PSI-3552 Fabricação e Carcaterização de Dispositivos Nanoeletrônicos

Interconexões

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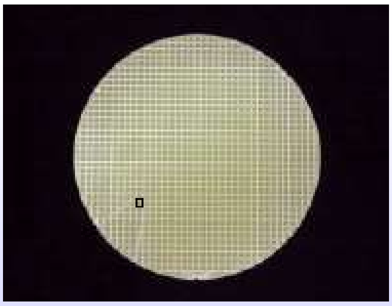
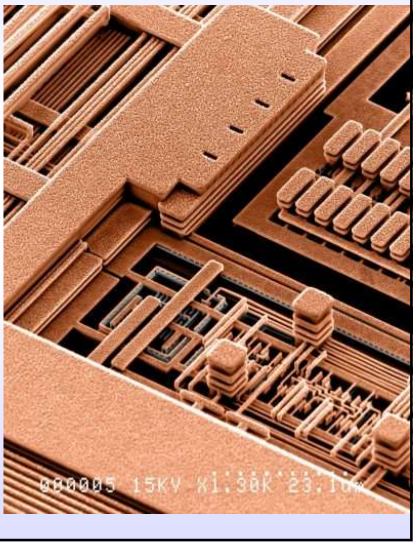
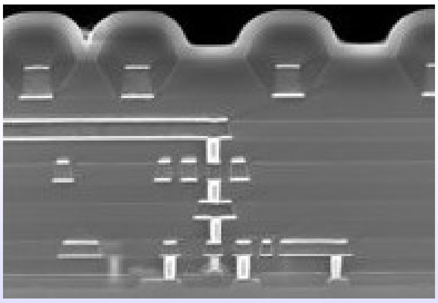




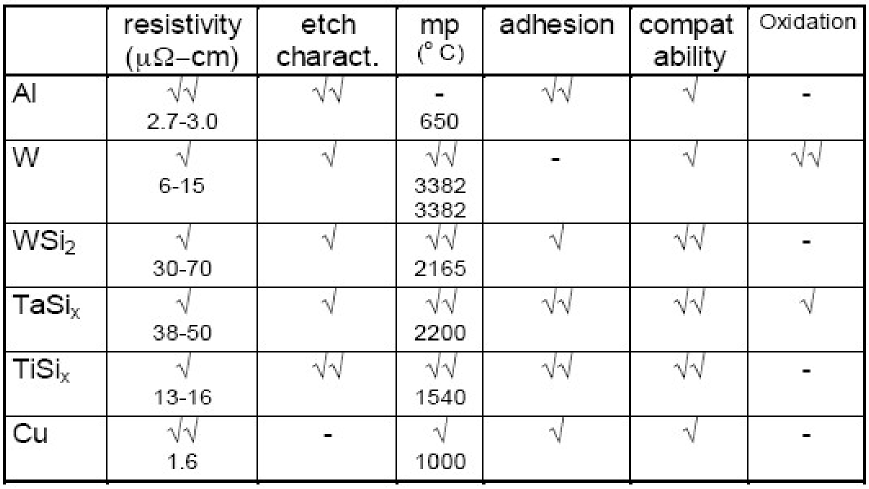
Introdução

Metalização

- é uma etapa do processo de fabricação de interconexões do circuito
- Alumínio é o metal mais popular para fazer as interconexões de Ics e, em conjunto com o contato ohmico, pads para ligar para fora do chip.
- outros Si-poli, cobre, silicetos, etc....

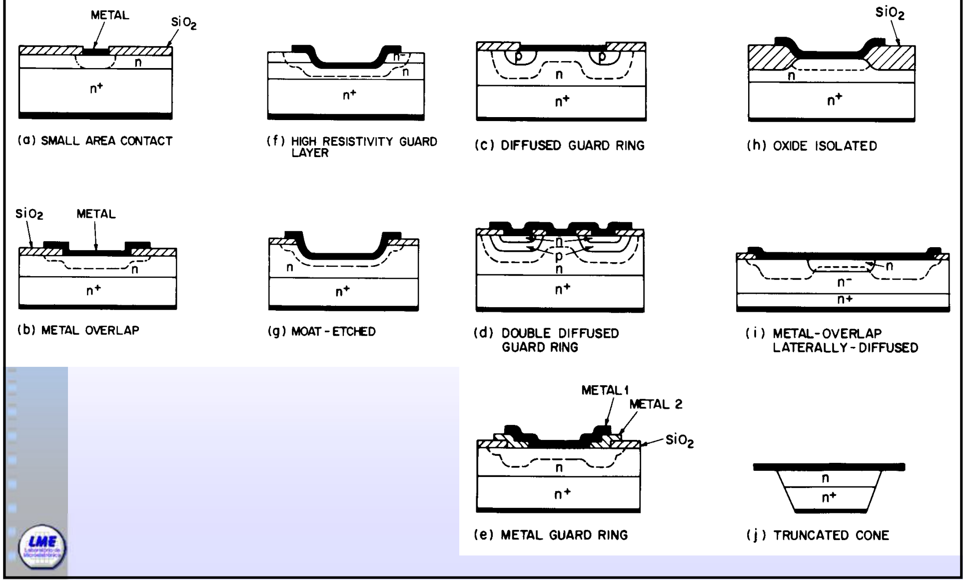


Características de Metais

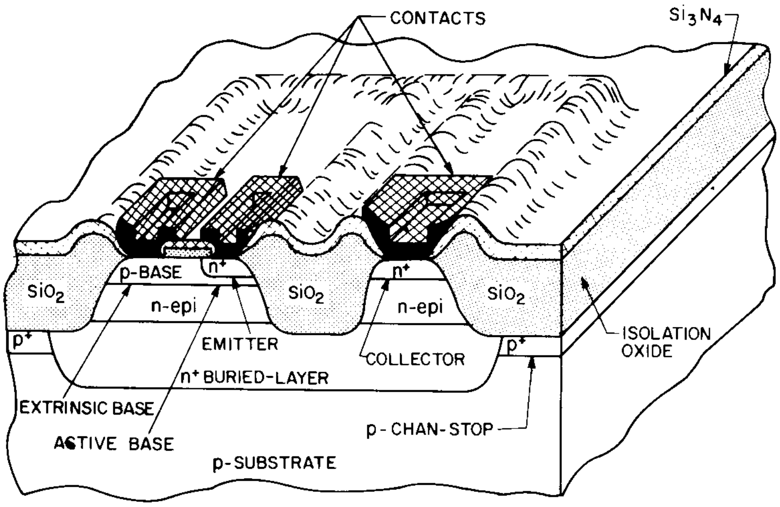


	resistivity ($\mu\Omega$–cm)	etch charact.	mp (° C)	adhesion	compat ability	Oxidation
Al	√√ 2.7-3.0	√√	- 650	√√	√	-
W	√ 6-15	√	√√ 3382 3382	-	√	√√
WSi_2	√ 30-70	√	√√ 2165	√	√√	-
$TaSi_x$	√ 38-50	√	√√ 2200	√√	√√	√
$TiSi_x$	√ 13-16	√√	√√ 1540	√√	√√	-
Cu	√√ 1.6	-	√ 1000	√	√	-

Várias Estruturas com Metalização



Metalização no BJT



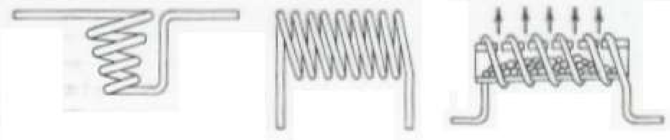
Three-dimensional views of oxide-isolated bipolar transistor.

