ECE 340 Lectures 25
Semiconductor Electronics

Spring 2022
10:00-10:50am
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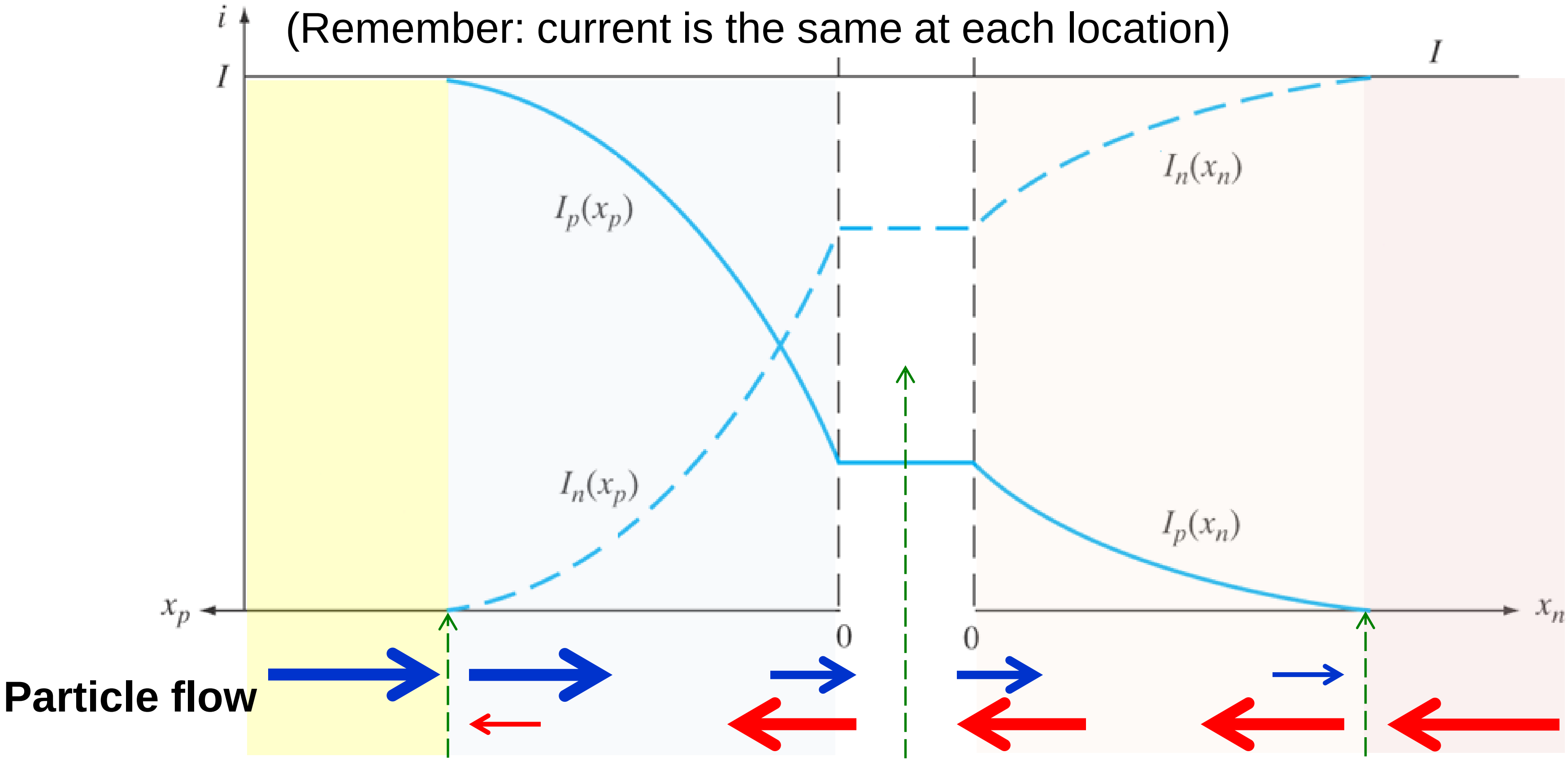
2062 ECE Building

Today's Discussion

- **Reverse bias**
- **Breakdown voltage**
- **Breakdown mechanisms**
  - **Zener effect**
  - **Avalanche**

Details of particle flows ($N_D > N_A$)

(Remember: current is the same at each location)



Current consists only of majority holes

Current consists of majority holes and minority electrons with recombination occurring

Current consists of majority electrons and minority electrons with recombination occurring

Current consists only of majority electrons

Practically all excess minority electrons have recombined

Assumption of no recombination

Practically all excess minority holes have recombined

Reverse saturation current

Reverse bias $V = -V_r$

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

$$I = -I_0 = -qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)$$

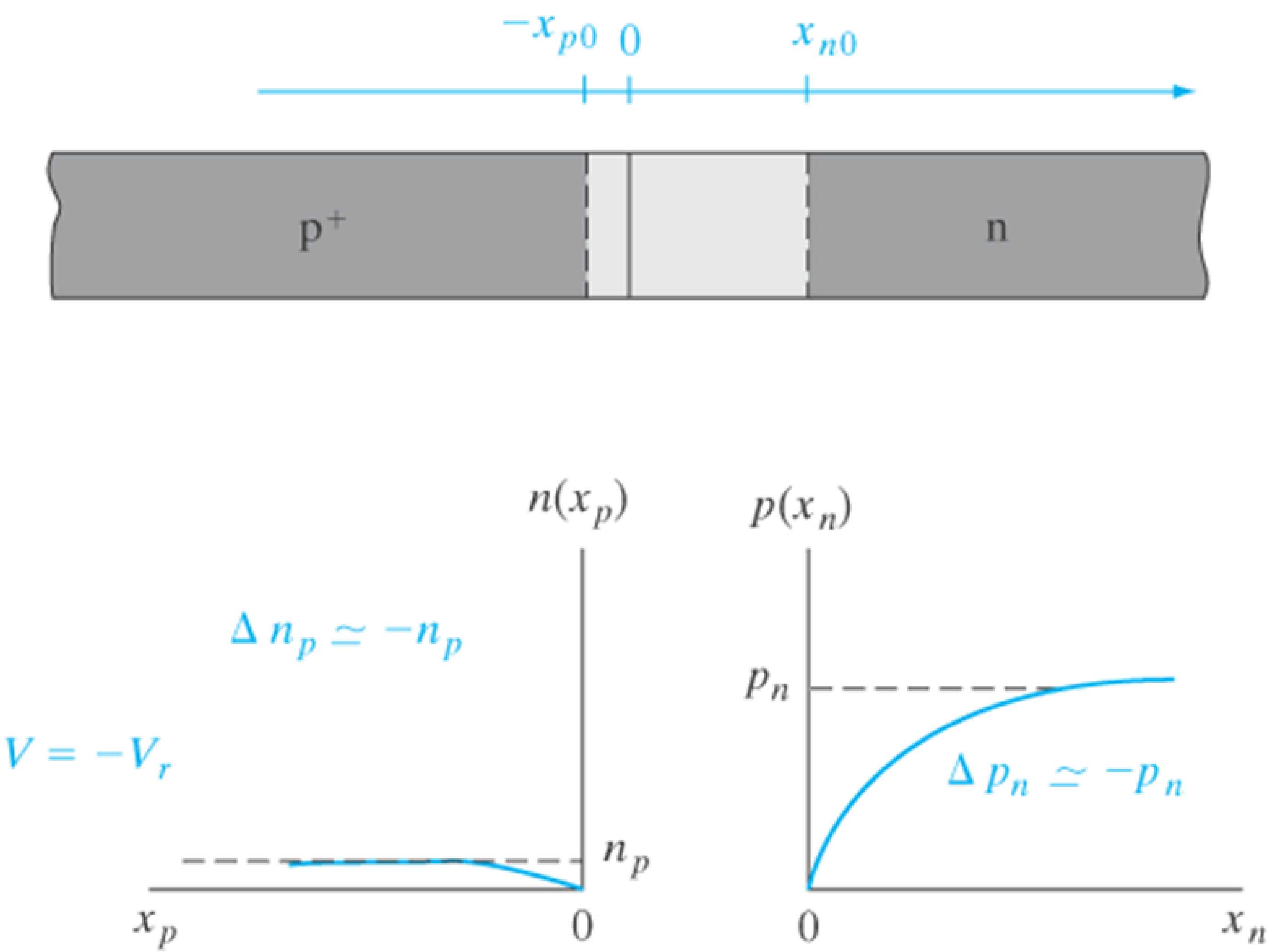
Reverse saturation current

Reverse bias $V = -V_r$ with $V_r \gg k_B T/q$

$$\Delta p_n = p_n \left[\exp\left(-\frac{qV_r}{k_B T}\right) - 1\right] \approx -p_n$$

$$\Delta n_p = n_p \left[\exp\left(-\frac{qV_r}{k_B T}\right) - 1\right] \approx -n_p$$

