Semiconductor Devices

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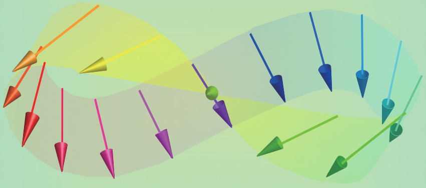

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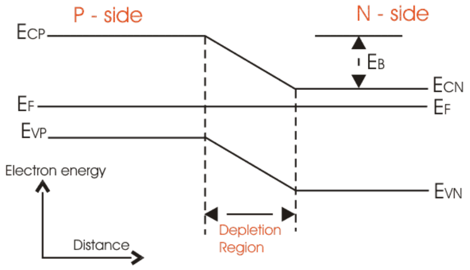
11:00 Monday, 1/December/2014 (P/L 005)

Exercise 4

Calculate the depletion layer width of an abrupt *p*-*n* junction diode which is made from Silicon and has the following properties:

p-region: doping density of $N_A = 2 \times 10^{21}$ m^{-3}
n-region: doping density of $N_D = 1 \times 10^{21}$ m^{-3}
permittivity: $\varepsilon = \varepsilon \times \varepsilon_0 = 12.0 \times 8.854 \times 10^{-12}$ F/m
and $q = 1.6 \times 10^{-19}$ C.



Answer to Exercise 4

The depletion layer widths are defined as

$x_p =$

(Here, V_{bi} = 590 mV from the previous exercise 3.)

$x_n =$

By substituting the given values into the above relationship,

$$x_p = \sqrt{\frac{2 \cdot 12.0 \times 8.854 \times 10^{-12} \cdot 0.59}{1.6 \times 10^{-19} \cdot 2 \times 10^{21}} \cdot \frac{1 \times 10^{21}}{2 \times 10^{21} + 1 \times 10^{21}}}$$

$$= 3.61 \cdots \times 10^{-7} [\mathrm{m}]$$

$$\approx$$

$$x_n = \sqrt{\frac{2 \cdot 12.0 \times 8.854 \times 10^{-12} \cdot 0.59}{1.6 \times 10^{-19} \cdot 1 \times 10^{21}} \cdot \frac{2 \times 10^{21}}{2 \times 10^{21} + 1 \times 10^{21}}}$$

$$= 7.23 \cdots \times 10^{-7} [\mathrm{m}]$$

$$\approx$$

$$x = x_p + x_n$$

$$= 360 [\mathrm{nm}] + 720 [\mathrm{nm}]$$

$$\approx$$

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25 Metal Semiconductor Junction

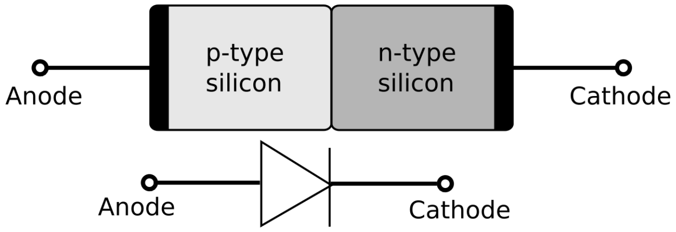
- Work function
- Metal / *n*-type semiconductor
- Metal / *p*-type semiconductor
- Einstein relationship
- Schottky barrier

