METAL SEMI-CONDUCTOR CONTACT

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Schottky diodes

Ohmic contacts

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Plan:

- Two types of contact:
  - Contact between Metal and heavily doped semiconductors:
    - Interconnections
    - Ohmic Contacts

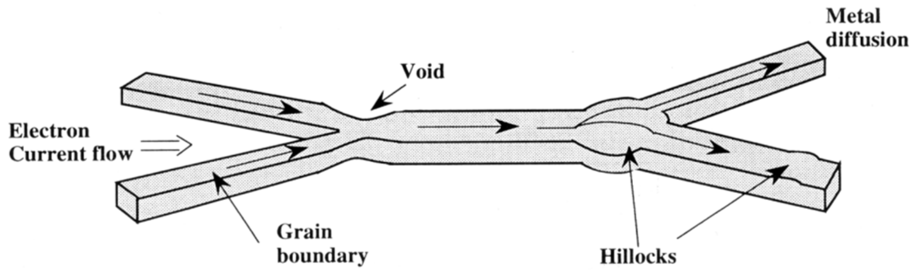
  - Contact between Metal and ligthly doped semiconductors:
    - Schottky diode

  - Comparison between Schottky and PN junction

interconnections

- ***Nowadays , in ULSI IC, 6 to 8 metal levels (=> 10)***
- ***Problems / Issues :***
    - ***delays***
    - ***heating***
    - ***Compatibility/ diffusion with devices***

- ***Copper technology used for interconnections***



Material	Resistivity ($\mu\Omega$-cm)
Aluminum (Al)	
Bulk	2.7
Thin Film	0.2-0.3
Alloys, $\Delta\rho$	
per %Si	+0.7%Si
per %Cu	+0.3%Cu
Titanium (Ti)	40.0
Tungsten (W)	5.6
Ti-W	15-50
Gold (Au)	2.44
Silver (Ag)	1.59
Copper (Cu)	1.77
Platinum (Pt)	10.0
Silicides	
PtSi	28-35
NiS_2	50

Interconnections / Insulating layers

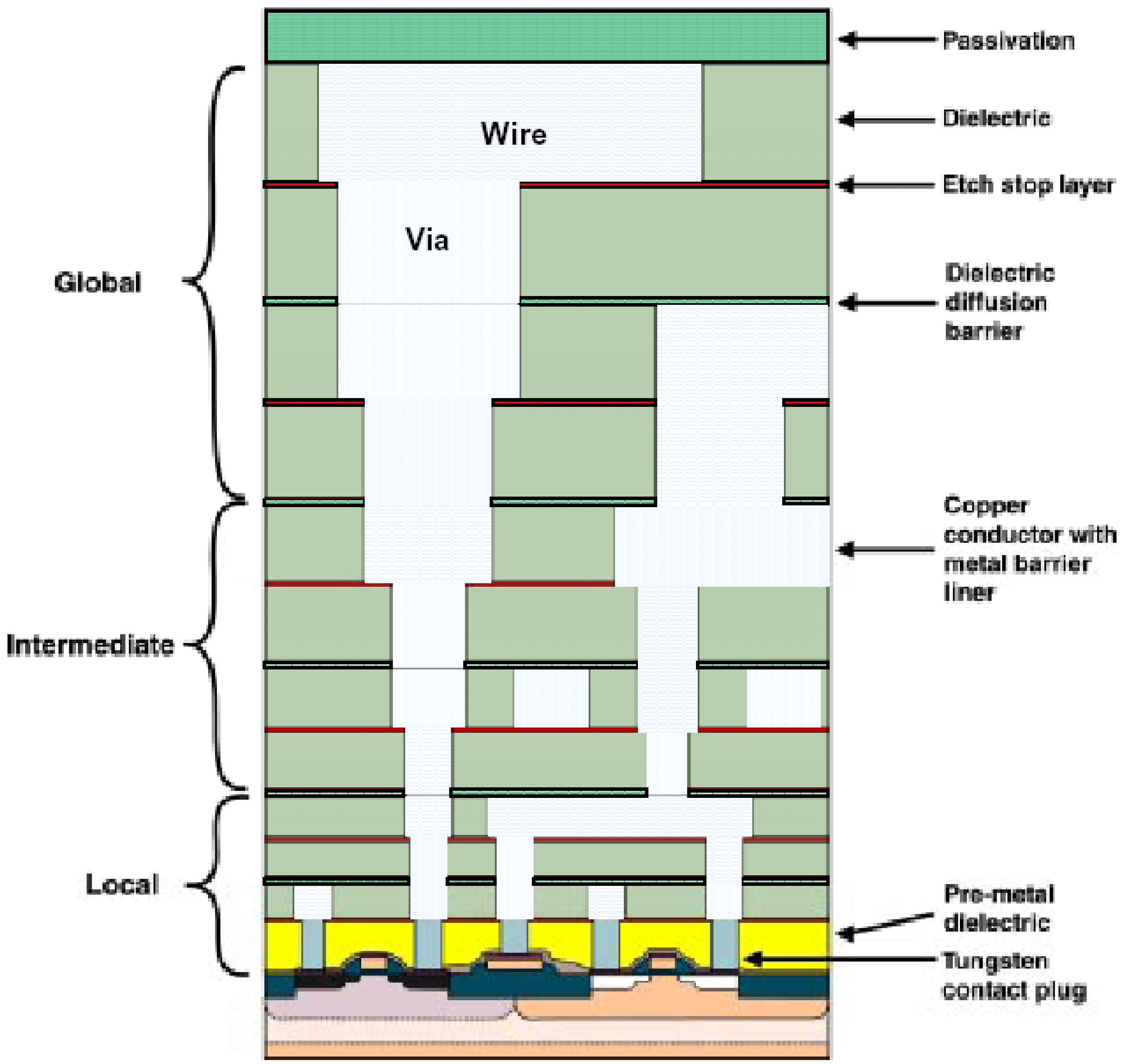
- *Low dielectric materials*
  « low k »

