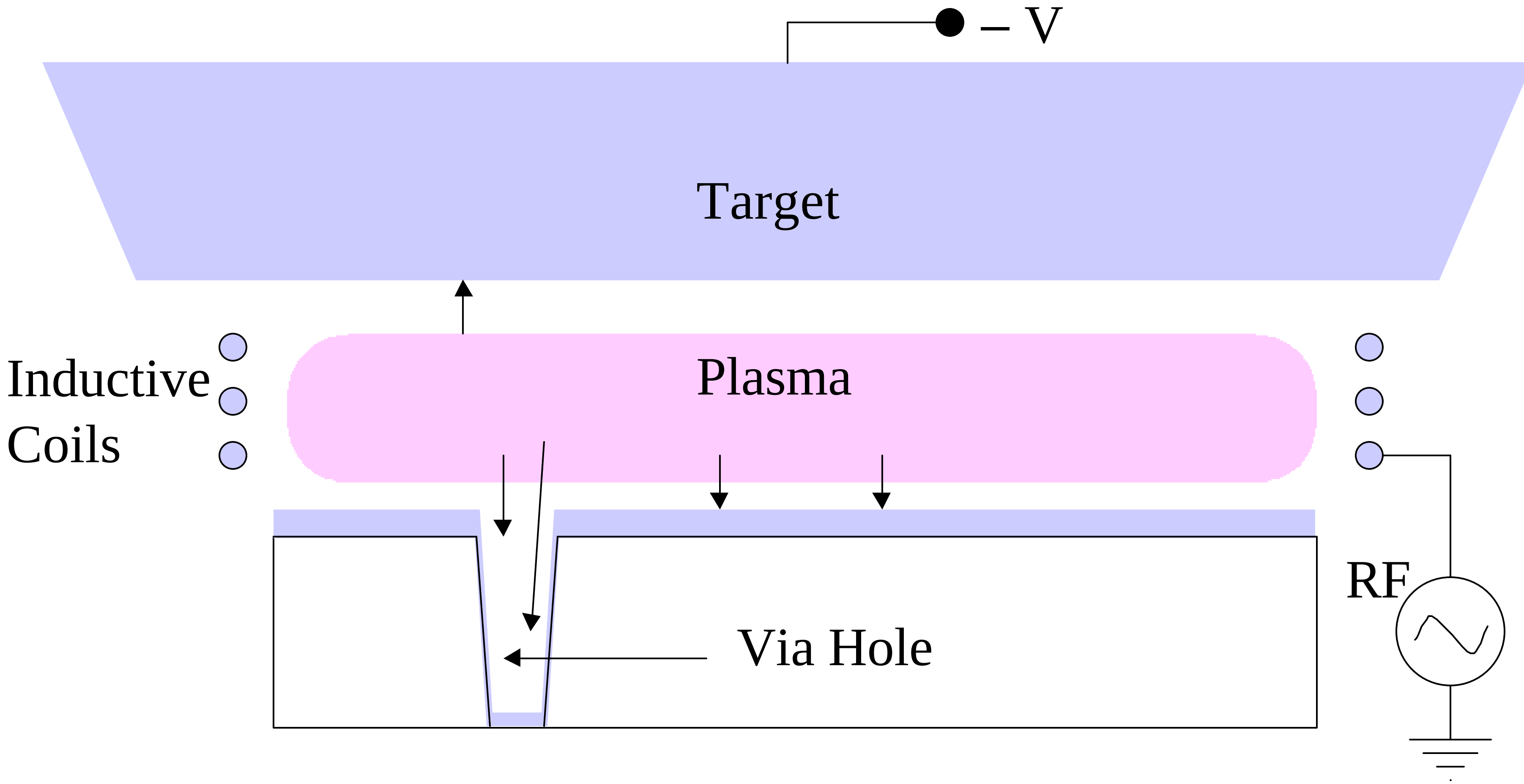
Collimated Sputtering



Metal Plasma System

- Ti, TiN, Ta, and TaN deposition
- Ionize metal atoms through inductive coupling of RF power in the RF coil
- Positive metal ions impact with the negatively charged wafer surface vertically
- Improving bottom step coverage
- Reduce contact resistance

