ECE 340 Lecture 30
Semiconductor Electronics

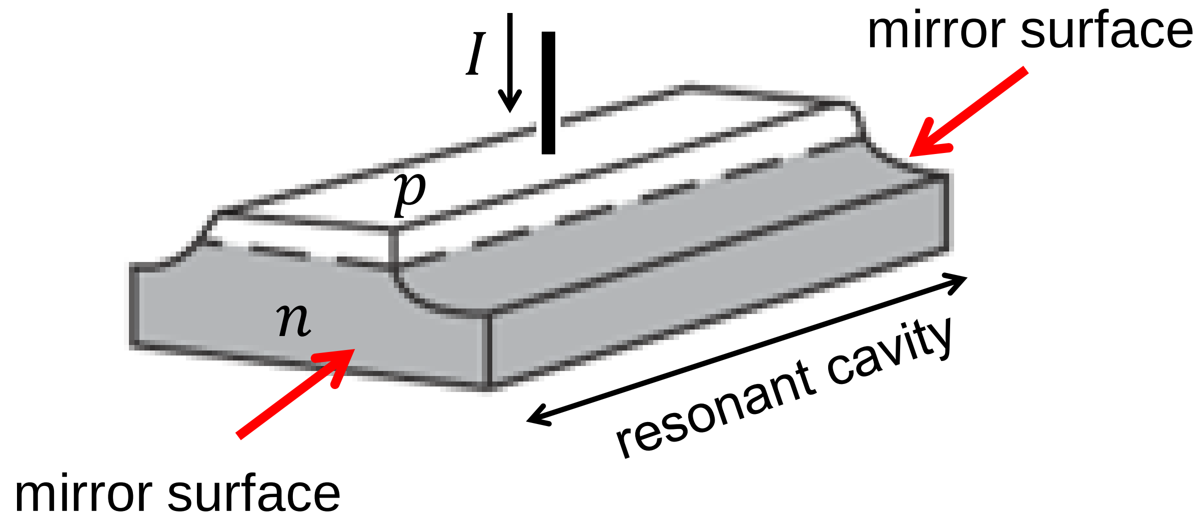
Spring 2022
10:00-10:50am
Professor Umberto Ravaioli
Department of Electrical and Computer Engineering
2062 ECE Building

Today's Discussion

- **Semiconductor Lasers Recap**
- **Metal-Semiconductor Junctions**
- **Schottky Barrier**
- **Rectifying Contacts**
- **Ohmic contacts**

Semiconductor Laser

- **Simple *p-n* junction (e.g., GaAs)**

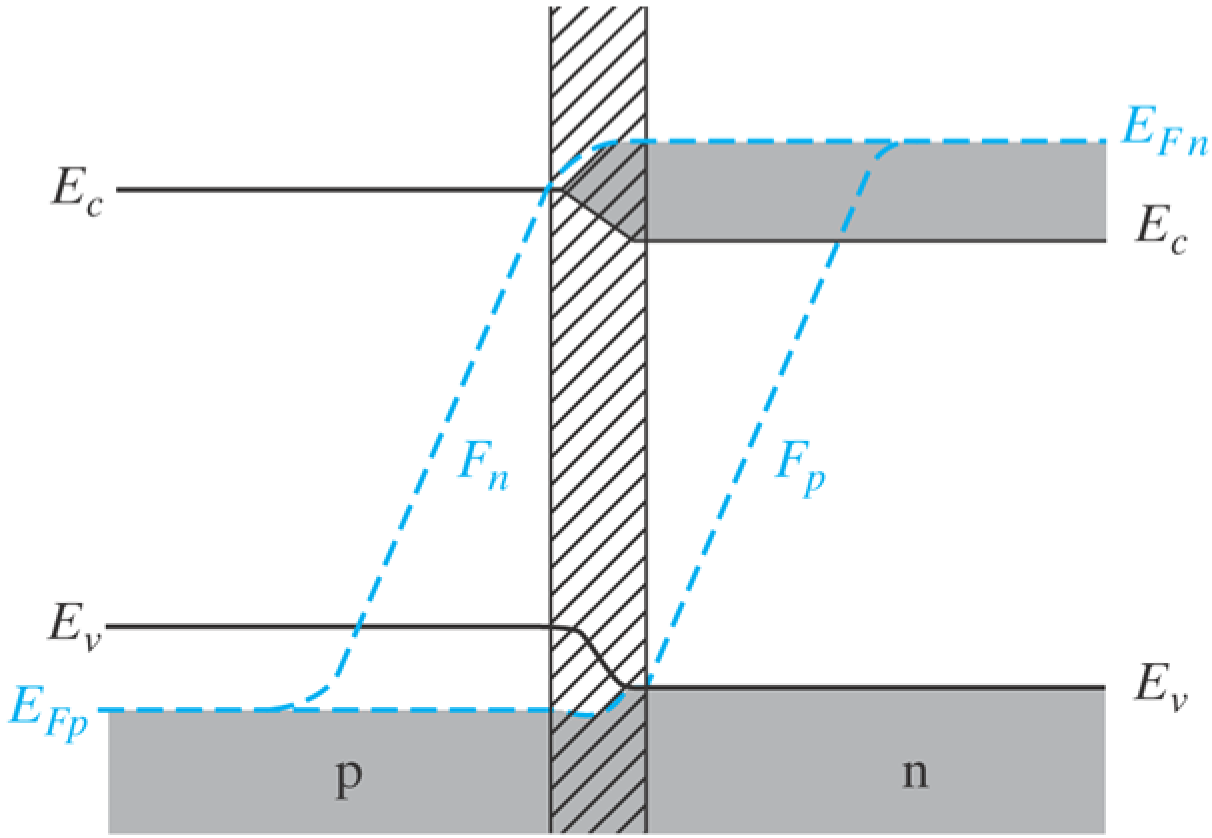


Two ingredients are needed to make a laser:

- population inversion (stable population of excited states)
- resonant cavity to build up a coherent photon population for stimulated emission to occur (coherence)

Population Inversion

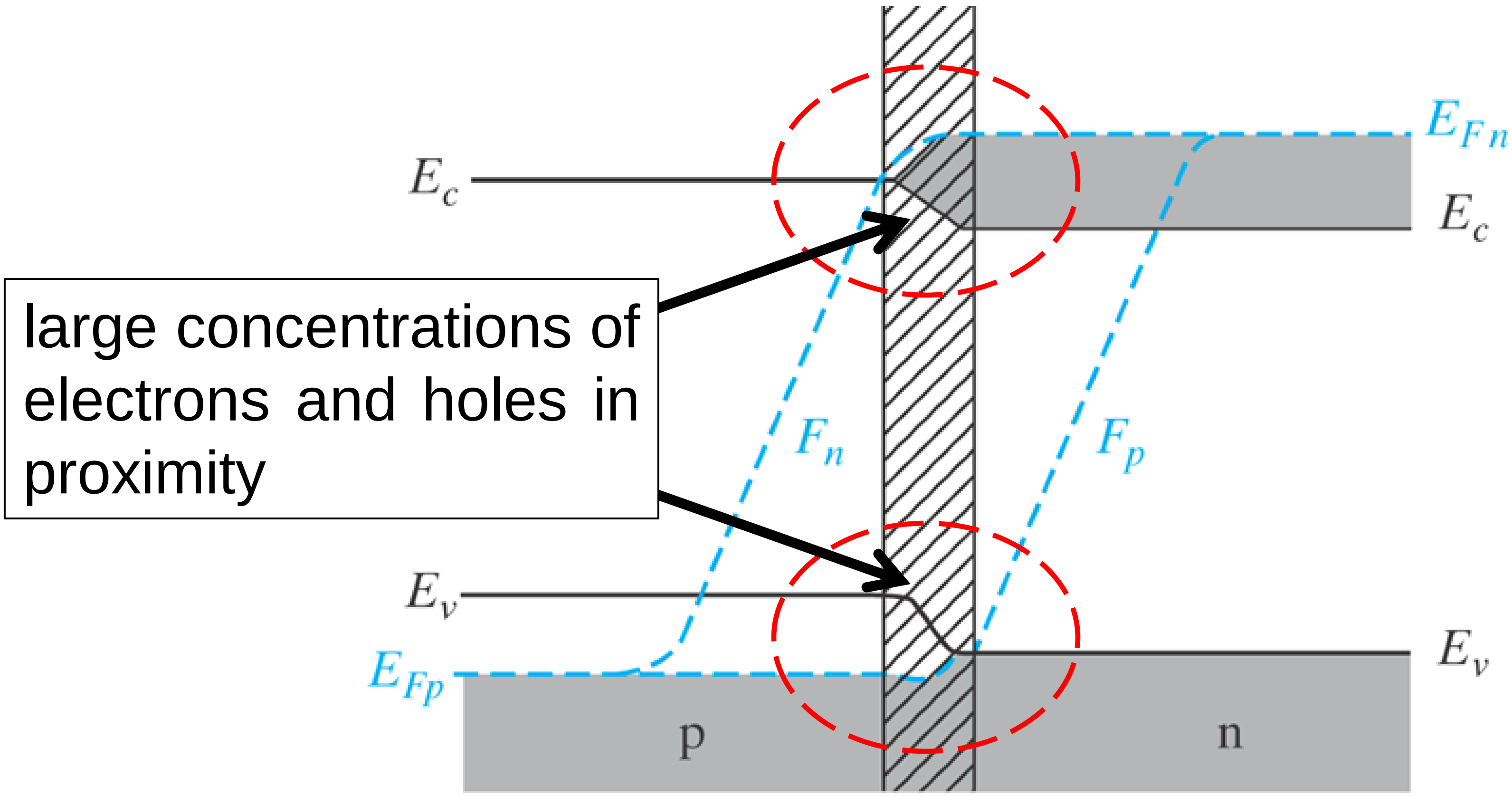
- **Heavily doped *p-n* junction in forward bias**



From *Solid State Electronic Devices,* Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.
ISBN 0-13-149726-X.

Population Inversion

- **Heavily doped *p-n* junction in forward bias**



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Population Inversion

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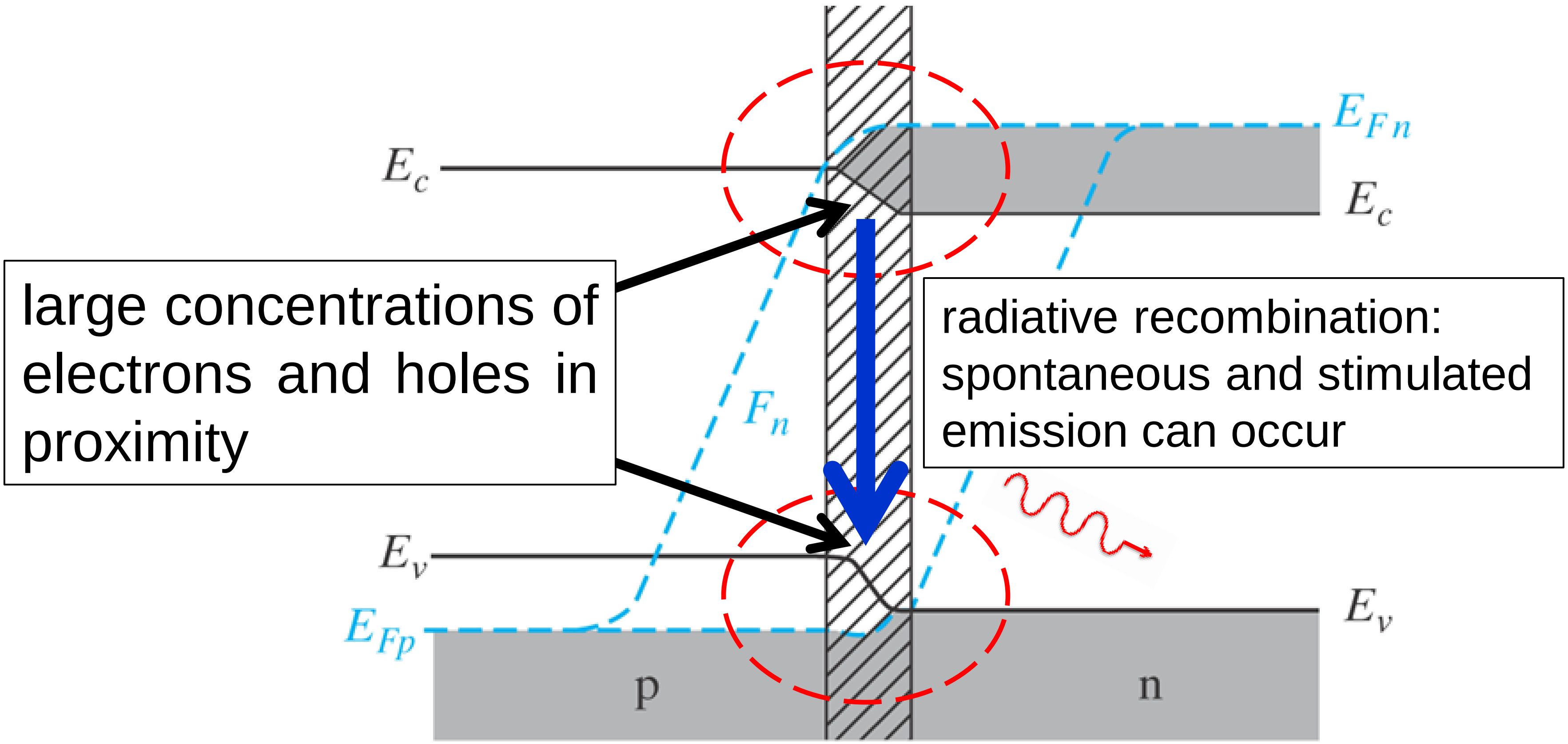

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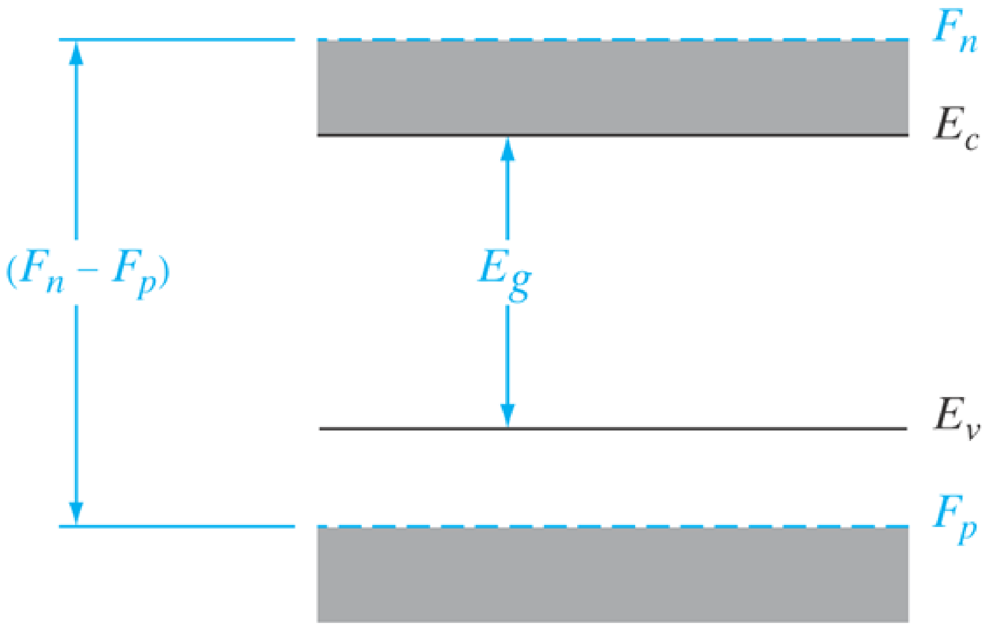
Population inversion

$$n = N_C \exp\left(\frac{E_C - F_n}{k_B T}\right) = n_i \exp\left(\frac{F_n - E_i}{k_B T}\right)$$

$$p = N_v \exp\left(\frac{F_p - E_V}{k_B T}\right) = n_i \exp\left(\frac{E_i - F_p}{k_B T}\right)$$



electrons can recombine approximately in the range of energies

$$E_g < h\nu < (F_n - F_p)$$

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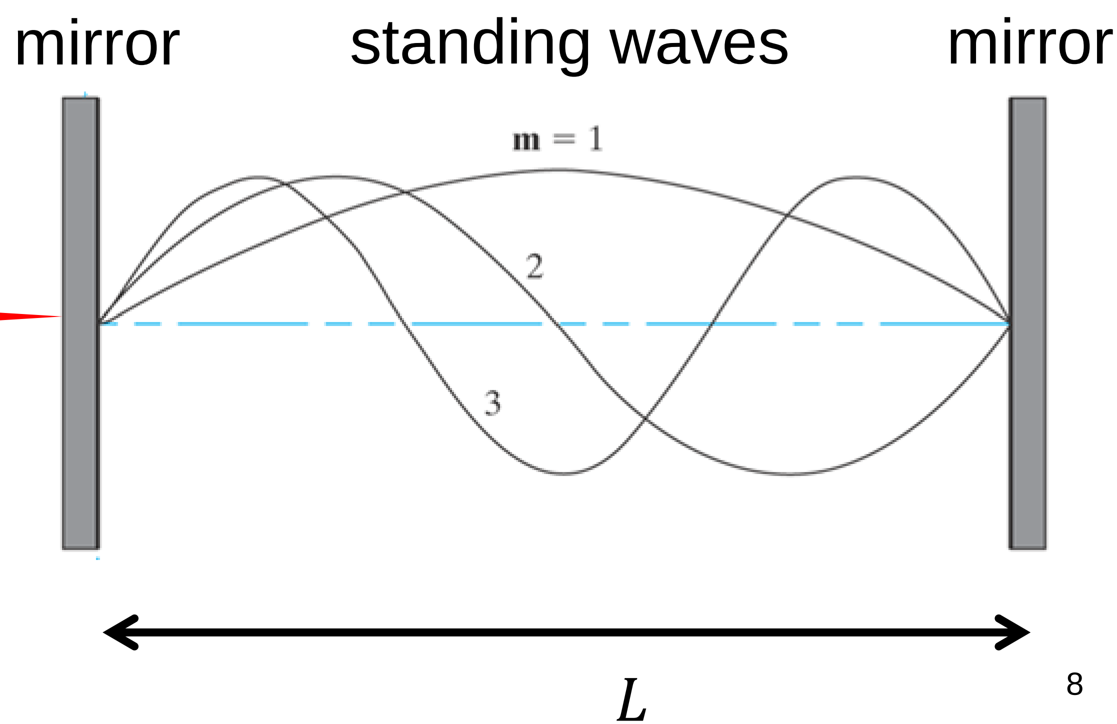
Cavity modes

$$L = \boldsymbol{m}\frac{\lambda}{2} \qquad \boldsymbol{n} = \sqrt{\varepsilon} \qquad \lambda_0(vacuum) = \lambda\boldsymbol{n}$$

