Semiconductor Devices

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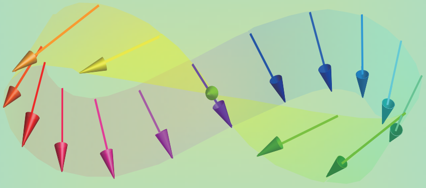

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11:00 Tuesday, 2/December/2014 (P/T 006)

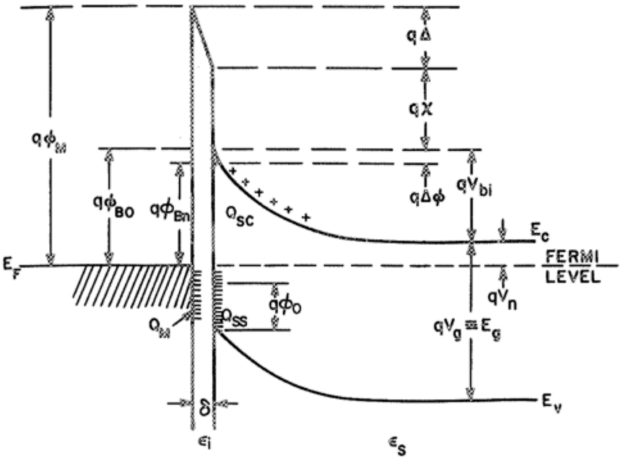
Exercise 5

State the following metals in contact with Si to form either Schottky or Ohmic contacts based on their energy diagram. Assume the following parameters:

Si electron affinity: χ = 4.05 eV

and Si bandgap: E_g = 1.11 eV.

Metal	Work function ϕ_M [eV]	*n*-type Si	*p*-type Si
Pt	6.30		
Au	4.80		
Cu	4.18		
Ni	4.01		



Answer to Exercise 5

The electron affinity is defined as

$$\chi = (\text{vacuum level}) - E_C$$

For an *n*-type contact,

$\phi_M < \chi$: ( ) contact

$\phi_M > \chi$: ( ) contact with the barrier height of $\phi_B = \phi_M - \chi$

For an *p*-type contact,

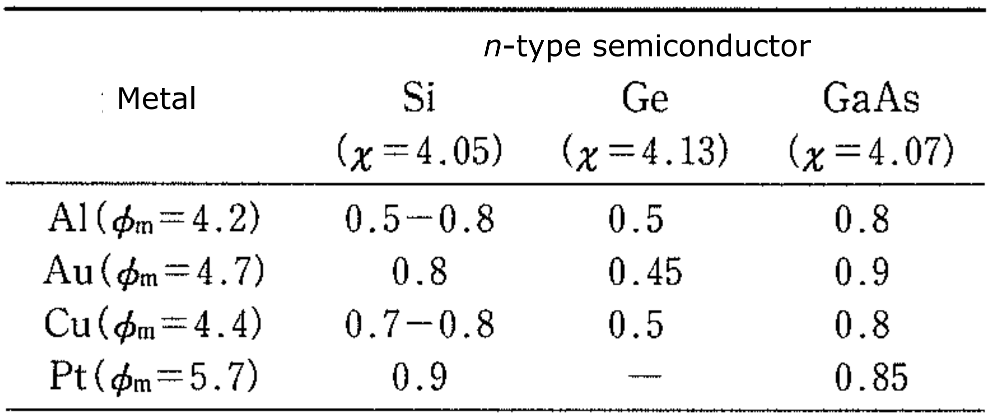
$\phi_M > \chi + E_g$: ( ) contact

$\phi_M < \chi + E_g$: ( ) contact with the barrier height of $\phi_B = \chi + E_g - \phi_M$

