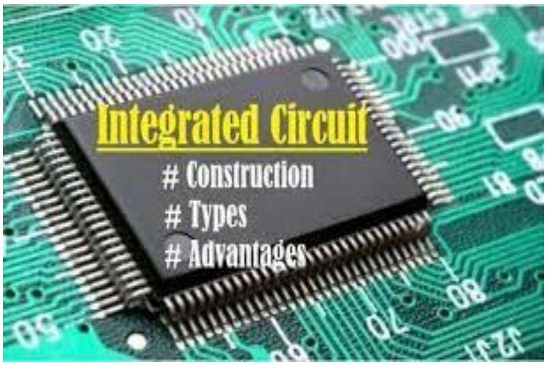
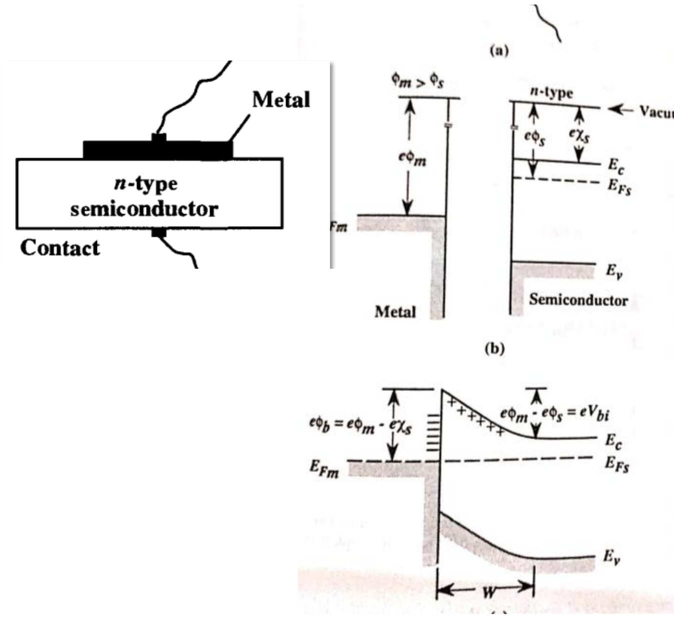
Metals in Electronic circuits:

1. As interconnects between two devices
2. As Schottky barrier junction with rectification
3. As Ohmic contacts, little resistance to current



Aluminium is a commonly used interconnect material, with very low resistivity.



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

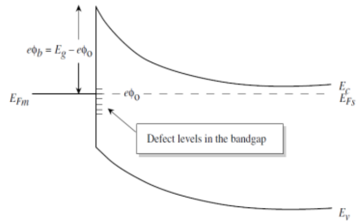
Fig. 41: A schematic of a Schottky barrier junction, (b) The junction potential produced when the metal and semiconductor are brought together. Due to the built-in potential at the junction, a depletion region of width W is created.

Metal-semiconductor contact: Schottky Barrier Diode

Electrons from semiconductor to metal face a barrier.

Barrier height

$$\phi_b = \phi_m - \phi_s + (E_c - E_{Fs}) = e\phi_n - e\chi_s$$
$$e\phi_b = E_g - e\phi_0$$



Real junction φ_b is independent of metal due to

Real barrier height lowers due to imaginary force.

C-V characteristic

Depletion approximation

$$W = \left[\frac{2\epsilon(V_{bi} - V)}{eN_d}\right]^{\frac{1}{2}}$$

Maximum field

$$F_m = -\frac{eN_d W}{\epsilon} = -\left\{\frac{2\epsilon N_d(V_{bi} - V)}{\epsilon}\right\}^{\frac{1}{2}}$$

$$Q = eN_d W = [2e\epsilon N_d(V_{bi} - V)]^{\frac{1}{2}}$$

$$C = A.\frac{dQ}{dV} = A.\left[\frac{e\epsilon N_d}{2(V_{bi} - V)}\right] = \frac{\epsilon A}{W}$$

So, plot of $\frac{1}{C^2}$ vs V provides information about V_{bi} and N_d.