$$\boldsymbol{m} = \frac{2L}{\lambda_0}\boldsymbol{n}$$

some energy passes through the semi-reflecting mirror (this is the output of the laser)



new photons are generated to make up for the ones lost

Stimulated emission

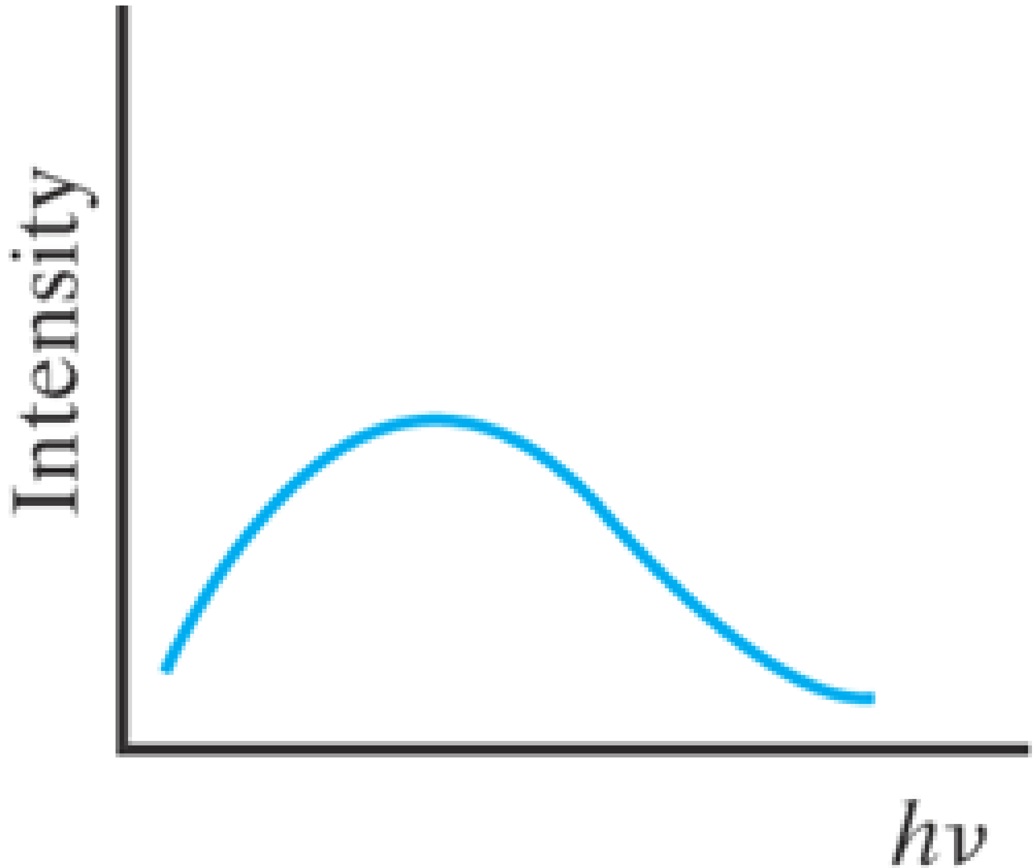
The process by which an incoming photon of specific frequency interacts with an excited electron, causing it to drop to a lower energy level (recombine) emitting a second phonon with the same:

- frequency
- phase
- direction
- polarization

This reinforces the coherent oscillation, replenishing photons lost through the mirror.

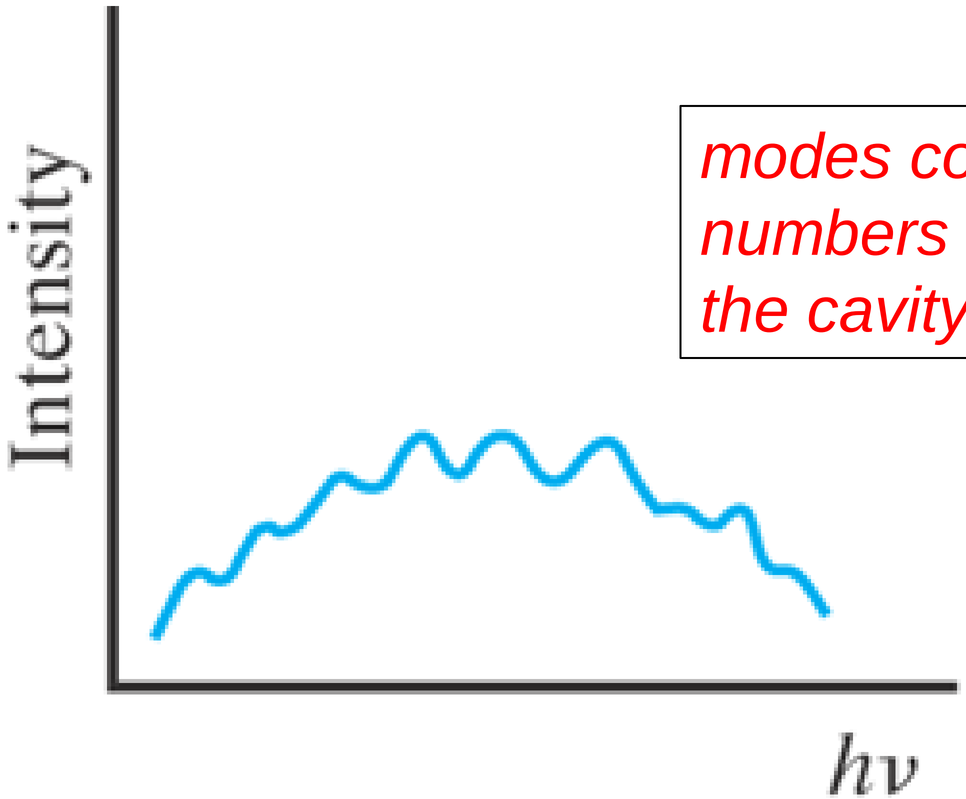
Below threshold

At *low current levels*, **spontaneous emission** dominates (incoherent emission) in the whole range of possible frequencies (behaving like LED):



Approaching threshold

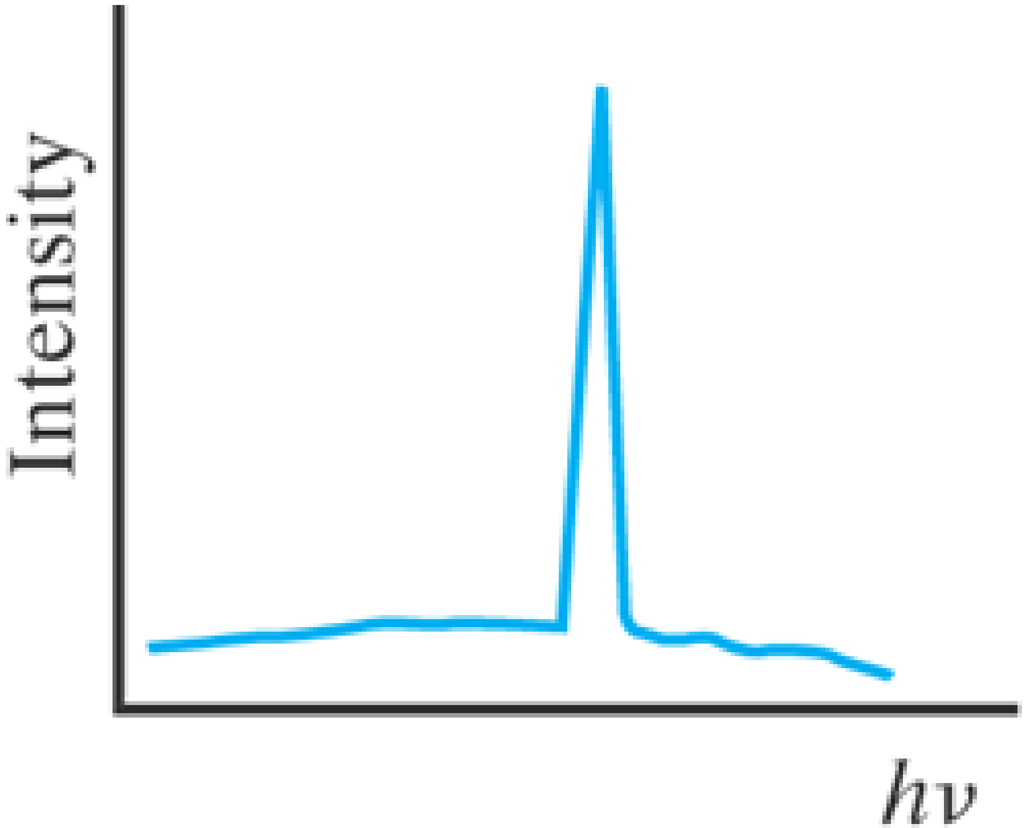
The photon wavelengths participating in the **stimulated emission** are determined by the length of the laser resonant cavity. As current increases, various cavity modes start to appear



modes correspond to successive numbers of integer $\lambda/2$ that fit in the cavity

The cavity structure favors stimulated emission

At *high current levels (above threshold)*, **stimulated emission** dominates (coherent emission) favoring a dominant mode:



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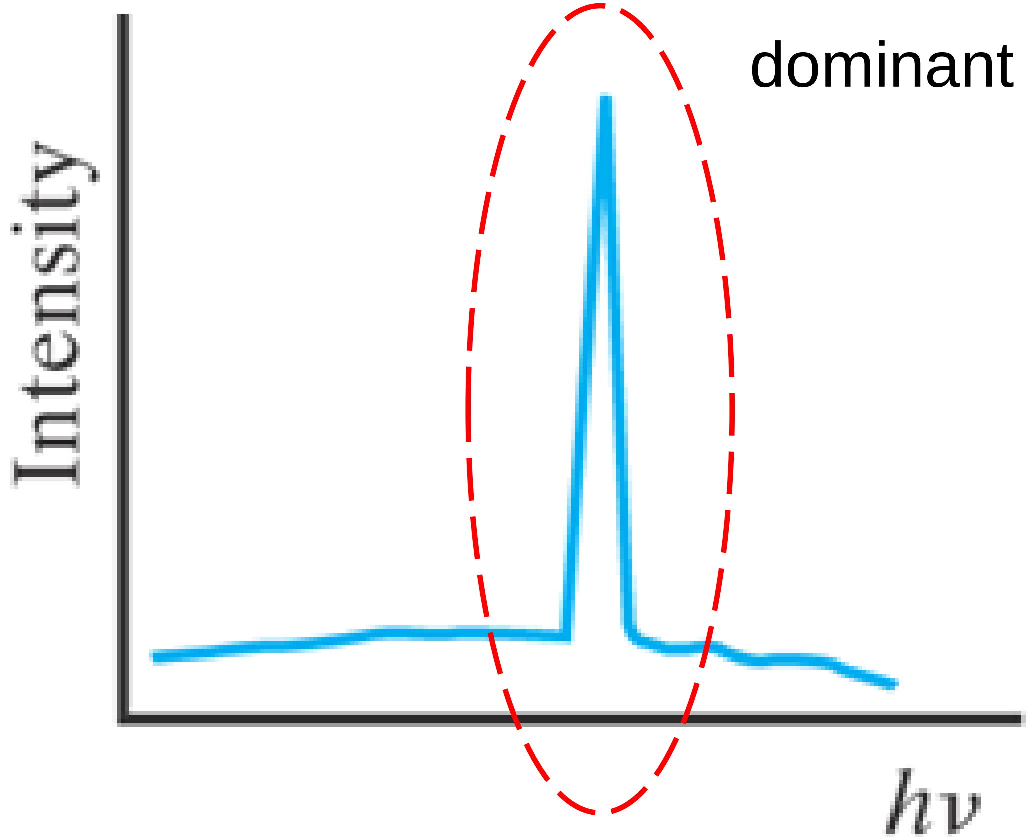
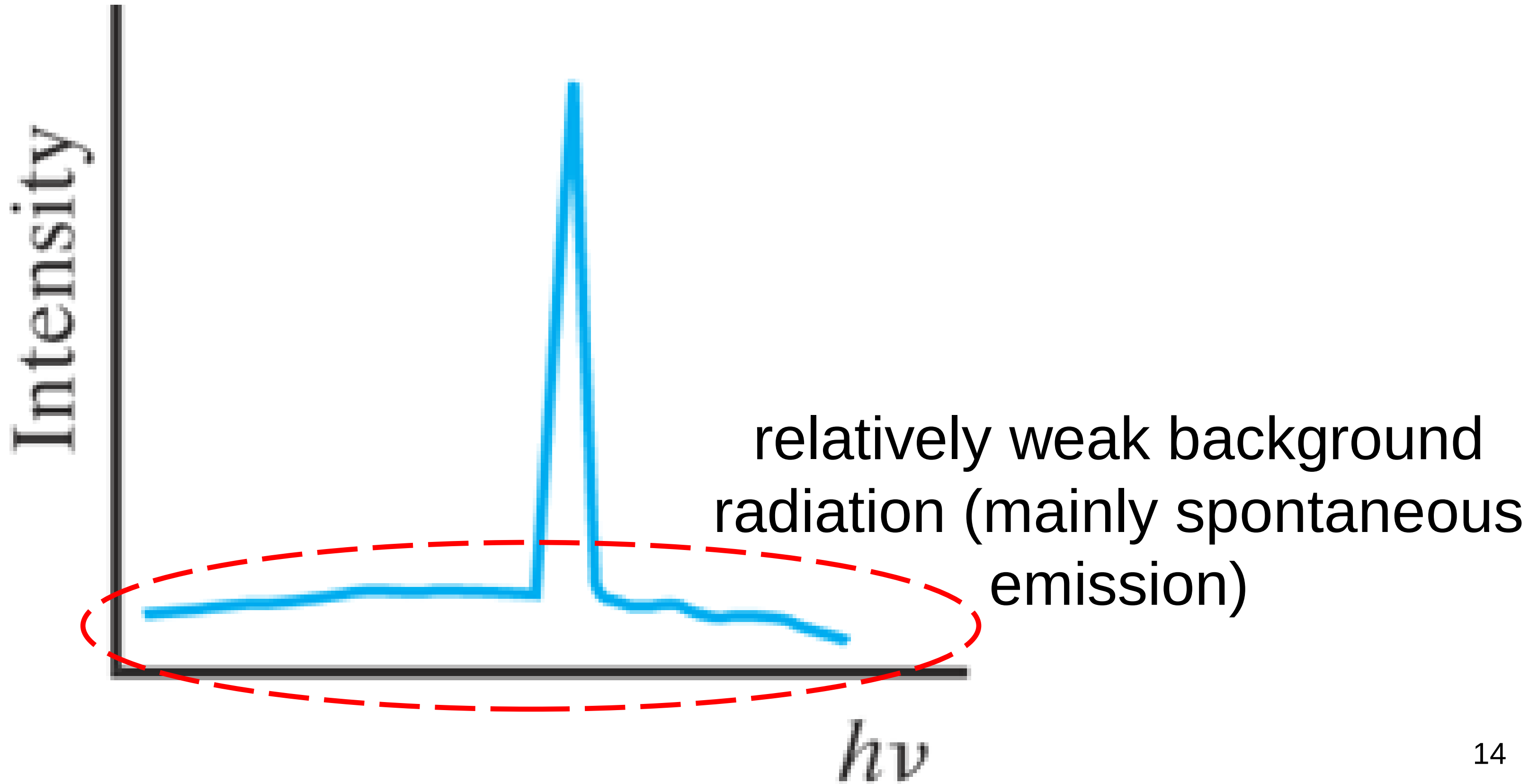


