EE143 – Fall 2016
Microfabrication Technologies

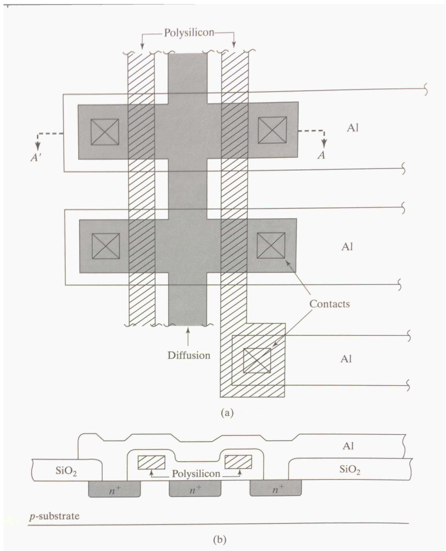
Lecture 9: Metallization
Reading: Jaeger Chapter 7

Prof. Ming C. Wu

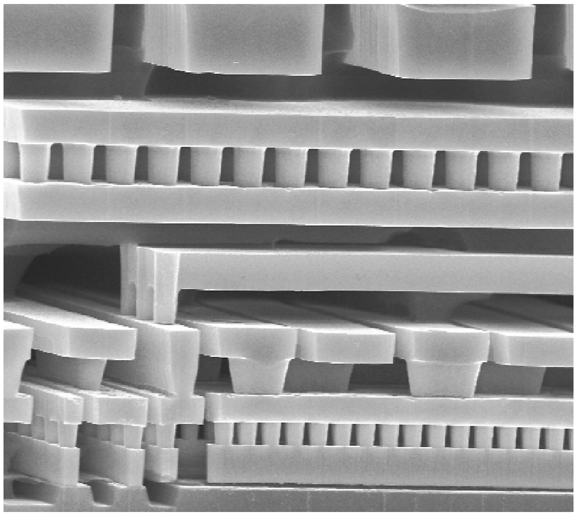
wu@eecs.berkeley.edu

511 Sutardja Dai Hall (SDH)

Interconnect



Multilevel Metallization



Interconnect RC Time Delay

- Interconnect circuit parameters are often normalized by length
  - Both resistance and capacitance are proportional to wire length
- Resistance per unit length:

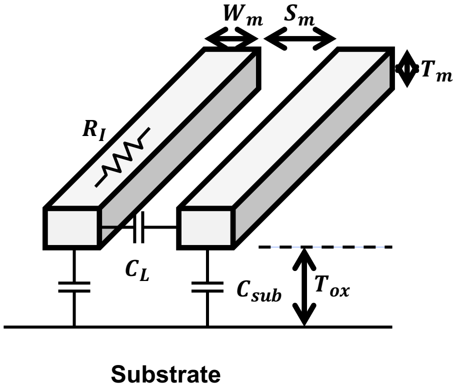
$$R_I = \frac{R}{L} = \frac{\rho}{W_m T_m}$$

- Interconnect-substrate capacitance per unit length:

$$C_{sub} = \frac{C}{L} = \frac{\epsilon_{ox} W_m}{T_{ox}}$$

- Interconnect-interconnect capacitance per unit length:

$$C_L = \frac{C}{L} = \frac{\epsilon_{ox} T_m}{S_m}$$



Interconnect Requirements

- Low Ohmic resistance
  - interconnects material has low resistivity
- low contact resistance to semiconductor device
- Long-term reliability

Resistivity of Metals

TABLE 7.1 Bulk Resistivity of Metals (μΩ-cm)