$$C=\frac{S\varepsilon}{d}$$

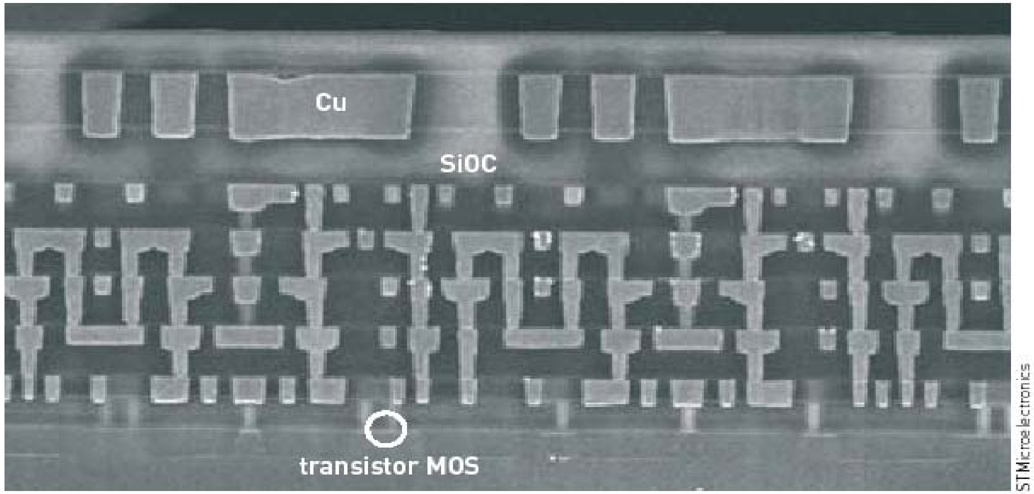
- *Low resistivity materials:*
  « Copper » solution

$$R=\rho\frac{l}{S}$$

$$\tau=RC$$


Passivation
Dielectric
Etch stop layer
Dielectric diffusion barrier
Copper conductor with metal barrier liner
Pre-metal dielectric
Tungsten contact plug
Wire
Via
Global
Intermediate
Local

Stack of metal layers



Des millions de transistors sont interconnectés par un empilement complexe de couches métalliques de cuivre isolées par un matériau de faible constante diélectrique (ici le SiOC). Ces résultats (ici sur une mémoire SRAM de 8 Mbit en technologie 90 nm à droite) ont été obtenus en collaboration entre le CEA-Leti et la ligne pilote de Crolles.

Schottky Diode

- Two definitions (only 2!)
  - Work Function (Travail de sortie) $e\phi_M$: this is the energy we have to give to an electron to extract it of metal without kinetic energy. It reaches the "vacuum level". Work function is the energy difference between the vacuum level and the highest occupied energy level, *ie* the Fermi level.
  - Electron Affinity (Affinité électronique) $e\chi_{SC}$: it’s the difference between the vacuum level and the bottom of the conduction band. It’s only defined for SC and not for Metal.
  - Unity : eV (electron volt)

Schottky Diode

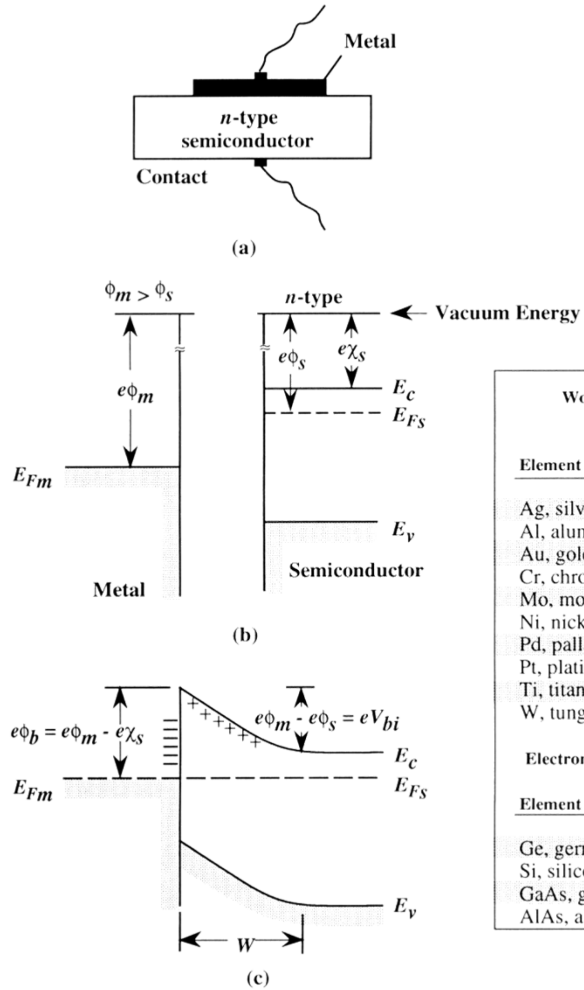
No bias !!
Fermi level is flat, aligned !!

- Contact Formation :
  - We assume $e\phi_M > e\phi_{SC}$
  - Onset of an energy barrier for electrons in the metal :

$$e\Phi_b = e\Phi_M - e\chi_{SC}$$

  - Onset of an energy barrier for electrons in the SC :

$$eV_{bi} = e\phi_{bi} = eV_d = e\Phi_M - e\Phi_{SC} = e\Phi_{MS}$$



Work functions of some metals

Element	Work function, ϕ_m (volt)
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Electron affinity of some semiconductors

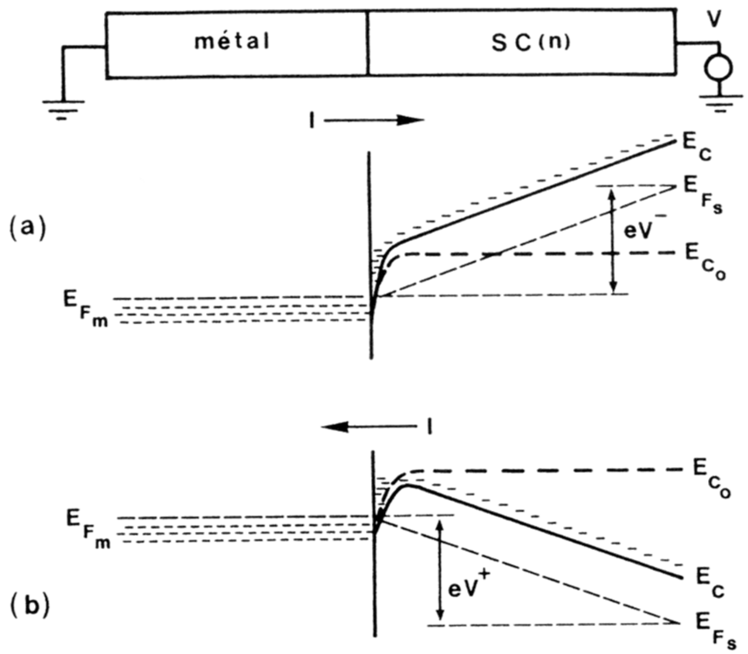
Element	Electron affinity, χ (volt)
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5