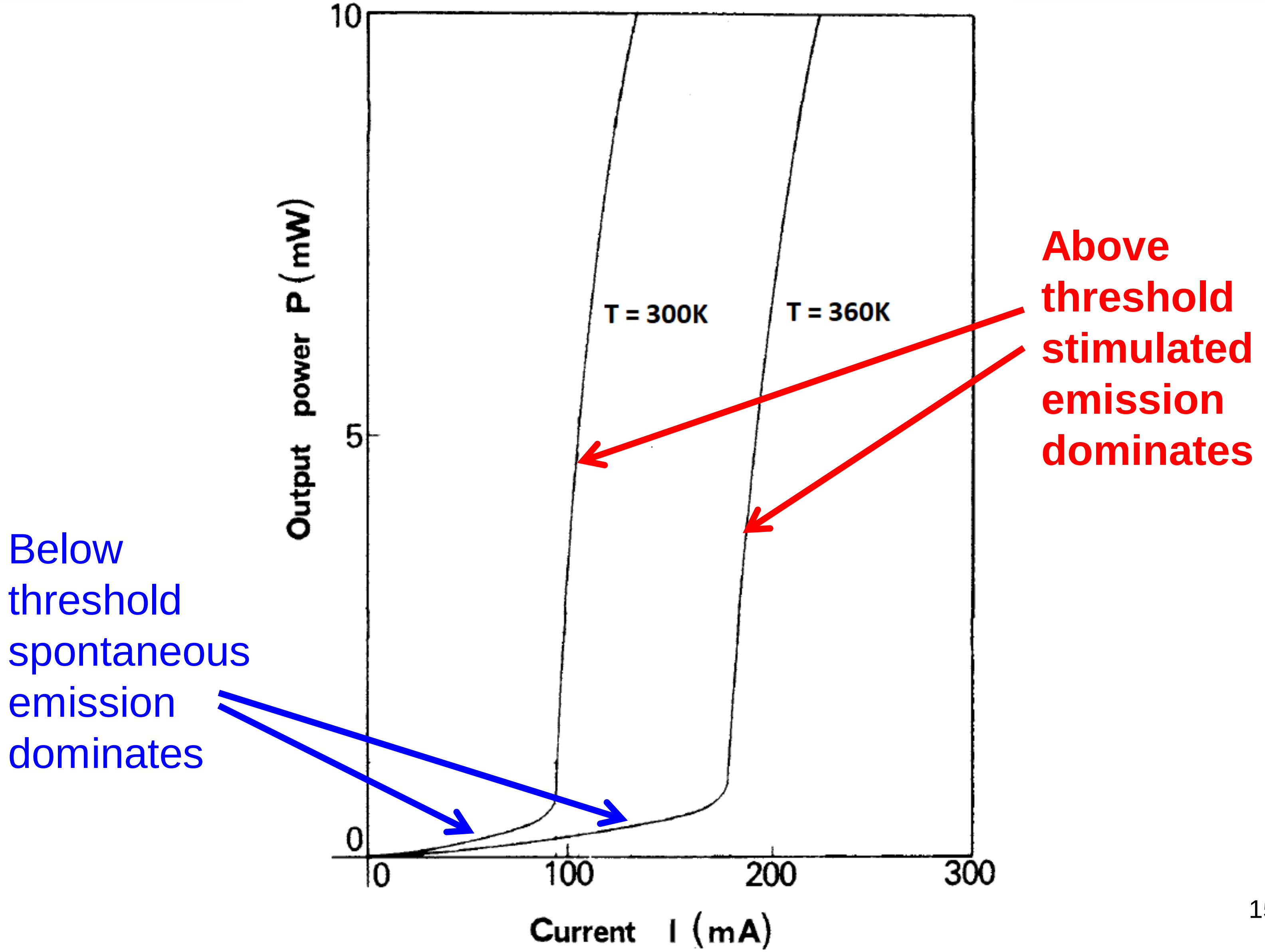
dominant nearly monochromatic radiation

The cavity structure favors stimulated emission

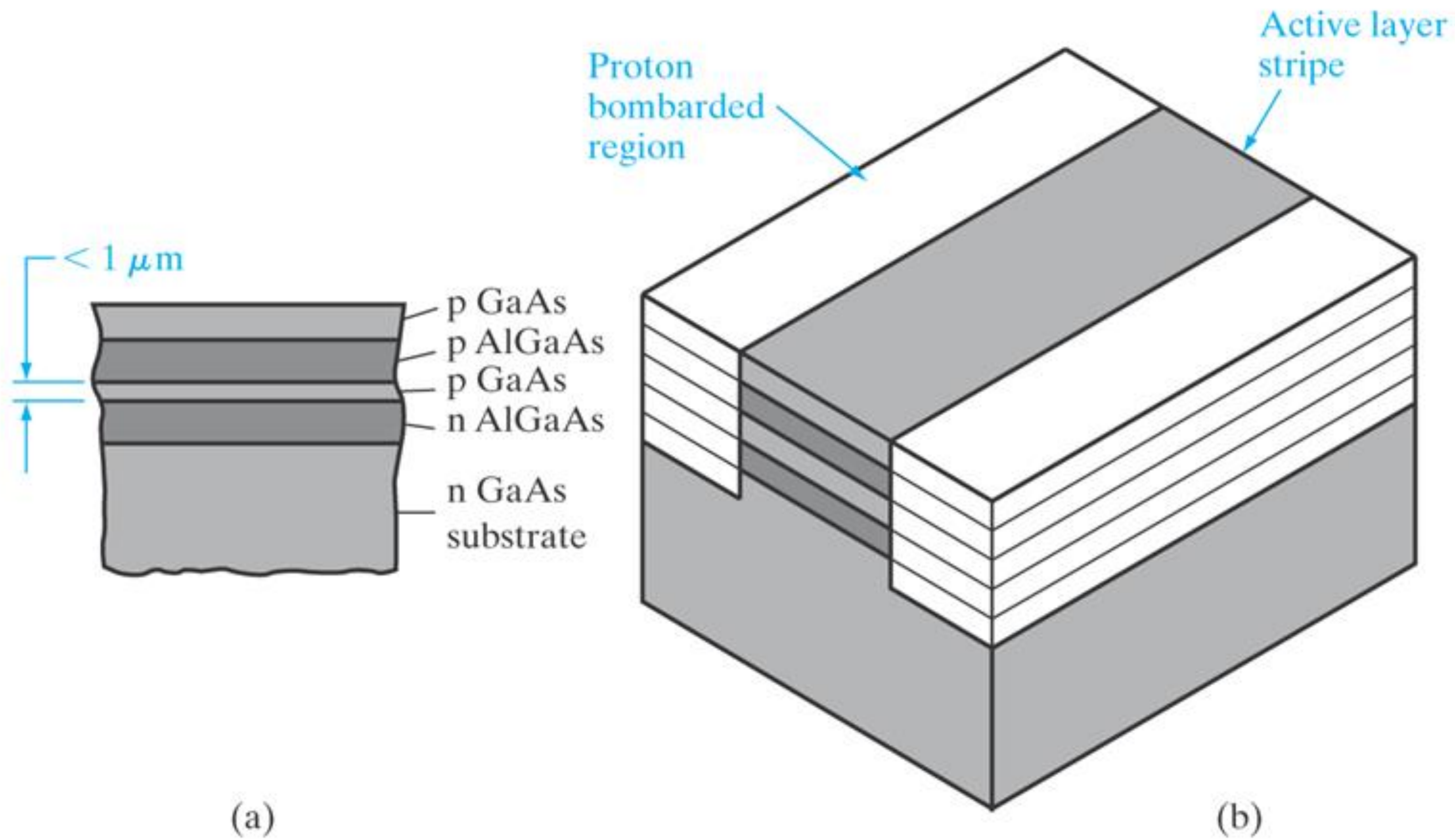
At *high current levels (above threshold)*, **stimulated emission** dominates (coherent emission) favoring a dominant mode:



Laser – Power emission characteristics



Modern Double Heterojunction Laser



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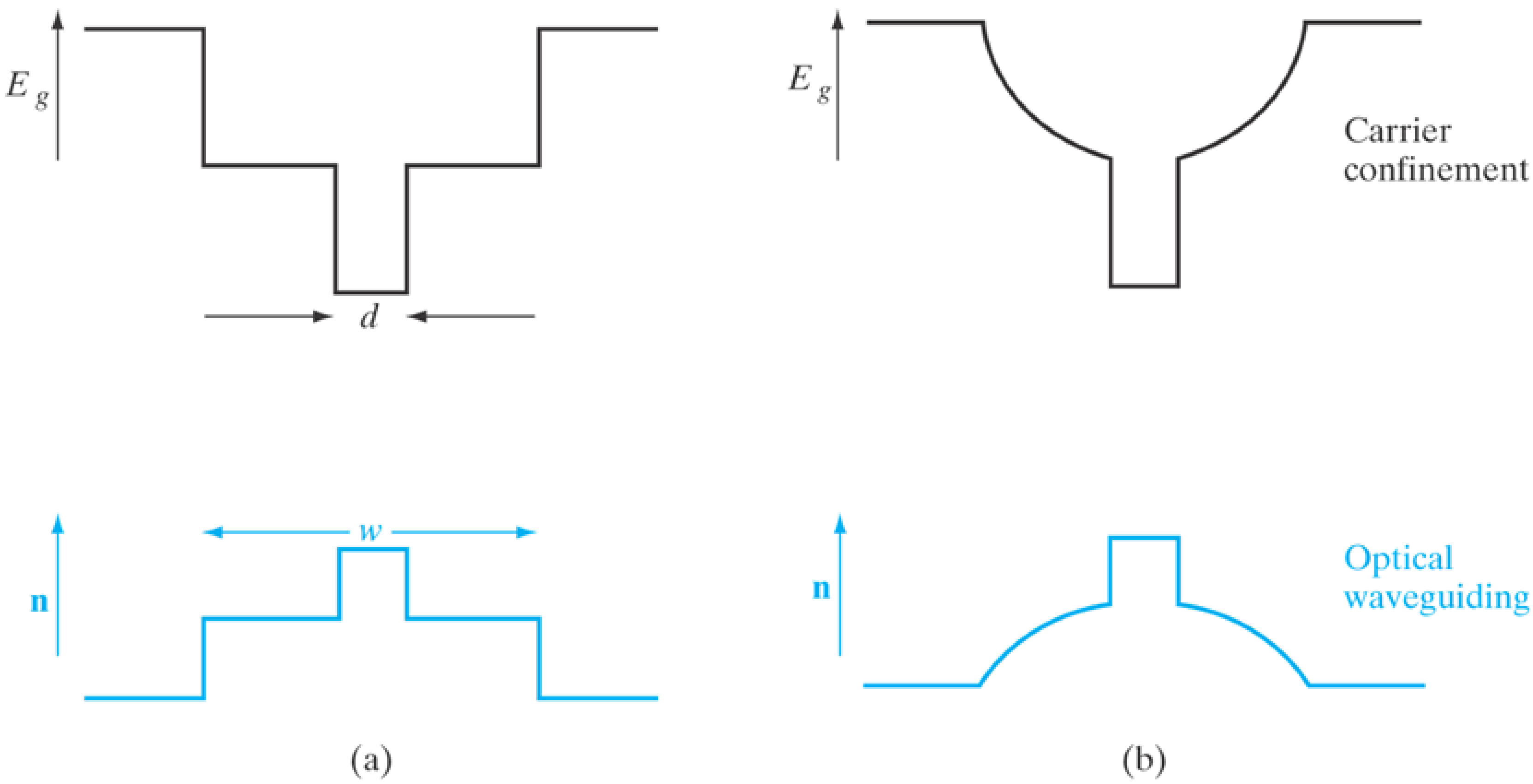
Optical waveguiding and Carrier confinement



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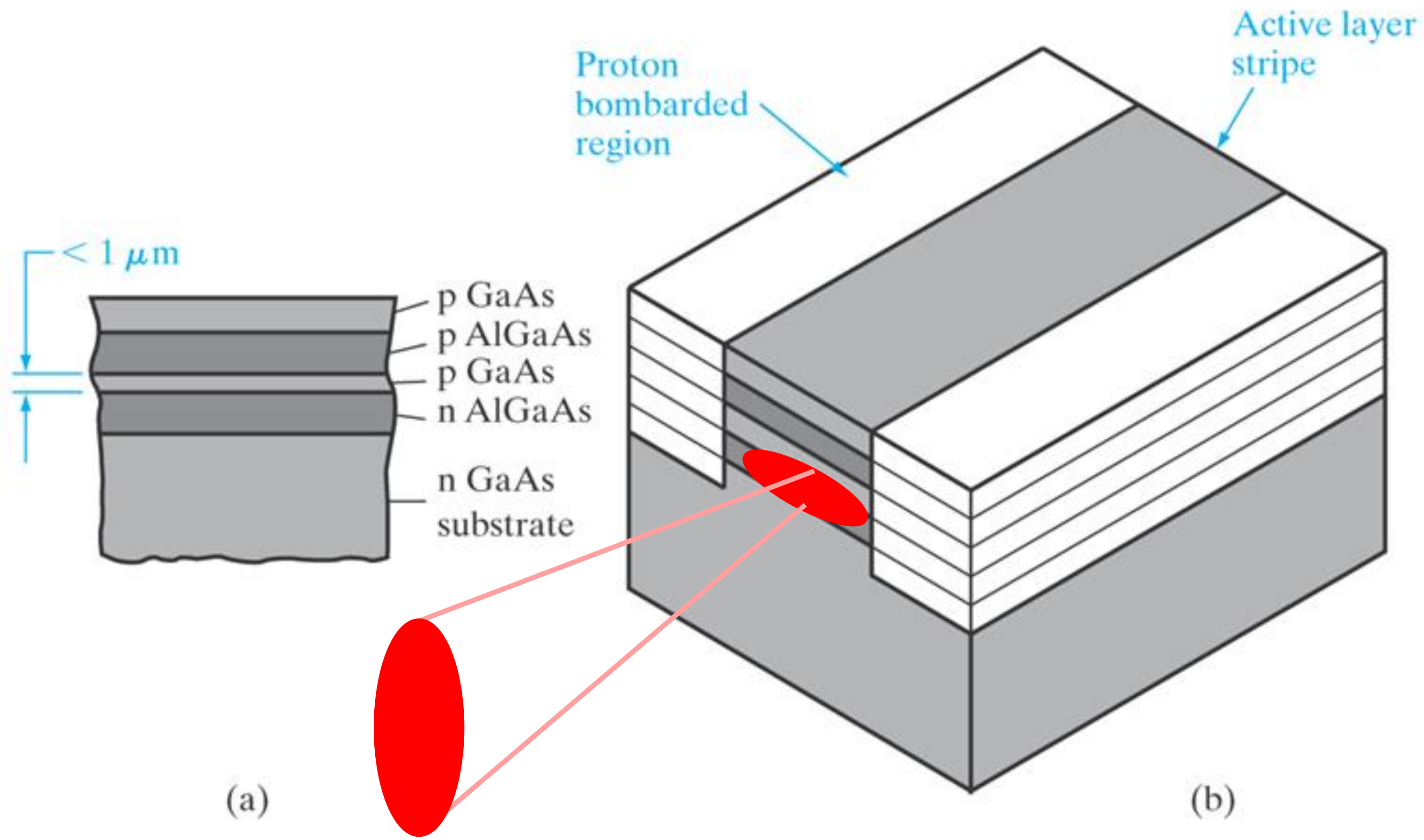
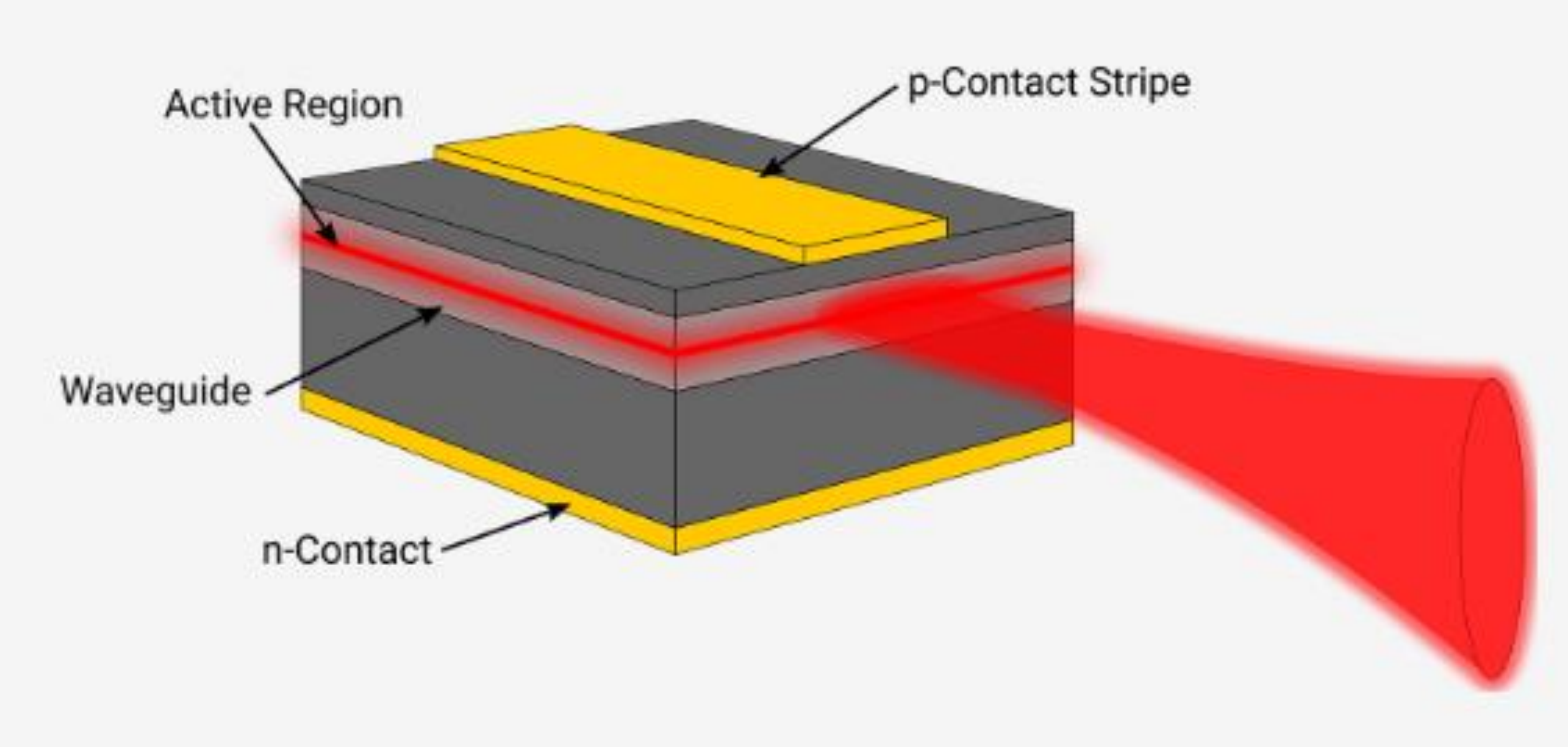