Técnicas para evaporação

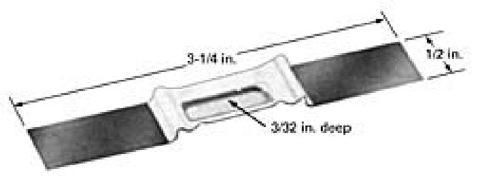
a) - aquecimento por resistência
b) - elétron beam
c) - aquecimento por RF

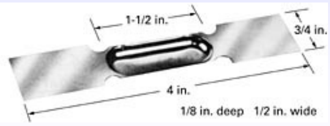
Outros métodos:	MOCVD MOPVD eletroquímico .....

A Evaporadora

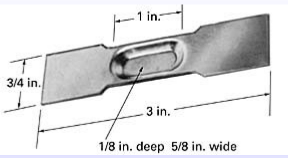


cadinhos



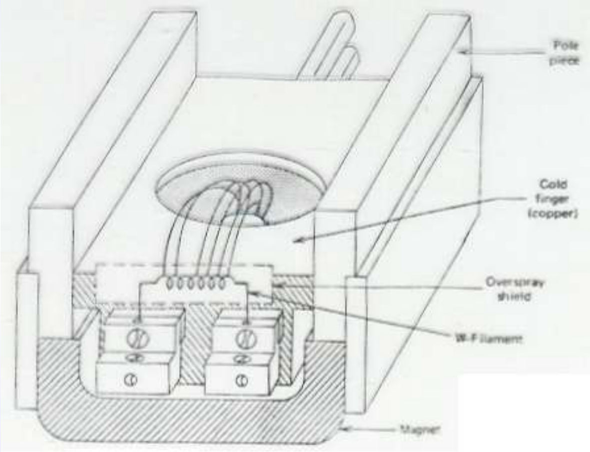


Tungsten Boats with Alumina Barriers
3-1/4" L x 1/2" W (82.5 x 12.7mm), trough: 1/4" W x 3/4" L (6.35 x 19.05mm) x 3/32" (2.38mm) deep.



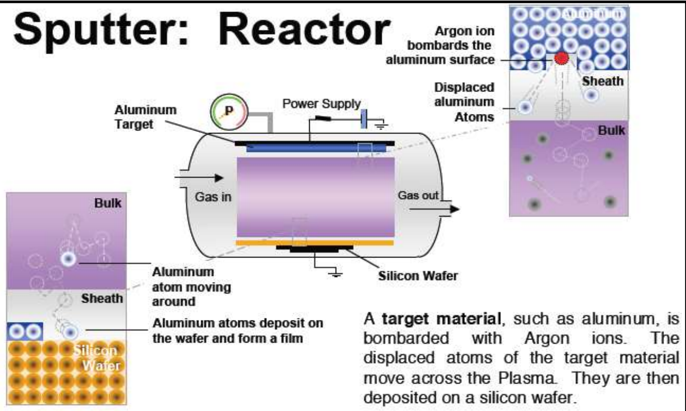
4" L x 3/4" W (101.6 x 19mm), trough: 1/2" W x 1-1/2" L x (12.7 x 38.1mm) x 1/8" (3.2mm) deep.
Tungsten thickness: 0.010" (0.25mm).

Eletron Beam



An electron beam evaporation system.

Sputtering



A **target material**, such as aluminum, is bombarded with Argon ions. The displaced atoms of the target material move across the Plasma. They are then deposited on a silicon wafer.

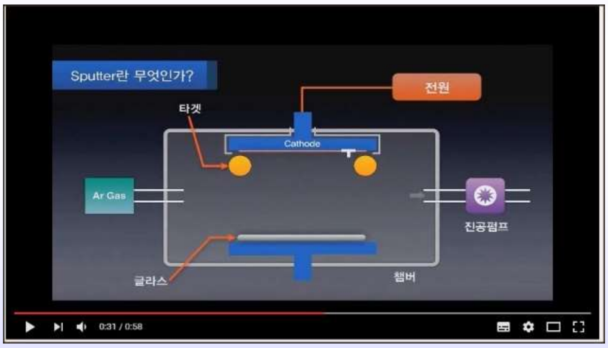
Vantagens:

- grande área
- vários tipos de metais
- controle de espessura
- stress pode ser controlado

Desvantagens: investimento muito alto (equipo)
baixa taxa para determinados materiais SiO_2
bombardeamento iônico pode alterar ou
danificar as amostras

Sputtering

https://youtu.be/7KPLRpKHE3Q



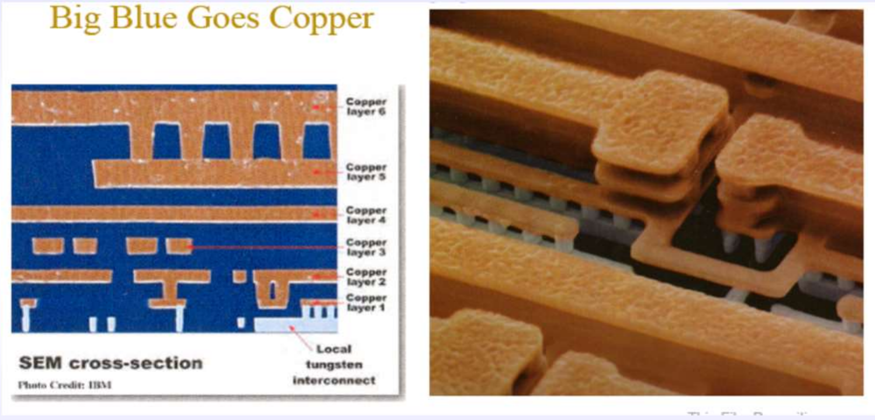
Interconexões e contatos

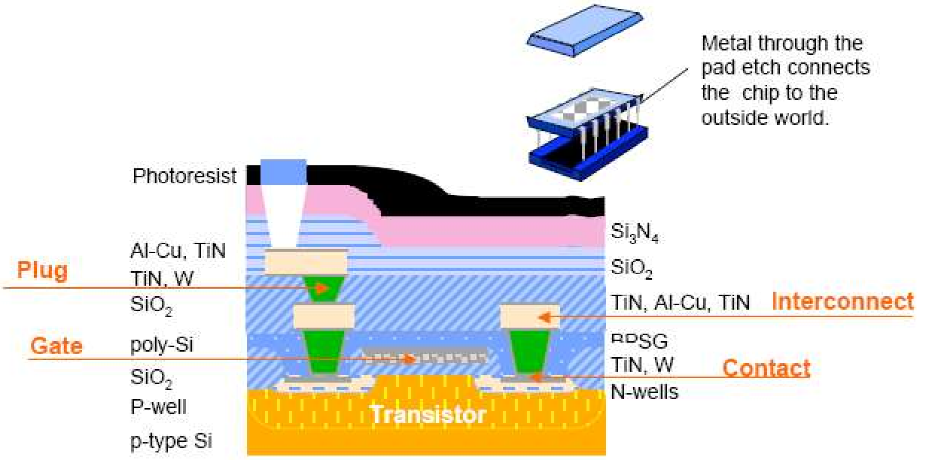
Estabilidade termodinânica
Boa aderência
Resistência a eletromigração
Resistência a corrosão
Facilidade de definição de geometrias