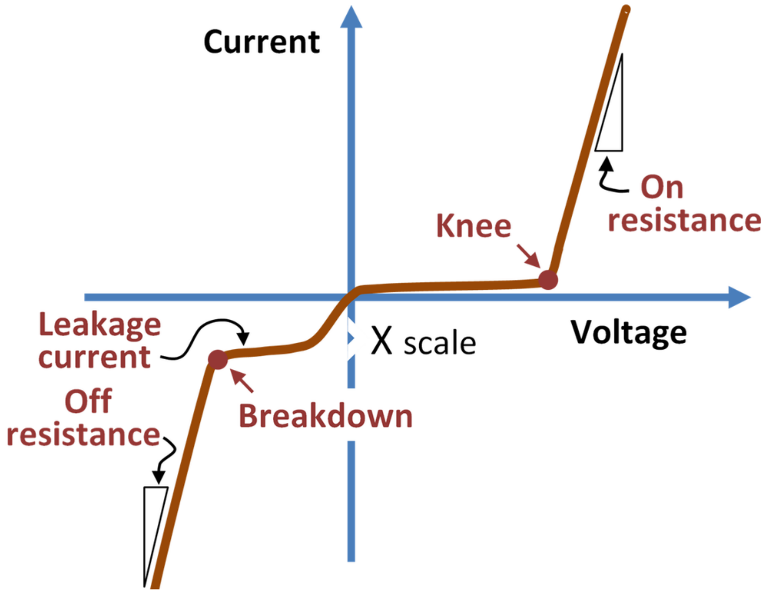
p-n Diode

A junction made by attaching *p*- and *n*-doped semiconductors :

Widely used to insulate transistors.

Common circuit to convert ac to dc in a battery charger.





* http://www.wikipedia.org/

Metal Junctions

Work function ϕ :

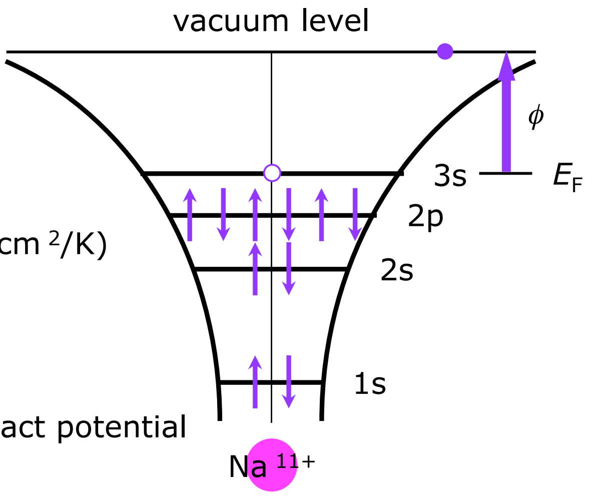
Current density of thermoelectrons :

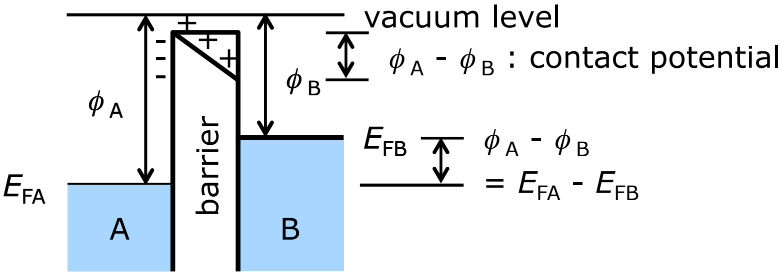
$J =$

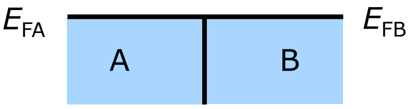
→ Richardson-Dushman equation

A : Richardson constant (~120 A·cm ^{2}/K)

Metal - metal junction :