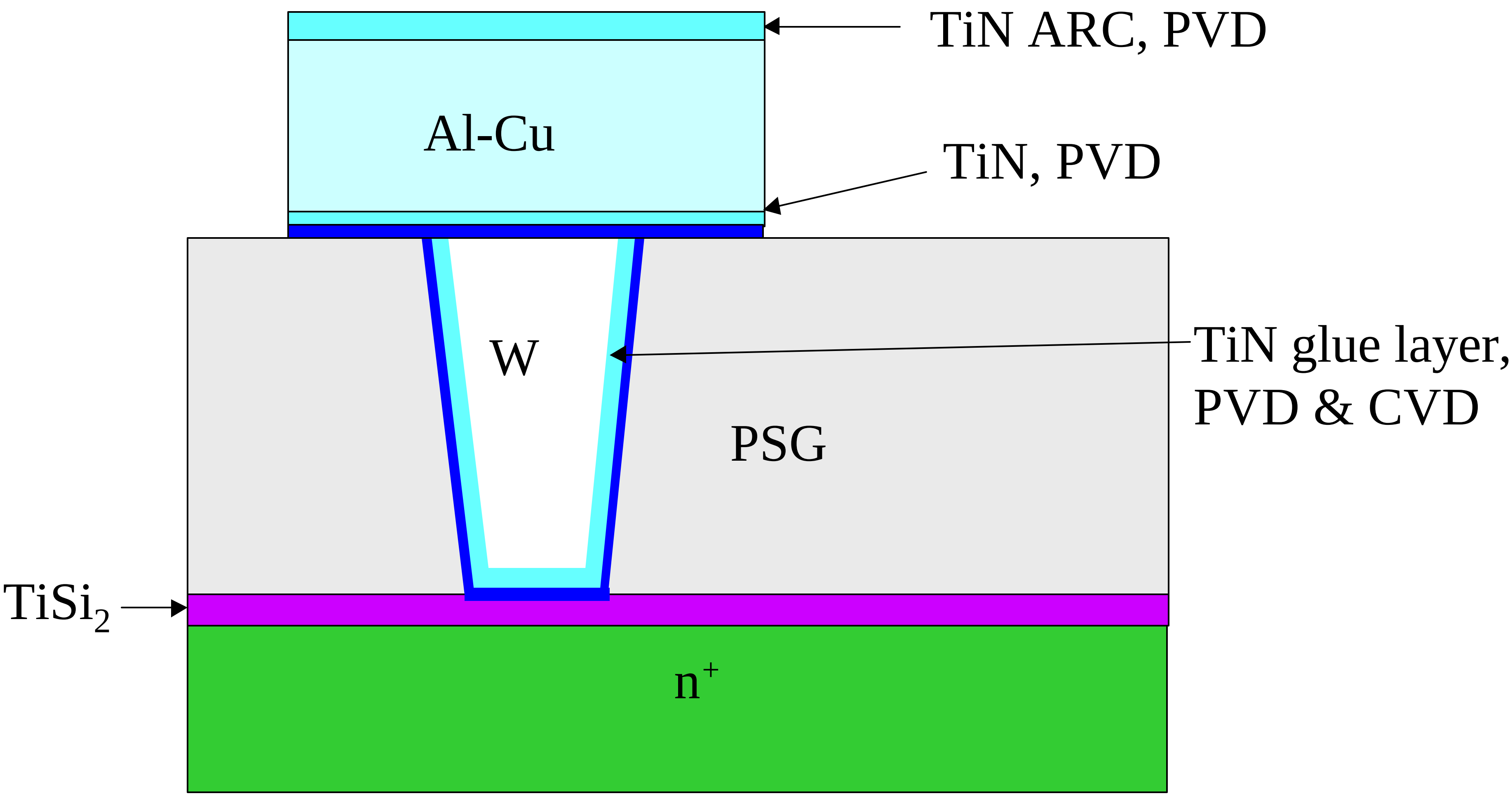
Ionized Metal Plasma



Titanium Nitride PVD

- Reactive sputtering process
- Ar and N_2
- N_2 molecules dissociate in plasma
- Free nitrogen radicals react with Ti to form a thin layer of TiN on target surface.
- Argon ions sputter the TiN from the target surface and deposit it on the wafer surface