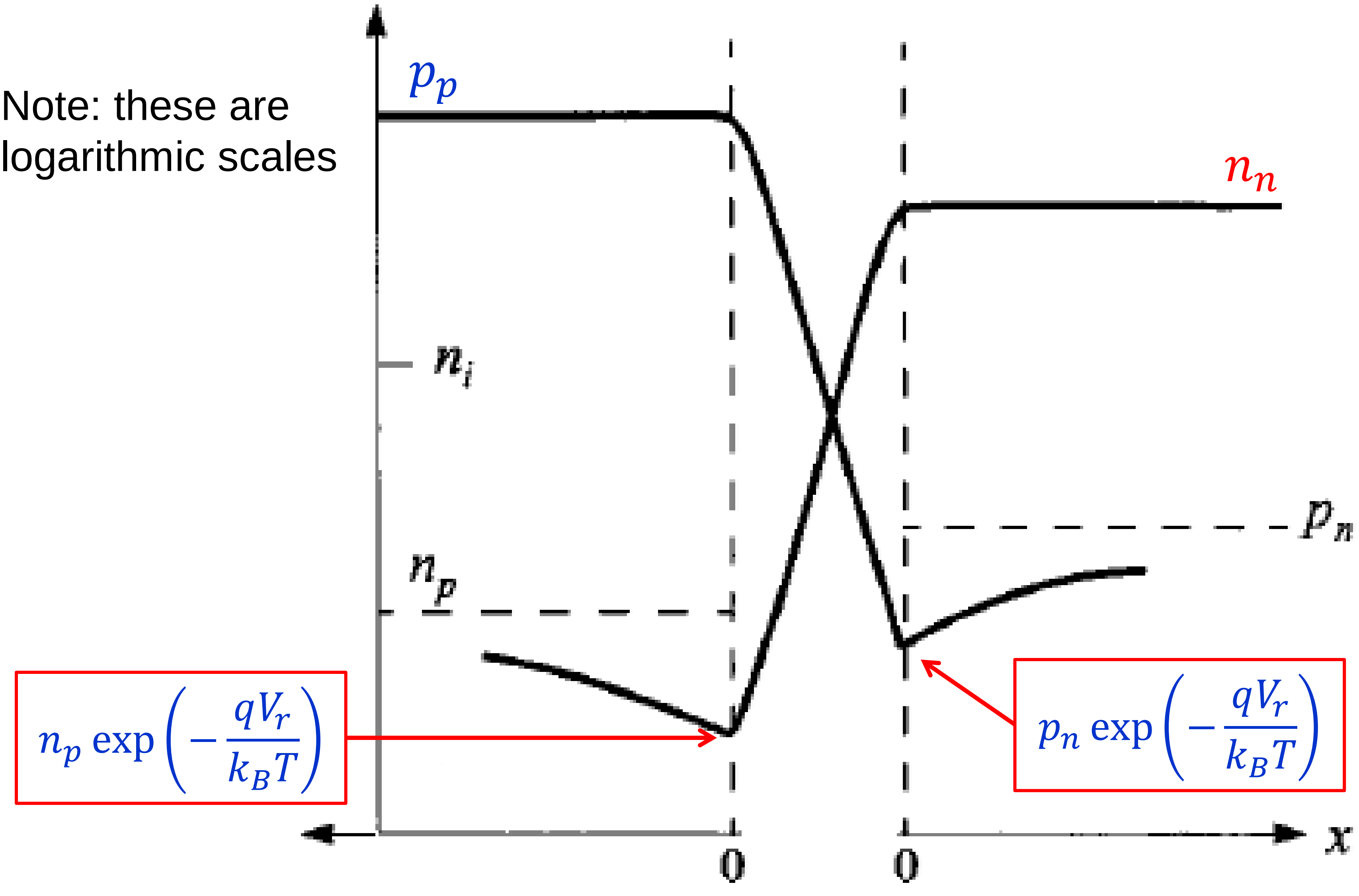
Reverse bias minority carriers



From *Solid State Electronic Devices,* Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.

Reverse bias carrier distributions

Note: these are logarithmic scales



Quasi-Fermi level reminder

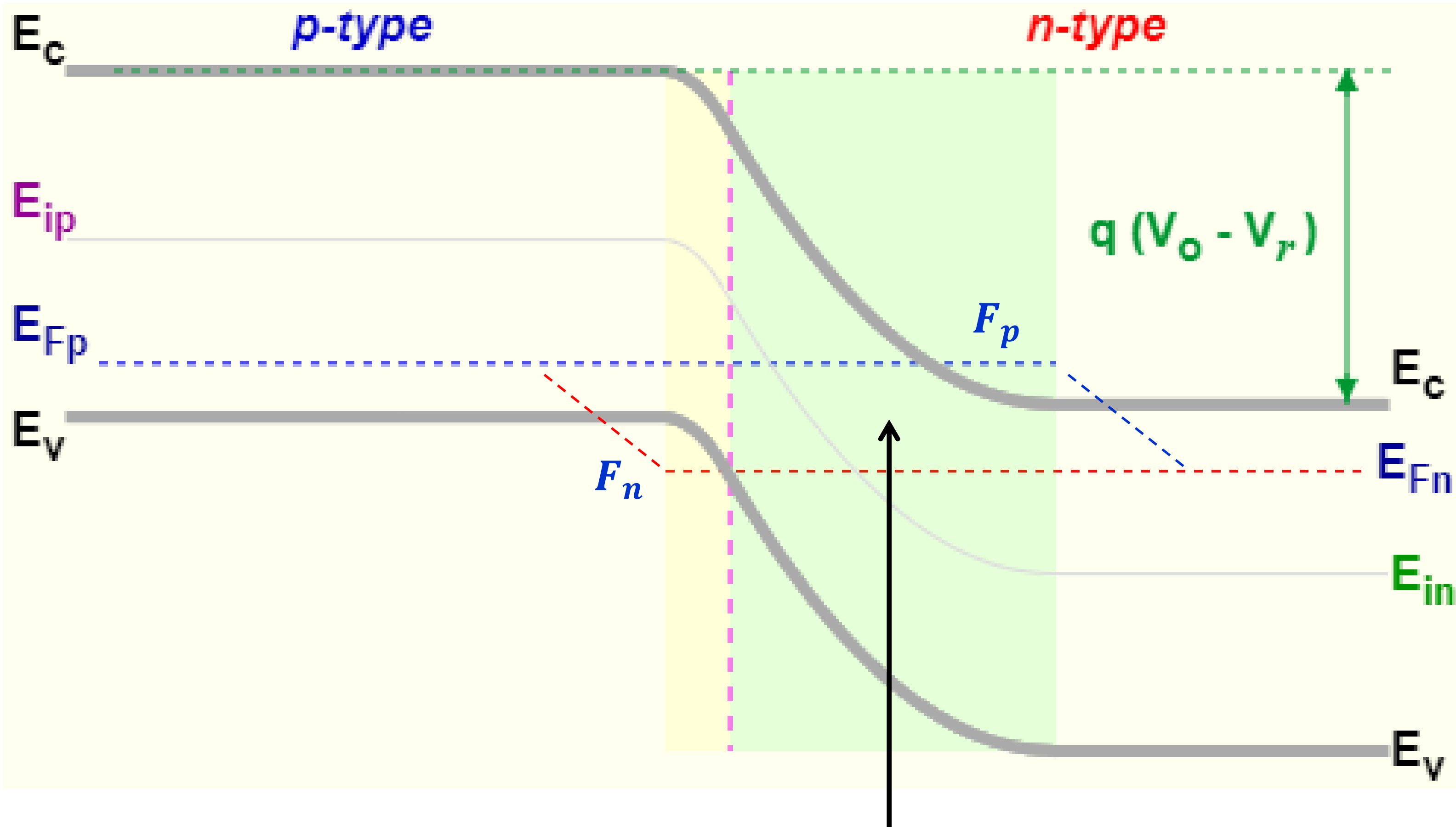
$$n = n_i \exp\left(\frac{F_n - E_i}{k_B T}\right)$$