Metal	Work function ϕ_M [eV]	*n*-type Si	*p*-type Si
Pt	6.30	Schottky contact ϕ_B = eV	Ohmic contact ϕ_M (= 6.30) > χ + E_g (= 4.05 + 1.11)
Au	4.80	Schottky contact ϕ_B = eV	Schottky contact ϕ_B = eV
Cu	4.18	Schottky contact ϕ_B = 4.18 − 4.05 = 0.13 eV	Schottky contact ϕ_B = 4.05 + 1.11 − 4.18 = 0.98 eV
Ni	4.01	Ohmic contact ϕ_M (= 4.01) < χ (=4.05)	Schottky contact ϕ_B = 4.05 + 1.11 − 4.01 = 1.15 eV

Answer to Exercise 5

Metal	Work function ϕ_M [eV]	*n*-type Si	*p*-type Si
Pt	6.30	Schottky contact ϕ_B = 6.30 − 4.05 = 2.25 eV	Ohmic contact ϕ_M (= 6.30) > χ + E_g (= 4.05 + 1.11)
Au	4.80	Schottky contact ϕ_B = 4.80 − 4.05 = 0.75 eV	Schottky contact ϕ_B = 4.05 + 1.11 − 4.80 = 0.36 eV
Cu	4.18	Schottky contact ϕ_B = 4.18 − 4.05 = 0.13 eV	Schottky contact ϕ_B = 4.05 + 1.11 − 4.18 = 0.98 eV
Ni	4.01	Ohmic contact ϕ_M (= 4.01) < χ (=4.05)	Schottky contact ϕ_B = 4.05 + 1.11 − 4.01 = 1.15 eV



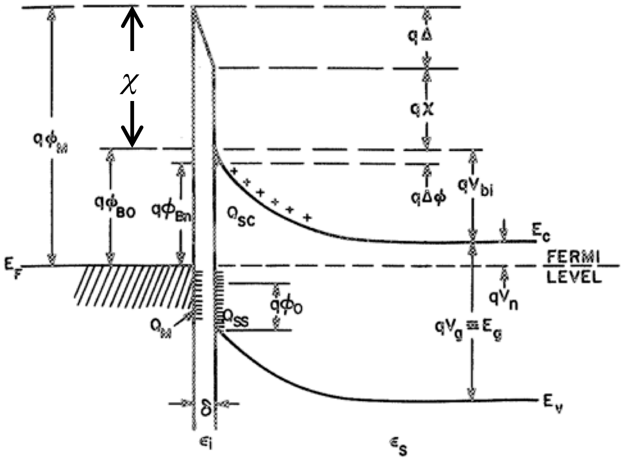
Metal	*n*-type semiconductor		
	Si (χ=4.05)	Ge (χ=4.13)	GaAs (χ=4.07)
Al (ϕ_m=4.2)	0.5−0.8	0.5	0.8
Au (ϕ_m=4.7)	0.8	0.45	0.9
Cu (ϕ_m=4.4)	0.7−0.8	0.5	0.8
Pt (ϕ_m=5.7)	0.9	—	0.85

26 Schottky Junction

- Image force
- Schottky effect
- Depletion layer capacity
- Ohmic contact

Schottky Barrier

Definition of energy at the Schottly barrier :

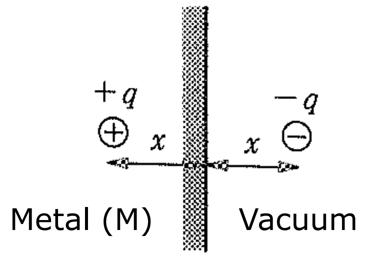


ϕ_M = WORK FUNCTION OF METAL
ϕ_{Bn} = BARRIER HEIGHT OF METAL-SEMICONDUCTOR BARRIER
ϕ_{B0} = ASYMPTOTIC VALUE OF ϕ_{Bn} AT ZERO ELECTRIC FIELD
ϕ_0 = ENERGY LEVEL AT SURFACE
$\Delta\phi$ = IMAGE FORCE BARRIER LOWERING
Δ = POTENTIAL ACROSS INTERFACIAL LAYER
χ = ELECTRON AFFINITY OF SEMICONDUCTOR
V_{bi} = BUILT-IN POTENTIAL
ϵ_s = PERMITTIVITY OF SEMICONDUCTOR
ϵ_i = PERMITTIVITY OF INTERFACIAL LAYER
δ = THICKNESS OF INTERFACIAL LAYER
Q_{sc} = SPACE-CHARGE DENSITY IN SEMICONDUCTOR
Q_{ss} = SURFACE-STATE DENSITY ON SEMICONDUCTOR
Q_M = SURFACE-CHARGE DENSITY ON METAL

* S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 2006).