Características de Metais

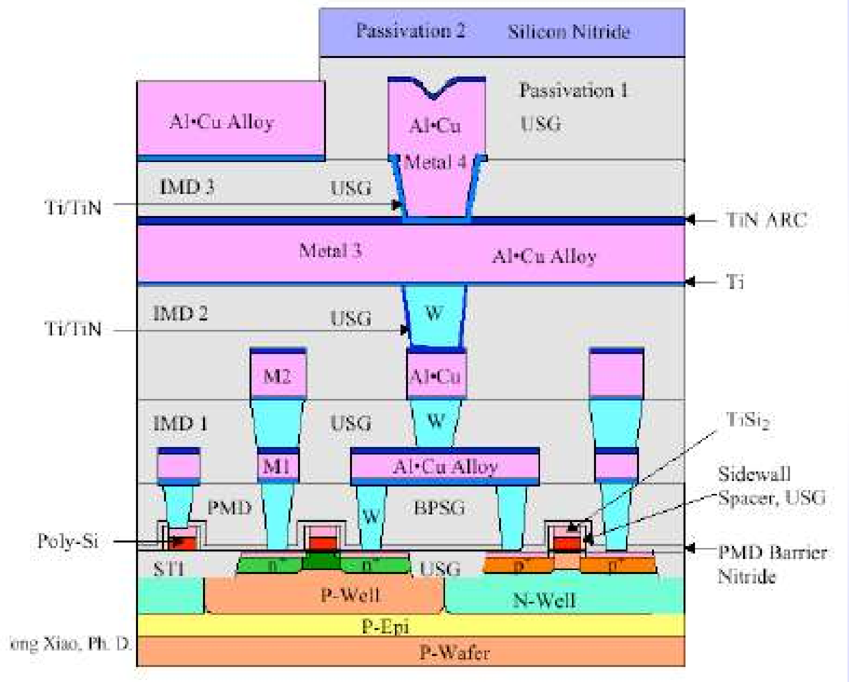
	resistivity ($\mu\Omega$–cm)	etch charact.	mp (° C)	adhesion	compat ability	Oxidation
Al	√√ 2.7-3.0	√√	- 650	√√	√	-
W	√ 6-15	√	√√ 3382 3382	-	√	√√
WSi_2	√ 30-70	√	√√ 2165	√	√√	-
$TaSi_x$	√ 38-50	√	√√ 2200	√√	√√	√
$TiSi_x$	√ 13-16	√√	√√ 1540	√√	√√	-
Cu	√√ 1.6	-	√ 1000	√	√	-

Cobre





Metal through the pad etch connects the chip to the outside world.

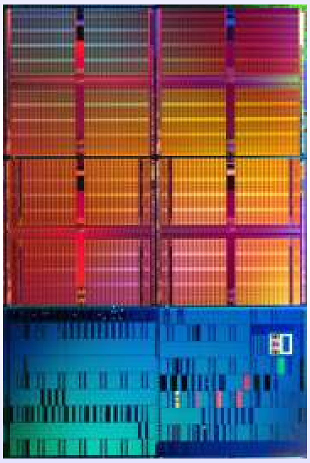


Melhor sistema para obter Al (27 μ.Ω.cm)

Sistema a vácuo

sistema limpo
controle de ambiente
facilidade – menor pressão de vapor
análise in situ – Auger, SIMS, SEM, TEM.

vapor de água
gordura implica em vazamento virtual
paredes – fonte de partículas e gases



Outros metais:
Platinum Melting Point: 1768°C
Molybdenum Melting Point: 2610°C
Tungsten Boat Melting Point: 3422°C

Evaporação de Alumínio

$$R = 5{,}83 \times 10^{-2} \times (M \times T)^{1/2} \times pe$$

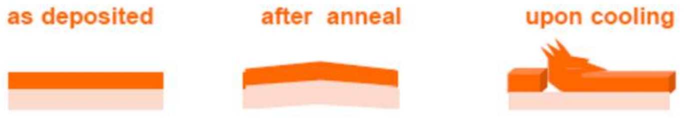
M = massa molecular
T = temperatura (K)
pe = pressão de vapor

Vantagens
- alta taxa de deposição 0,5 um/min Al
- baixa energia para levar Al até o alvo
- alto vácuo tem baixa contaminação
- baixo aquecimento das amostras

Desvantagens
- dificuldade de controlar as ligas
- não é possível realizar limpeza in situ
- step coverage é melhor por sputtering
- danos por raio X
- contaminação do aquecedor (cadinho/filamento)

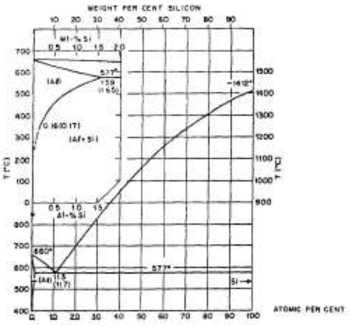
Al: Hillock formation

- Thermal expansion coefficients:
  - Al: 25×10^{-6} (°C)$^{-1}$
  - SiO_2: 0.5×10^{-6} (°C)$^{-1}$
- After annealing sputtered Al, what happens upon cooling?

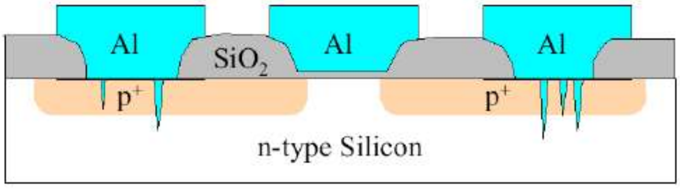


- Add 2-4% Cu reduces hillock formation (problems??)

Al: Junction Spiking



- Si high solubility and diffusivity (grain boundaries) in Al
- Si moves into Al leaving voids in Si which are filled by Al.
- can “short” junction
- Junction spiking reduced by:
  - decreased time/temp
  - diffusion barrier (W, Ti:W, Cr...)
  - Add Si to Al (problems??)



Al: Electromigration

- Caused by electrons transfering momentum to Al under high current densities
- An “electron wind” moves Al atoms towards anode
- can lead to open circuits
- The flux of Al, F_{Al}, is given by: $F_{Al} = \frac{\delta}{d}\frac{NDZ^{*}q}{\sigma kT}J$

δ: width of g.b.

d: diameter of grain

N: atomic # density (atoms cm^{-3})

D: Diffusion coefficient

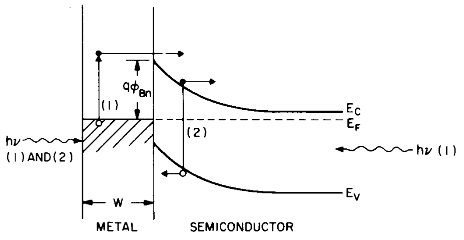
$Z^{*}q$: effective charge of Al

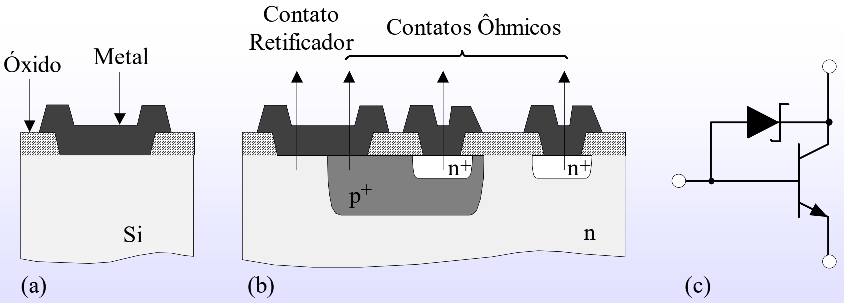
σ: conductivity

J: current density

- Add 1-4% Cu (or Ni, Cr, Mg,...) to prevent; increases self-diffusivity of Al along grain boundaries (g.b.)

Retificadores ou Ohmicos?