Three Applications of TiN



Al-Cu PVD

- Ultra high vacuum to remove moisture and achieve low film resistivity.
- Cluster tool with staged vacuum
- dry pumps, turbo pumps and cryopump
- A cryopump can help a PVD chamber to reach up to 10^{-10} Torr base pressure by freezing the residue gases in a frozen trap

Al-Cu PVD

- Standard process and hot aluminum process
- Standard process: Al-Cu over tungsten plug after Ti and TiN deposition
- Normally deposit at ~ 200 °C
- Smaller grain size, easier to etch
- Metal annealing to form larger grain size
  – lower resistivity
  – high EMR

Al-Cu PVD

- Hot aluminum process
- fill contact and via holes, reduces contact resistance
- Several process steps:
  - Ti deposition
  - Al-Cu seed layer is deposited at low <200°C
  - Bulk Al-Cu layer is deposited at higher temperatures (450°C to 500°C)

Copper Metallization

Copper

- Better conductor than aluminum
- Higher speed and less power consumption
- Higher electromigration resistance
- *Diffusing freely in silicon and silicon dioxide, causing heavy metal contamination, need diffusion barrier layer*
- *Hard to dry etch, no simple gaseous chemical compounds*

Copper

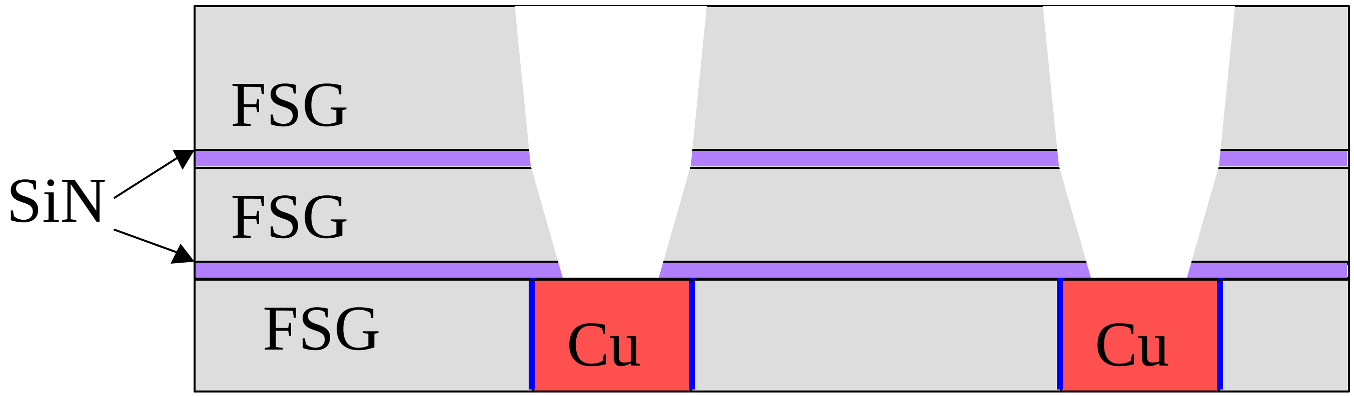
- Damascene process with CMP
- Ta and/or TaN as barrier layer
- Start using in IC fabrication