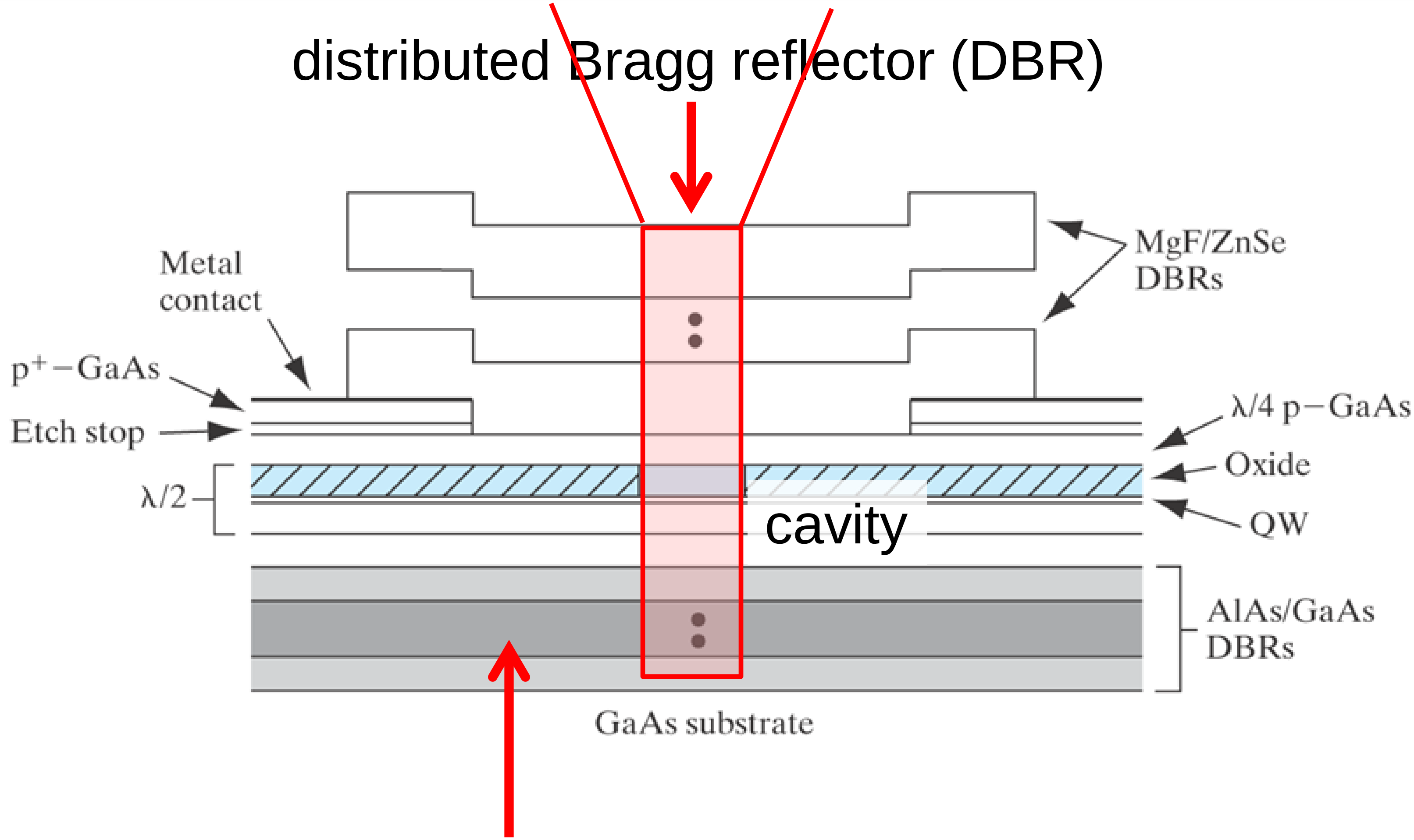
EDGE EMITTING LASER

Modern Double Heterojunction Laser

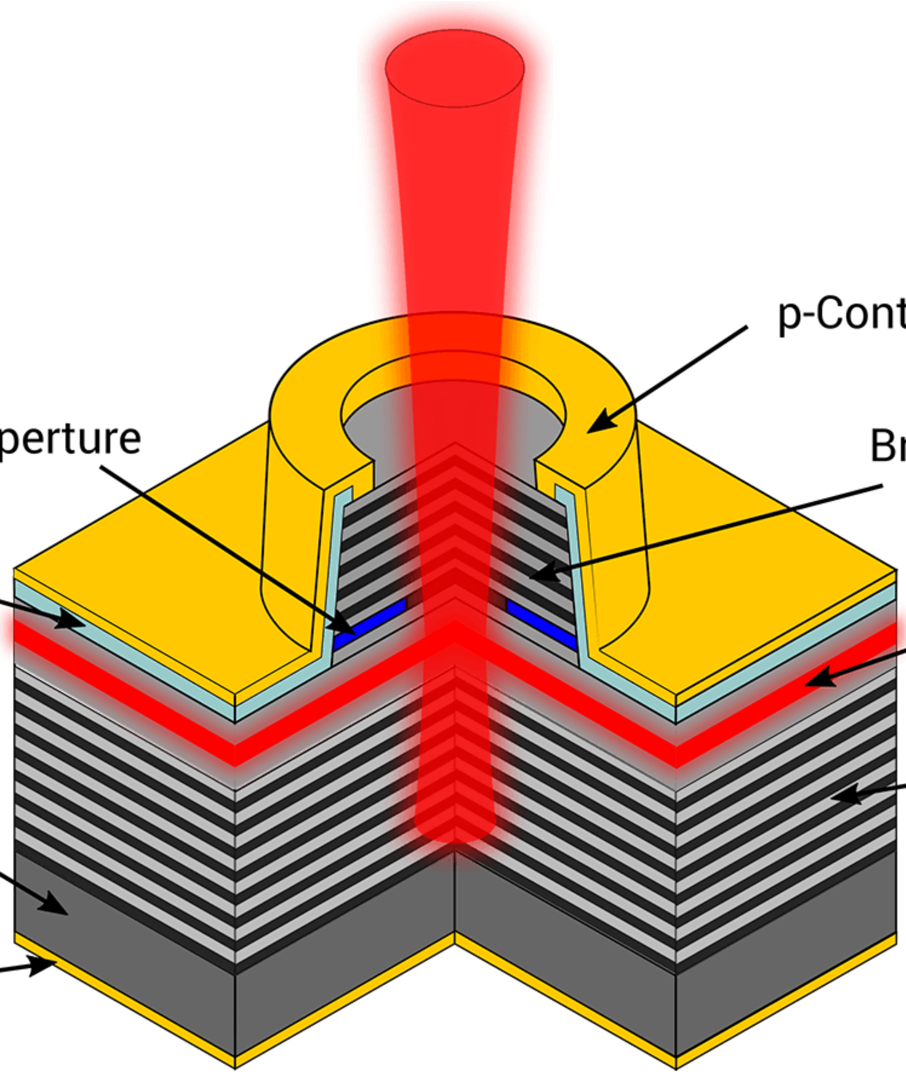


EDGE EMITTING LASER

Vertical Cavity Surface Emitting Laser (VCSEL)

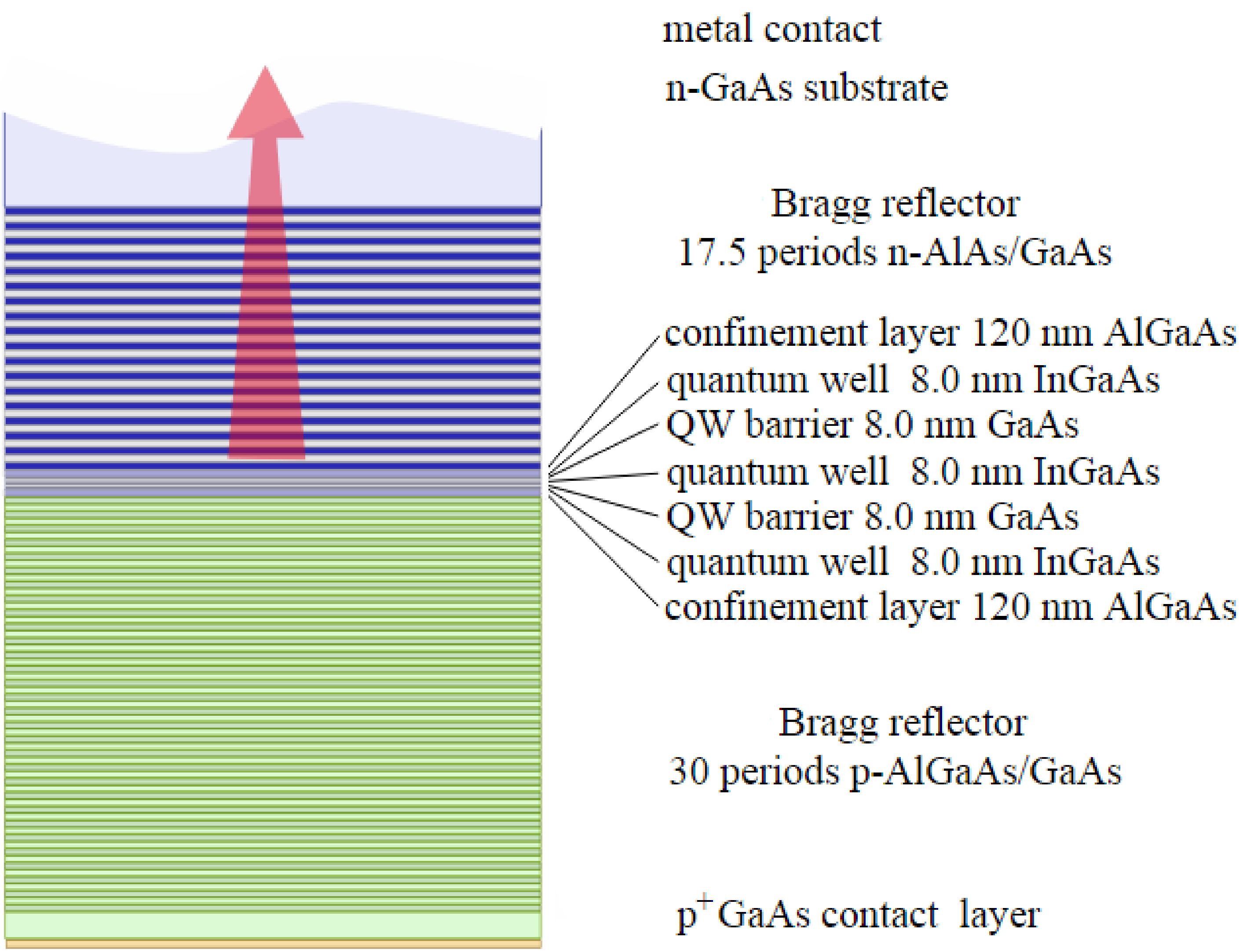


Vertical Cavity Surface Emitting Laser (VCSEL)



Reference: [Jetter, Roßbach, Michler (2013). Red Emitting VCSEL. In *VCSELs* (pp. 379-401). Springer Verlag]

Vertical Cavity Surface Emitting Laser (VCSEL)

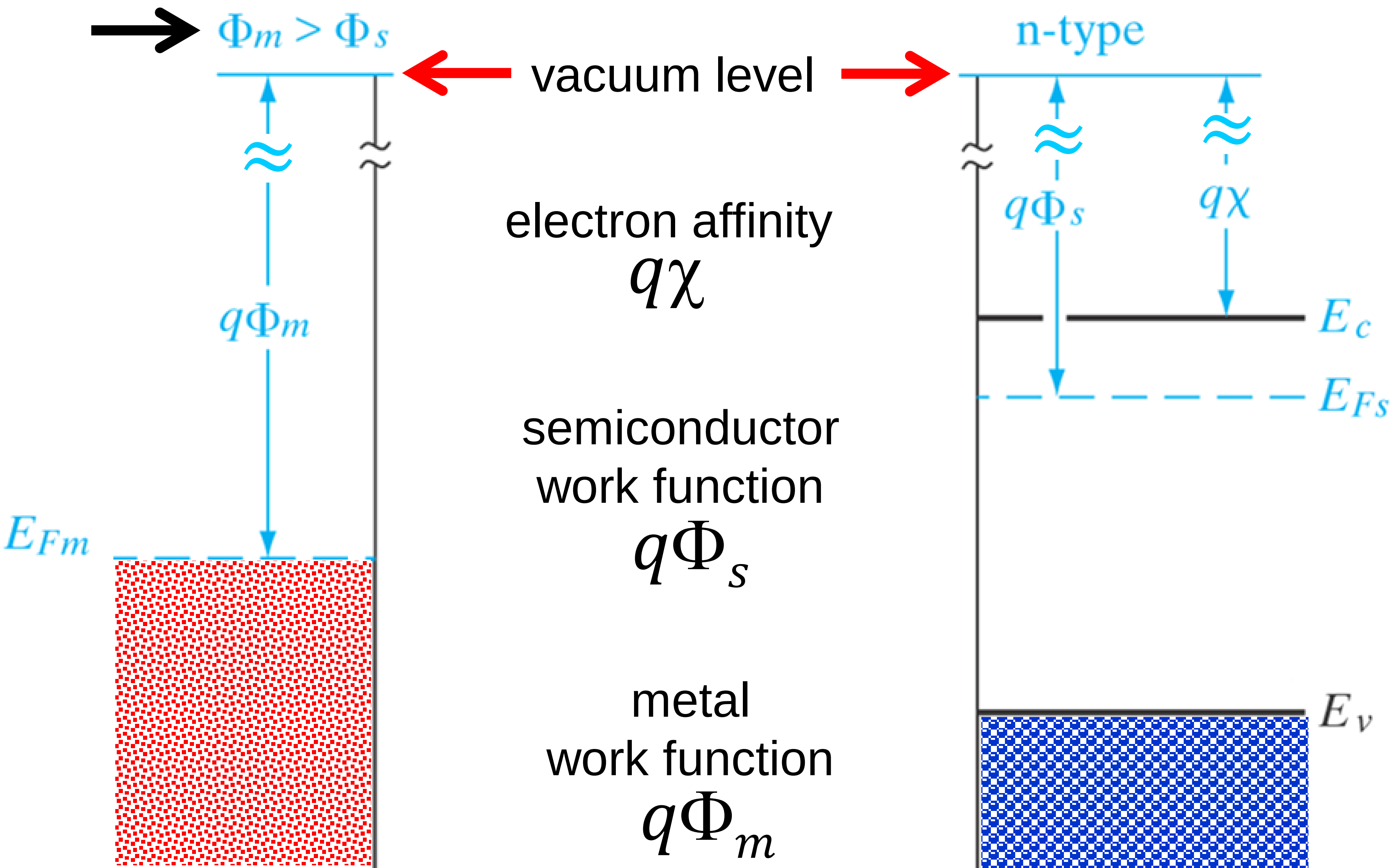


Metal-Semiconductor Junction

We start by assuming ideal interfaces

(no interface states)

Metal-Semiconductor Junction (n-type)

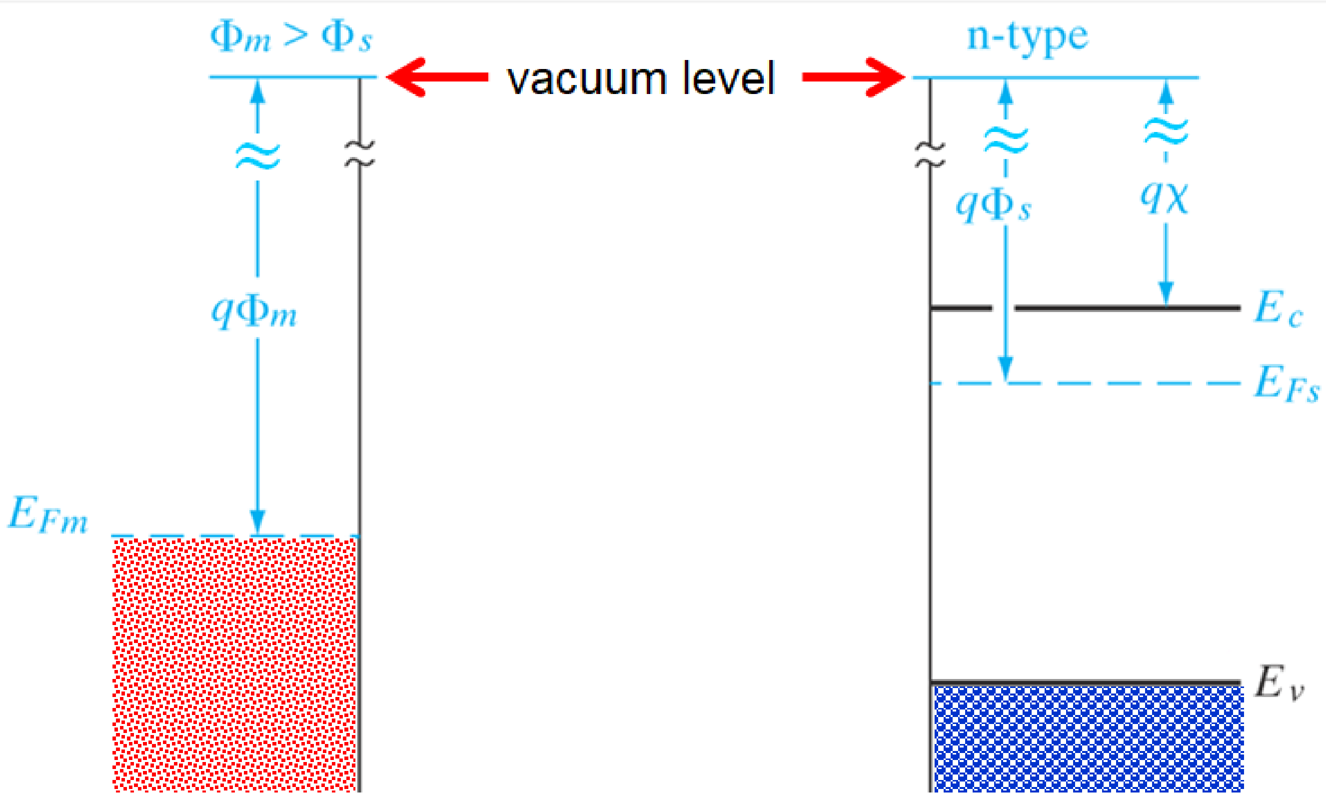


Metal-Semiconductor Junction (n-type)

electron affinity $q\chi$ is fixed for a given semiconductor

electron work-function $q\Phi_s$ in semiconductor depends on doping

metal work-function $q\Phi_m$ is $\approx$ fixed for a given metal



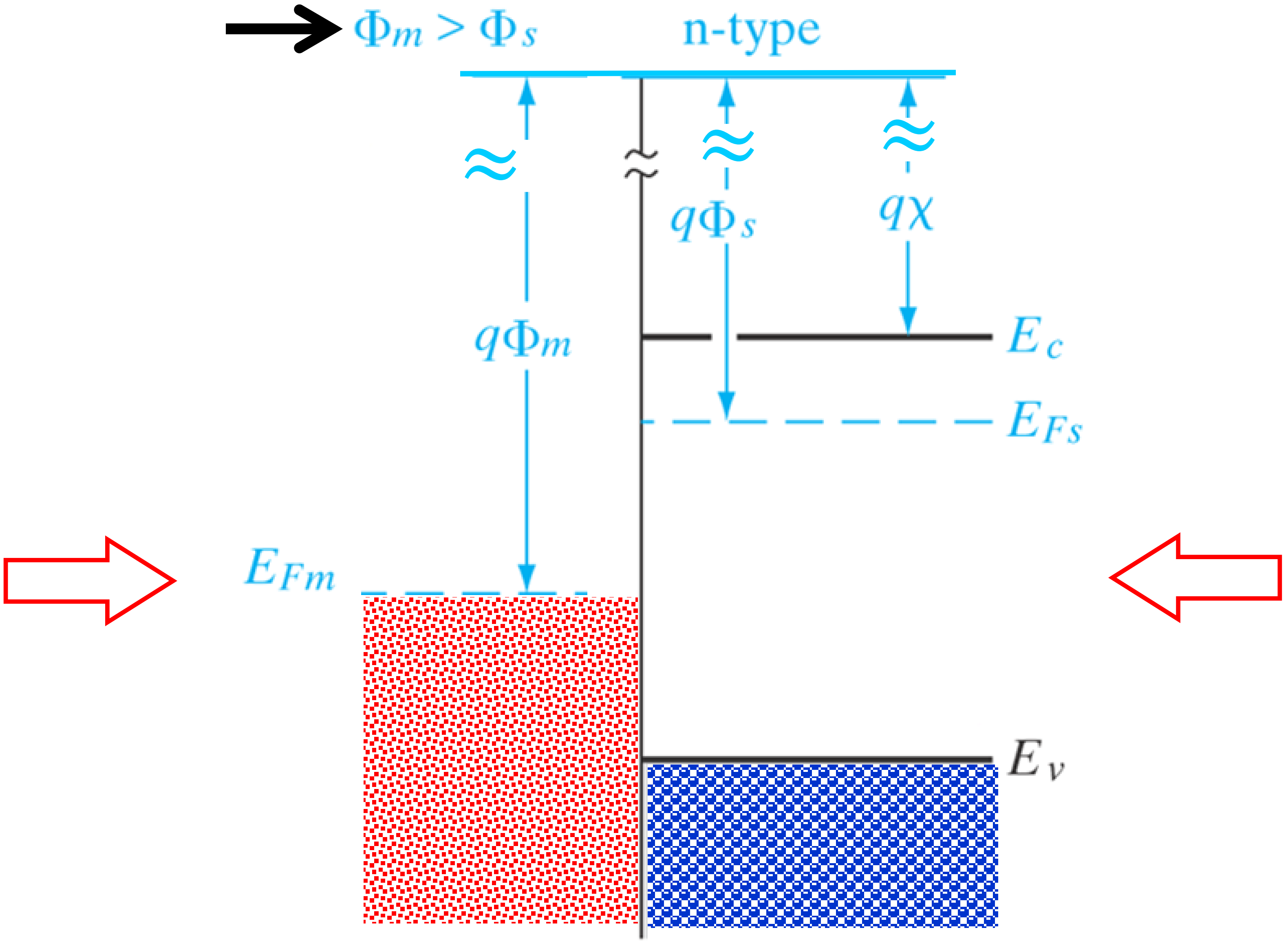
Examples of work function

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

Examples of electron affinity

Element	Electron affinity, χ
Ge, germanium	4.13 [eV]
Si, silicon	4.01 [eV]
GaAs, gallium arsenide	4.07 [eV]
AlAs, aluminum arsenide	3.5 [eV]