Óxido

Metal

Contato Retificador

Contatos Ôhmicos

Si

p^+

n^+

n^+

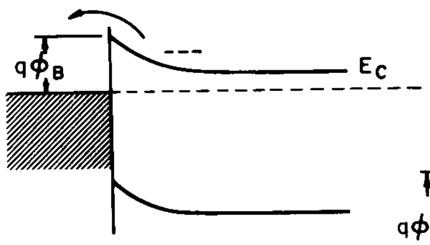
n

(a)

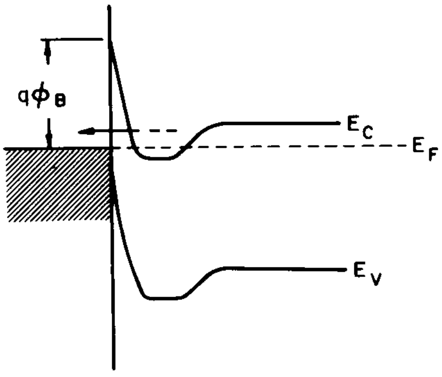
(b)

(c)

Baixa e Alta Dopagem



(a) LOW BARRIER HEIGHT



(b) HIGH DOPING

Barreira de Potencial

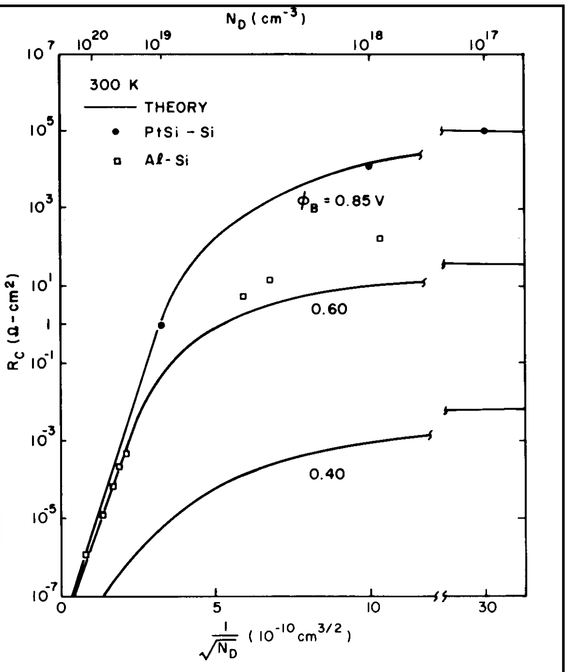
Table 3 Measured Schottky-Barrier Heights (Volts at 300 K)

Semiconductor	Type	E_g (eV)	Ag	Al	Au	Cr	Cu	Hf	In	Mg	Mo	Ni	Pb	Pd	Pt	Ta	Ti	W
Diamond	*p*	5.47			1.71													
Ge	*n*	0.66	0.54	0.48	0.59		0.52		0.64			0.49	0.38					0.48
Ge	*p*		0.50		0.30				0.55									
Si	*n*	1.12	0.78	0.72	0.80	0.61	0.58	0.58		0.40	0.68	0.61		0.81	0.90		0.50	0.67
Si	*p*		0.54	0.58	0.34	0.50	0.46				0.42	0.51	0.55				0.61	0.45
SiC	*n*	3.00		2.00	1.95													
AlAs	*n*	2.16			1.20										1.00			
AlSb	*p*	1.63			0.55													
BN	*p*	7.50			3.10													
BP	*p*	6.00			0.87													
GaSb	*n*	0.67			0.60													
GaAs	*n*	1.42	0.88	0.80	0.90		0.82	0.72							0.84	0.85		0.80
GaAs	*p*		0.63		0.42			0.68										
GaP	*n*	2.24	1.20	1.07	1.30	1.06	1.20	1.84		1.04	1.13	1.27			1.45		1.12	
GaP	*p*				0.72													
InSb	*n*	0.16	0.18^a		0.17^a													
InAs	*p*	0.33			0.47^a													
InP	*n*	1.29	0.54		0.52													
InP	*p*				0.76													
CdS	*n*	2.43	0.56	Ohmic	0.78		0.50					0.45	0.59	0.62	1.10		0.84	
CdSe	*n*	1.70	0.43		0.49		0.33								0.37			
CdTe	*n*		0.81	0.76	0.71										0.76			
ZnO	*n*	3.20		0.68	0.65		0.45		0.30					0.68	0.75	0.30		
ZnS	*n*	3.60	1.65	0.80	2.00		1.75		1.50	0.82				1.87	1.84	1.10		
ZnSe	*n*		1.21	0.76	1.36		1.10		0.91				1.16		1.40			
PbO	*n*		0.95						0.93			0.96	0.95					

[a] 77 K.

Dependência com a Dopagem

$$R_c \sim \exp\left(\frac{q\phi_{Bn}}{E_{00}}\right) = \exp\left[\frac{2\sqrt{\epsilon_s m^*}}{\hbar}\left(\frac{\phi_{Bn}}{\sqrt{N_D}}\right)\right]$$



Theoretical and experimental values of specific contact resistance.

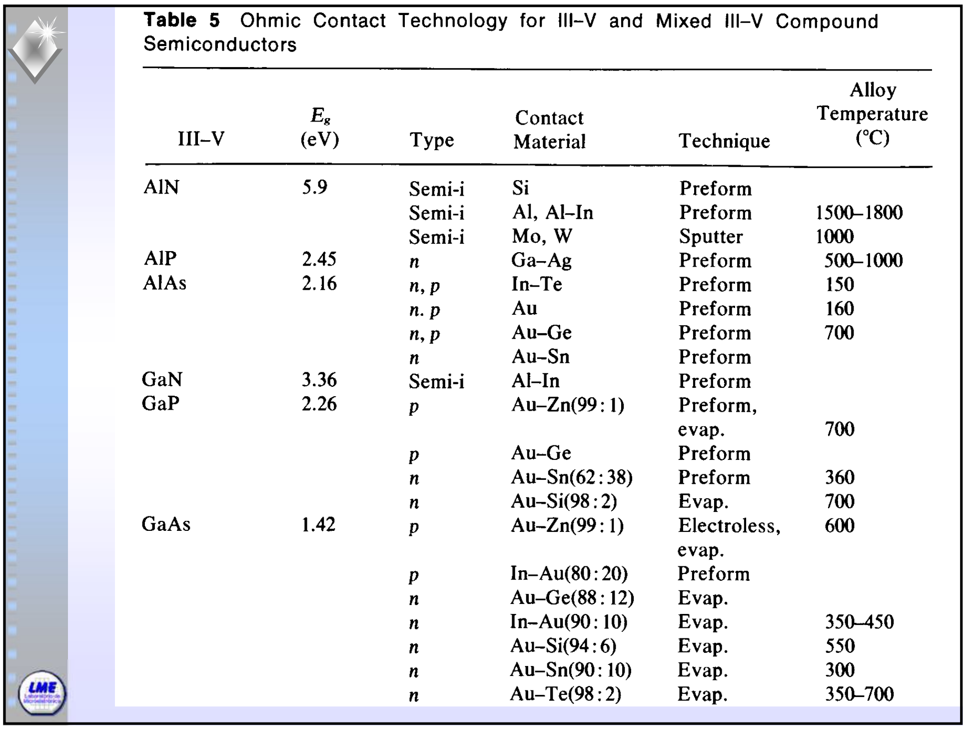
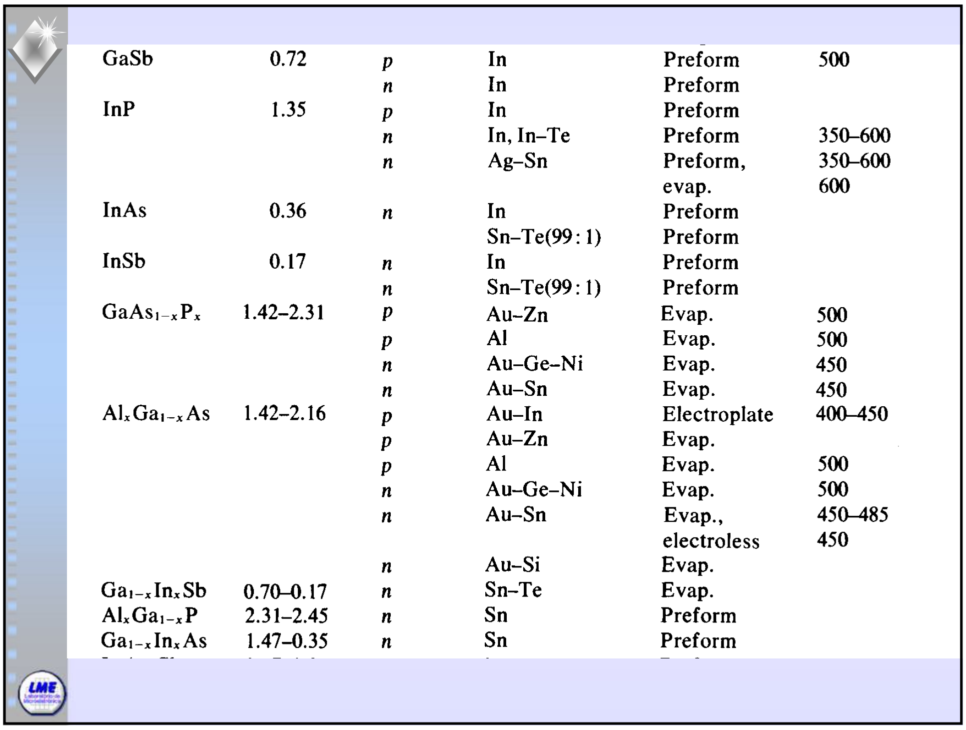