Copper

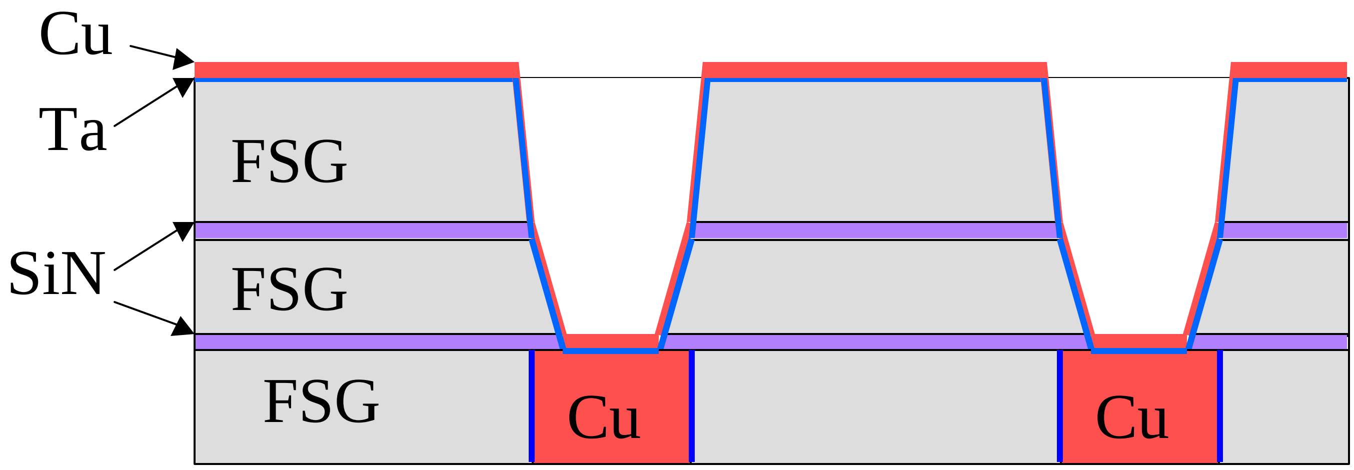
- Pre-deposition clean
- PVD barrier layer (Ta or TaN, or both)
- PVD copper seed layer
- Electrochemical plating bulk copper layer