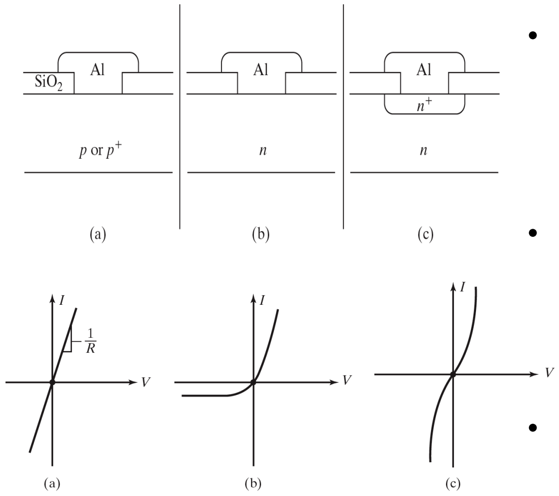
Ag: Silver	1.6
Al: Aluminum	2.65
Au: Gold	2.2
Co: Cobalt	6
Cu: Copper	1.7
Mo: Molybdenum	5
Ni: Nickel	7
Pd: Paladium	10
Pt: Platinum	10.6
Ti: Titanium	50
W: Tungsten	5

Source: WebElements [http://www.webelements.com]

Commonly Used Metals
Aluminum
Titanium
Tungsten
Copper

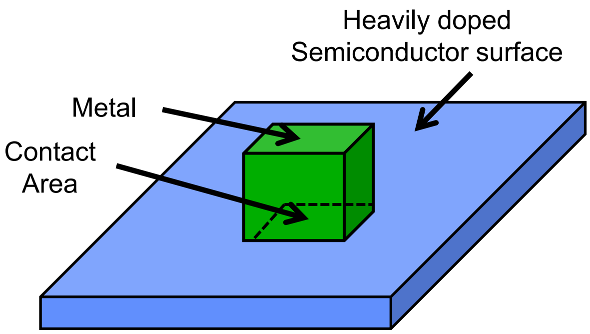
Less Frequently Utilized
Nickel
Platinum
Paladium

Ohmic Contact Formation



- **Aluminum to p-type silicon forms an Ohmic contact** [Remember Al is p-type dopant]
- **Aluminum to n-type silicon can form a rectifying contact (Schottky barrier diode)**
- **Aluminum to n+ silicon yields a tunneling contact**

Contact Resistance Rc



For a *uniform* current density flowing across the contact area:

$$R_c = \frac{\rho_c}{Contact\ Area}$$

ρ_c of Metal-Si contacts ~ 10^{-5} to 10^{-7} Ω-cm^2
ρ_c of Metal-Metal contacts < 10^{-8} Ω-cm^2

Contact Resistivity ρ_c

- Specific contact resistivity

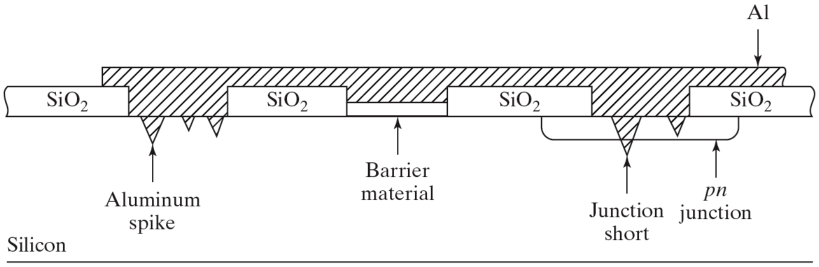
$$\rho_c = \left(\frac{\partial J}{\partial V}\right)^{-1} = \rho_{c0} exp\left[\frac{2\sqrt{m^* \epsilon_s}}{\hbar}\left(\frac{\phi_B}{\sqrt{N}}\right)\right]$$

ϕ_B is the Schottky barrier height
N = surface doping concentration
ρ_c = specific contact resistivity in ohm-cm^2

m = electron mass
$\hbar$ =Planck's constant
ϵ_s = Si dielectric constant

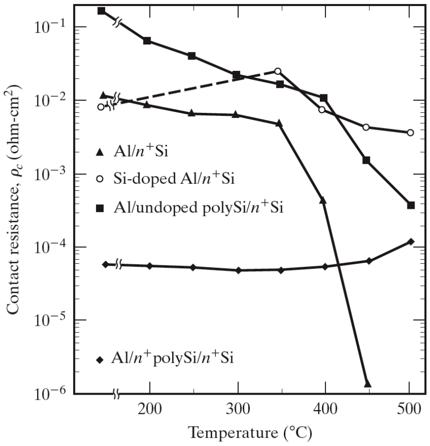
- Approaches to lowering of contact resistance:
  - Use highly doped Si as contact semiconductor
  - Choose metal with lower Schottky barrier height