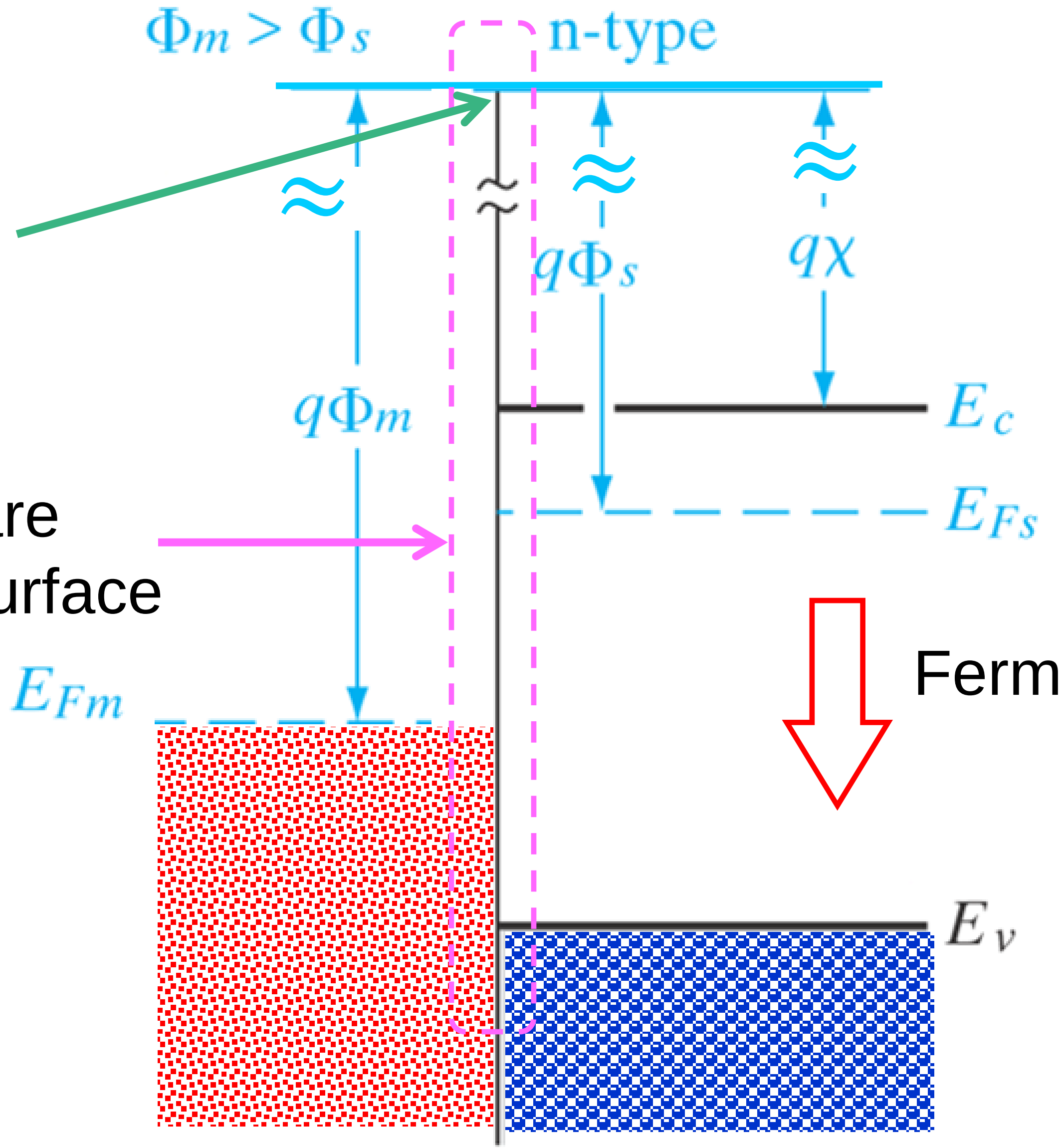
Now form the Junction



Now form the Junction

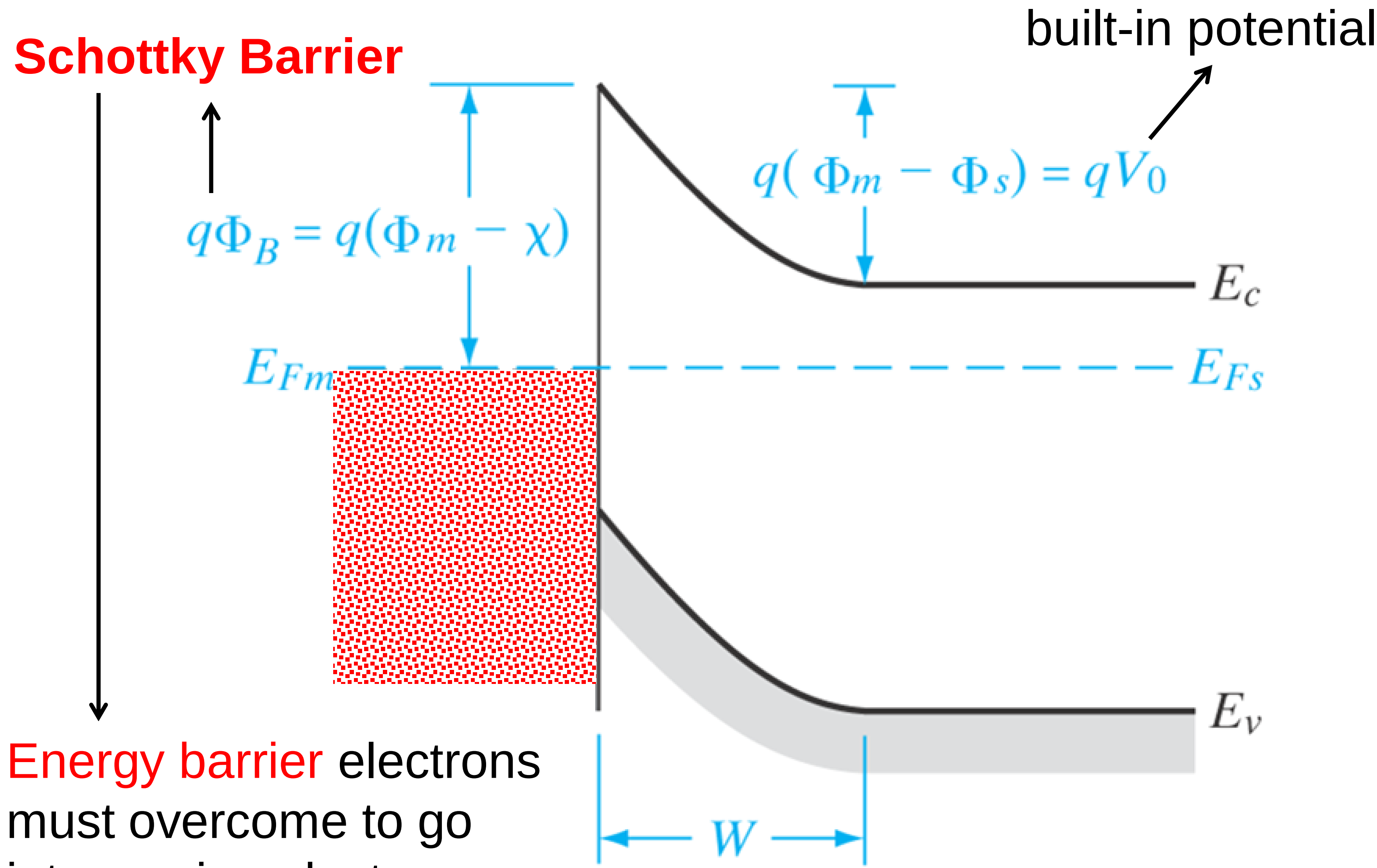
Continuity of vacuum level

Energy levels are pinned at the surface



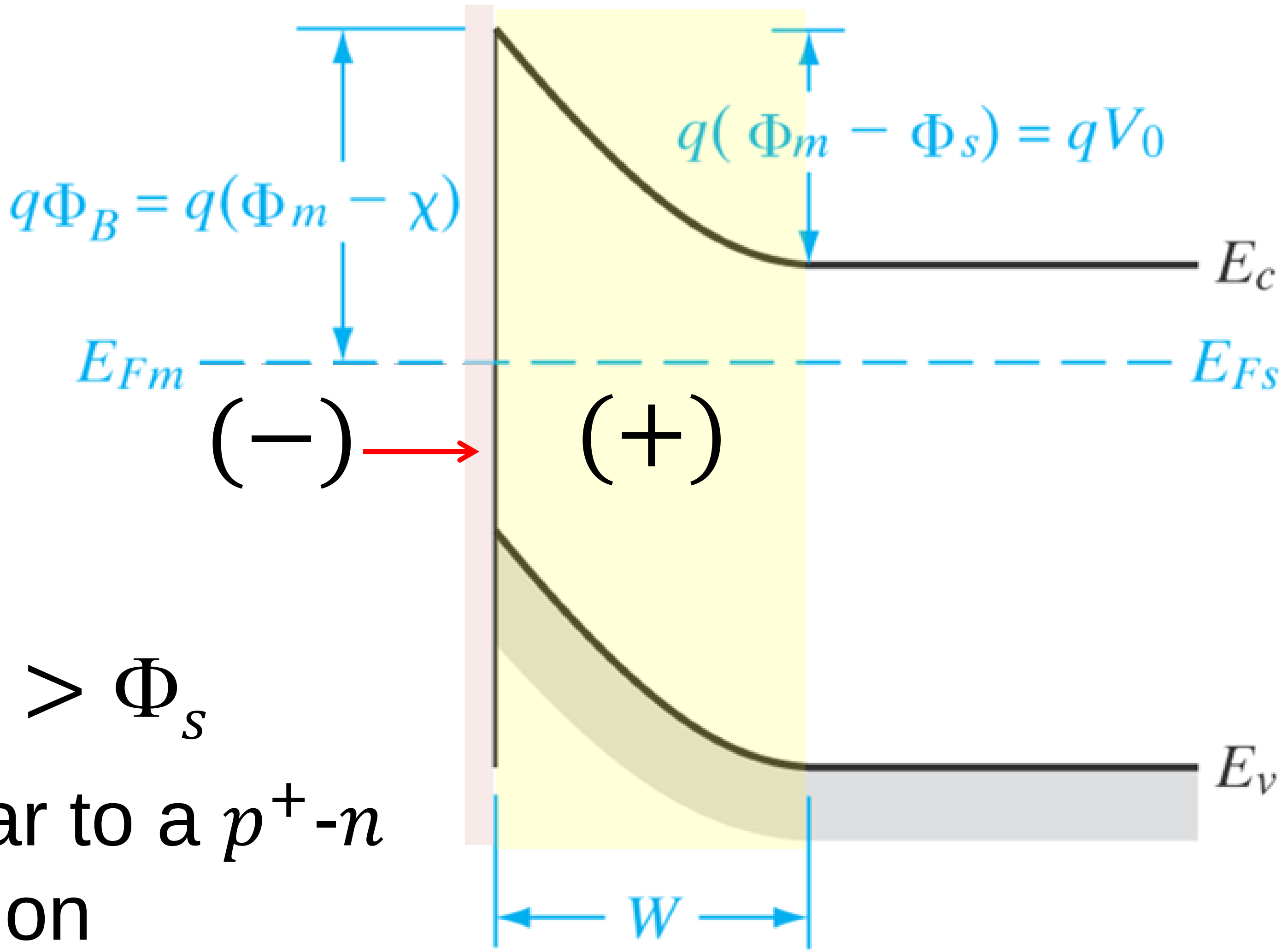
Fermi levels align

Metal-Semiconductor Junction



Energy barrier electrons must overcome to go into semiconductor

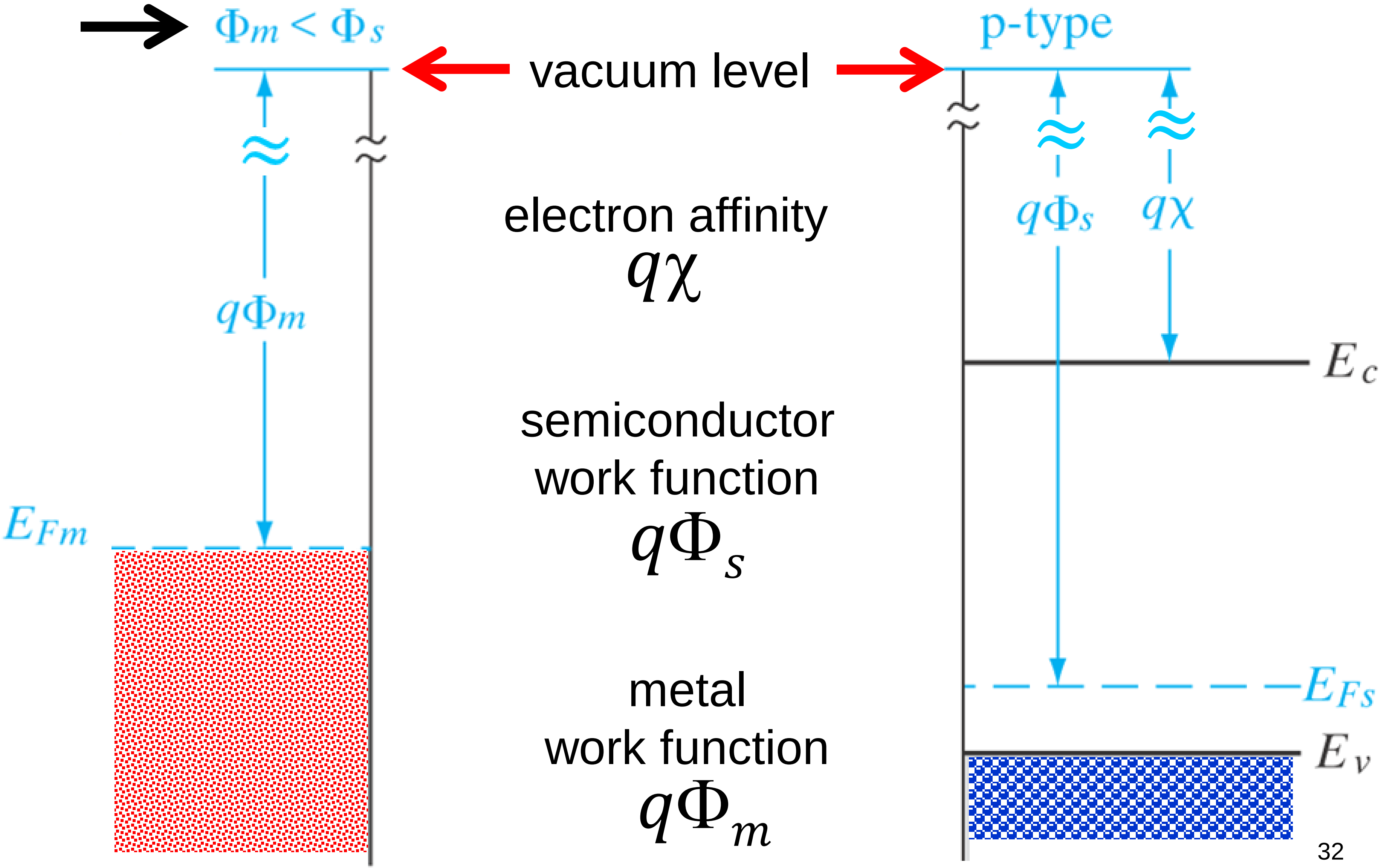
Metal-Semiconductor Junction



$\Phi_m > \Phi_s$

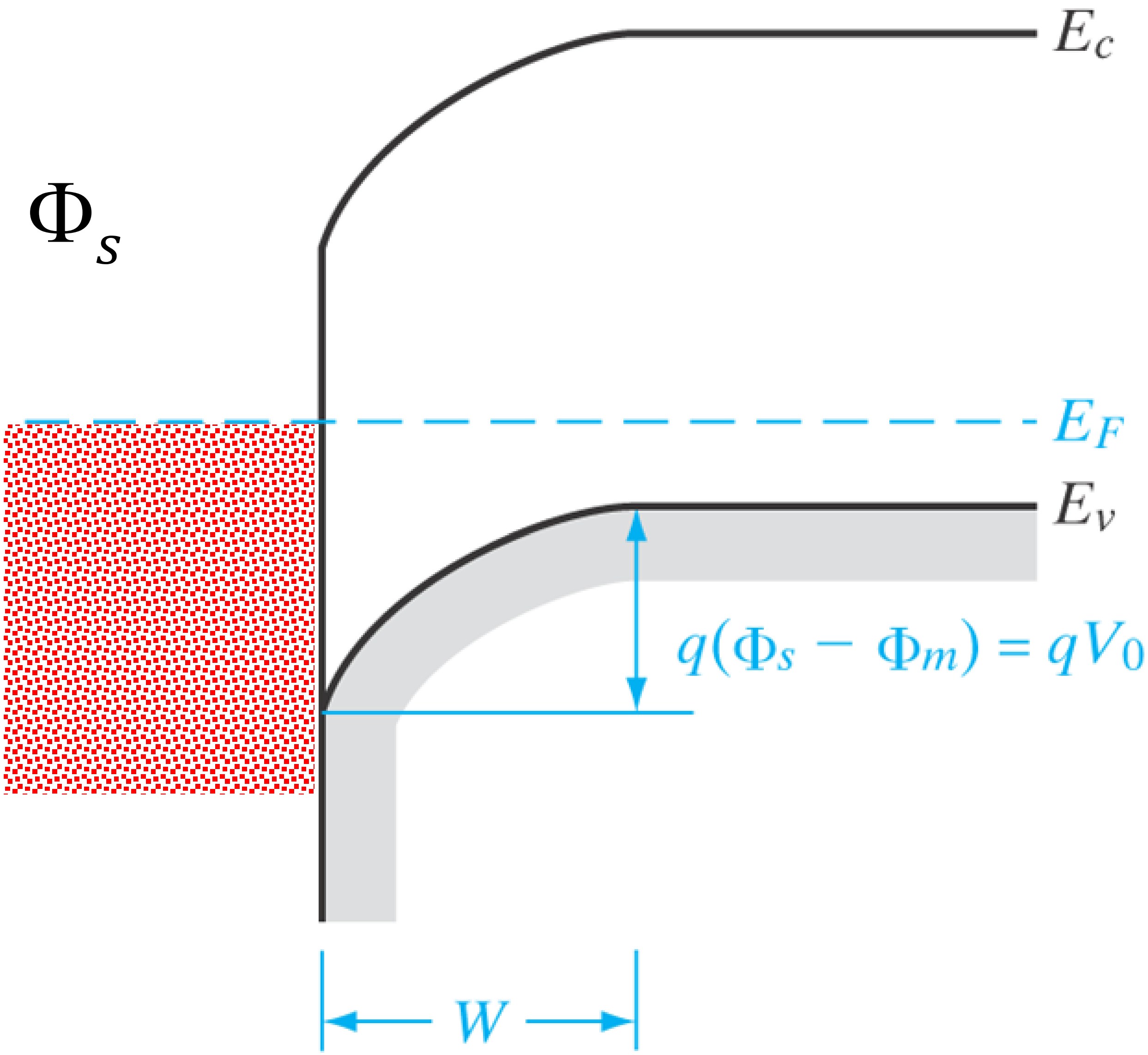
similar to a p^+-n junction

Metal-Semiconductor Junction (p-type)