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

$$pn = n_i^2 \exp\left(\frac{F_n - E_i + E_i - F_p}{k_B T}\right)$$

$$= n_i^2 \exp\left(\frac{F_n - F_p}{k_B T}\right)$$

Reverse bias minority carriers



$$pn = n_i^2 \exp\left(\frac{F_n - F_p}{k_B T}\right) \approx 0$$

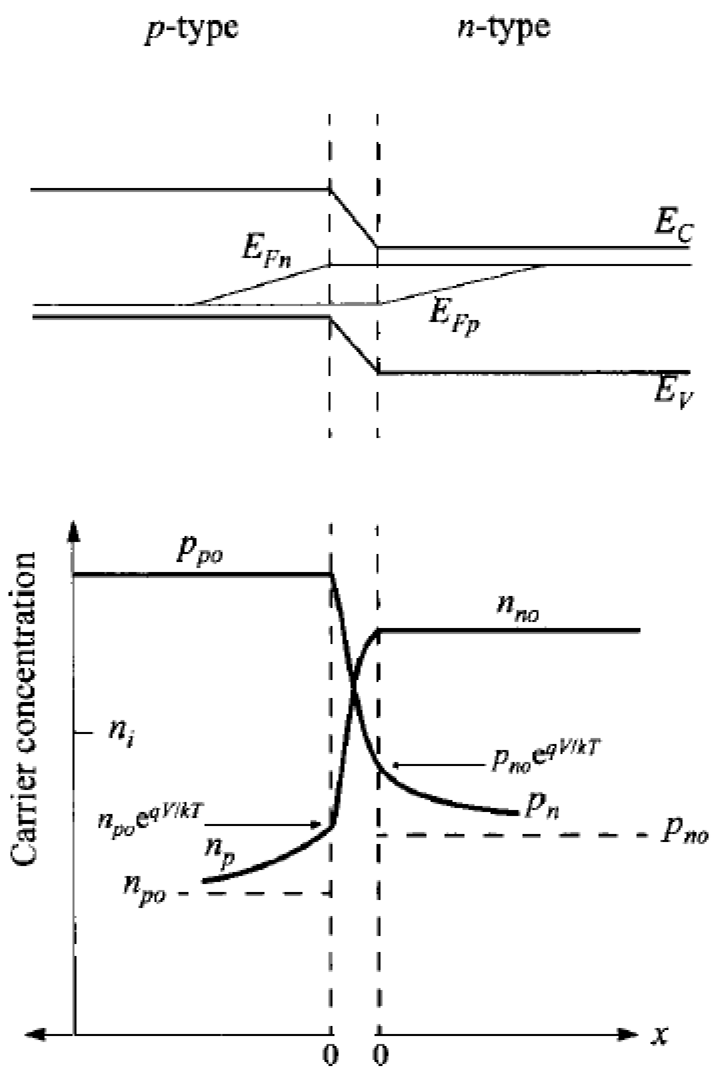
Pictorial summary of a p+/n junction

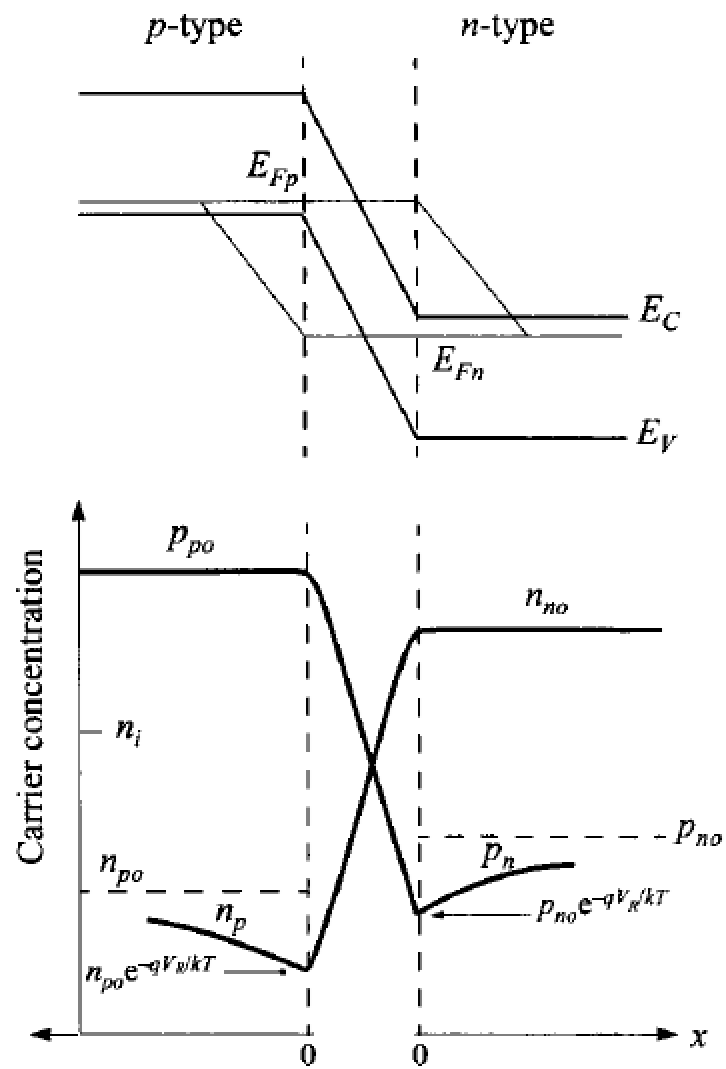
The following summary slides are adapted from the most recent edition (2006) of a classic comprehensive book on semiconductor devices. This book can be downloaded through the University Library:

S.M. Sze and K.K. Ng "Physics of Semiconductor Devices"

from the Wiley Online Library. For students who are interested in continuing with semiconductors or who simply want to have the standard reference which most professionals have used since the 1970's, this is highly recommended.