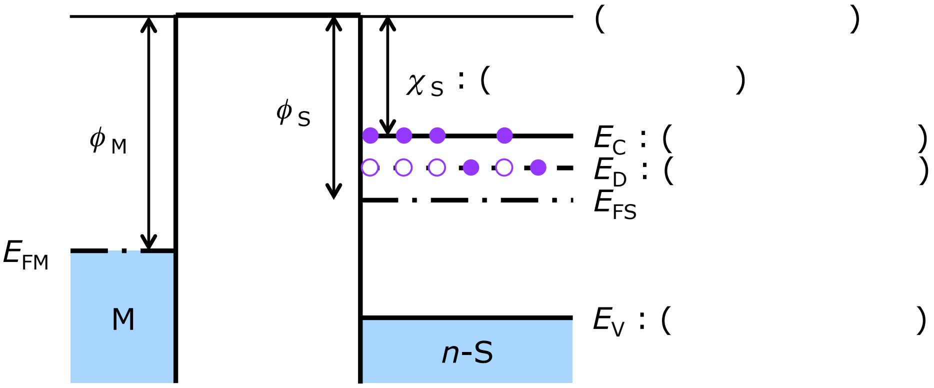


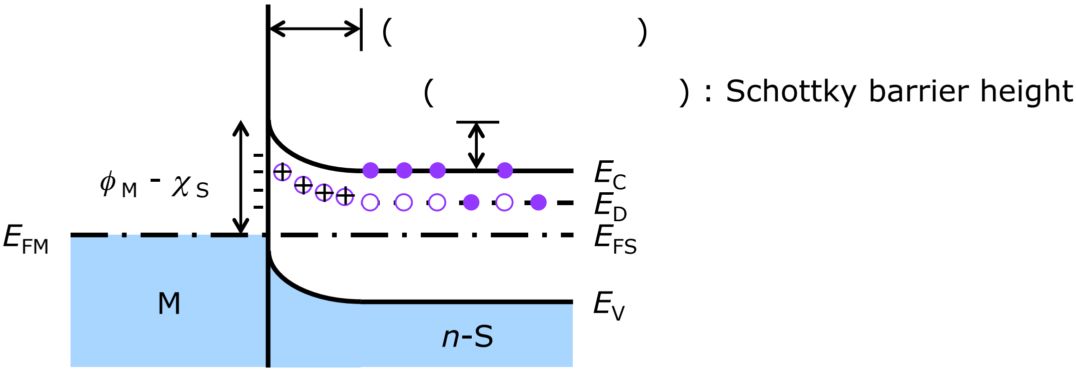


$E_{FA} = E_{FB}$

Metal - Semiconductor Junction - *n*-Type

Metal - *n*-type semiconductor junction :