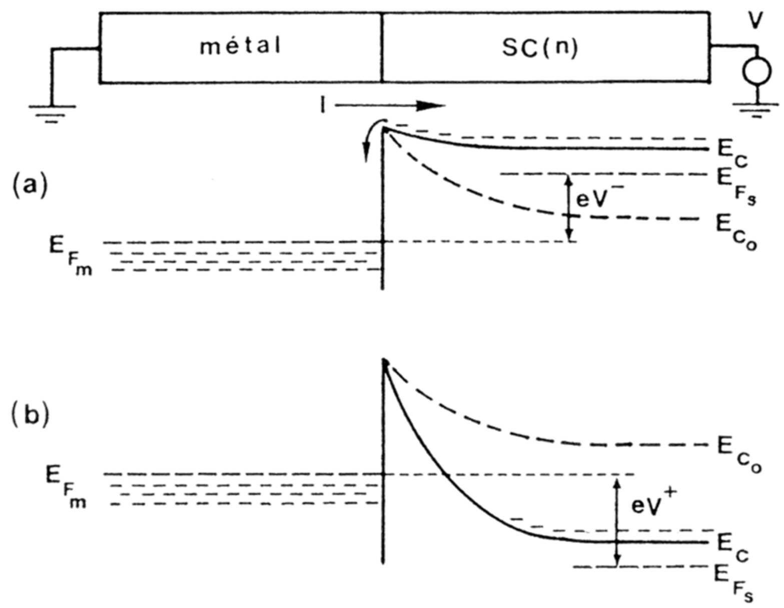
Ohmic contact or diode ?

« ohmic »

N type Semi-conductor

« rectifier »





$$e\phi_m < e\phi_s$$

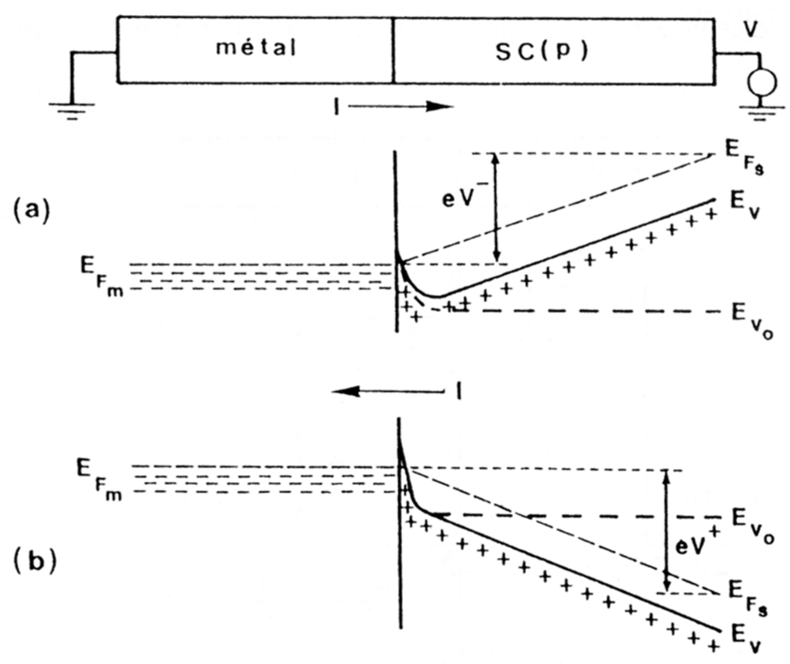
$$e\phi_m > e\phi_s$$

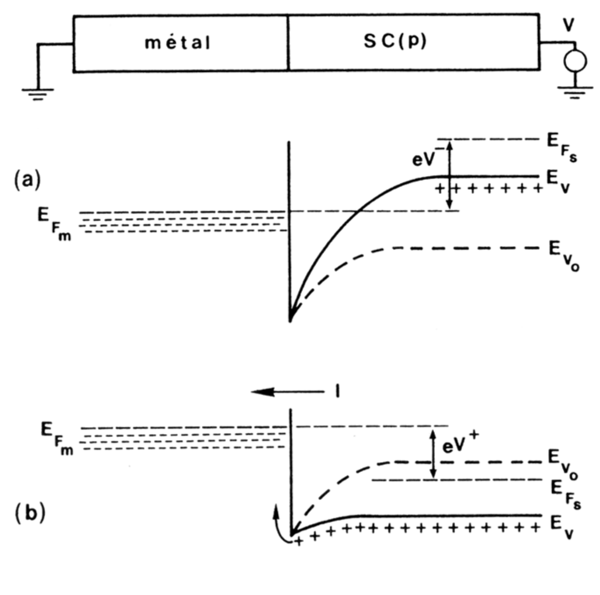
Ohmic contact or diode ?

« ohmic »

P type Semi-conductor

« rectifier »