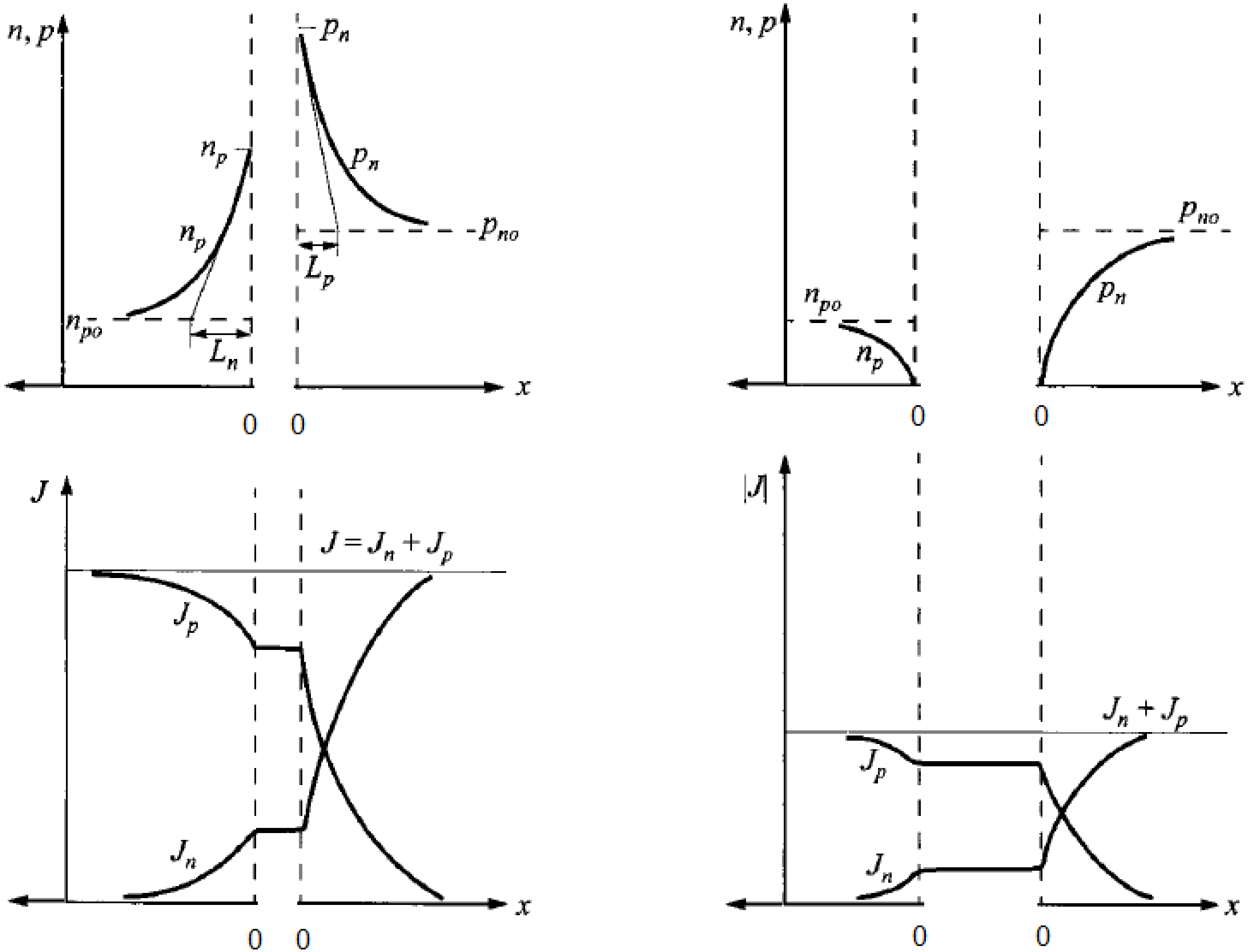
Forward bias Reverse bias





Adapted from S.M. Sze and K.K. Ng “Physics of Semiconductor Devices”

Forward bias Reverse bias



Adapted from S.M. Sze and K.K. Ng “Physics of Semiconductor Devices”

Exercise

- **Consider an abrupt *p-n* junction with cross-sectional area A = 1 mm^2 at T = 300K, with:**

p-side	*n*-side
$N_A = 10^{16}\text{cm}^{-3}$	$N_D = 10^{18}\text{cm}^{-3}$
$\mu_p = 370\text{cm}^2/\text{Vs}$	$\mu_n = 550\text{cm}^2/\text{Vs}$
$\mu_n = 1{,}000\text{cm}^2/\text{Vs}$	$\mu_p = 150\text{cm}^2/\text{Vs}$
$\tau_n = 1.0\ \mu s$	$\tau_p = 1.0\ \mu s$

- **Find the reverse saturation current**

Exercise

- **Reverse saturation current**

$$I = -I_0 = -qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)$$

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5 \times 10^{10})^2}{10^{18}} = 2.25 \times 10^2\text{cm}^{-3}$$

$$n_p = \frac{n_i^2}{p_p} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4\text{cm}^{-3}$$

$$\left(D_p\right)_n = \frac{k_B T}{q}\left(\mu_p\right)_n = 0.0259 \times 150 = 3.89\text{cm}^2\text{s}$$

$$(D_n)_p = \frac{k_B T}{q}(\mu_n)_p = 0.0259 \times 1000 = 25.9\text{cm}^2\text{s}$$

Exercise

- **Reverse saturation current**

$$I = -I_0 = -qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)$$

$$L_p = \sqrt{D_p\tau_p} = \sqrt{25.9 \times 10^{-6}} = 0.00197\text{cm}$$

$$L_n = \sqrt{D_n\tau_n} = \sqrt{3.89 \times 10^{-6}} = 0.00509\text{cm}$$

$$I = -1.602 \times 10^{-19} \times 10^{-2} \times$$

$$\times \left(\frac{3.89}{0.00197}2.25 \times 10^{2} + \frac{25.9}{0.00509}2.25 \times 10^{4}\right)$$

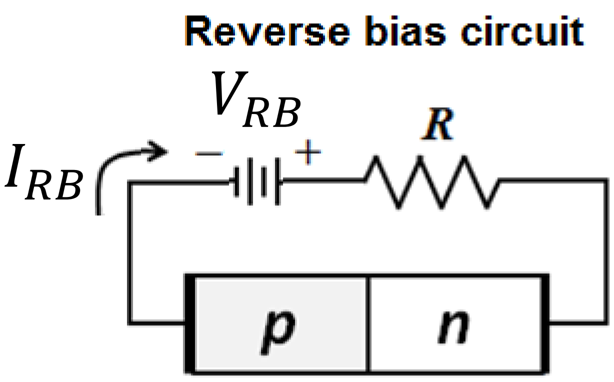
$$= -1.839 \times 10^{-13}\text{A}$$

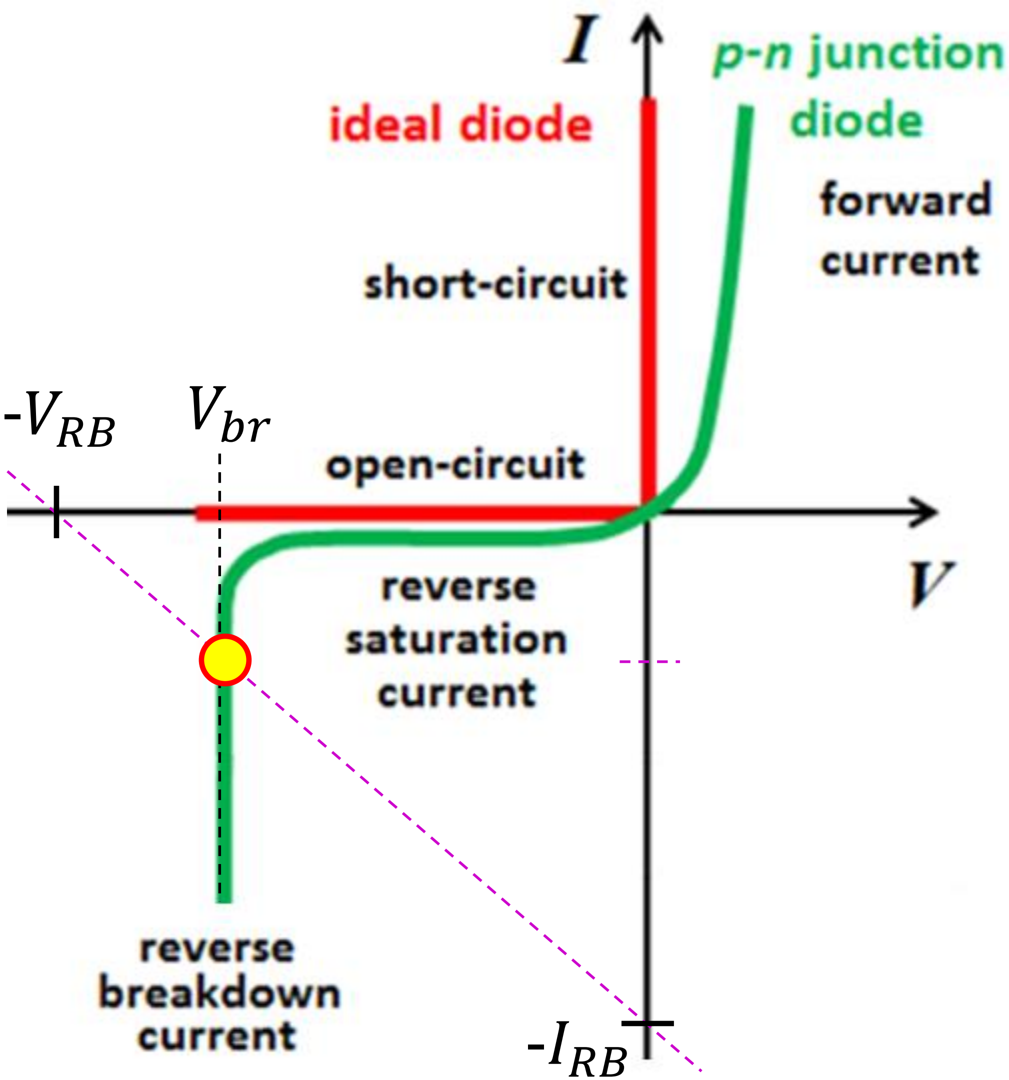
p-n junction *I-V* curve under reverse bias

Circuit considerations:

The resistor $\boldsymbol{R}$ helps constrain the current in the **reverse breakdown regime**.