Image Force

Origin of image force :



Force between the two electrons :

$$F = \frac{q\cdot(-q)}{4\pi\varepsilon_0 (2x)^2} \qquad [\qquad\qquad\qquad\qquad]$$

* S. Kishino, *Physics of Semiconductor Devices* (Maruzen, Tokyo, 1995).

Image Force at a Metal Semiconductor Interface

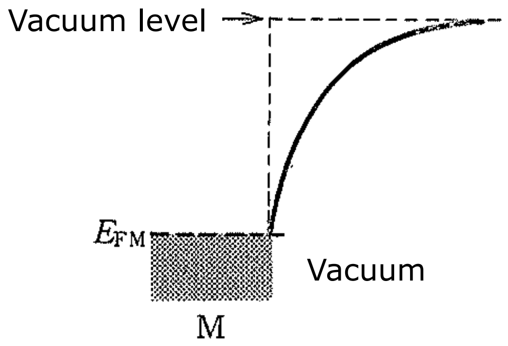
Potential energy for an electron :

$$E(x) = \int_\infty^x F\,dx = \int_\infty^x \frac{q\cdot(-q)}{4\pi\varepsilon_0 (2x)^2}dx = -\int_\infty^x \frac{q^2}{16\pi\varepsilon_0 x^2}dx$$

$$= \left[\frac{-q^2}{16\pi\varepsilon_0}\cdot\frac{x^{-2+1}}{(-2+1)}\right]_\infty^x = \left[\frac{q^2}{16\pi\varepsilon_0}\cdot\frac{1}{x}\right]_\infty^x = \frac{q^2}{16\pi\varepsilon_0}\left(\frac{1}{x}-\frac{1}{\infty}\right)$$

$$=$$

Image force at a metal semiconductor interface :



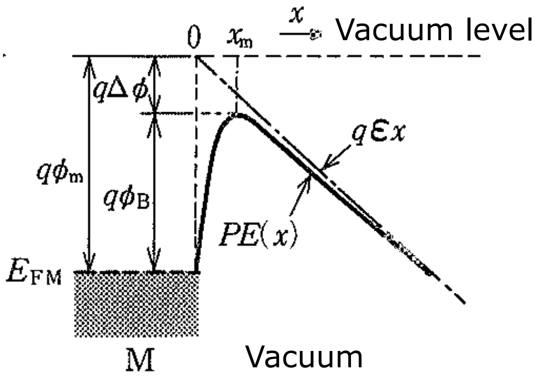
* S. Kishino, *Physics of Semiconductor Devices* (Maruzen, Tokyo, 1995).

External Electric Field Application

Under an electric field ***E*** :

$$E(x) =$$

Schottky barrier at a metal semiconductor interface :

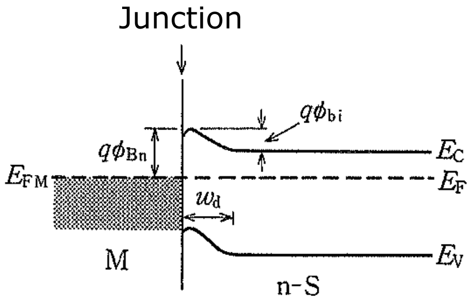


( ) effect

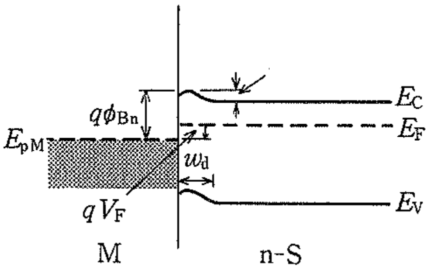
* S. Kishino, *Physics of Semiconductor Devices* (Maruzen, Tokyo, 1995).