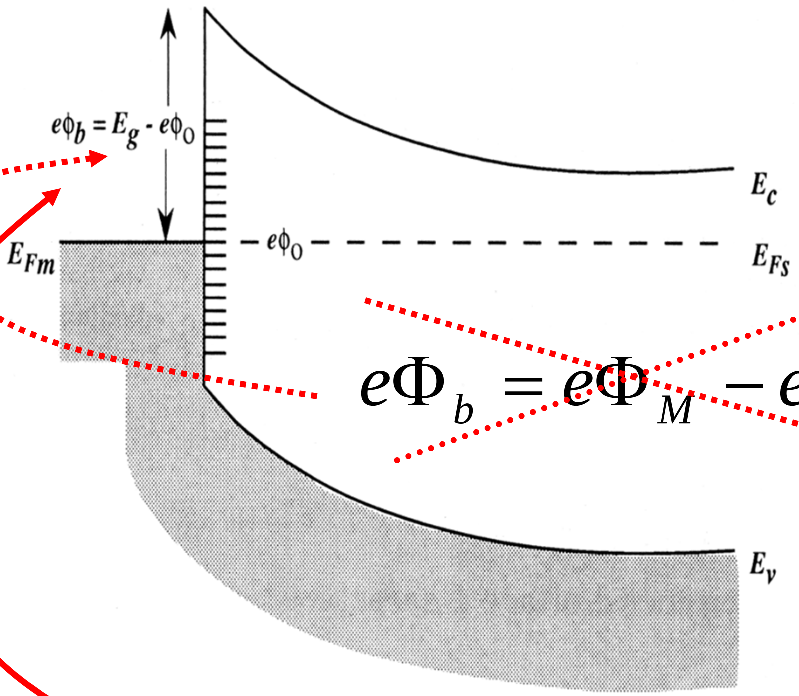
$$e\phi_m > e\phi_s$$

$$e\phi_m < e\phi_s$$

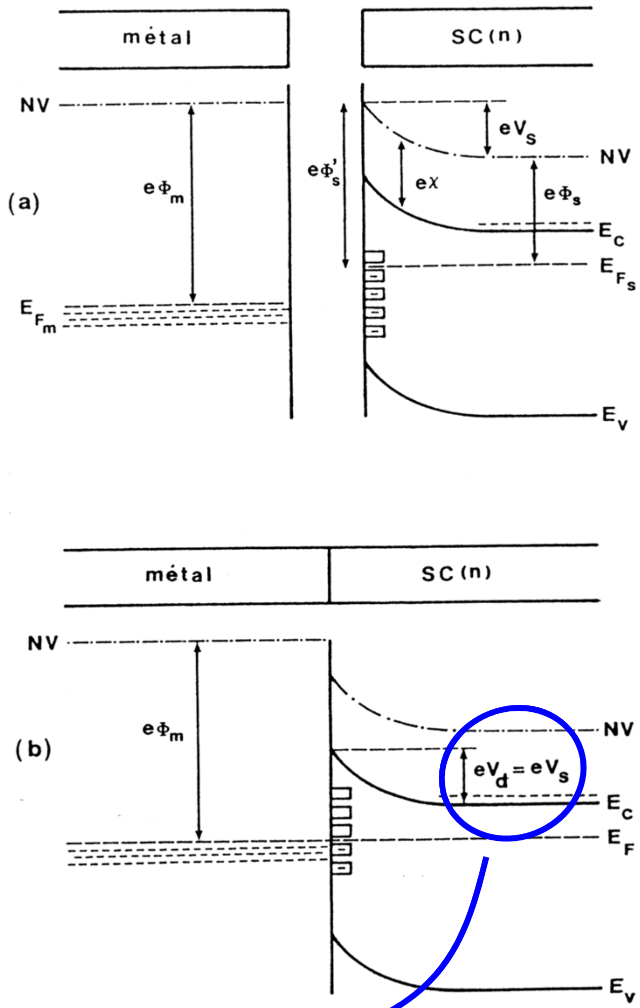
Ohmic contact or diode ?

- *At the real metal - SC interface, large number of interface states in the bandgap region ⇔ the previous simplist model has to be improved*

Non ideal Schottky Diode: interface states



$$\cancel{e\Phi_b = e\Phi_M - e\chi_{SC}}$$



$$e\Phi_b = E_g - e\Phi_0 = cte$$

$$eV_{bi} = eV_d = e\Phi_M - e\Phi_{SC} = e\Phi_{MS}$$

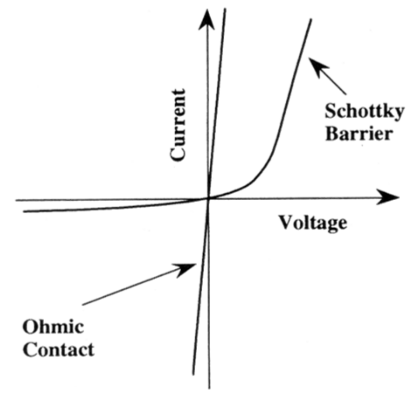
Ohmic Contacts

- The end of interconnections on the devices.
- Ohmic contact:
  - No drop voltage (short circuit?)
  - No resistance to current flow

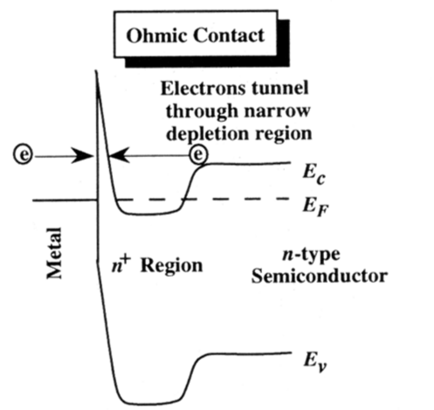
- *how ?*
  - *1st method : chose the metal with appropriate work function (see above), but not always possible (and problem with interface states)*
  - *2nd method : use heavily doped semiconductors*

Ohmic Contacts

- Ohmic contact
  - Very high doping to the interface region
  - Depletion layer will be extremely narrow, thin
  - Electrons tunneling allowed



(a)



(b)

$$R_c \propto \exp\left(-\frac{4\pi}{h}\phi_b\sqrt{(\varepsilon_{sc}m_e^*)/(eNd)}\right)$$

Voltage - Capacitance characteristic C(V).

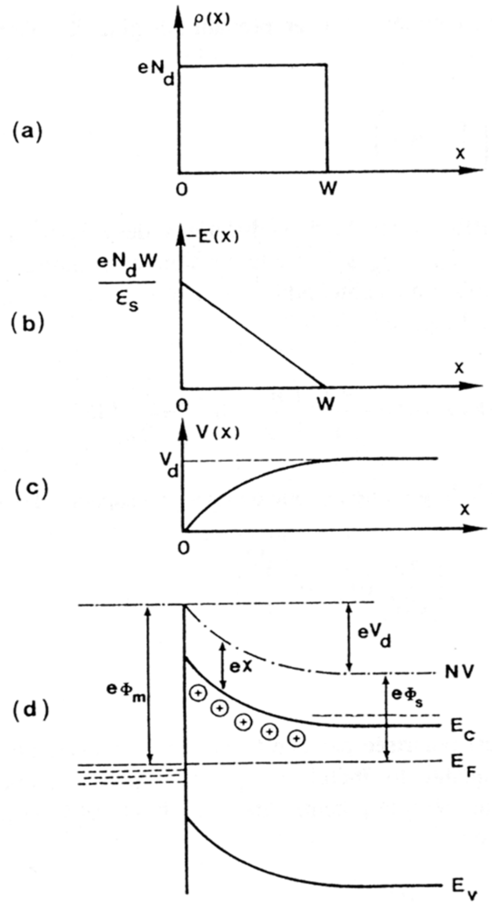
- We get the same results as with the PN Junction:

$$\frac{d^2V(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_{SC}}$$

$$E(x) = -\frac{eN_d}{\varepsilon_{SC}}(x - W) \qquad V(x) = -\frac{eN_d}{\varepsilon_{SC}}\left(\frac{x^2}{2} - Wx\right)$$