- Thermal anneal to improve conductivity

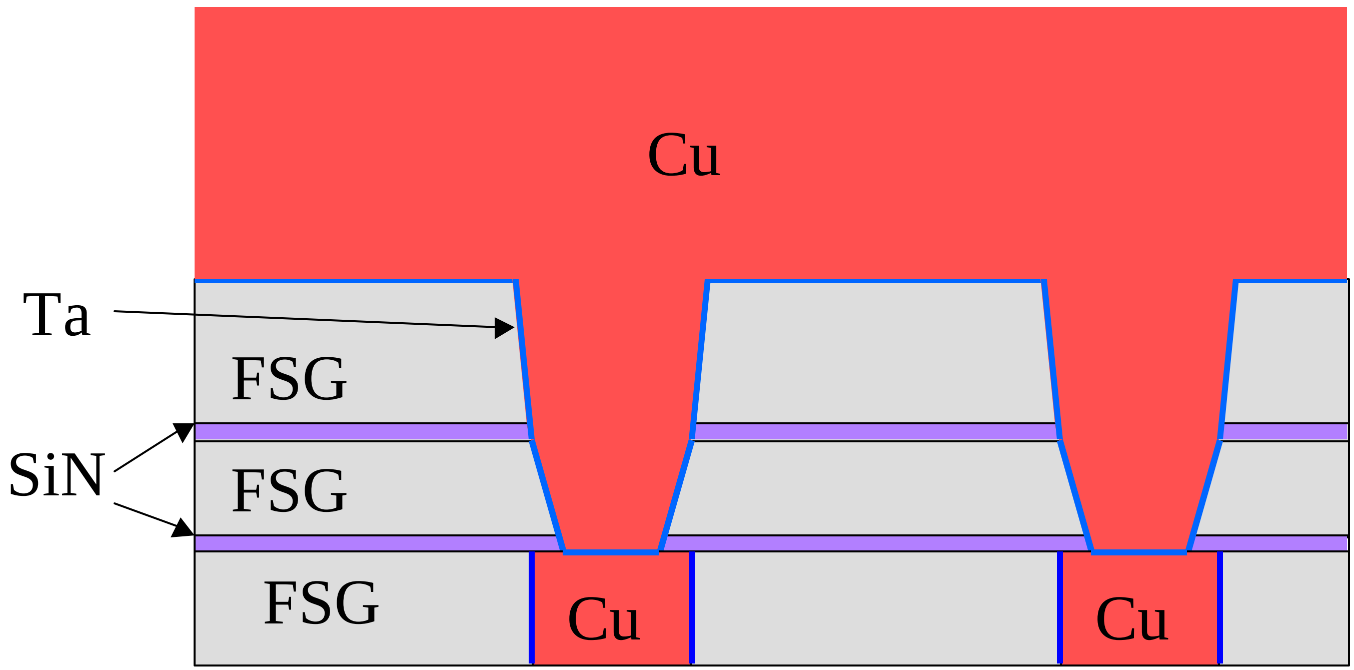
Etch trenches and via holes



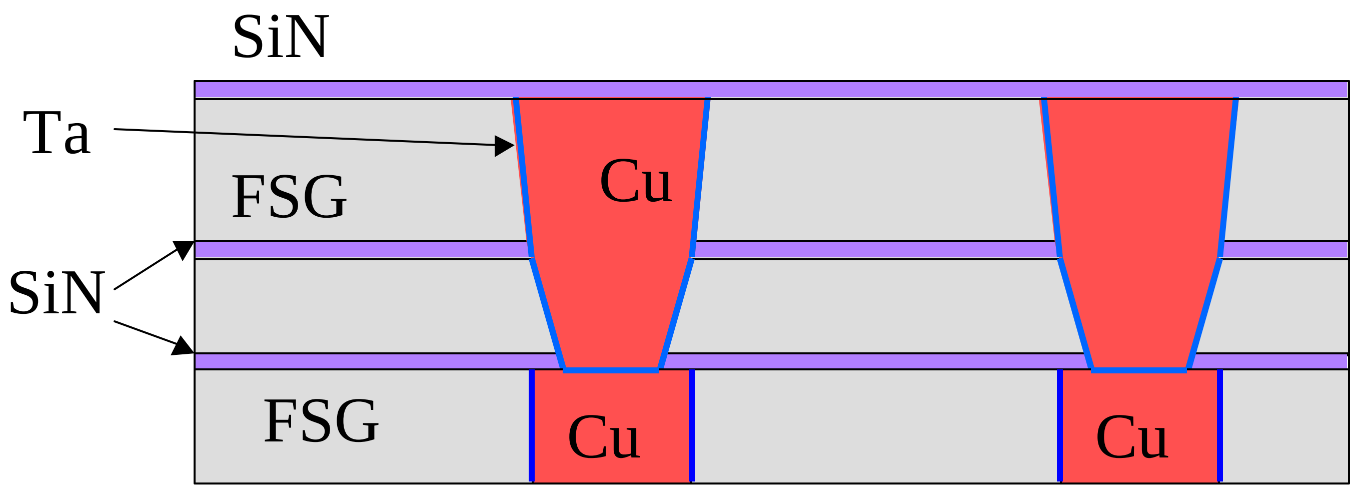
Tantalum Barrier Layer and Copper Seed Layer Deposition



Electrochemical Plating Copper



CMP Copper and Tantalum, CVD Nitride



Pre-clean

- Argon sputtering pre-deposition clean
  - Commonly used
  - Possible copper contamination due to sputtering
- Chemical pre-clean
  - H_2 and He plasma
  - H radicals react with CuO_2

$$4\ H + CuO_2 \rightarrow\ Cu + 2\ H_2O$$

Barrier Layer

- Copper diffusion into silicon can cause device damaging
- Need barrier layer
- Ti, TiN, Ta, TaN, W, WN,
- Few hundred Å Ta is commonly used
- Combination of Ta and TaN in near future

Copper Seed Layer

- PVD copper layer (500 to 2000 Å)
- Nucleation sites for bulk copper grain and film formation.
- Without seed layer
  - No deposition
  - or deposition with very poor quality and uniformity