Metal - Semiconductor Junction

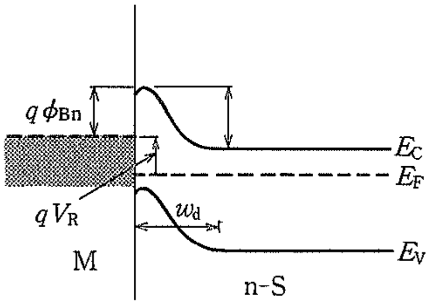
Realistic energy diagram of a Schottky junction :



Under a forward bias application :



Under a reverse bias application :



* S. Kishino, *Physics of Semiconductor Devices* (Maruzen, Tokyo, 1995).

Depletion Layer Capacity

Under reverse bias, Poisson's equation is defined as

$$\frac{d^2V_R}{dx^2} = -q\frac{N_D}{\varepsilon} \qquad (0 \le x \le w)$$

where the donor density is assumed to be constant.

Here, the boundary conditions are

$$V(0) = 0 \quad \text{at} \quad x = 0$$

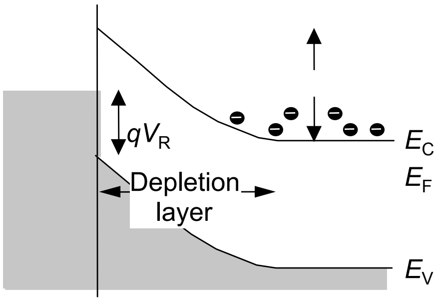
$$V(w) = V_{bi} + V_R, \quad \frac{dV(w)}{dx} = 0 \quad \text{at} \quad x = w$$

Therefore, the depletion layer width w can be determined by

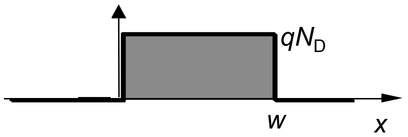
$$w = \sqrt{\frac{2\varepsilon(V_{bi}+V_R)}{qN_D}}$$

Depletion layer capacity C is

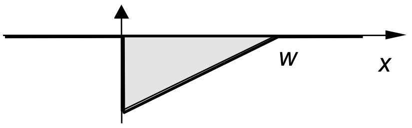
$$C = \frac{\varepsilon}{w} = \sqrt{\frac{q\varepsilon N_D}{2(V_{bi}+V_R)}}$$



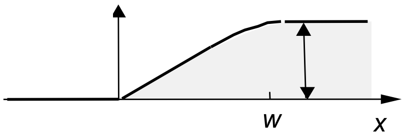
Charge distributions



Electric field distributions



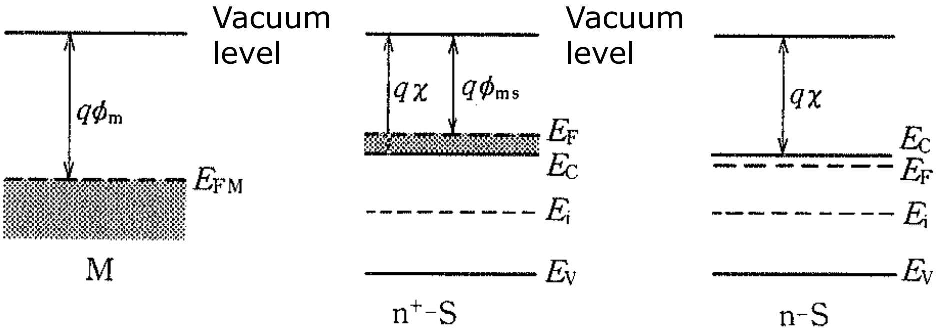
Potential distributions



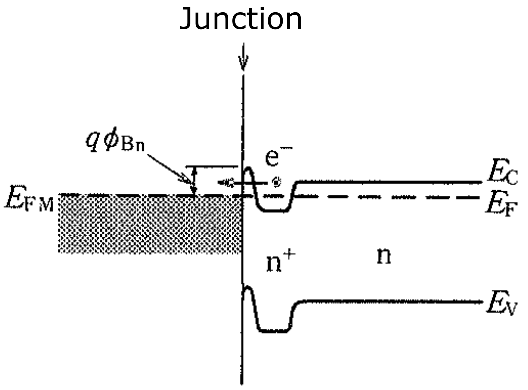
* www.tc.knct.ac.jp/~hayama/denshi/chapter3.ppt