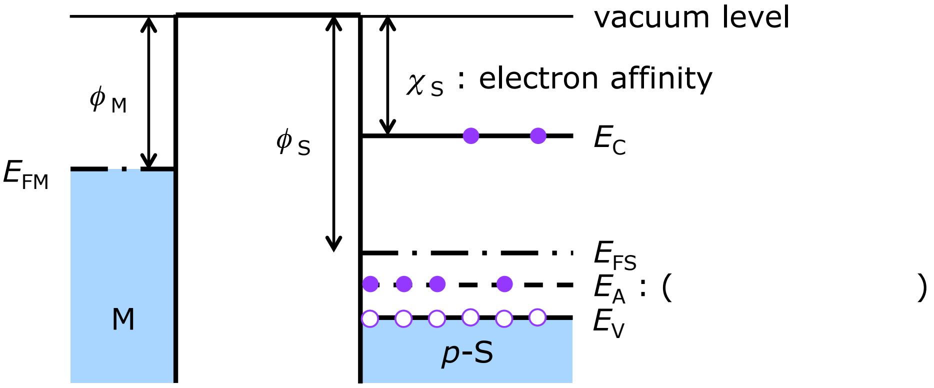


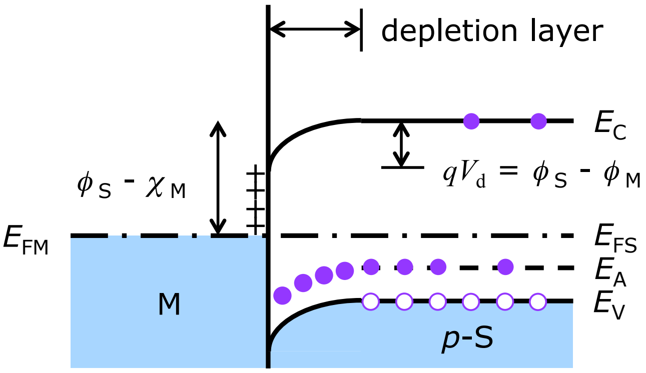


* http://www.dpg-physik.de/

Metal - Semiconductor Junction - *p*-Type

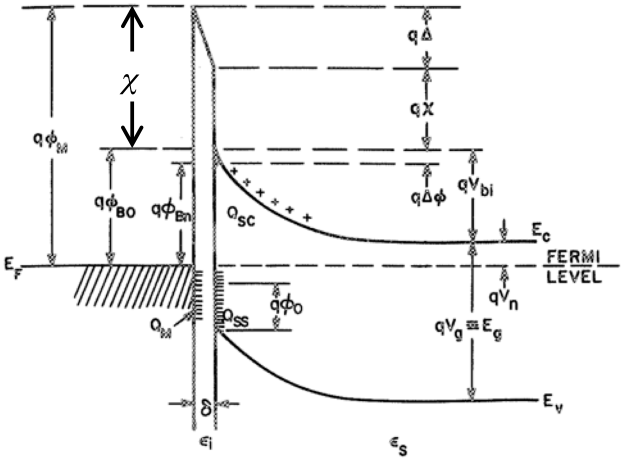
Metal - *p*-type semiconductor junction :





Schottky Barrier

Definition of energy at the Schottly barrier :



ϕ_M = WORK FUNCTION OF METAL
ϕ_{Bn} = BARRIER HEIGHT OF METAL-SEMICONDUCTOR BARRIER
ϕ_{Bo} = 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).

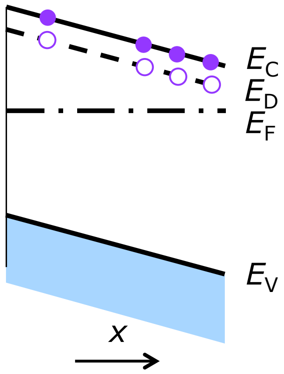
Einstein Relationship

At the equillibrium state,

Numbers of electrons diffuses towards -*x* direction are

$$-D_{\mathrm{e}}\frac{dn}{dx} \qquad \text{(-}x\text{ direction)}$$

(n : electron number density, D_{e} : diffusion coefficient)



Drift velocity of electrons with mobility μ_{e} under *E* is

$$v_{\mathrm{d}} = -\mu_{\mathrm{e}} E$$

Numbers of electrons travel towards +*x* direction under *E* are

$$n v_{\mathrm{d}} = -\mu_{\mathrm{e}} n E \qquad \text{(+}x\text{ direction)}$$

As *E* is generated by the gradient of E_C, *E* is along -*x* and v_{d} is +*x*.

$$-\mu_{\mathrm{e}} n E - D_{\mathrm{e}}\frac{dn}{dx} = 0 \qquad \text{(equillibrium state)}$$

Assuming $E_V = 0$, electron number density is defined as

$$n = N_{\mathrm{e}} \exp\left(-\frac{E_{\mathrm{C}} - E_{\mathrm{F}}}{k_{\mathrm{B}} T}\right)$$

Einstein Relationship (Cont'd)

Now, an electric field E produces voltage $V_{\mathrm{CF}} = V_{\mathrm{C}} - V_{\mathrm{F}}$

$$E_{\mathrm{C}} - E_{\mathrm{F}} = -qV_{\mathrm{CF}} = -q\left(V_{\mathrm{C}} - V_{\mathrm{F}}\right)$$

$$\therefore E = -\frac{dV_{\mathrm{CF}}}{dx} = \frac{1}{q}\frac{d\left(E_{\mathrm{C}} - E_{\mathrm{F}}\right)}{dx}$$

Accordingly,

$$\frac{dn}{dx} = \frac{dn}{d\left(E_{\mathrm{C}} - E_{\mathrm{F}}\right)} \cdot \frac{d\left(E_{\mathrm{C}} - E_{\mathrm{F}}\right)}{dx} = -\frac{1}{k_{\mathrm{B}}T} n \cdot qE$$

$$\therefore \mu_{\mathrm{e}} nE = D_{\mathrm{e}} \frac{nqE}{k_{\mathrm{B}}T}$$

$$\therefore D_{\mathrm{e}} = \mu_{\mathrm{e}} \frac{k_{\mathrm{B}}T}{q} \quad \rightarrow (\qquad\qquad\qquad\qquad)$$