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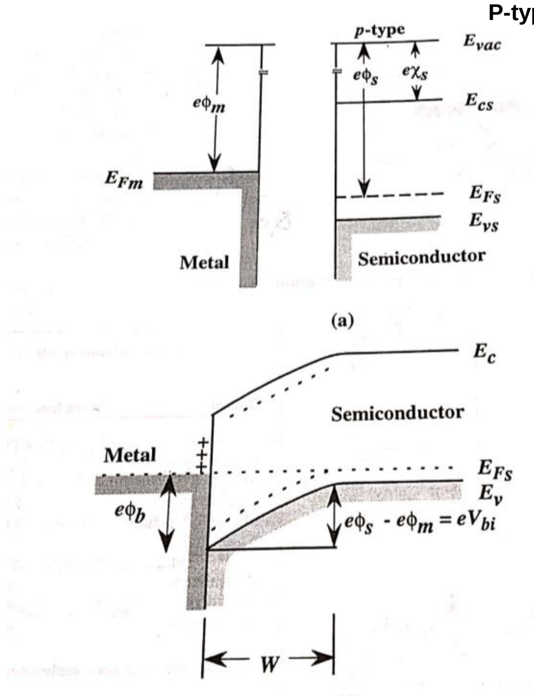
P-type Semiconductor/ Metal Junction



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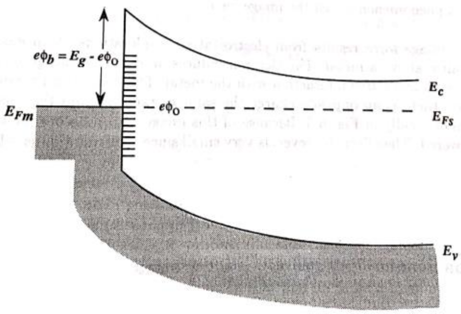
Schottky Metal	n Si	p Si	nGaAs
Aluminum, Al	0.7	0.8	
Titanium, Ti	0.5	0.61	
Tungsten, W	0.67		
Gold, Au	0.79	0.25	0.9
Silver, Ag			0.88
Platinum, Pt			0.86
PtSi	0.85	0.2	
$NiSi_2$	0.7	0.45	

Table 6.2: Schottky barrier heights (in volts) for several metals on *n*- and *p*-type semiconductors. The barrier height is seen to have a rather weak dependence upon the metal used.

A neutral level φ_o is defined so that the interface states above φ_o are neutral if they are empty and those below φ_o are filled.



Pinned Fermi level, barrier height is independent of metal.

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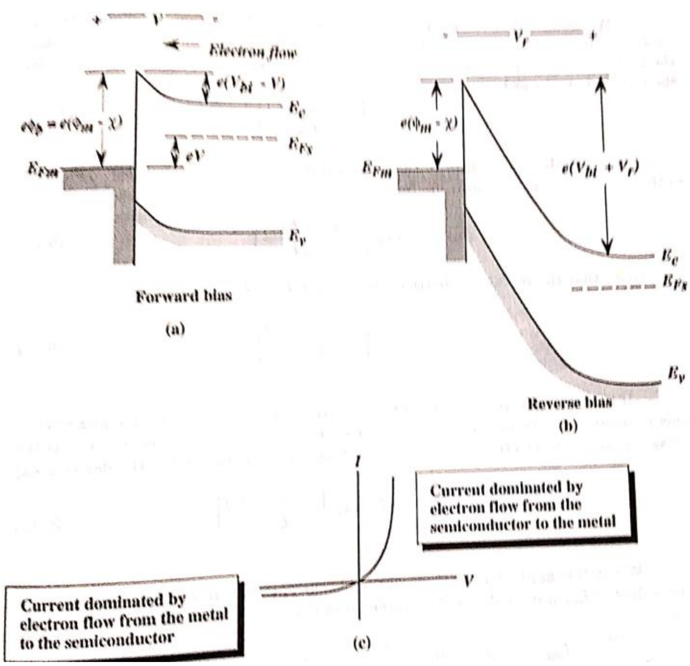
Under bias



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I-V characteristics

Electron with energy greater than the barrier e (V_{bi}-V) ,

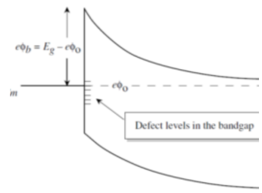
(i) Thermionic emission , (ii) Tunneling current (heavily doped, thin depletion layer).