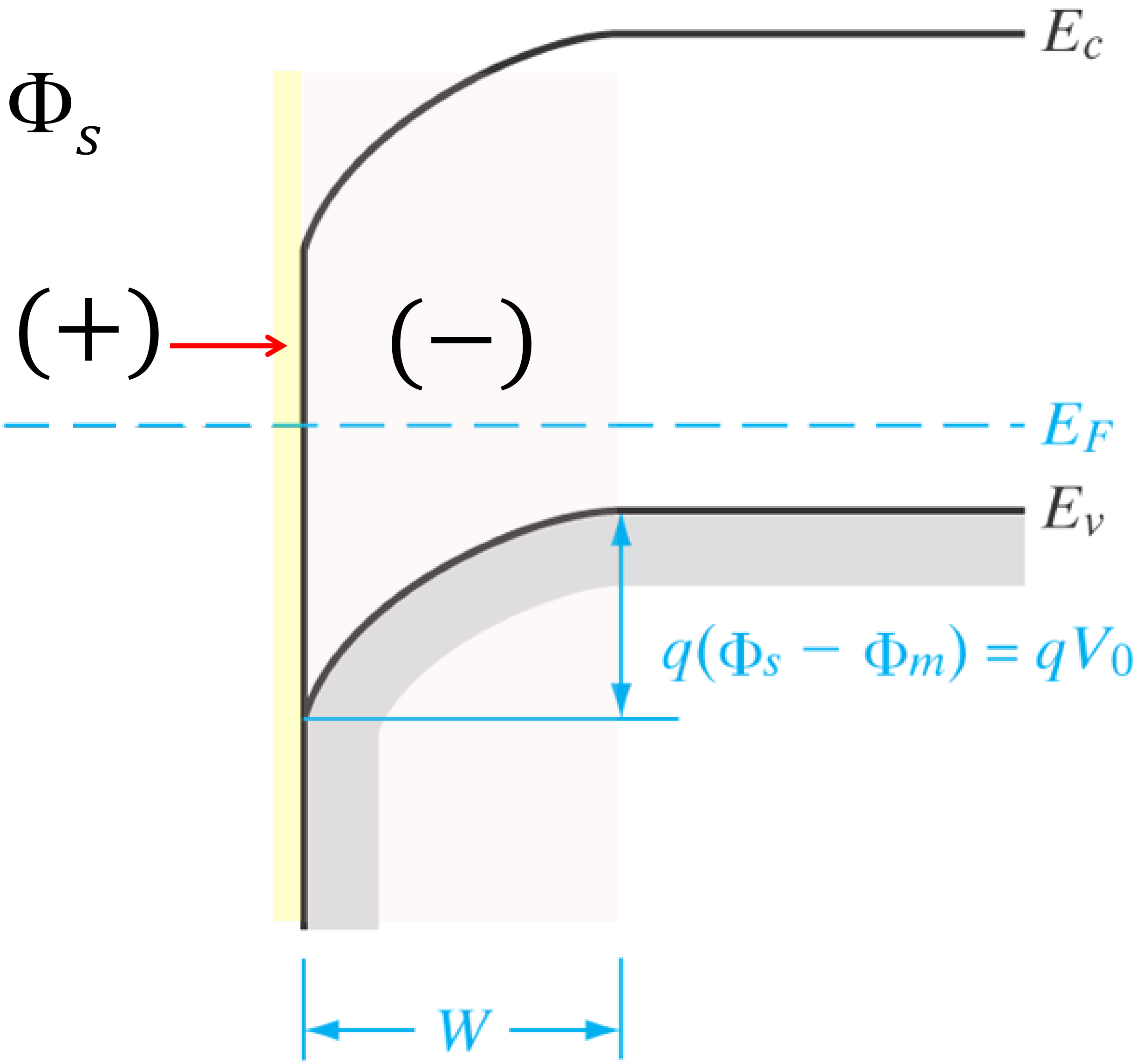
Metal-Semiconductor Junction (p-type)

$$\Phi_m < \Phi_s$$



Metal-Semiconductor Junction (p-type)

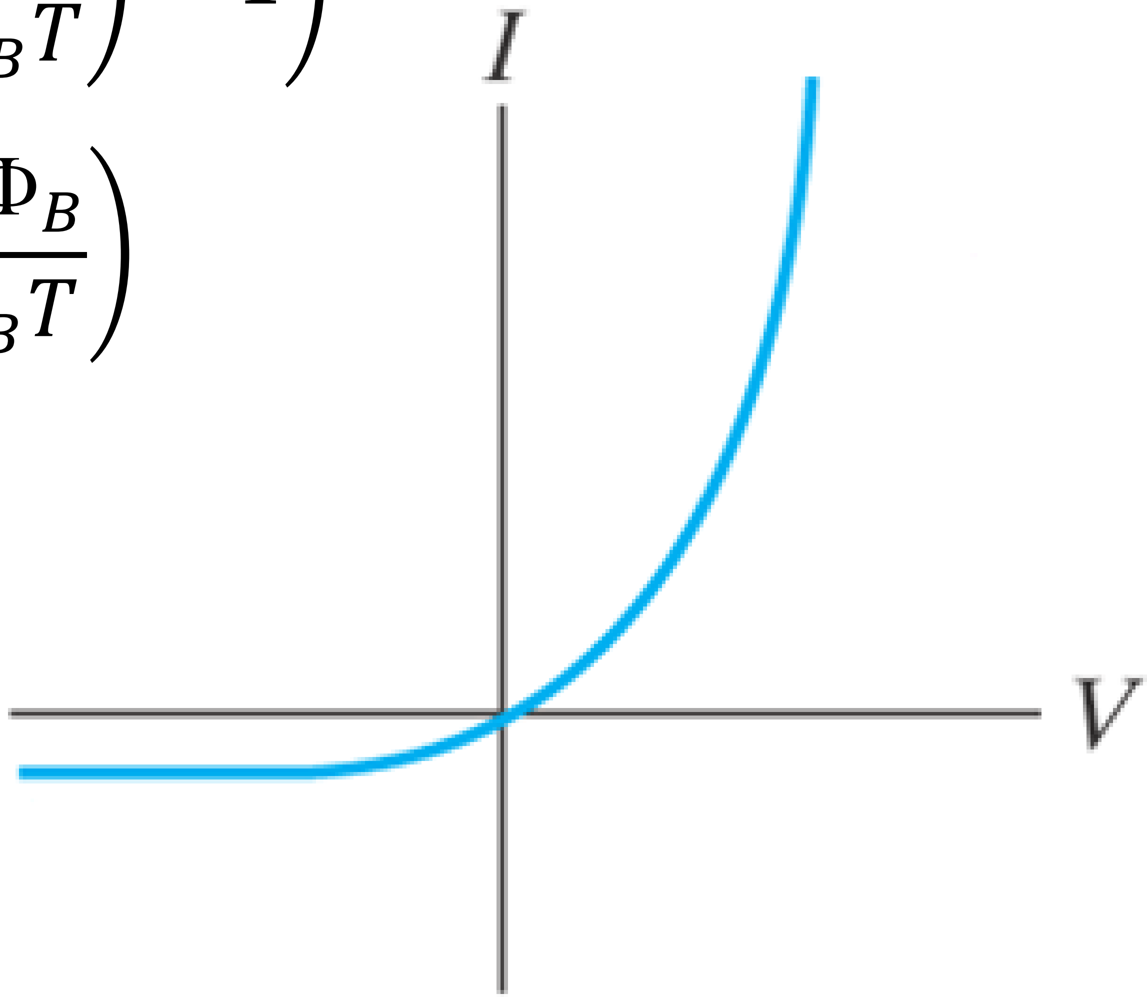
$$\Phi_m < \Phi_s$$



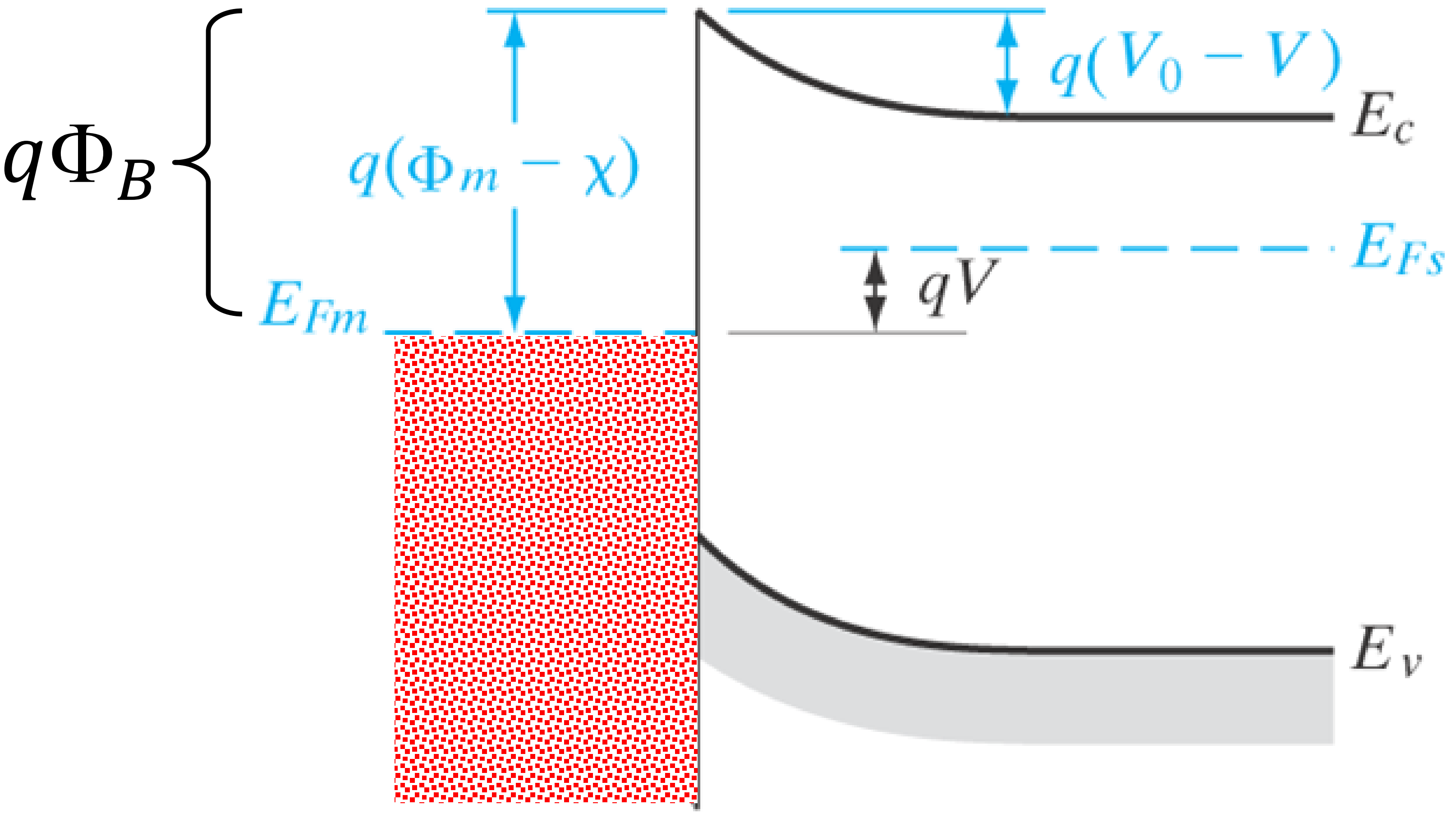
Rectifying contact

$$I = I_0\left(\exp\left(\frac{qV}{k_BT}\right) - 1\right)$$

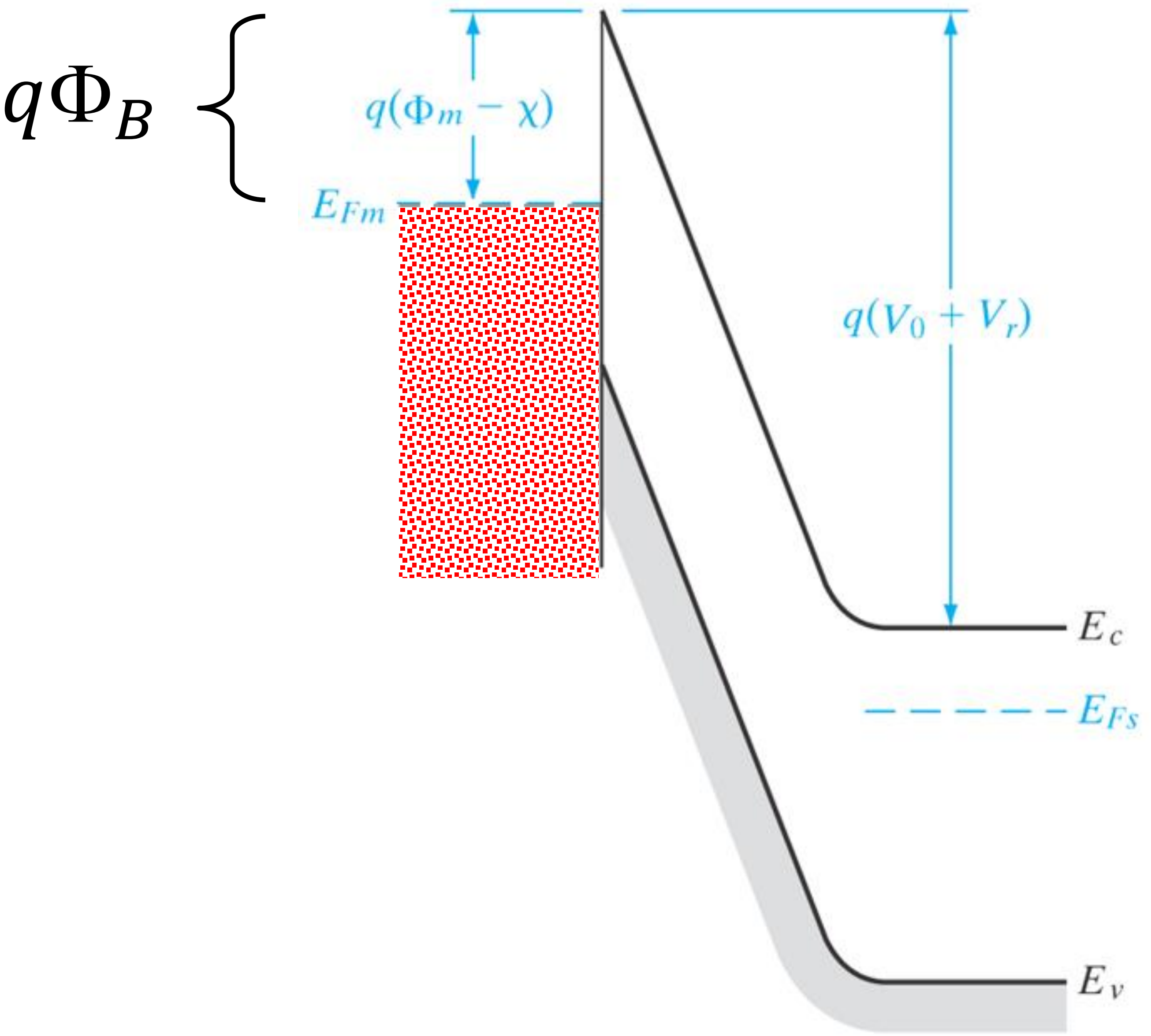
$$I_0 \propto \exp\left(-\frac{q\Phi_B}{k_BT}\right)$$