Aluminum Spiking and Junction Penetration



- Aluminum spiking:
  - Si absorption into the aluminum results in Al spikes
  - Short-circuit junctions or cause excess leakage
- To prevent Al spiking
  - Barrier metal deposited prior to metallization
  - Sputter deposition of Al with 1% Si

Alloying of Contacts



- Alloy to obtain very low contact resistivity
- Specific contact resistivity

$$\rho_c = 1.2\times10^{-6}\Omega\cdot cm^2$$

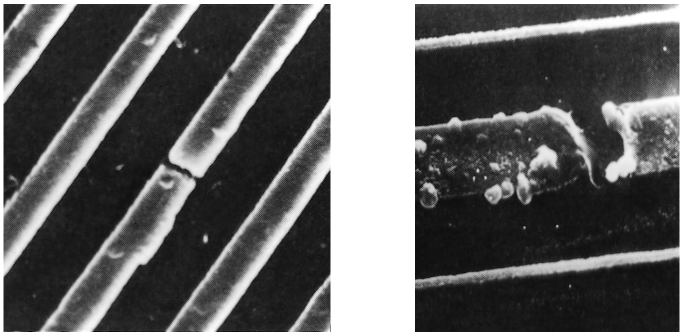
- Contact resistance

$$R_c = \frac{\rho_c}{A}$$

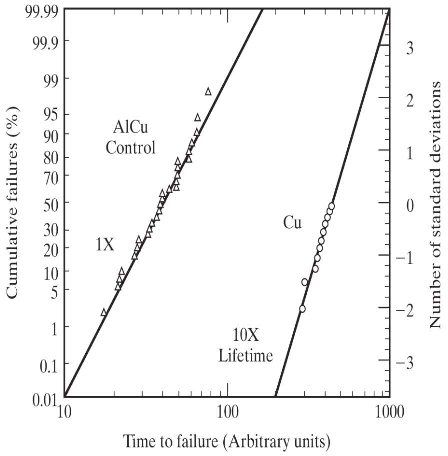
A: contact area

Electromigration

- High current density causes voids to form in interconnections
- "Electron wind" causes movement of metal atoms



Electromigration



- Copper added to aluminum to improve lifetime (Al with 4% Cu, 1% Si)
- Mean time to failure (MTF)

$$MTF \propto \frac{1}{J^2} exp\left(\frac{E_A}{kT}\right)$$

$J: current\ density$

$E_A: activation\ energy$

- Heavier metals (e.g., Cu) have higher activation energy

Metal Deposition Techniques

- Sputtering has been the technique of choice
  - High deposition rate
  - Capability to deposit complex alloy compositions
  - Capability to deposit refractory metals
  - Uniform deposition on large wafers
  - Capability to clean contact before depositing metal
- CVD processes have recently been developed
  - (e.g. for W, TiN, Cu)
  - Better step coverage
  - Selective deposition is possible
  - Plasma enhanced deposition is possible for lower deposition temperature

Metal CVD Processes

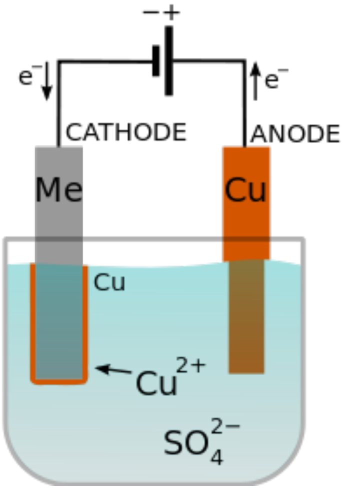
- TiN
  - Used as barrier-metal layer
    - Electrical resistivity ~ 10 to 100 $\mu\Omega \cdot cm$
  - Deposition processes:

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

$$2\,TiCl_4 + 2\,NH_3 + H_2 \rightarrow 2\,TiN + 8\,HCl$$

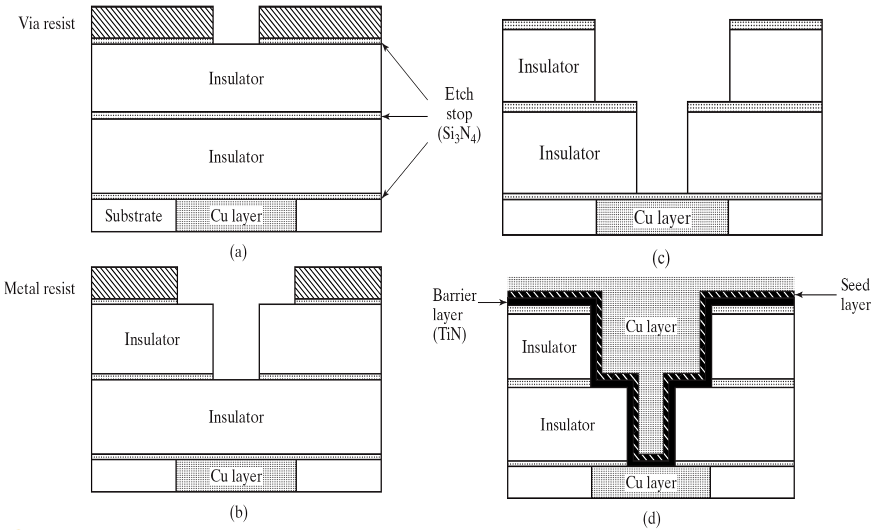
$$2\,TiCl_4 + N_2 + 4\,H_2 \rightarrow 2\,TiN + 8\,HCl$$

Electroplating

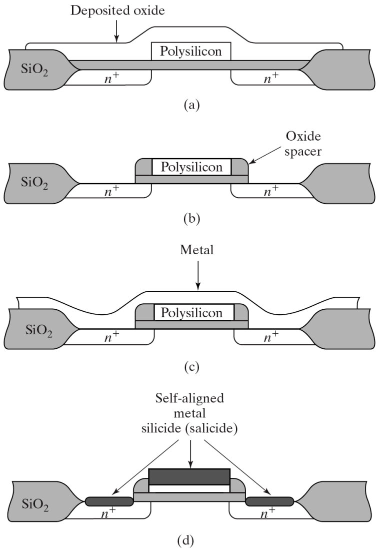


https://en.wikipedia.org/wiki/Electroplating

Dual Damascene Process



Salicides



- **Self-aligned silicide on silicon and polysilicon**
- **Often termed "Salicide"**

Properties of Silicides

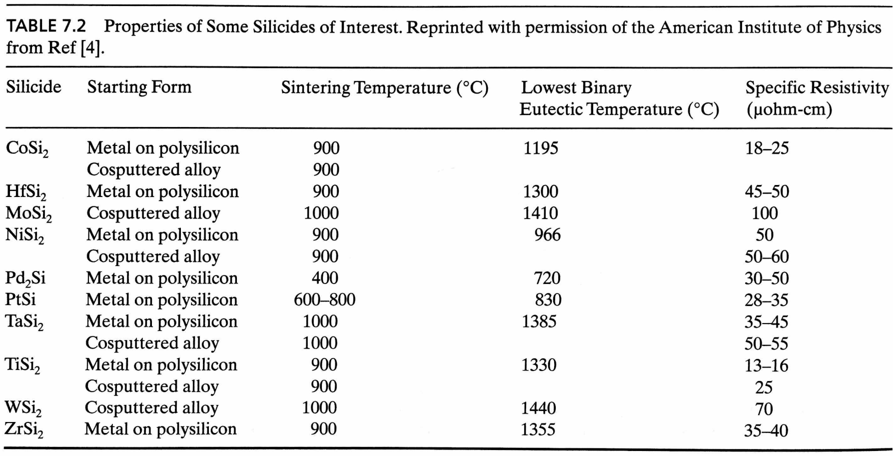


TABLE 7.2 Properties of Some Silicides of Interest. Reprinted with permission of the American Institute of Physics from Ref [4].