(Remember ECE 110)

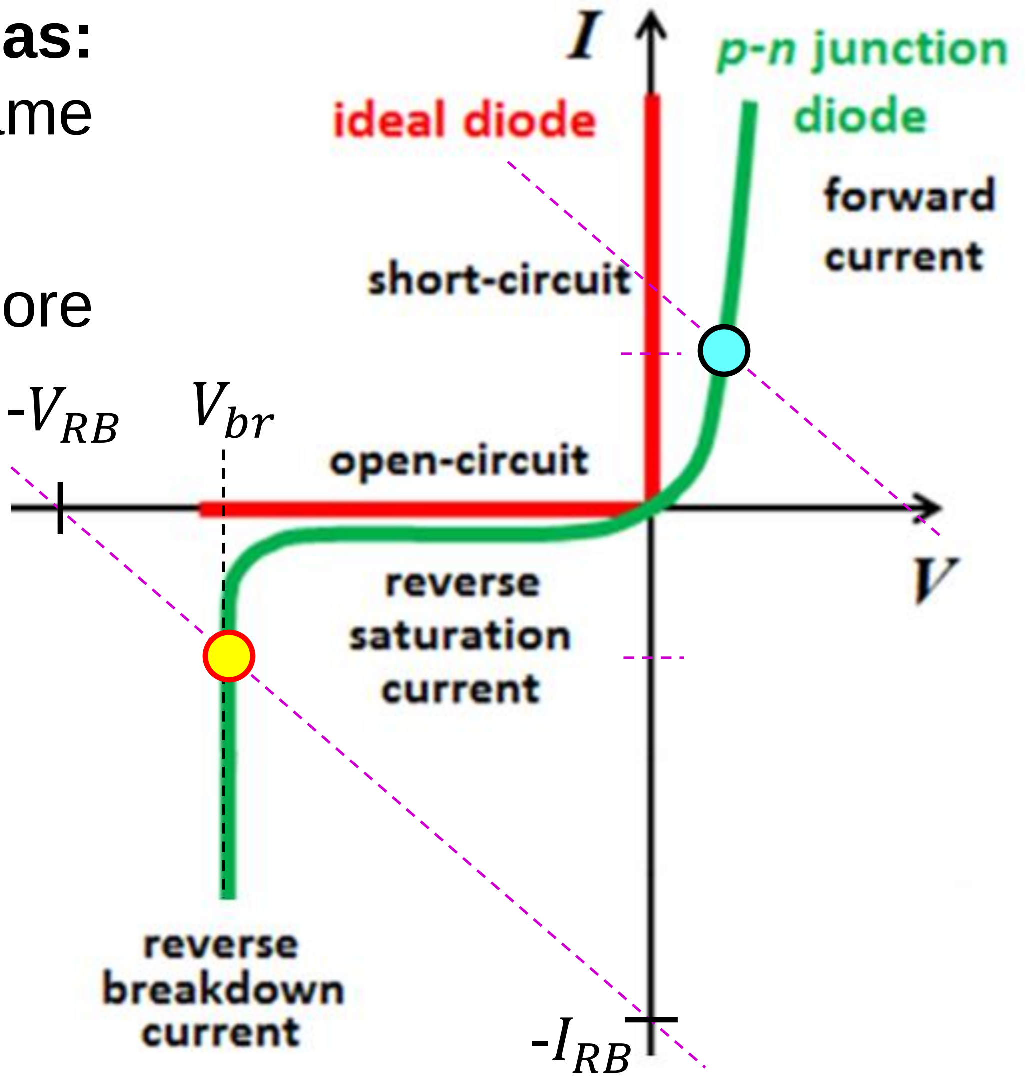




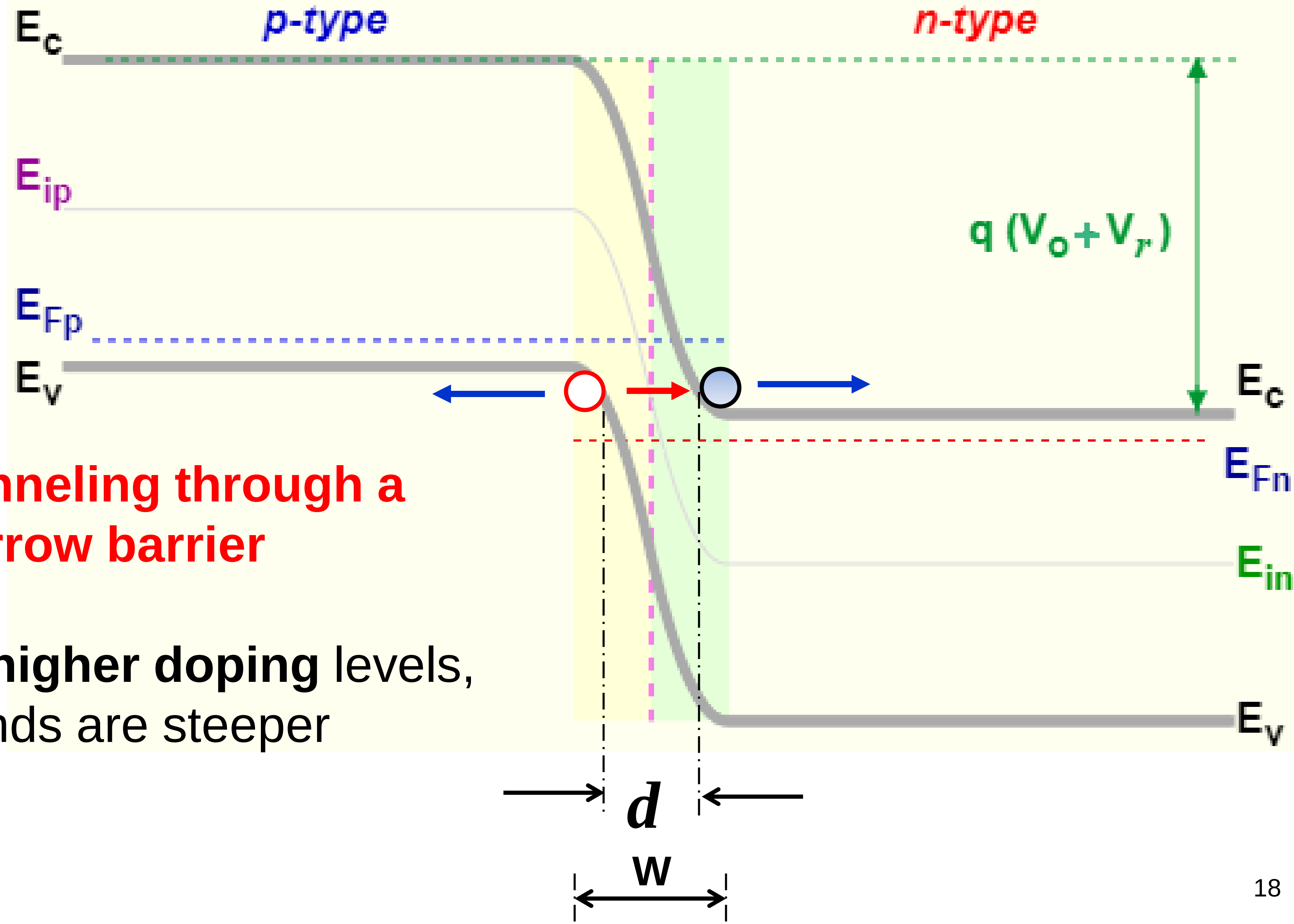
p-n junction *I-V* curve under reverse bias

Compare with forward bias: same current magnitude, same resistance (same slope).

Which condition uses more power?