Fraction of electrons with energy greater than e(V_{bi}-V) $\mathbf{n_b = n_0 \exp\{-\frac{e(V_{bi}-V)}{kT}\}}$

$$\mathbf{n_0 = N_c \exp\{-\left(\frac{E_c - E_{Fs}}{kT}\right)\}} \qquad \mathbf{e\phi_b = eV_{bi} + E_c - E_{Fs}}$$

n_0= neutral region density

$$\boxed{\mathbf{n_0 = N_c \exp\left[-\frac{(e\phi_b - eV)}{kT}\right]}}$$



$$\mathbf{I_{sm} = \frac{eA < v >}{4} . N_c \exp\left[-\frac{e(\phi_b - V)}{kT}\right]}$$

$$\mathbf{I_{ms} = I_{sm}(V=0) = -\frac{eA < v >}{4} . N_c \exp\left(-\frac{e\phi_b}{kT}\right) = I_s}$$

Average flux of electron impinging on the M-S barrier is

Average flux of electrons impinging $\mathbf{< v > . \frac{n_b}{4}}$

$$\mathbf{F = I_{sm} - I_{ms} = I_s\left[\exp\left(\frac{eV}{kT}\right) - 1\right]}$$

From MB distribution function, for electron $\mathbf{< v > = \left(\frac{8kT}{\pi m^*}\right)^{\frac{1}{2}}}$

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So, $$\mathbf{I_s = A\left(\frac{m^* e k^2}{2\pi^2 \hbar^3}\right) T^2 \exp\left(-\frac{e\phi_b}{kT}\right)}$$

$$\mathbf{\left(\frac{m^* e k^2}{2\pi^2 \hbar^3}\right) = R^*}$$

$$\mathbf{R^* = 120\left(\frac{m^*}{m_0}\right) = Richardson\ constant}$$

$$\mathbf{= 110\ A\ cm^{-2} k^{-2}\ for\ Si}$$

I_s in Schottky diode is much higher than that in p-n junction.

If φ_b is small, I_s is higher (not good). So, large barrier is required.

Real device $\mathbf{I = I_s\left[\exp\left(\frac{eV}{mkT}\right) - 1\right]}$ m ≈ 1 as recombination count is low, no minority carrier.

For highly doped semiconductor , tunneling current dominates

$$\mathbf{I = AJ_0{}^t \exp\left(\frac{eV}{E_0}\right)}$$

For low voltage $I \propto V$ [Ohmic]

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Comparison of Schottky and p-n diode:

	Schottky	p-n
1. Temperature dependence	weak	strong
2. Speed	high	low
3. Recombination	no	large
4. Ideality factor	m~ 1	m ~ 1.2-2.0
5. T-E current	I-F is high	I-F low (V const.

Device very fast: switching speed controlled by thermalization of "hot" injected electrons across the barrier ~ few picoseconds

Switching speed controlled by recombination (elimination) of minority injected carriers

Schottky application : Photodetector (electron field), Thin metal film for transparency.

Insulator - semiconductor junction:

SiO_2 – Si lattice mismatched.

Thermal oxidation

MOS capacitor/ device.

$SiO_2 \rightarrow$ mask for dopant diffusion.

Example 5.2 In a W-n-type Si Schottky barrier the semiconductor has a doping of 10^{16} cm^{-3} and an area of 10^{-3} cm^2.
(a) Calculate the 300 K diode current at a forward bias of 0.3 V.
(b) Consider an Si $p^+ - n$ junction diode with the same area with doping of $N_a = 10^{19}$ cm^{-3} and $N_d = 10^{16}$ cm^{-3}, and $\tau_p = \tau_n = 10^{-6}$ s. At what forward bias will the p-n diode have the same current as the Schottky diode? $D_p = 10.5$ cm^2/s.