Therefore, a current density J_n can be calculated as

$$J_n = -\left(-q\mu_{\mathrm{e}} nE - qD_{\mathrm{e}}\frac{dn}{dx}\right) = qD_{\mathrm{e}}\left(-\frac{qn}{k_{\mathrm{B}}T} \cdot \frac{dV_x}{dx} + \frac{dn}{dx}\right)$$

$$\therefore J_n = B\left[\exp\left(-\frac{q\left(V_{\mathrm{d}} - V\right)}{k_{\mathrm{B}}T}\right) - \exp\left(-\frac{qV_{\mathrm{d}}}{k_{\mathrm{B}}T}\right)\right]$$

Rectification in a Schottky Junction

By applying a bias voltage V onto a metal - n-type semiconductor junction :

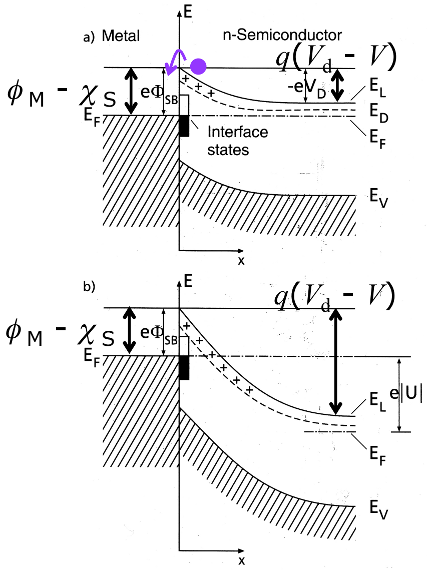
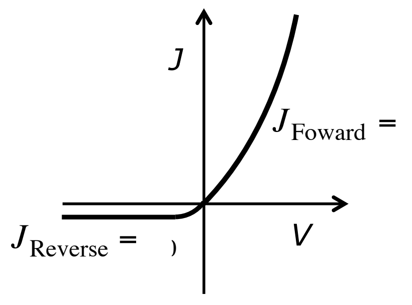


Fig. 12.22. Electronic band scheme of a metal/semiconductor (n-doped) junction; pinning of the Fermi-level E_{F} in interface states near the neutrality level causes the formation of a Schottky-barrier $e\phi_{\mathrm{SB}}$ and a depletion space charge layer within the semiconductor. V_{D} is the "built-in" diffusion voltage. (**a**) In thermal equilibrium, (**b**) under external bias U

forward bias

$$J_{\mathrm{Foward}} = J_{\mathrm{M}\rightarrow\mathrm{S}} - J_{\mathrm{S}\rightarrow\mathrm{M}} = B\left[\exp\left(-\frac{q\left(V_{\mathrm{d}} - V\right)}{k_{\mathrm{B}}T}\right) - \exp\left(-\frac{qV_{\mathrm{d}}}{k_{\mathrm{B}}T}\right)\right]$$

$$= J_0\left[\exp\left(\frac{qV}{k_{\mathrm{B}}T}\right) - 1\right] \approx J_0 \exp\left(\frac{qV}{k_{\mathrm{B}}T}\right) \qquad (V : \mathrm{large})$$