Table 5 Ohmic Contact Technology for III–V and Mixed III–V Compound Semiconductors

III–V	E_g (eV)	Type	Contact Material	Technique	Alloy Temperature (°C)
AlN	5.9	Semi-i	Si	Preform	
		Semi-i	Al, Al–In	Preform	1500–1800
		Semi-i	Mo, W	Sputter	1000
AlP	2.45	*n*	Ga–Ag	Preform	500–1000
AlAs	2.16	*n*, *p*	In–Te	Preform	150
		n. *p*	Au	Preform	160
		n, *p*	Au–Ge	Preform	700
		n	Au–Sn	Preform	
GaN	3.36	Semi-i	Al–In	Preform	
GaP	2.26	*p*	Au–Zn(99 : 1)	Preform, evap.	700
		p	Au–Ge	Preform	
		n	Au–Sn(62 : 38)	Preform	360
		n	Au–Si(98 : 2)	Evap.	700
GaAs	1.42	*p*	Au–Zn(99 : 1)	Electroless, evap.	600
		p	In–Au(80 : 20)	Preform	
		n	Au–Ge(88 : 12)	Evap.	
		n	In–Au(90 : 10)	Evap.	350–450
		n	Au–Si(94 : 6)	Evap.	550
		n	Au–Sn(90 : 10)	Evap.	300
		n	Au–Te(98 : 2)	Evap.	350–700



III–V	E_g (eV)	Type	Contact Material	Technique	Alloy Temperature (°C)
GaSb	0.72	*p*	In	Preform	500
		n	In	Preform	
InP	1.35	*p*	In	Preform	
		n	In, In–Te	Preform	350–600
		n	Ag–Sn	Preform, evap.	350–600 600
InAs	0.36	*n*	In	Preform	
			Sn–Te(99 : 1)	Preform	
InSb	0.17	*n*	In	Preform	
		n	Sn–Te(99 : 1)	Preform	
$GaAs_{1-x}P_x$	1.42–2.31	*p*	Au–Zn	Evap.	500
		p	Al	Evap.	500
		n	Au–Ge–Ni	Evap.	450
		n	Au–Sn	Evap.	450
$Al_xGa_{1-x}As$	1.42–2.16	*p*	Au–In	Electroplate	400–450
		p	Au–Zn	Evap.	
		p	Al	Evap.	500
		n	Au–Ge–Ni	Evap.	500
		n	Au–Sn	Evap., electroless	450–485 450
		n	Au–Si	Evap.	
$Ga_{1-x}In_xSb$	0.70–0.17	*n*	Sn–Te	Evap.	
$Al_xGa_{1-x}P$	2.31–2.45	*n*	Sn	Preform	
$Ga_{1-x}In_xAs$	1.47–0.35	*n*	Sn	Preform	

Problemas da Metalização

Cobertura de degraus
Ligas metálicas – composição
Resistência de contato
Partículas geradas na camara de deposição
Protuberâncias (hillocks) causadas pelo TT
Decapagem úmida convencional

Solução

Cobertura de degraus – elevar a temperatura (300) Para aumentar a mobilidade

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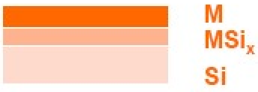
Silicides (MSi_x)

- Alloy formed brtween transition metal and Si
- Types of silicides
  - refractory metal silicides (W, Ta, Ti, Mo)
    - form Si rich compounds at over 400 C
    - Si diffusing atom
  - Noble metal silicides (Co, Pt, Pd, Ni)
    - form metal rich compounds at 200 C
    - metal diffusing atom



- Deposition
  - Deposit pure metal (sputter, evaporate, CVD) on Si and anneal
  - co-evaporation of metal and Si
  - Sputtering of metal silicide
- Salicides (Self Aligned silicide)