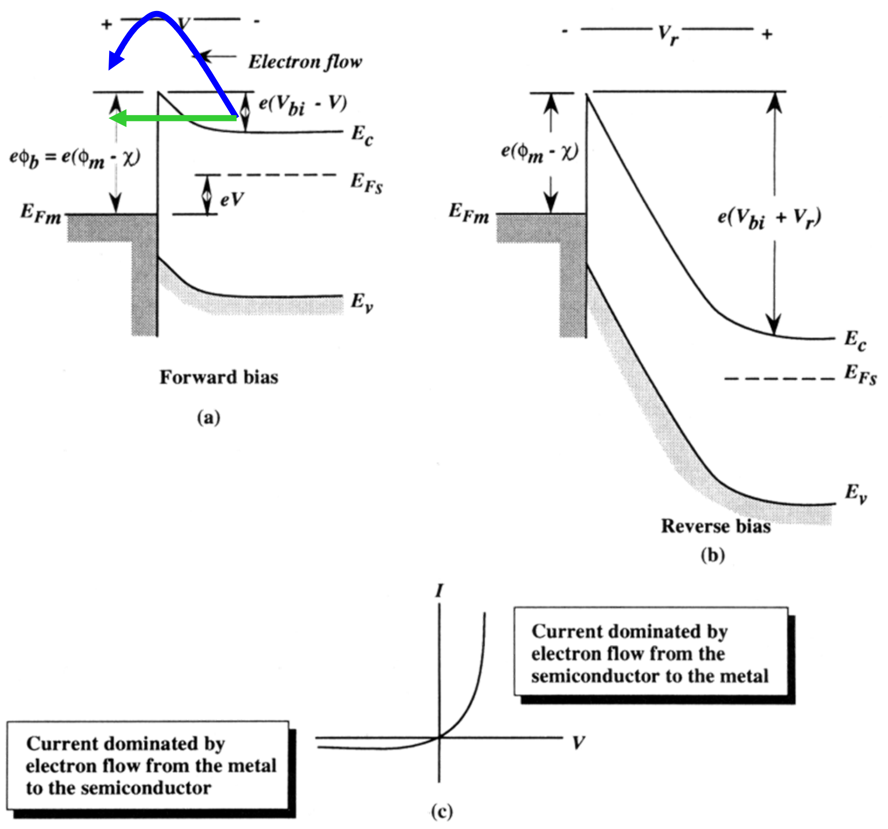
$$W = \sqrt{\frac{2\varepsilon_{SC}(V_{bi} - V)}{eN_d}}$$

$$C = A\left|\frac{dQ}{dV}\right| = A\left[\frac{e\varepsilon_{SC}N_d}{2(V_{bi} - V)}\right]^{\frac{1}{2}} = \frac{\varepsilon_{SC}A}{W}$$



Current in the Schottky diode :I(V)

- Several mechanisms are responsible of current:
  - Thermionic emission
  - Tunnel flowing
- The main difference with PN junction:
  - Current only due to majoritary carriers !!

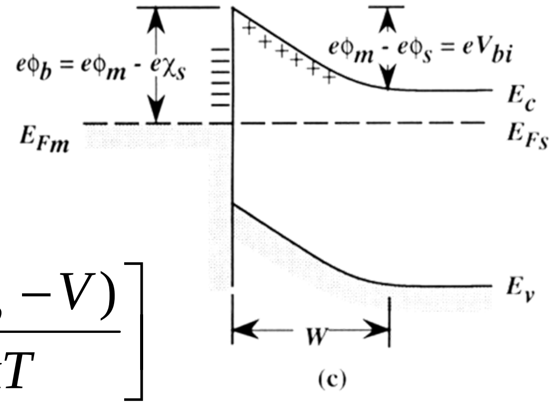


Current in the Schottky diode :I(V)

Thermionic current: the electrons which can overcome the barrier $e(V_{bi}\text{-}V)$ will contribute to the current:

$$n_b = n_0 \exp\left[-\frac{e(V_{bi}-V)}{kT}\right] \qquad \text{avec} \qquad n_0 = N_C \exp\left[-\frac{E_C-E_F}{kT}\right]$$

or:



$$n_b = N_C \exp\left[-\frac{E_C-E_F+V_{bi}-V}{kT}\right] = N_C \exp\left[-\frac{e(\Phi_b-V)}{kT}\right]$$

Current in the Schottky diode :I(V)

- We can show (Singh) that the average flux of electrons impinging the Metal/SC barrier is $< v > n_b/4$ where $< v >$ is the average speed of the electrons.

- The corresponding current is then given by (A is the device area) :

$$I_{SM}(V) = \frac{e < v > A}{4} N_C \exp\left[-\frac{e(\Phi_b - V)}{kT}\right]$$

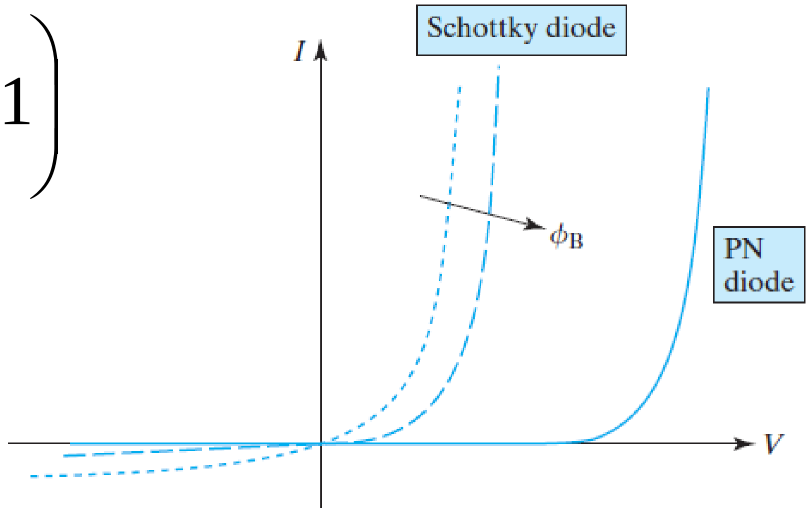
- When the applied voltage is zero, the current is null. In fact the current I_{MS} flowing from metal to SC is balanced by the current I_{SM} from SC to Metal.