Forward Bias



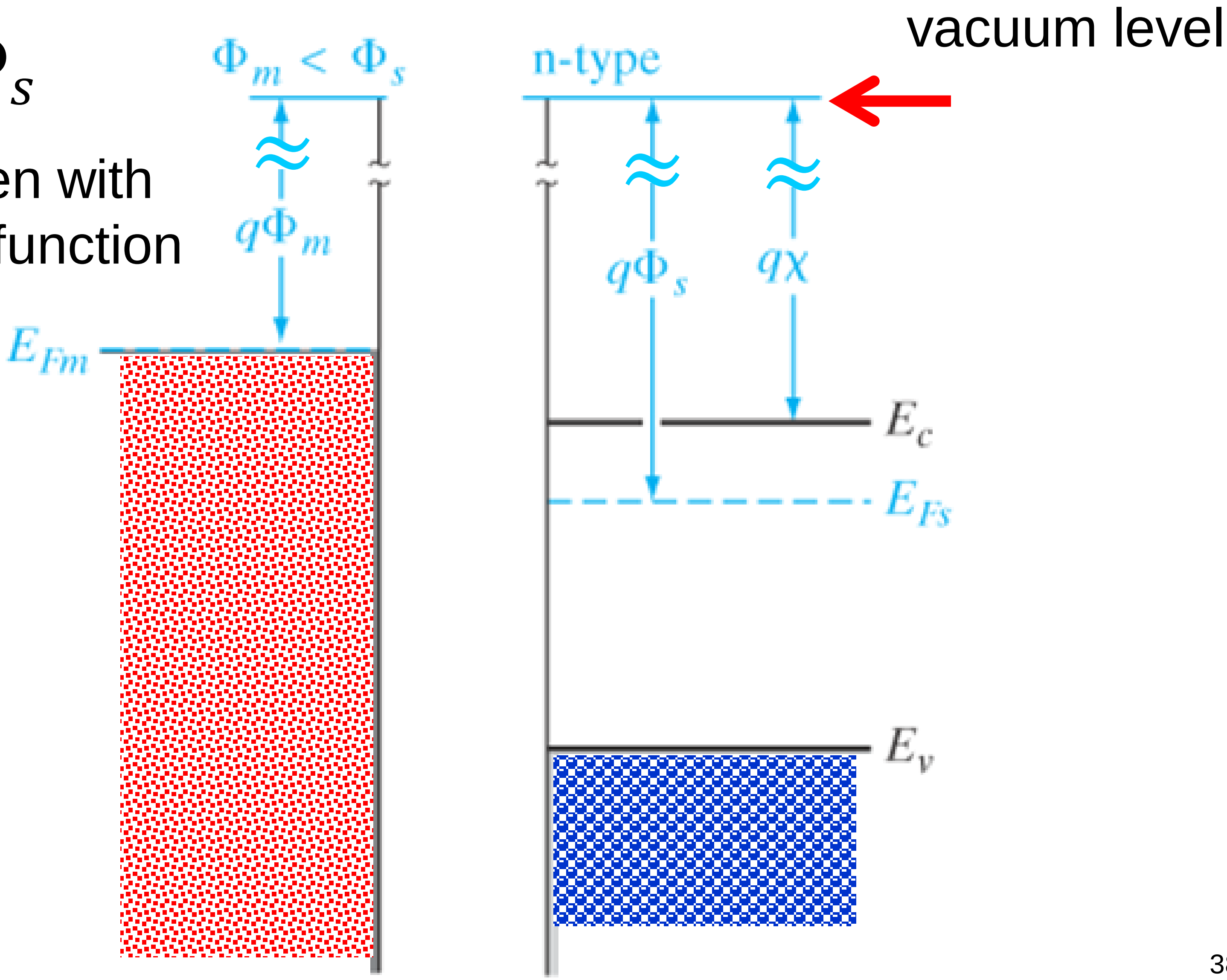
Reverse Bias



Ohmic contact (*n*-type semiconductor)

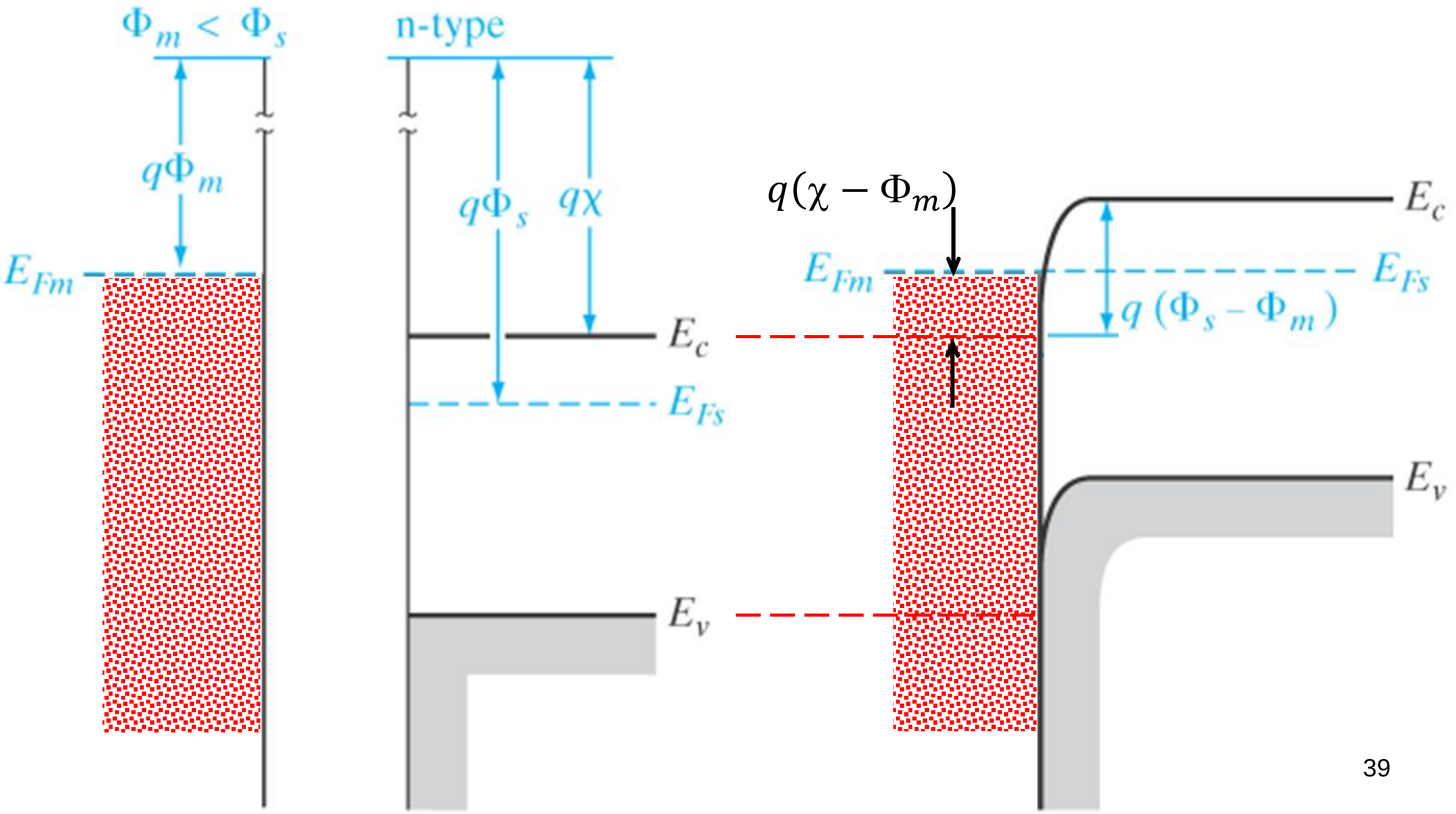
$\Phi_m < \Phi_s$

metal chosen with small work function



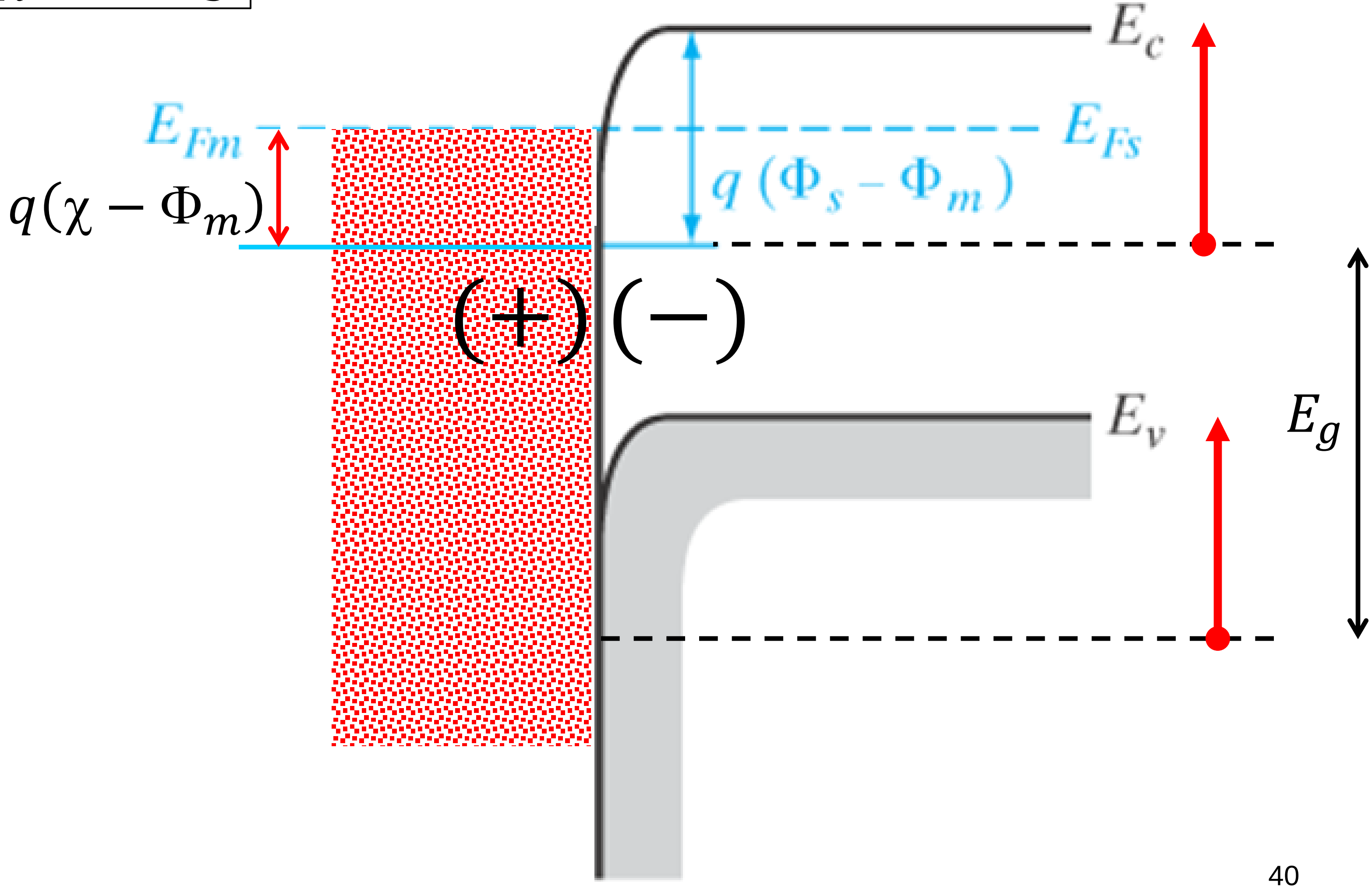
Ohmic contact (n-type semiconductor)

$$\Phi_m < \Phi_s$$



Ohmic contact (n-type semiconductor)

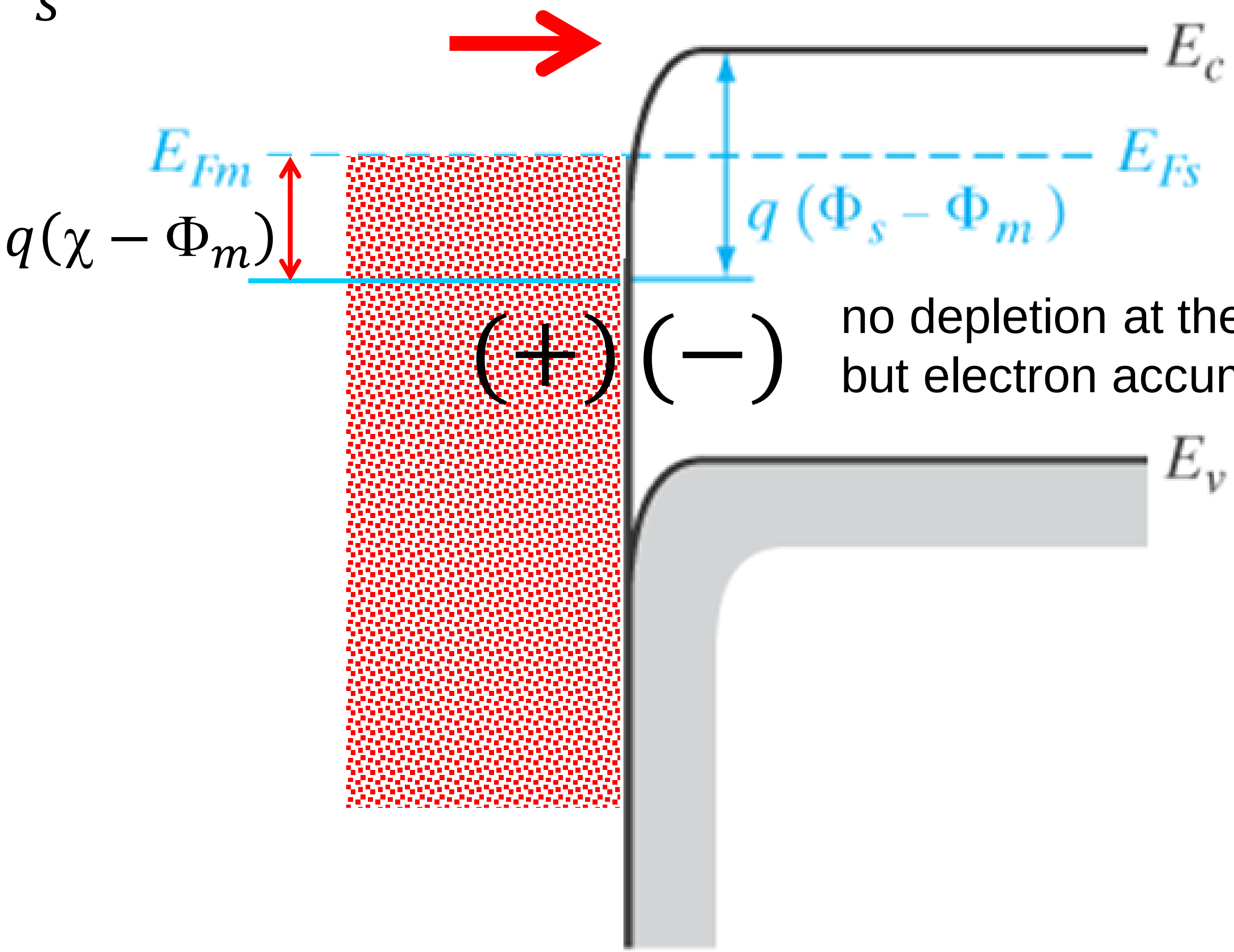
$\rightarrow$ $\Phi_m < \Phi_s$



Ohmic contact (n-type semiconductor)

$\Phi_m < \Phi_s$

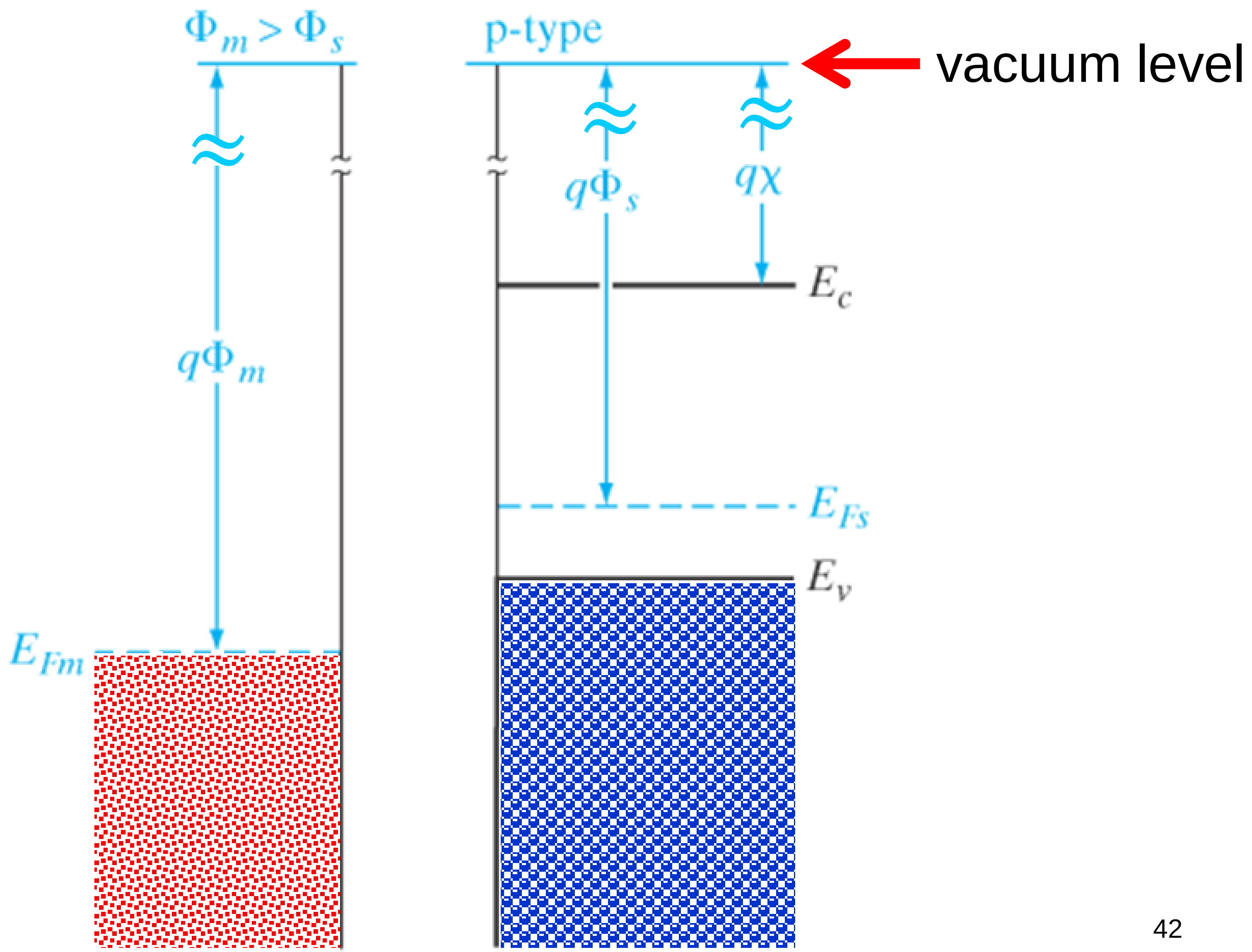
small barrier (not rectifying structure)



no depletion at the interface
but electron accumulation

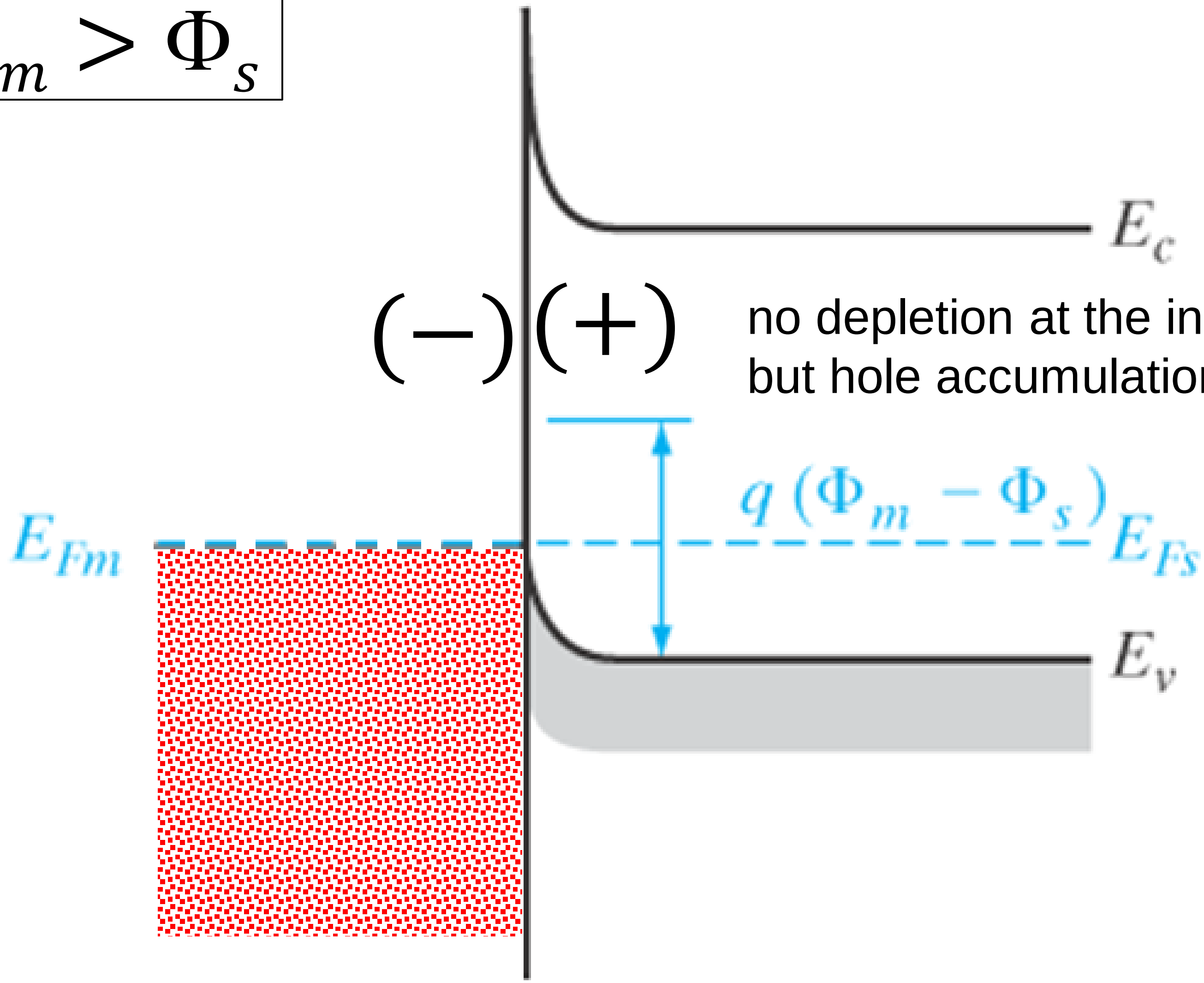
Ohmic contact (p-type semiconductor)