Copper Seed Layer

- Copper vapor can be easily ionized
- Low pressure, long MFP
- Copper ions throw into via and trench
  - good step coverage and smooth film surface
- Very narrow via hole, PVD copper will be in trouble due to its poor step coverage
- CVD copper process may be needed

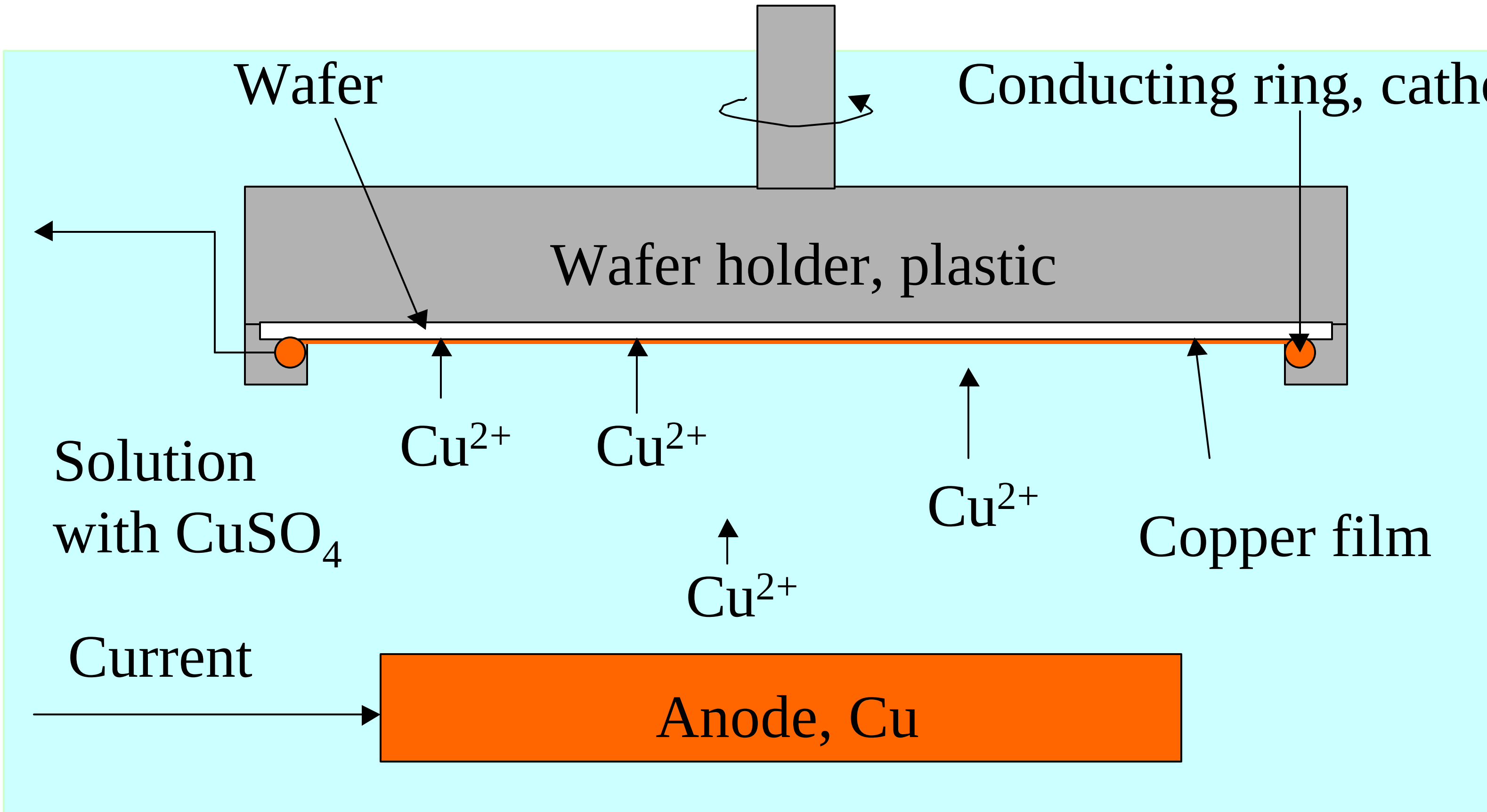
Electrochemical Plating (ECP)