$$I_{MS} = -I_{SM}(0) = -\frac{e < v > A}{4} N_C \exp\left[-\frac{e(\Phi_b)}{kT}\right]$$

Current in the Schottky diode :I(V)

- When a potential V is applied, $I_{MS} = cte = I_S$ and the current is given by:

$$I = I_{SM} - I_{MS} = I_S\left(\exp\left[\frac{eV}{kT}\right] - 1\right)$$



The above expression can be rewritten (MB statistics):

$$I = \underbrace{A\left(\frac{m^* ek^2}{2\pi^2\hbar^3}\right)}_{\text{constant of Richardson } \mathfrak{R}} T^2 \exp\left(-\frac{e\Phi_b}{kT}\right)\left[\exp\left[\frac{eV}{kT}\right] - 1\right]$$

Small signal equivalent circuit

- *Equivalent circuit components:*
  - Differential resistance

$$R_d = \frac{dV}{dI}$$

  - Differential capacitance of depletion layer

$$C_d = A\left(\frac{eN_d \varepsilon_{SC}}{2(V_{bi} - V)}\right)^{\frac{1}{2}}$$

  - Serie resistance

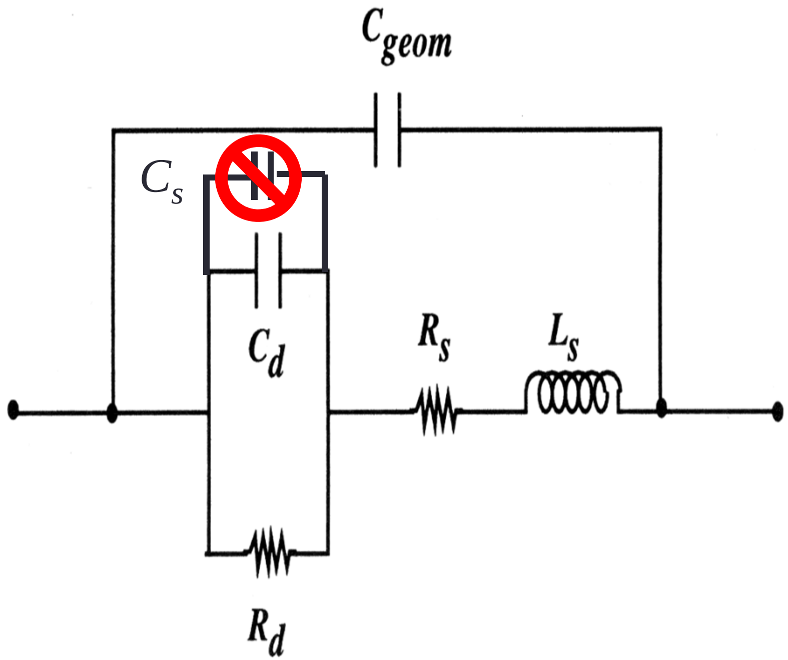
$$R_S = R_{contacts} + R_{RN}$$

  - Parasitic Inductance

$$L_S$$

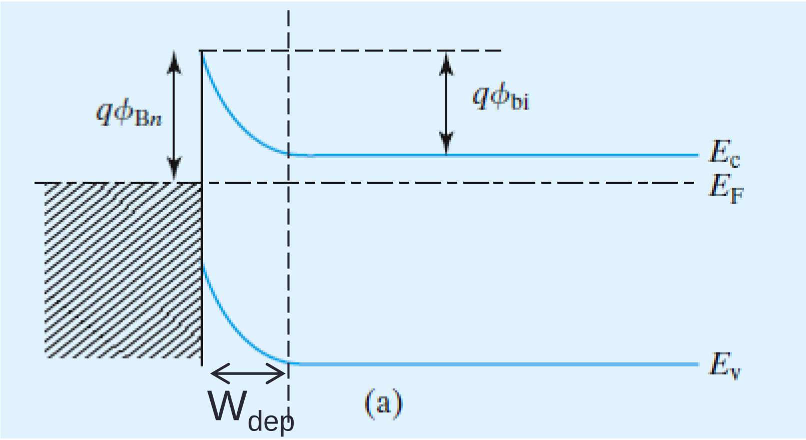
  - Device geometric capacitance (L: device length)

$$C_{géom} = \frac{\varepsilon_{SC} A}{L}$$

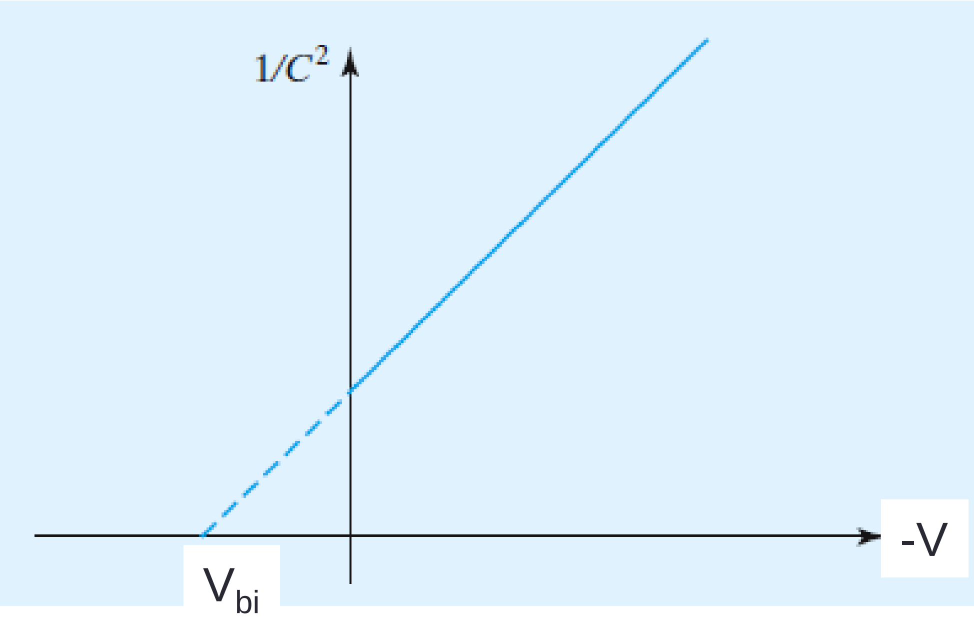


C - V Data

$$C_d = \frac{A\varepsilon_{sc}}{W_{dep}} = A\left(\frac{eN_d\varepsilon_{SC}}{2(V_{bi}-V)}\right)^{\frac{1}{2}}$$