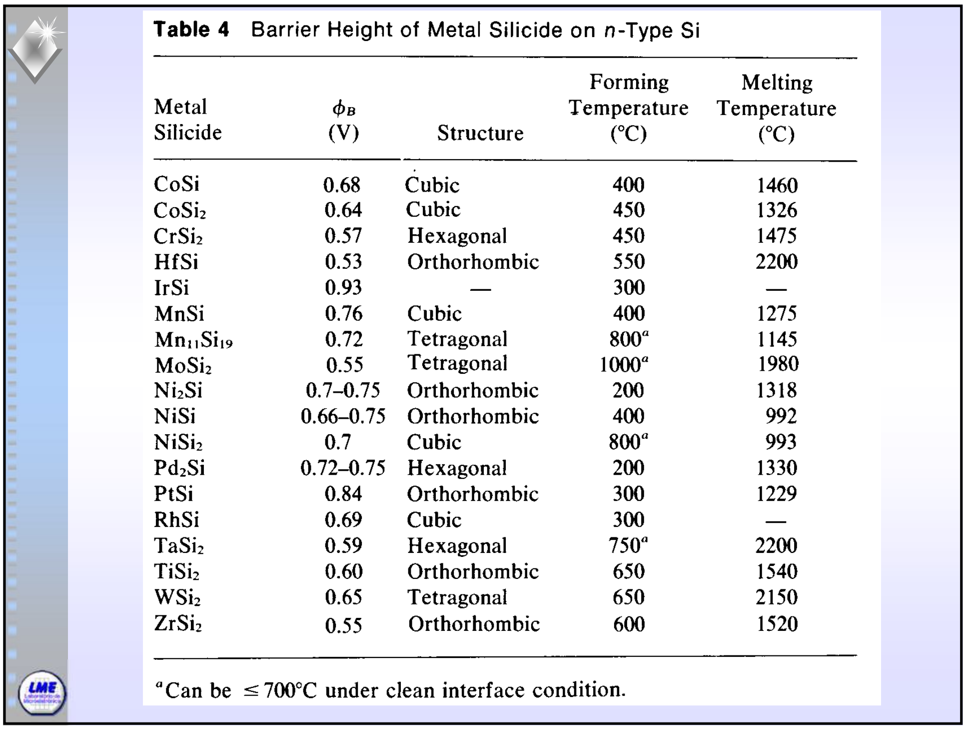
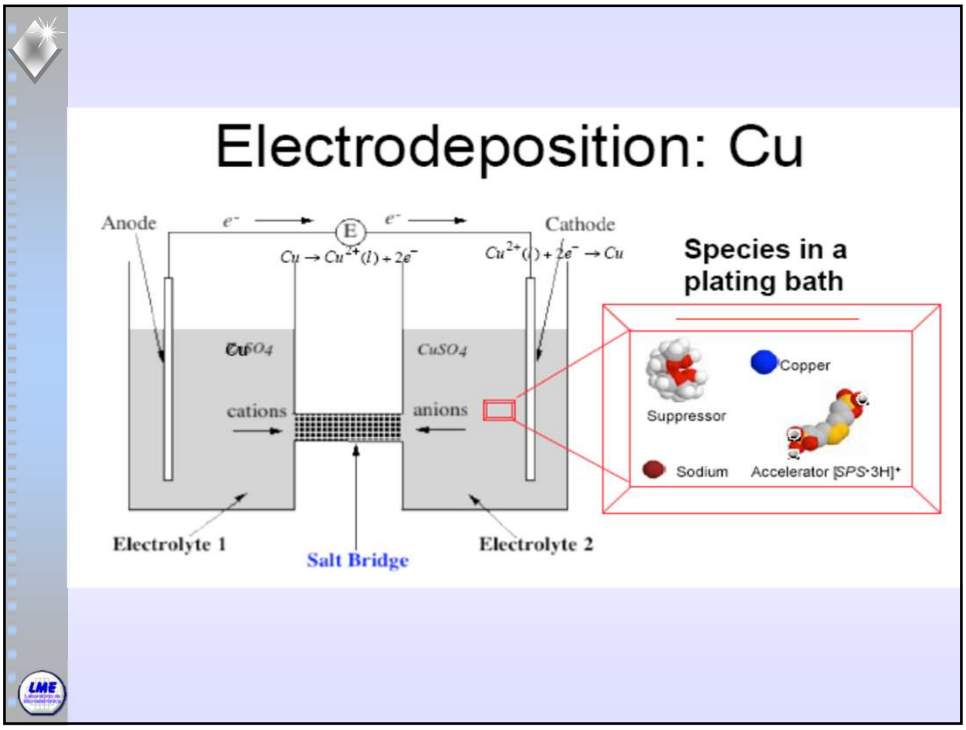


Table 4 Barrier Height of Metal Silicide on n-Type Si

Metal Silicide	ϕ_B (V)	Structure	Forming Temperature (°C)	Melting Temperature (°C)
CoSi	0.68	Cubic	400	1460
$CoSi_2$	0.64	Cubic	450	1326
$CrSi_2$	0.57	Hexagonal	450	1475
HfSi	0.53	Orthorhombic	550	2200
IrSi	0.93	—	300	—
MnSi	0.76	Cubic	400	1275
$Mn_{11}Si_{19}$	0.72	Tetragonal	800[a]	1145
$MoSi_2$	0.55	Tetragonal	1000[a]	1980
Ni_2Si	0.7–0.75	Orthorhombic	200	1318
NiSi	0.66–0.75	Orthorhombic	400	992
$NiSi_2$	0.7	Cubic	800[a]	993
Pd_2Si	0.72–0.75	Hexagonal	200	1330
PtSi	0.84	Orthorhombic	300	1229
RhSi	0.69	Cubic	300	—
$TaSi_2$	0.59	Hexagonal	750[a]	2200
$TiSi_2$	0.60	Orthorhombic	650	1540
WSi_2	0.65	Tetragonal	650	2150
$ZrSi_2$	0.55	Orthorhombic	600	1520

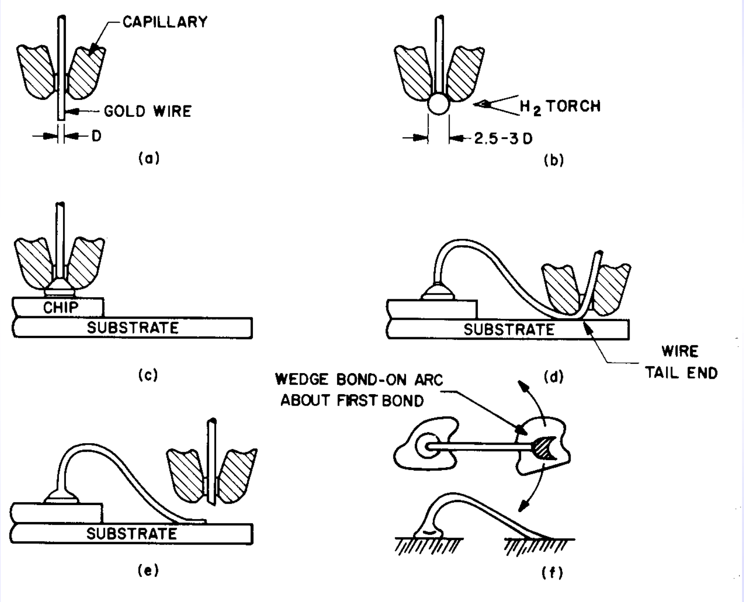
[a] Can be ≤ 700°C under clean interface condition.



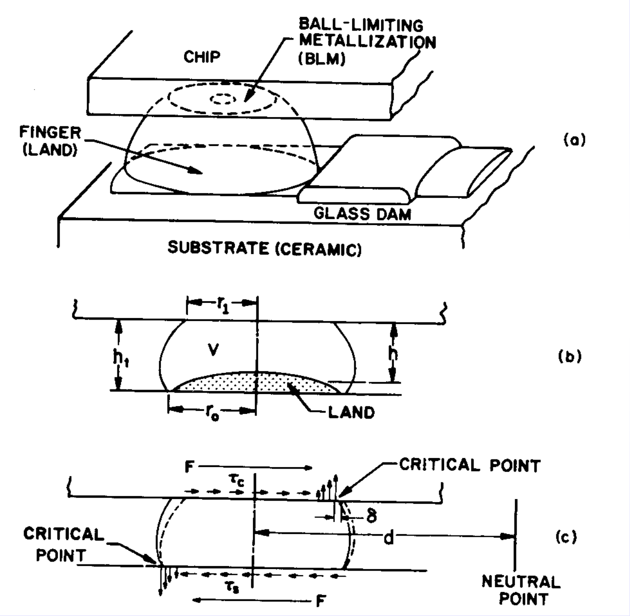
Electrodeposition: Cu

Species in a plating bath

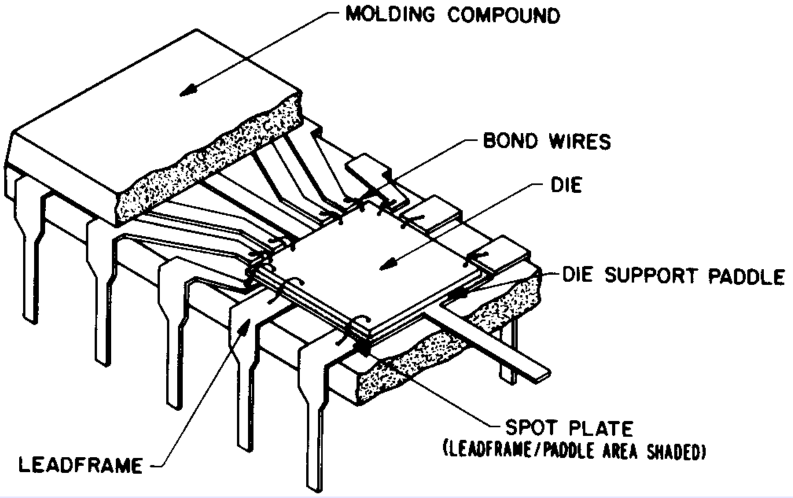
Conexões de Ouro



Conexão tipo "bolha"