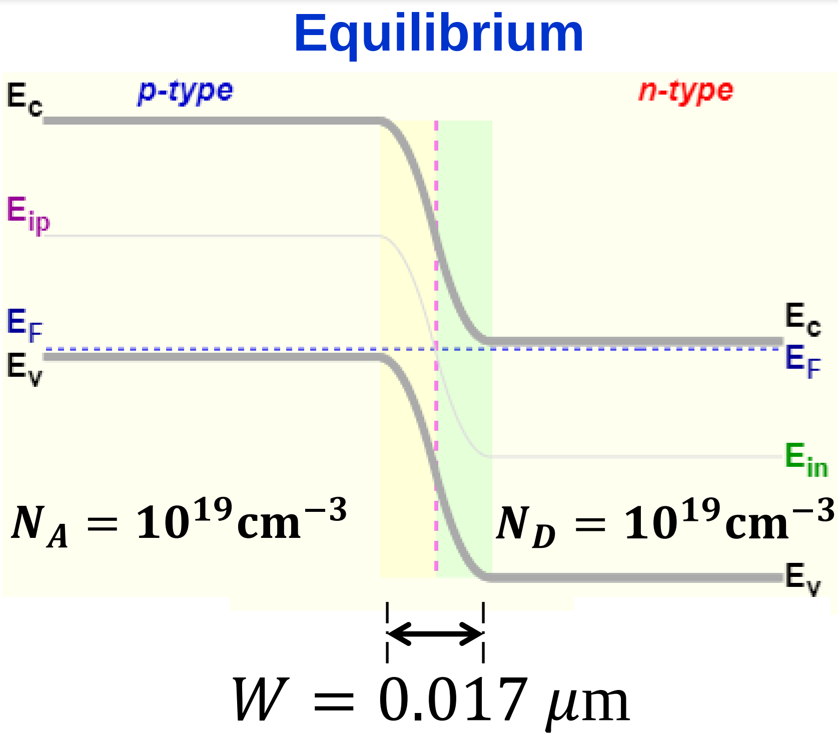
Reverse breakdown (A) = Zener effect

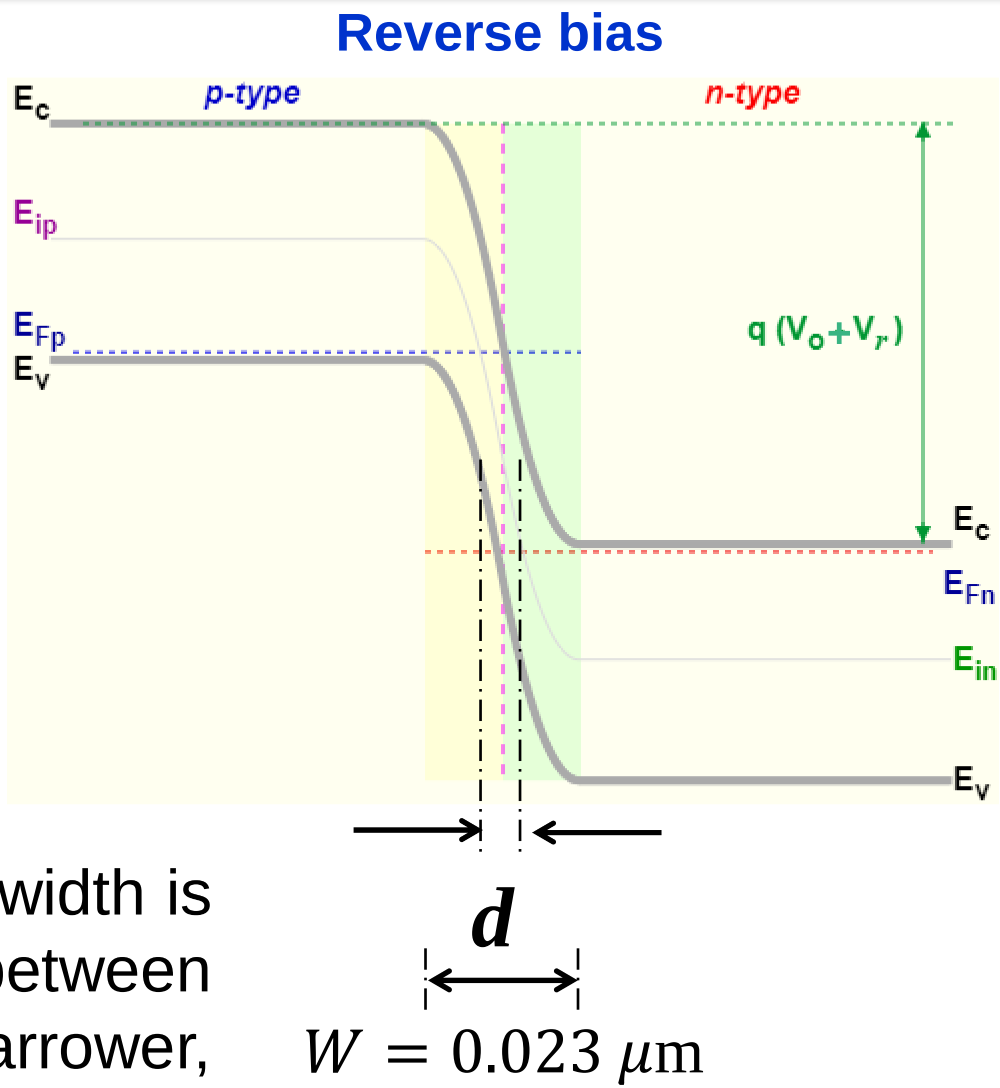


Tunneling through a narrow barrier

At **higher doping** levels, bands are steeper

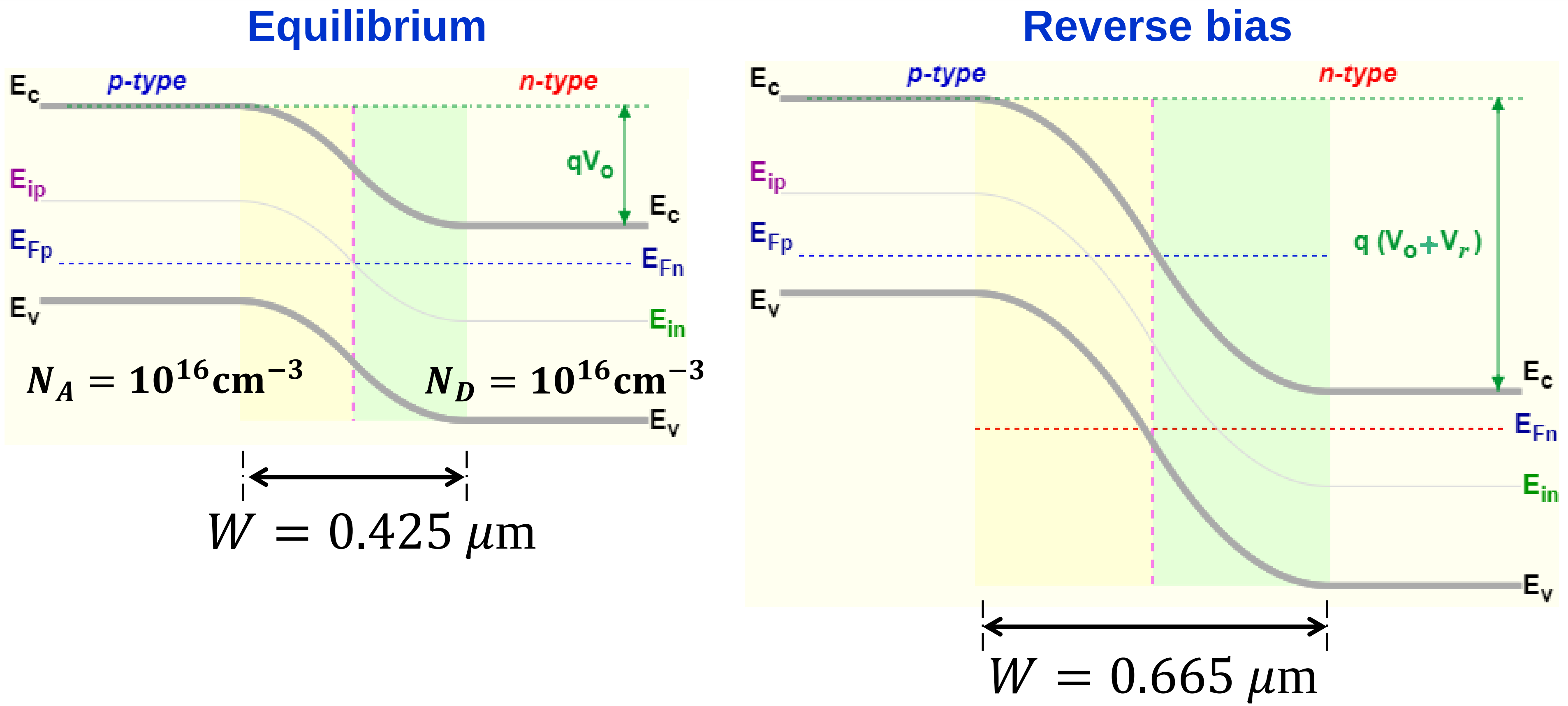
Reverse breakdown (A) = Zener effect





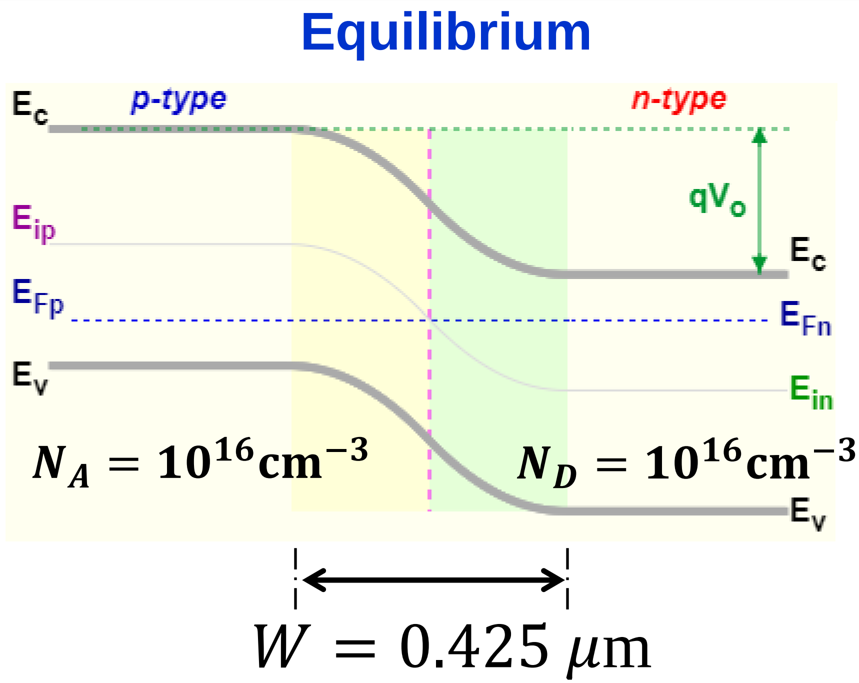
In reverse bias the depletion width is wider but space separation between band edges is actually narrower, making tunneling more likely.