- Old technology
- Still used in hardware, glass, auto, and electronics industries.
- Recently introduced in IC industry
- Bulk copper deposition
- Low-temperature process
- Compatible with low-κ polymeric dielectric

Electrochemical Plating (ECP)

- $CuSO_4$ solution
- Copper anode
- Wafer with copper seed layer as cathode
- Fixed electric current
- Cu^{2+} ion diffuse and deposit on wafer

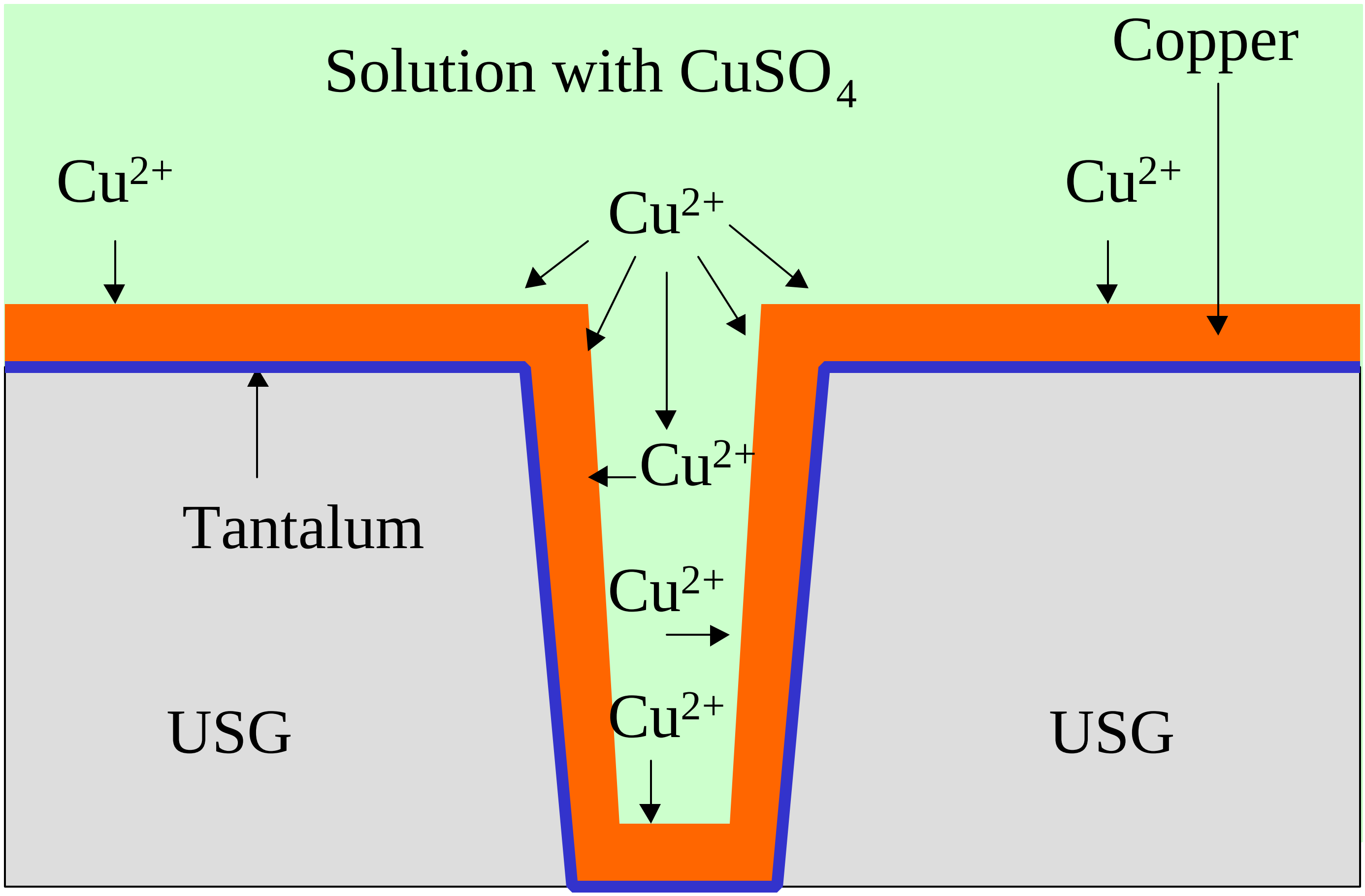
Copper Electrochemical Plating



Via and Trench Fill

- To achieve better gap-fill, pulse current with large forward amperage and small reversed amperage is used.
- Reversed current removes copper, which reduces overhang of the gap.
- Similar to dep/etch/dep process
- Additives reduces deposition on the corner to improve the via fill capability

Electrochemical Plating Via Fill



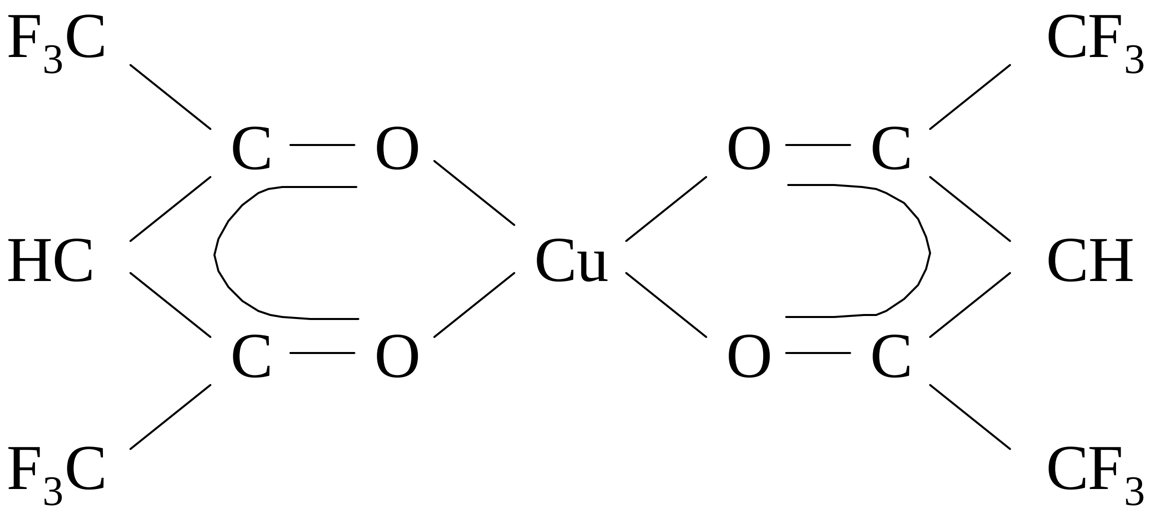
Copper CVD

- bis-hexafluoroacetyl-acetonate copper, or $Cu(hfac)_2$

$$Cu(hfac)_2 + H_2 \rightarrow Cu + 2\ H(hfac)$$

- 350 to 450 °C
- Too high for polymeric low-κ dielectric

$Cu^{II}(hfac)_2$



Copper CVD

- Organiometallic compound
- Cu(hfac)(tmvs): $C_{10}H_{13}CuF_6O_2Si$

$$2\ Cu(hfac)(tmvs) \rightarrow Cu + Cu(hfac)_2 + 2\ tmvs$$

- Thermal process ~ 175 °C, 1 to 3 Torr
- Excellent step coverage and gap fill capability

Copper CVD

- Cu(hfac)(vtms) process is the the more promising copper CVD process.
- Tough competition from the production-proven copper ECP process
- PVD/CVD copper seed layer deposition

Summary

- Mainly application: interconnection
- CVD (W, TiN, Ti) and PVD (Al-Cu, Ti, TiN)
- Al-Cu alloy is still dominant
- Need UHV for Al-Cu PVD
- W used as plug
- Ti used as welding layer
- TiN: barrier, adhesion and ARC layers
- The future: Cu and Ta/TaN