$\Phi_m > \Phi_s$



Ohmic contact (p-type semiconductor)

$\rightarrow$ $\Phi_m > \Phi_s$



no depletion at the interface but hole accumulation

SUMMARY

Rectifying Junction

$$\Phi_m > \Phi_s$$ *n*-type semiconductor

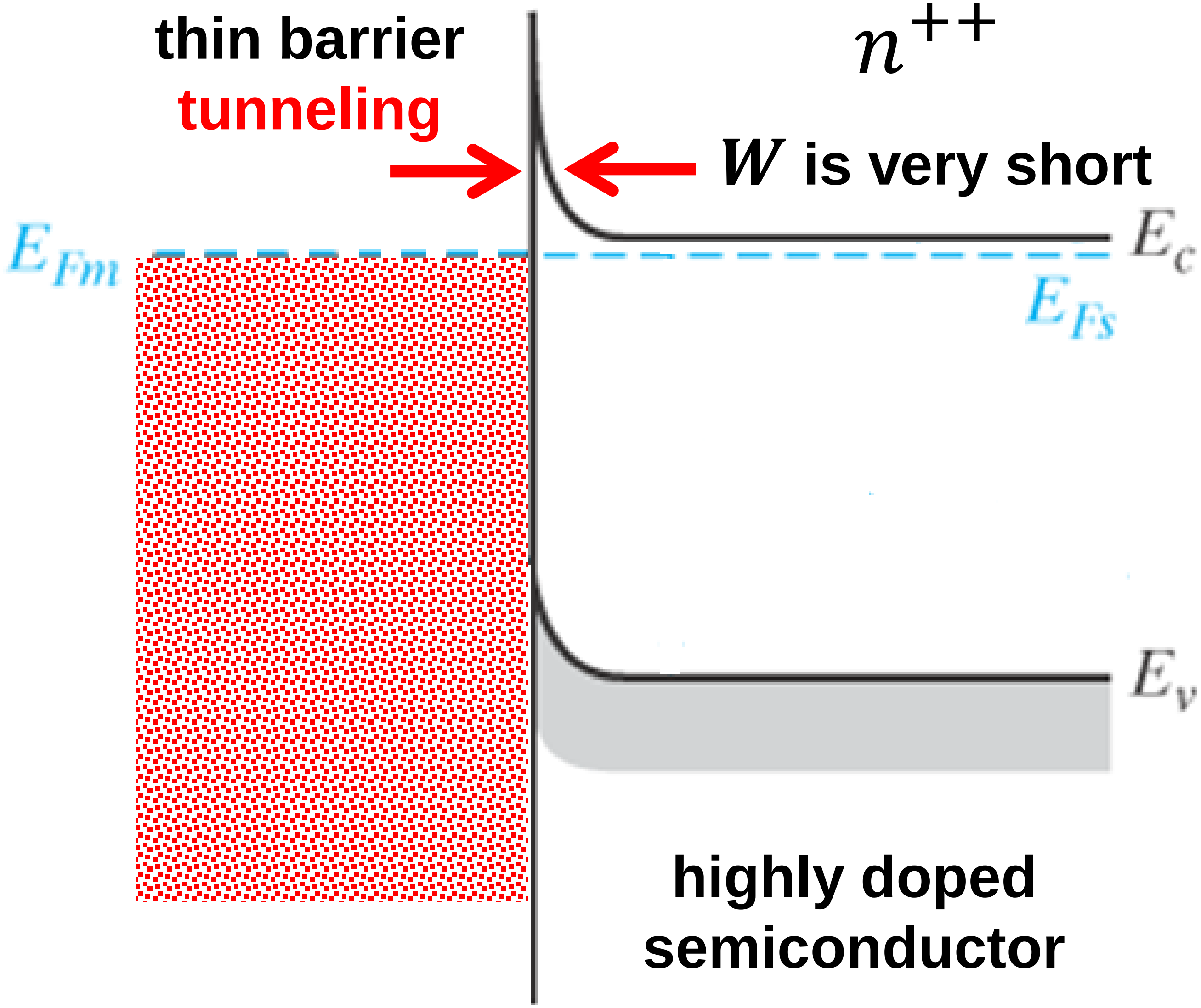
$$\Phi_m < \Phi_s$$ *p*-type semiconductor

Ohmic Contact

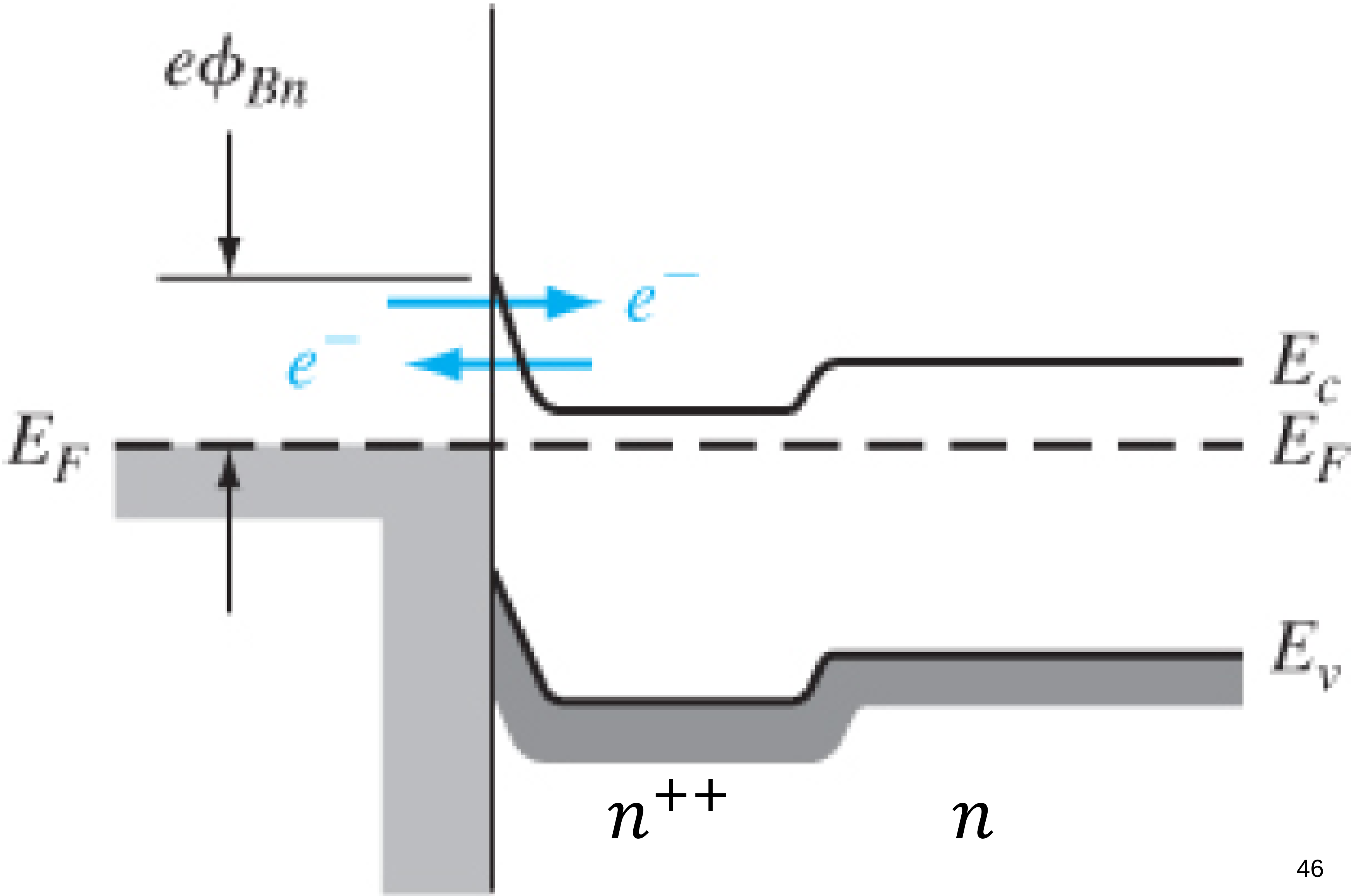
$$\Phi_m < \Phi_s$$ *n*-type semiconductor

$$\Phi_m > \Phi_s$$ *p*-type semiconductor

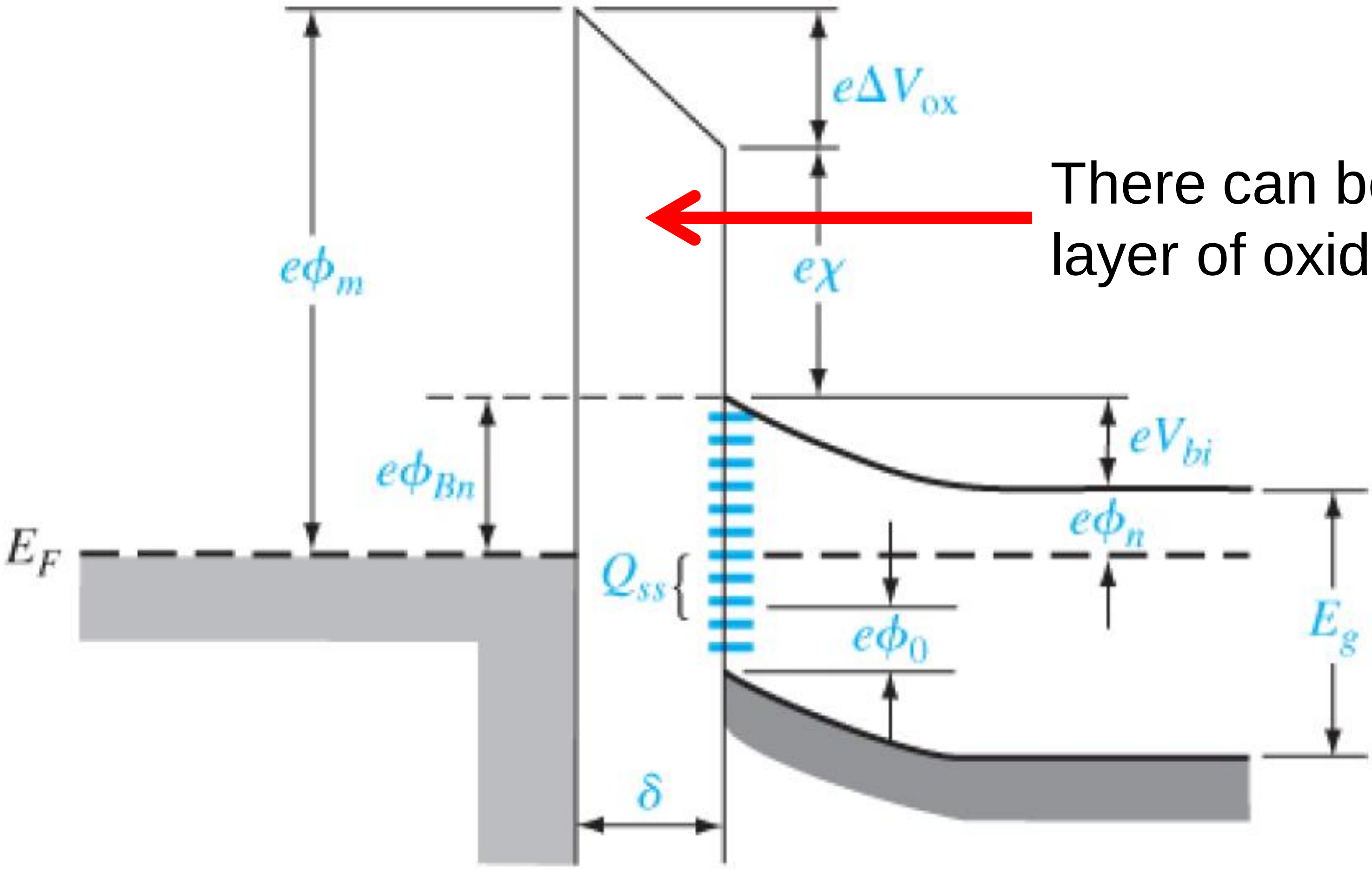
Other type of Ohmic contact



Other type of Ohmic contact (zoom out)



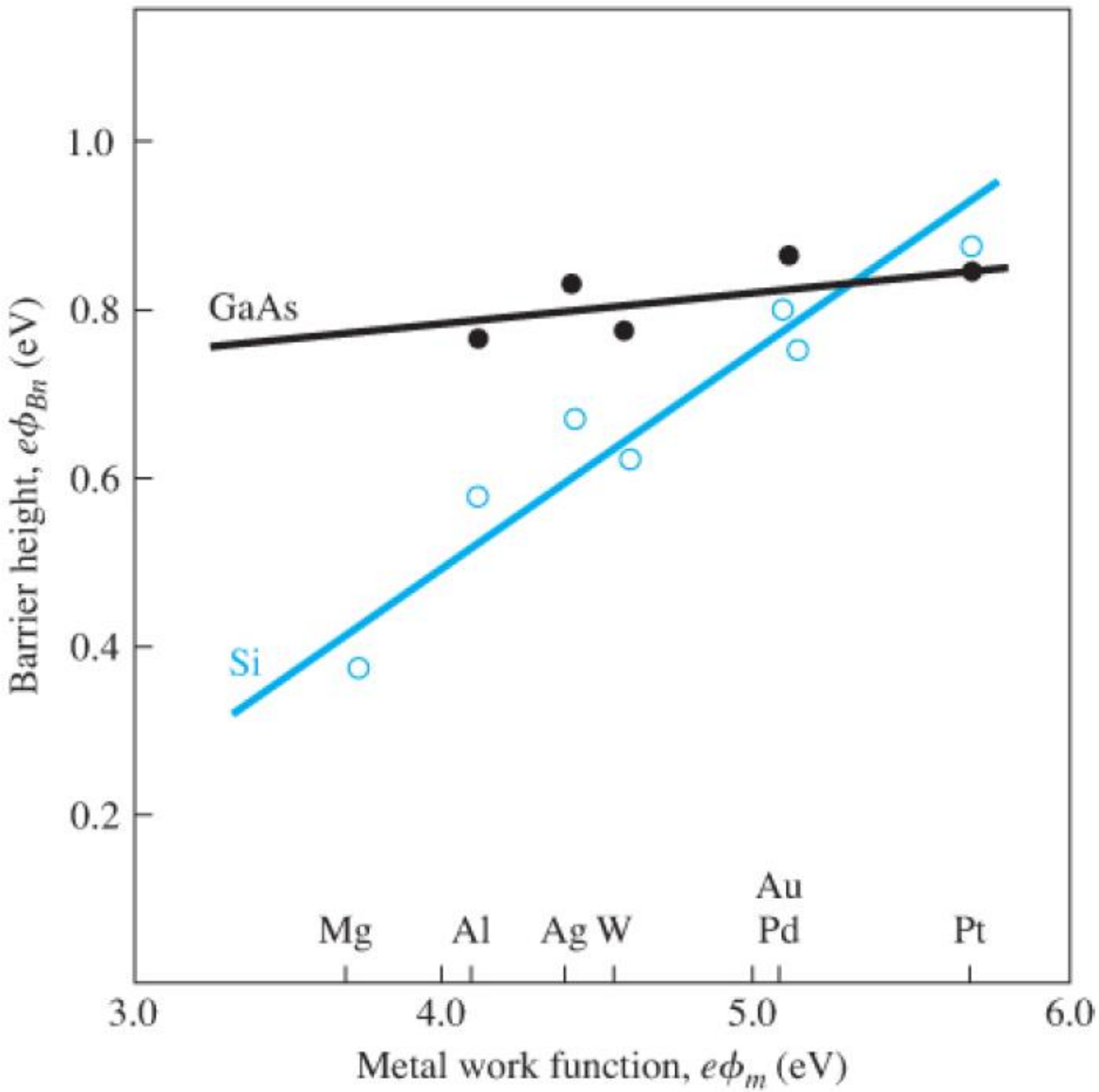
Realistic M-S junctions



There can be a thin layer of oxide

Energy-band diagram of a metal–semiconductor junction with an interfacial layer and interface states.

Experimental barrier heights as a function of metal work functions for GaAs and Si. *(From Crowley and Sze)*



Fermi level is “pinned” by surface states which influence the actual barrier height