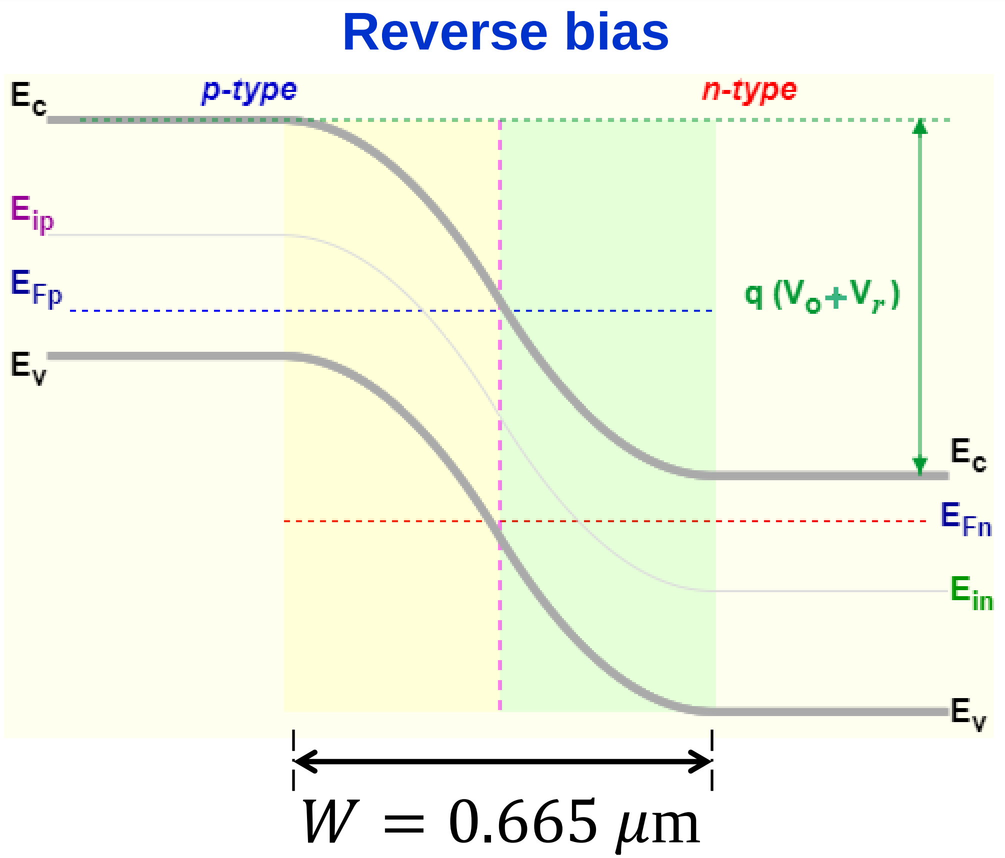
Reverse breakdown (A) = Zener effect



At shallow doping the depletion region is not sufficiently wide to allow tunneling between bands and there is no appreciable Zener effect.

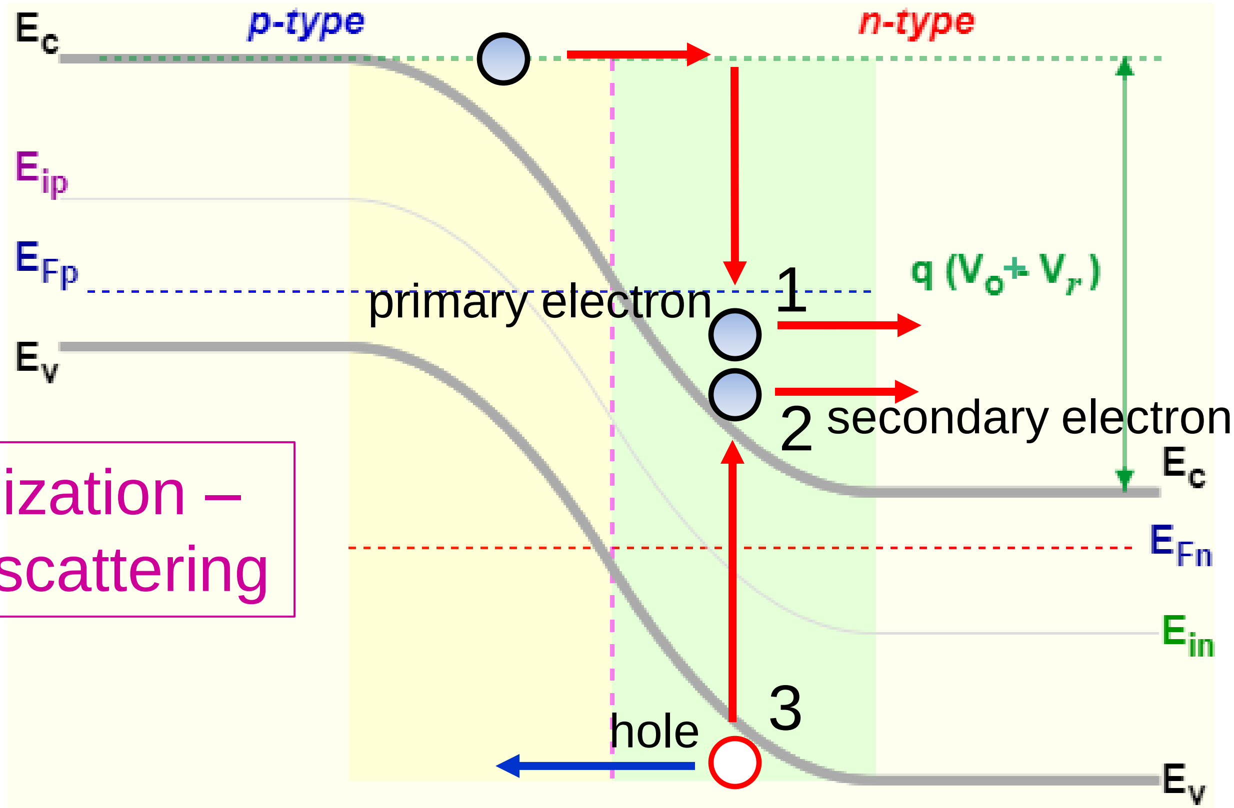
Reverse breakdown (A) = Zener effect





At shallow doping the distance between bands is not sufficiently wide to allow tunneling.