From table 5.2 the Schottky barrier of W on Si is 0.67 V. Using an effective Richardson constant of 110 A cm$^{-2}K^{-1}$, we get for the reverse saturation current

$$
\begin{aligned}
I_s &= (10^{-3}\ \mathrm{cm}^2) \times (110\ \mathrm{A\ cm}^{-2}K^{-2}) \times (300K)^2 \ \exp\left(\frac{-0.67(\mathrm{eV})}{0.026(\mathrm{eV})}\right) \\
&= 6.37 \times 10^{-8}\ \mathrm{A}
\end{aligned}
$$

For a forward bias of 0.3 V, the current becomes (neglecting 1 in comparison to exp (0.3/0.026))

$$
\begin{aligned}
I &= 6.37 \times 10^{-8} A\ \exp(0.3/0.026) \\
&= 6.53 \times 10^{-3}\ \mathrm{A}
\end{aligned}
$$

In the case of the p-n diode, we need to know the appropriate diffusion coefficients and lengths. The diffusion coefficient is 10.5 cm^2/s, and using a value of $\tau_p = 10^{-6}$s we get $L_p = 3.24 \times 10^{-3}$ cm. Using the results for the abrupt $p^+ - n$ junction, we get for the saturation current ($p_n = 2.2 \times 10^4$ cm^{-3}) (note that the saturation current is essentially due to hole injection into the n-side for a p^+-n diode)

$$\begin{aligned} I_o &= (10^{-3}\ \mathrm{cm}^2) \times (1.6 \times 10^{-19}\ \mathrm{C}) \times \frac{(10.5\ \mathrm{cm}^2/\mathrm{s}^{-1})}{(3.24 \times 10^{-3}\ \mathrm{cm})} \times (2.25 \times 10^4\ \mathrm{cm}^{-3}) \\ &= 1.17 \times 10^{-14}\ \mathrm{A} \end{aligned}$$

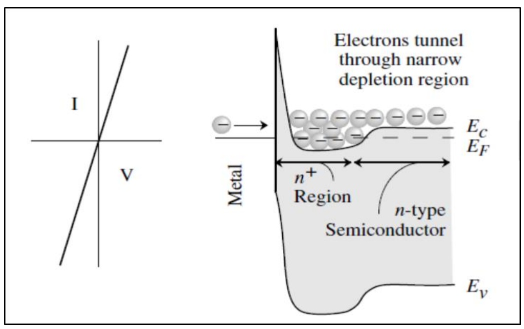
This is an extremely small value of the current. At 0.3 V, the diode current becomes

$$I = I_s \exp\left(\frac{eV}{k_B T}\right) = 1.2 \times 10^{-9}\ \mathrm{A}$$

a value which is almost six orders of magnitude smaller than the value in the Schottky diode. For the p-n diode to have the same current that the Schottky diode has at 0.3 V, the voltage required is 0.71 V.

This example highlights the important differences between Schottky and junction diodes. The Schottky diode turns on (i.e., the current is $\sim$1 mA) at 0.3 V while the p-n diode turns on at closer to 0.7 V.

Ohmic contact



$$W = \left[\frac{2\epsilon V_{bi}}{eN_d}\right]^{1/2}$$

The quality of an Ohmic contact is usually defined through the resistance R of the contact over a certain area A. The normalized resistance is called the specific **contact resistance r_c** and is given by $r_c = R \cdot A$

$$\ln\,(r_c) \propto \frac{1}{\ell n(T)} \propto \frac{(V_{bi})^{3/2}}{F}$$

Where T is the tunneling probability.

$$\frac{V_{bi}}{W} \propto (V_{bi})^{1/2}\,(N_d)^{1/2}$$

Thus, $$\ell n\,(r_c) \propto V_{bi} \propto \frac{1}{\sqrt{N_d}}$$

Alloying to produce heavily doped semiconductors

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- The resistance can be reduced by using a low Schottky barrier height and doping as heavily as possible.
- The predicted dependence of the contact resistance on the doping density is, indeed, observed experimentally.
- It is observed from experiments that it is usually more difficult to obtain contacts with p−type semiconductors with low resistance. This is due to the difficulty in p-doping.
- It is also due to the fact that in many materials the relatively high effective mass of holes, leads to reduced tunnelling currents.
- In the case of many wide bandgap semiconductors, such as GaN, the barrier heights between available metals and the valence band is much greater than that of the conduction band.