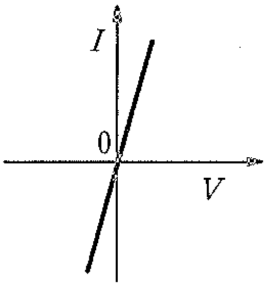
Ohmic Contact

By highly doping an interfacial region :



Metal ( ) semiconductor Semiconductor

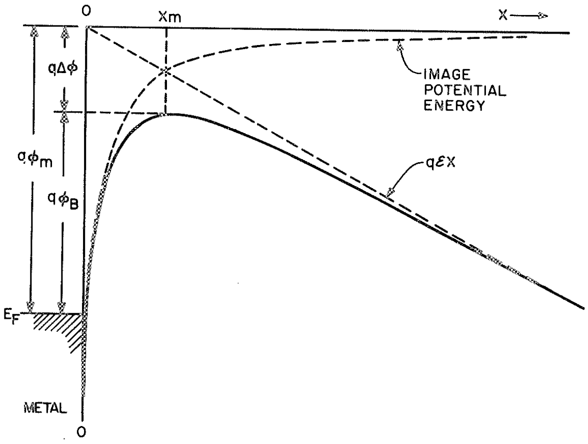


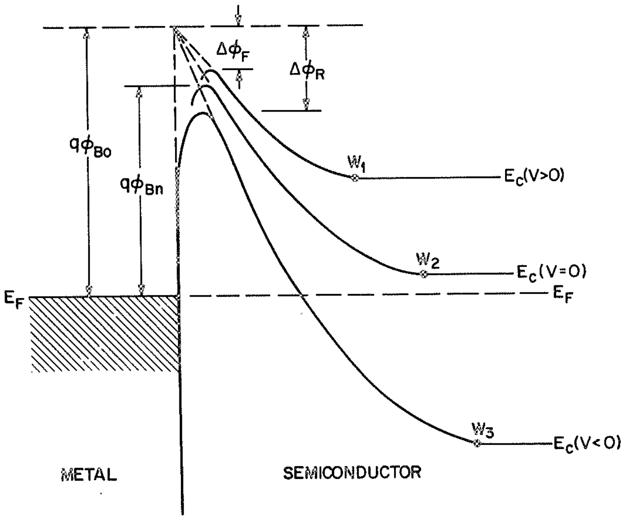


* S. Kishino, *Physics of Semiconductor Devices* (Maruzen, Tokyo, 1995).

Realistic Schottky Barrier

Image force and Shottky barrier :

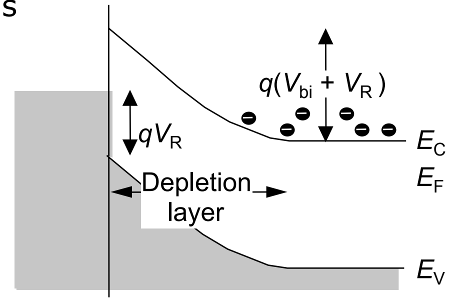




* S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 2006).

Exercise 6

Calculate the depletion layer capacity at a reverse bias V_R = 0.5 V in a Au/*n*-Si Schottky diode. Assume the following parameters:



Au work function: $\phi_M = 4.80$ eV

n-region: doping density of $N_D = 1 \times 10^{21}$ m^{-3}

Si electron affinity: $\chi = 4.05$ eV

Si Fermi level: $E_F = E_C - 0.15$ eV

permittivity: $\varepsilon = \varepsilon \times \varepsilon_0 = 12.0 \times 8.854 \times 10^{-12}$ F/m

and $q = 1.6 \times 10^{-19}$ C.