reverse bias

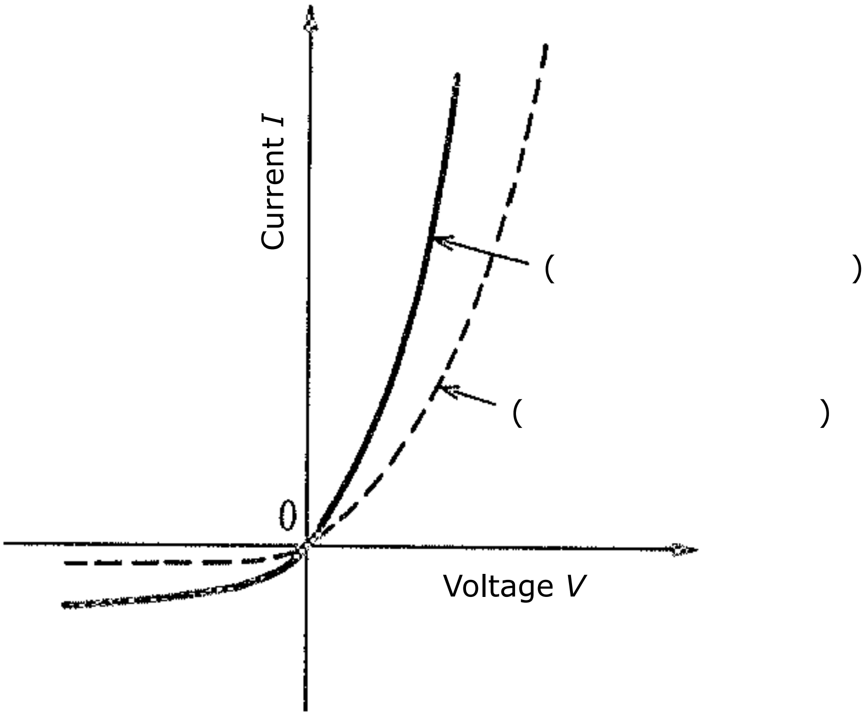
$$J_{\mathrm{Reverse}} = J_{\mathrm{M}\rightarrow\mathrm{S}} - J_{\mathrm{S}\rightarrow\mathrm{M}} = B\left[\exp\left(-\frac{q\left(V_{\mathrm{d}} + V\right)}{k_{\mathrm{B}}T}\right) - \exp\left(-\frac{qV_{\mathrm{d}}}{k_{\mathrm{B}}T}\right)\right]$$

$$= J_0\left[\exp\left(-\frac{qV}{k_{\mathrm{B}}T}\right) - 1\right] \approx J_0 \qquad (V : \mathrm{large})$$

* H. Ibach and H. Lüth, *Solid-State Physics* (Springer, Berlin, 2003).

Comparison between *p-n* and Schottky Junctions

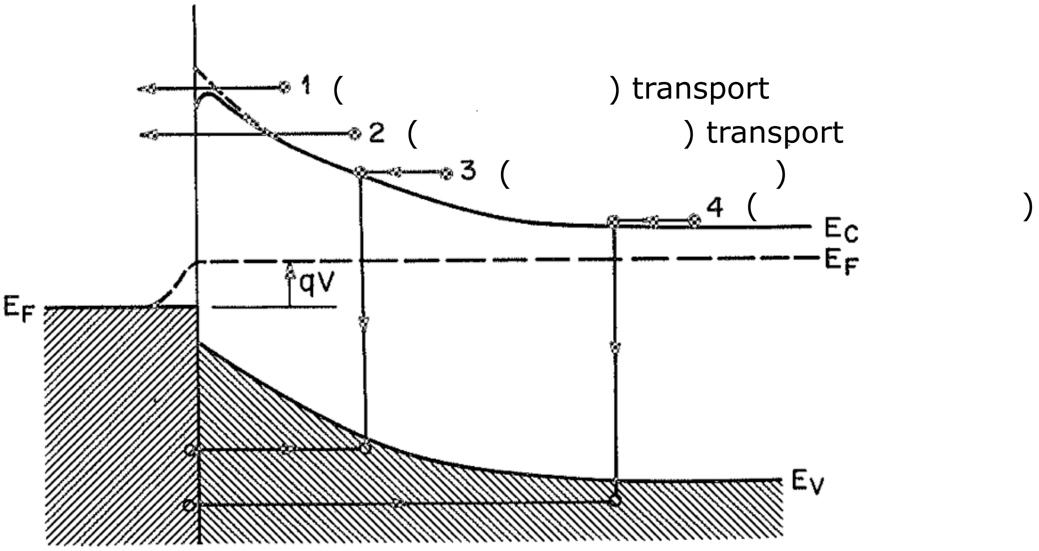
Current-voltage characteristics :



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

Transport across a Schottky Barrier

Four major transport across the Schottly barrier :



Forward bias

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

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