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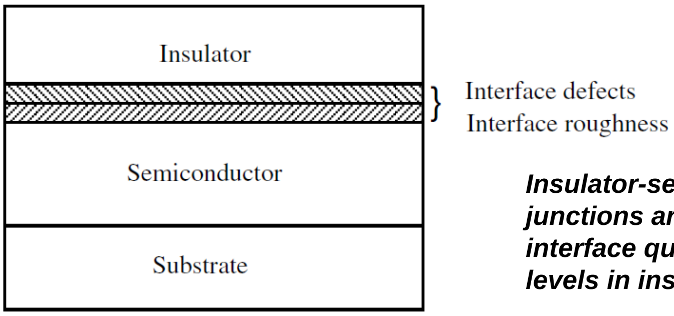
INSULATOR-SEMICONDUCTOR JUNCTIONS

- Materials with large bandgaps are called insulators.
- These materials have very high resistivity and are used to isolate regions to prevent current flow.
- Most insulator-semiconductor combinations involve structures that are *not lattice-matched*. In most cases the insulator and the semiconductor do not even share the same basic lattice type.



Insulator-semiconductor junctions are dominated by interface quality and defect levels in insulators.

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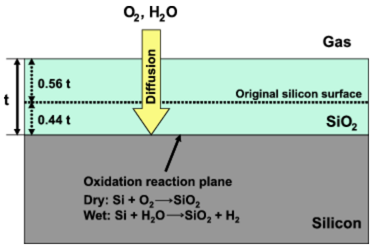


$$Si + O_2 \rightarrow SiO_2$$

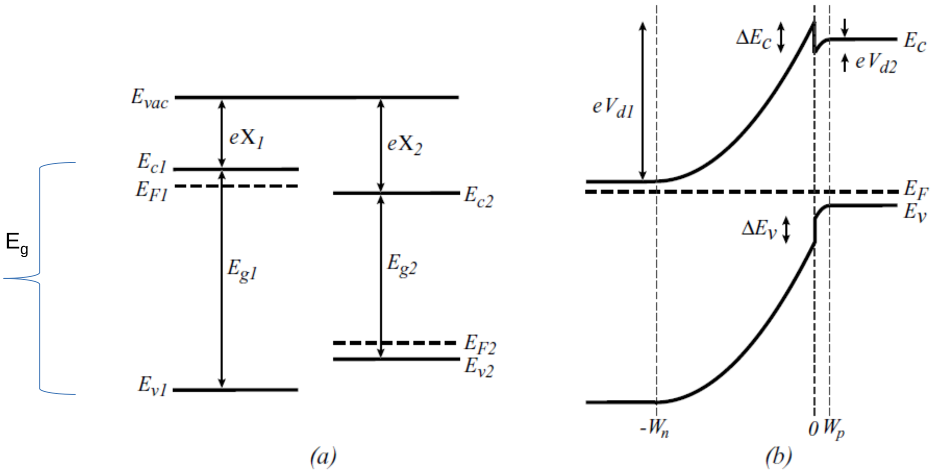
$$Si + 2H_2O \rightarrow SiO_2 + 2H_2$$

Insulator-Silicon

- The most important junction in solid state electronics is the **SiO_2-Si** system.
- In spite of the severe mismatch between SiO_2 structure and Si structure, the interface quality is quite good.
- Mid-gap interface state density as low as 10^{10} eV^{-1} cm^{-2}can be readily obtained.
- The ability to produce such high-quality interfaces is responsible for the remarkable success of the **metal-oxide-silicon (MOS) devices**.
- Typical electron mobility in Si MOSFETs is ~600 $cm^2/(V \cdot s)$ compared to a mobility of ~1100 $cm^2/(V \cdot s)$ (300 K) for bulk pure Si.

- **Silicon nitride (Si_3N_4)** is another important film that forms modest-quality junctions with Si.
- Silicon nitride can be used in a metal-insulator-semiconductor device in Si technology, but its applications are limited. The film is used more as *a* **mask for oxidation of the Si film**.
- It also makes a good material for **passivation of finished devices.**
- **Silicon oxy-nitride** forms high-quality interfaces with silicon and can be used in FETs.

SEMICONDUCTOR HETEROJUNCTIONS



(a) Band line-ups of two distinct materials prior to the formation of a junction. (b) Band diagram of a heterojunction formed between the two materials.