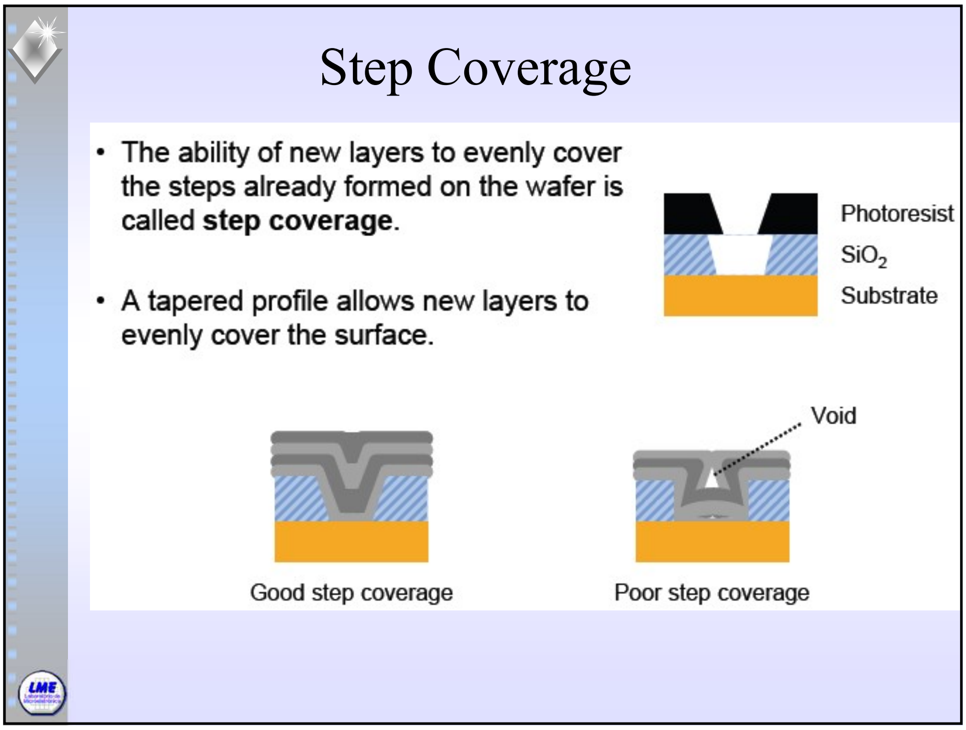


Encapsuramento



Problemas de deposição

- Step coverage
- Contaminação
- Adesão
- Espessura e uniformidade

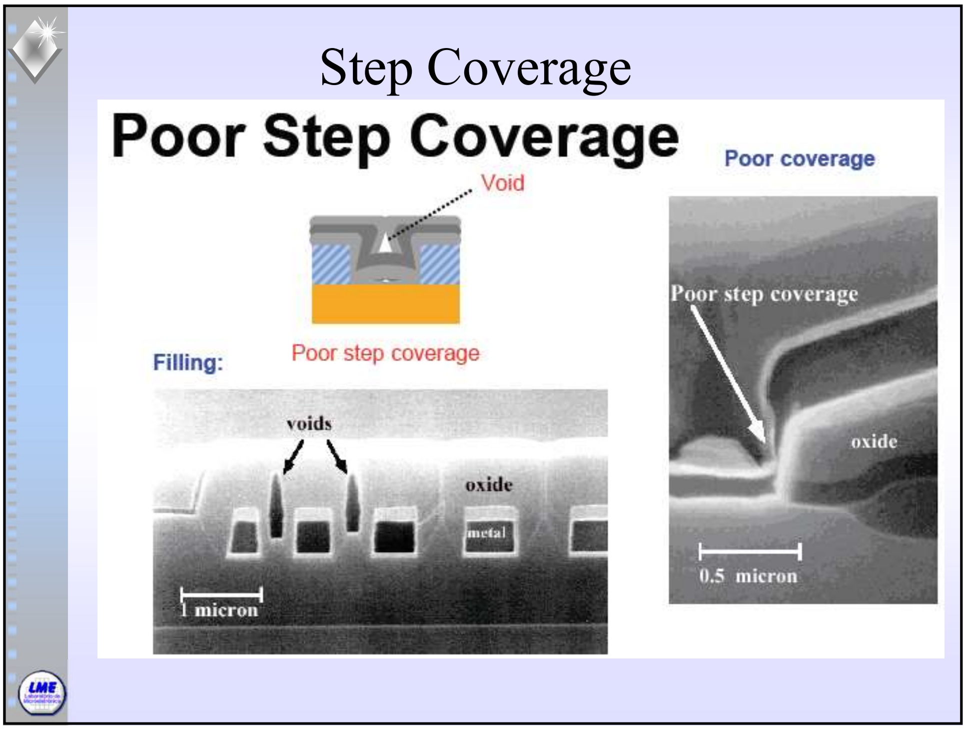


Step Coverage

- The ability of new layers to evenly cover the steps already formed on the wafer is called **step coverage**.
- A tapered profile allows new layers to evenly cover the surface.

Good step coverage

Poor step coverage



Step Coverage

Poor Step Coverage

Poor step coverage

Filling:

Poor coverage

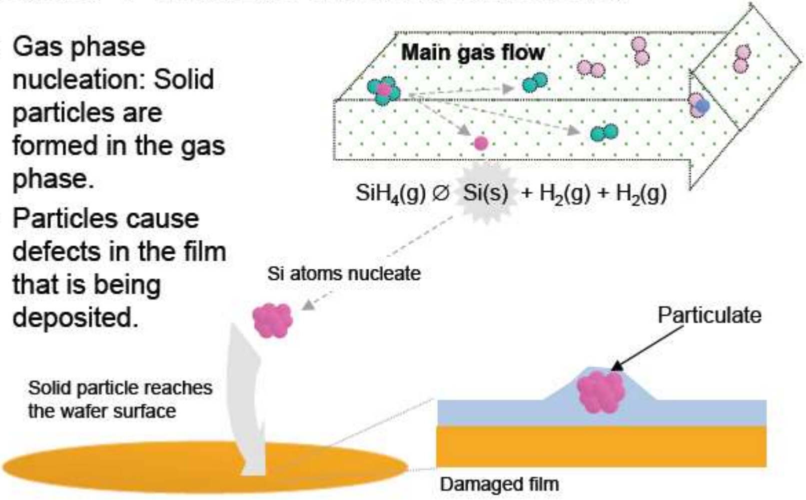
Contaminação

Location of particulate	**Source**
(1) Under the deposited film	• Dirty wafer surface
(2) In the deposited surface	• Gas phase nucleation • Leaks into the system • Contamination in gas source/flow lines • Sputter off walls
(3) On the deposited film walls	• Film build-up on chamber • Handling and transportation

Contaminação

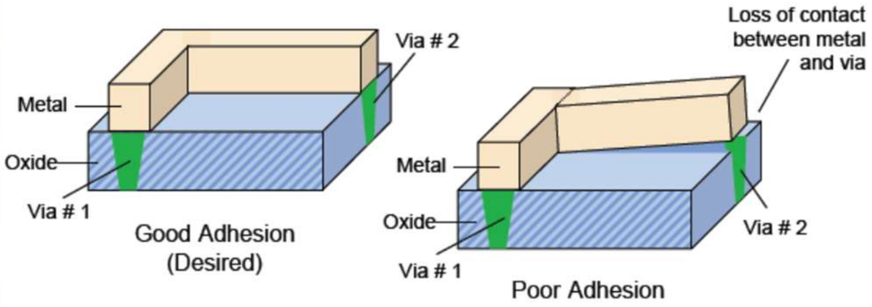
Gas Phase Nucleation

- Gas phase nucleation: Solid particles are formed in the gas phase.
- Particles cause defects in the film that is being deposited.