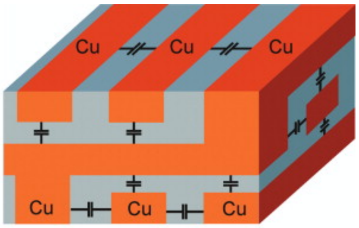
Silicide	Starting Form	Sintering Temperature (°C)	Lowest Binary Eutectic Temperature (°C)	Specific Resistivity (μohm-cm)
$CoSi_2$	Metal on polysilicon	900	1195	18–25
	Cosputtered alloy	900		
$HfSi_2$	Metal on polysilicon	900	1300	45–50
$MoSi_2$	Cosputtered alloy	1000	1410	100
$NiSi_2$	Metal on polysilicon	900	966	50
	Cosputtered alloy	900		50–60
Pd_2Si	Metal on polysilicon	400	720	30–50
PtSi	Metal on polysilicon	600–800	830	28–35
$TaSi_2$	Metal on polysilicon	1000	1385	35–45
	Cosputtered alloy	1000		50–55
$TiSi_2$	Metal on polysilicon	900	1330	13–16
	Cosputtered alloy	900		25
WSi_2	Cosputtered alloy	1000	1440	70
$ZrSi_2$	Metal on polysilicon	900	1355	35–40

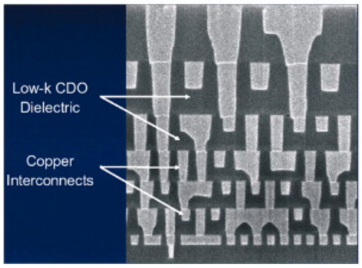
Low-K Dielectric

- Reduce parasitic capacitances by replacing silicon dioxide with a low-dielectric constant (low-K) materials:

$$C_{sub} = \frac{C}{L} = \frac{\epsilon_{low-K} W_m}{T_{ox}}$$

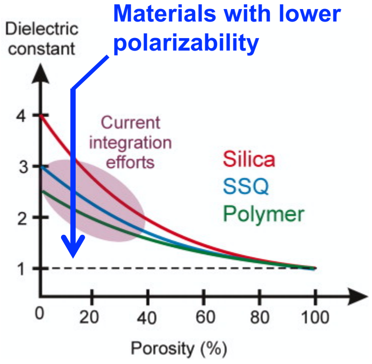
$$C_L = \frac{C}{L} = \frac{\epsilon_{low-K} T_m}{S_m}$$



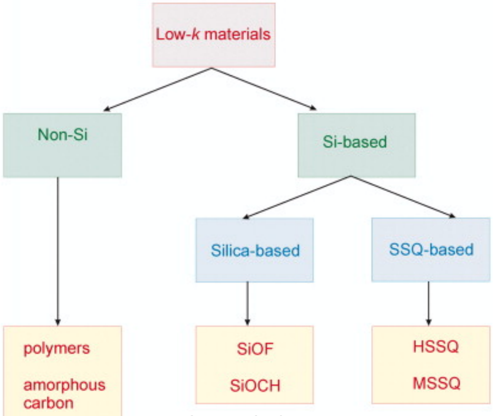


Approaches for Low-K Dielectric Materials

Materials with lower polarizability



Higher porosity (Lower Density)



Organic polymers with virtually nonpolar bonds, C-C or C-H

Si-F or Si-C bonds have lower polarizability than SiO bond

silsesquioxane (SSQ)

D. Shamiryan, T. Abell, F. Iacopi, and K. Maex, “Low-k dielectric materials,” *Materials Today*, vol. 7, no. 1, pp. 34–39, Jan. 2004.

Silica-Based Low-K Materials

SiO$_2$

SiOCH material with an oxygen atom replaced by a CH$_3$ group reduces the k value by introducing a less polar bond and by creating additional free volume (constitutive porosity).

Silsesquioxane (SSQ)