- The difference in the bandgap between the two materials is equal to the sum of the conduction band and valence band discontinuities, or

$$\Delta E_g = E_{g1} - E_{g2} = \Delta E_c + \Delta E_v$$

- The built-in voltage is equal to the sum of the band bending on the n-side (V_{d1}) and the bend bending on the p-side (V_{d2}).

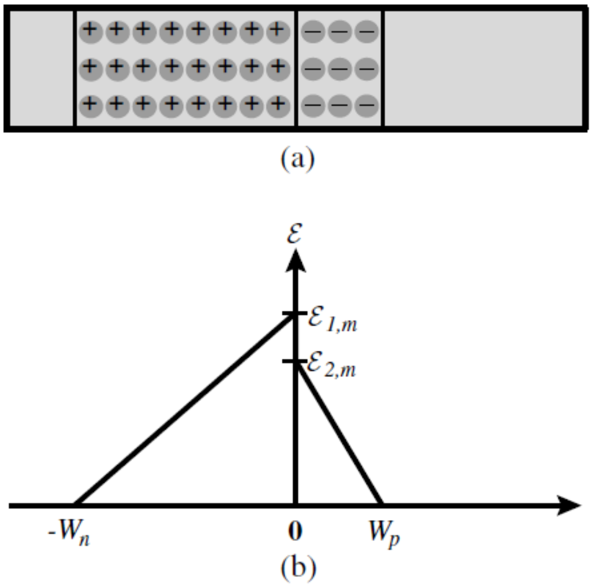
$$eV_{bi} = eV_{d1} + eV_{d2} = E_{g2} - (E_F - E_v)_p - (E_c - E_F)_n + \Delta E_c$$

- Comparing this expression to that of the p-n homojunction , we see that the only difference is the additional ΔE_c.

built-in potential: $$\boxed{V_{bi} = \frac{1}{e}(\Delta E_c + E_{g2}) - \frac{k_B T}{e}\,\ell n\left[\frac{N_{c1}N_{v2}}{n_1 p_2}\right]}$$

By Making the same substitutions for $(EF - Ev)_p$ and $(Ec - EF)_n$ as we made in the p-n homojunction case

(a) Space-charge density and (b) electric field profiles in an n-p heterostructure



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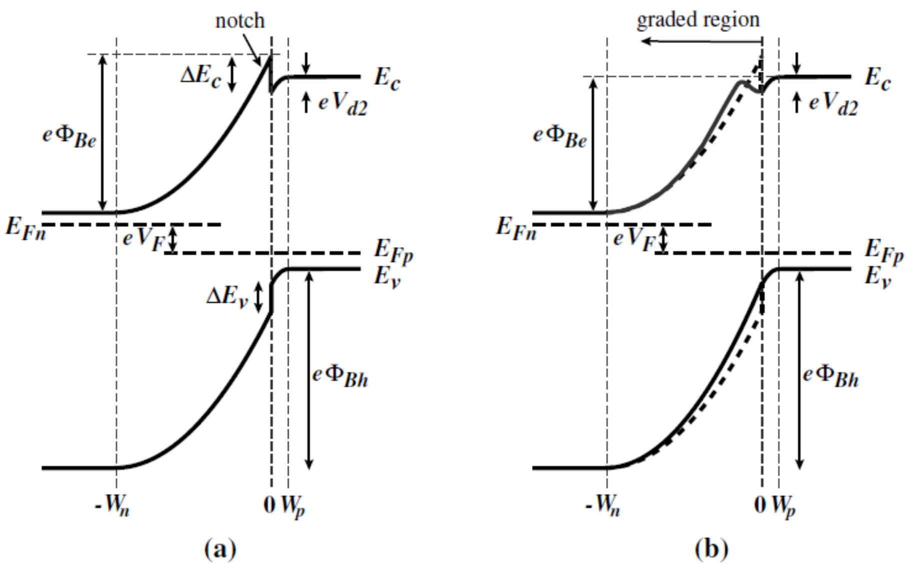
Band diagrams of (a) a forward biased abrupt p-n junction and (b) a forward biased graded p-n junction



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