$$\frac{1}{C_d^2} = \frac{2(V_{bi}-V)}{eN_D\varepsilon_{SC}A^2}$$



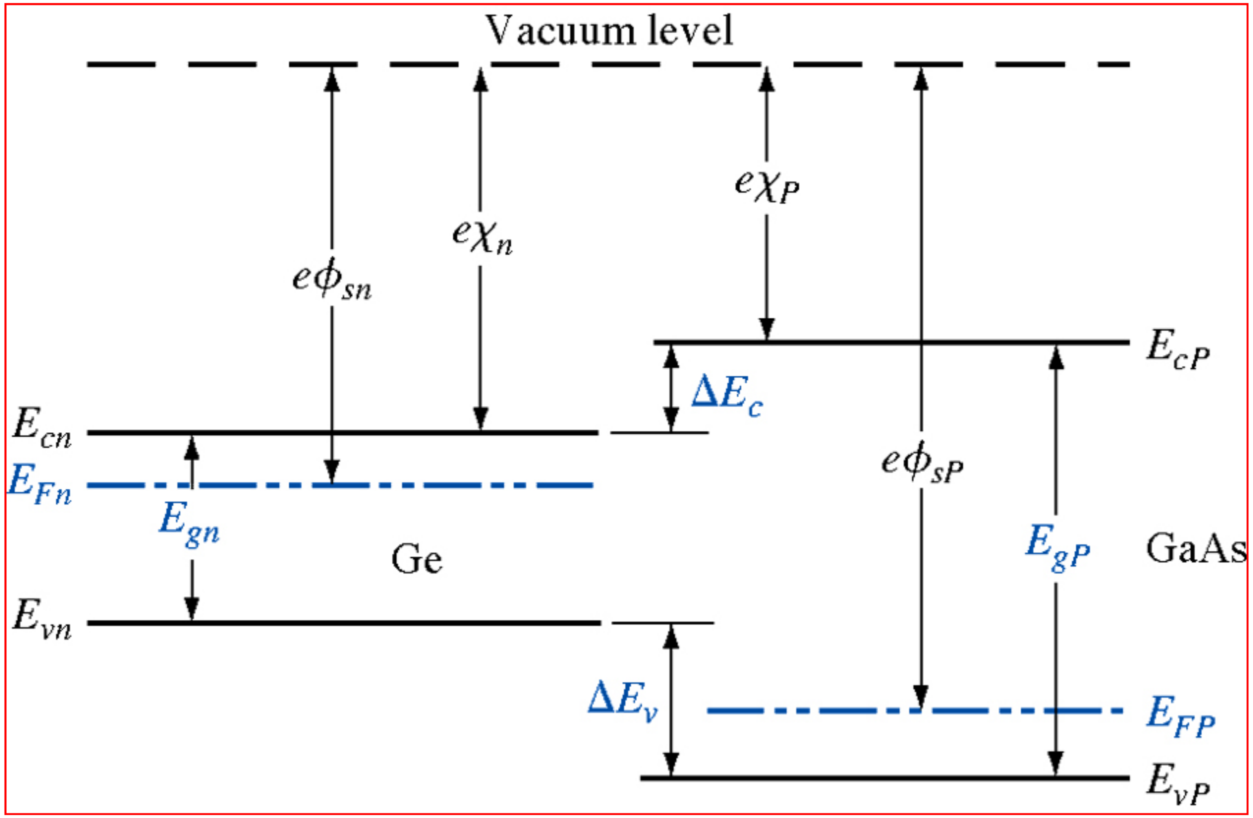
By determining V_{bi} and N_d (slope), we can get ϕ_b (if χ_{SC} is unknown)

Comparison PN vs Schottky (from Singh)

PN Diode	Schottky Diode
Reverse current due to minority carriers diffusion => strong temperature dependance	Reverse current due to minority carriers diffusion => strong temperature dependance
Forward current due to Minoritary carriers from n and p regions	Forward current due to majoritary carriers from the SC
Forward bias (the « on voltage ») needed to make the device on is quite large	The « on voltage » is small
Switching controlled by elimination of minority injected carriers	Switching speed controlled by thermalisation of electrons across the barrier : few ps
Ideality factor between 1 and 2 due to recombination process in depletion layer	Essentially no recombination in depletion region => Ideality factor ~ 1