Adesão

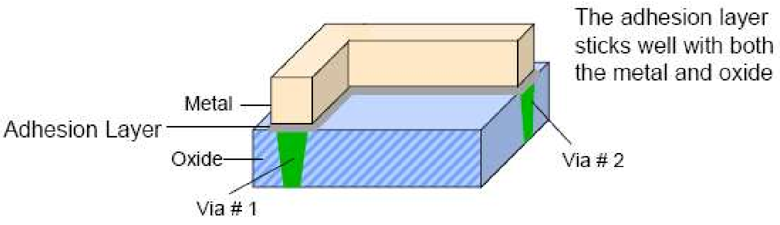
- Adhesion of films on a wafer should be excellent.
- The films should stick strongly to each other when they are deposited and also after processing.



Adhesion: Ways to get good adhesion

- Adhesion between films can be improved by:

(1) Cleaning surfaces before deposition.
(2) Proper roughness of underlying surface.
(3) Deposition of an "Adhesion-Layer" between films.



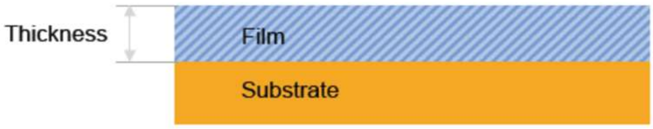
Espessura e taxa de deposição

- Especificado para cada projeto
- Taxa de deposição determina o tempo de deposição/evaporação do metal
- A taxa de deposição é definida por:

$$\text{Deposition Rate} = \frac{\text{Thickness of film}}{\text{Time to grow film}} \left(\frac{\text{Å}}{\text{min}}\right)$$

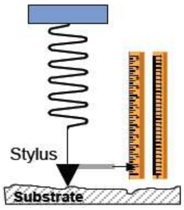
Espessura

- There are a number of ways to measure film thickness and check uniformity.
- A **profilometer** measures thickness directly with a stylus.
- A **four-point-probe** measures thickness by calibrating the relation between thickness and resistance.
- An **ellipsometer** measures thickness by calibrating the relation between thickness and refractive index.

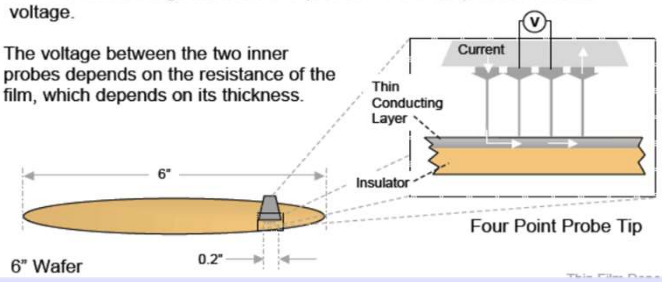


Perfilômetro e 4 pontas

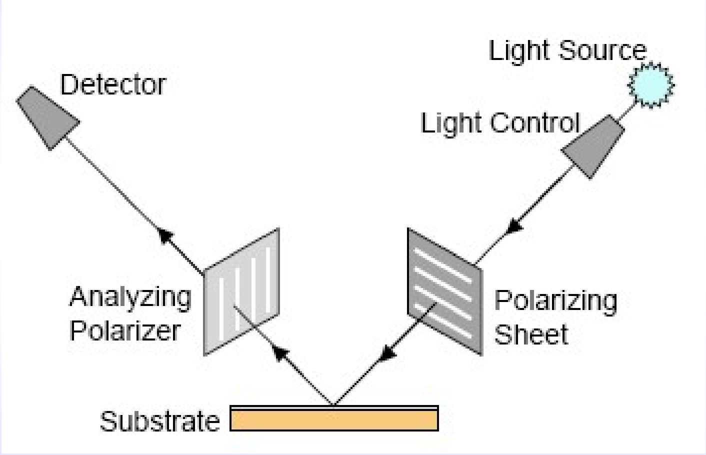
- A profilometer is used to measure thickness after a material is deposited.
- It is made of a diamond tipped stylus that touches the surface.
- When the profilometer moves across the surface, the stylus moves up and down as the thickness changes.
- The movement of the stylus is calibrated to read thickness.

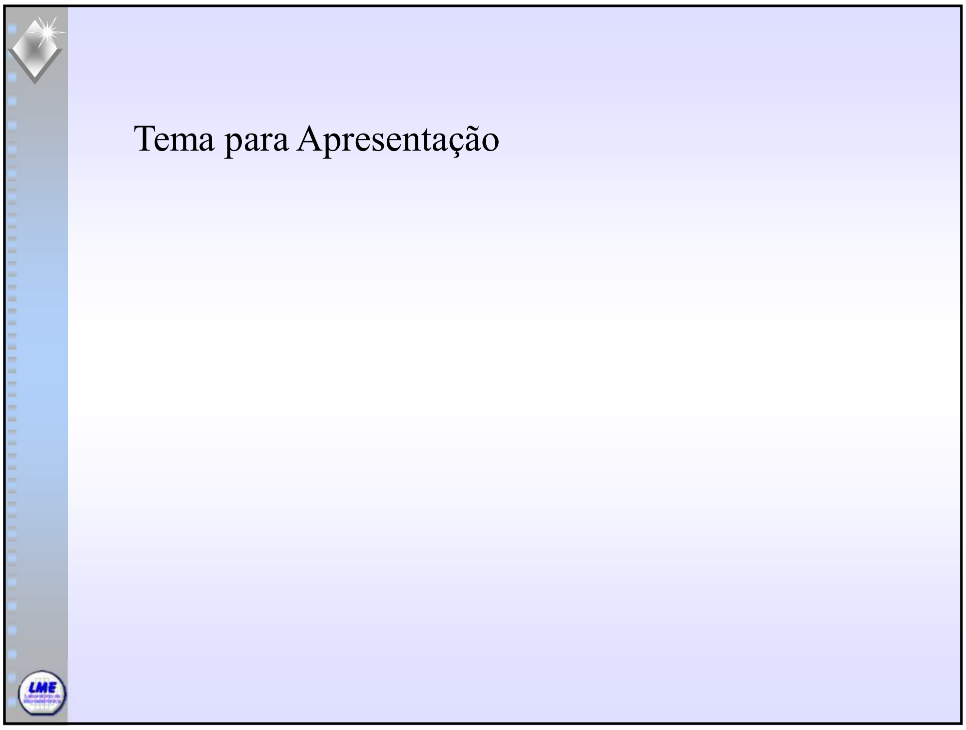


- The four point probe is used to measure thickness of conductors which are deposited on insulators. It is made of four probes which move across the surface.
- Current flows through the outer two probes. The inner probes measure voltage.
- The voltage between the two inner probes depends on the resistance of the film, which depends on its thickness.



Elipsômetro





Tema para Apresentação