heterojunction

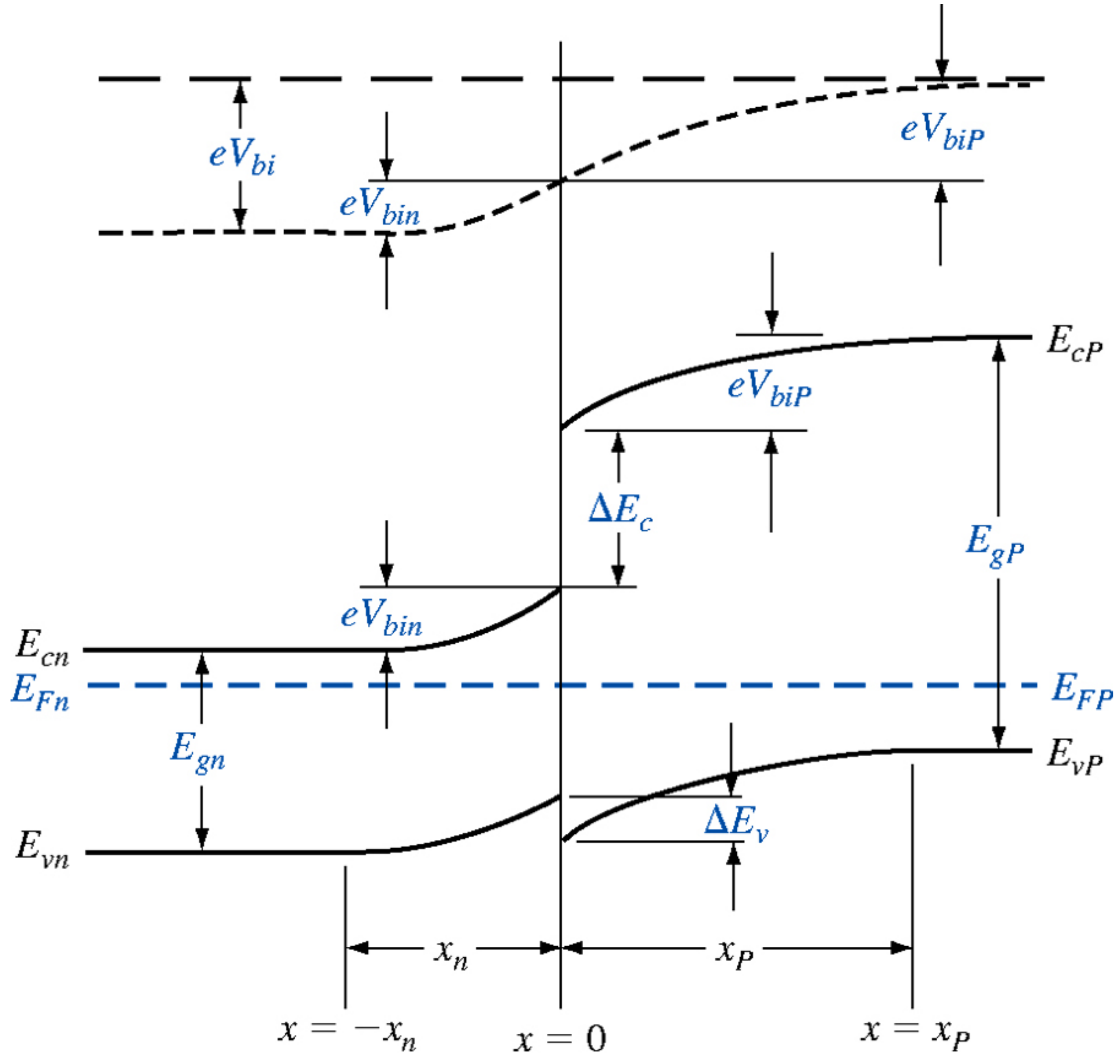
- Contact between two different semiconductor materials⇔ different gaps ⇔ energy bands discontinuity at interface.



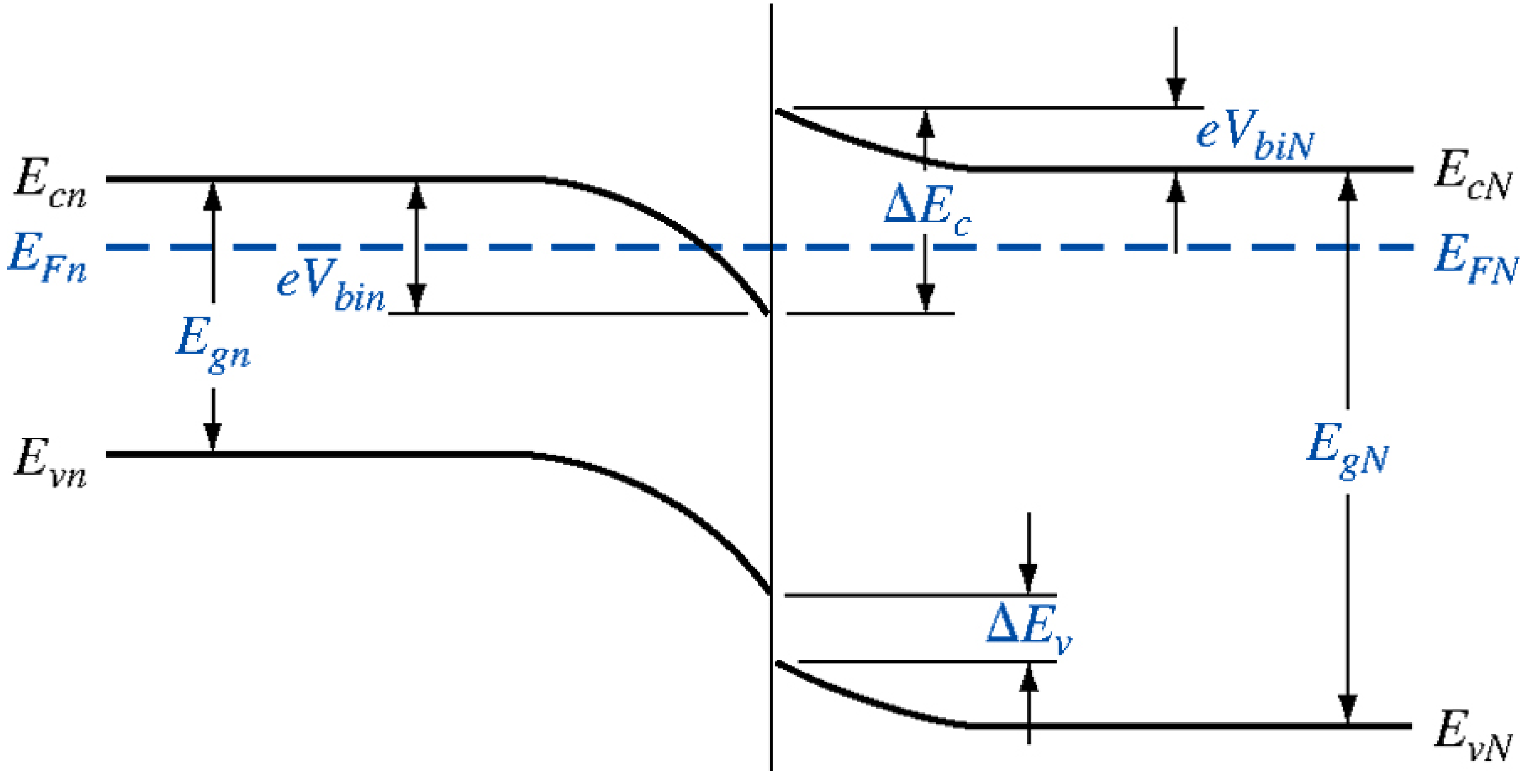
$$\Delta E_C = e(\chi_n - \chi_p)$$

$$\Delta E_C + \Delta E_V = \Delta E_g$$

Junction formation SC(n)/SC(P)



Junction formation SC(n)/SC(N)



Occurrence of a two-dimensional electron gas