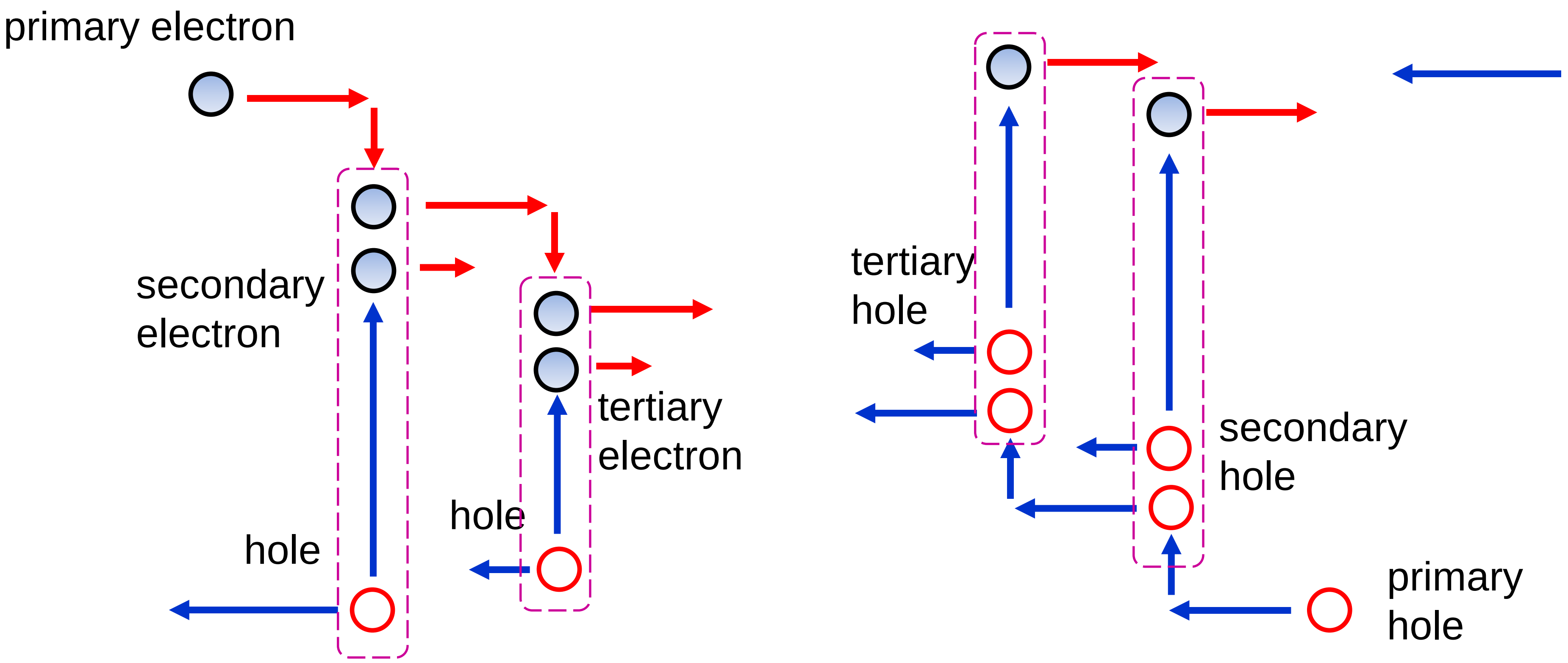
Reverse breakdown (B) = Avalanche



impact ionization –
3-particle scattering

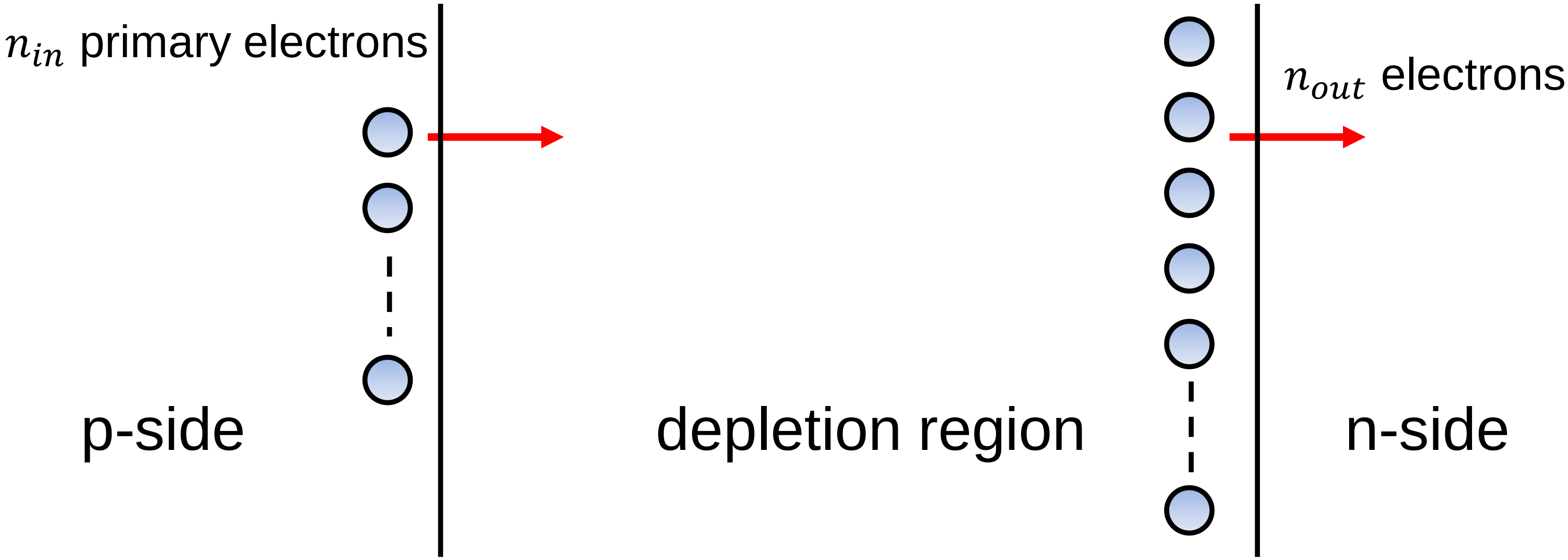
At relatively higher reverse voltages [about $q(V_0 - V_r) > E_g$], avalanche generation dominates, due to a high energy scattering mechanism called "**impact ionization**".

Reverse breakdown (B) = Avalanche



Both energetic electrons and holes may have multiple impact ionization collisions. Secondary electrons and holes with sufficient energy may also experience impact ionization collisions. An so on until carriers exit the depletion region...

Reverse breakdown (B) = Avalanche



multiplication factor

$$M_n = \frac{n_{out}}{n_{in}}$$

Reverse breakdown (B) = Avalanche

n_{in} primary electrons → | n_{out} electrons →

p-side | depletion region W | n-side

Simple model $P =$ probability of impact ionization within W

primary n_{in}

secondary $n_{in}P$

tertiary $n_{in}P^2$

quaternary $n_{in}P^3$

… …

n-ary $n_{in}P^n$

NOTE: recombinations are neglected in this simple model

$$n_{out} = n_{in}(1 + P + P^2 + P^3 + \cdots) = n_{in}\frac{1}{1-P}$$

multiplication factor

$$M_n = \frac{n_{out}}{n_{in}} = \frac{1}{1-P}$$

Reverse breakdown (B) = Avalanche

multiplication factor

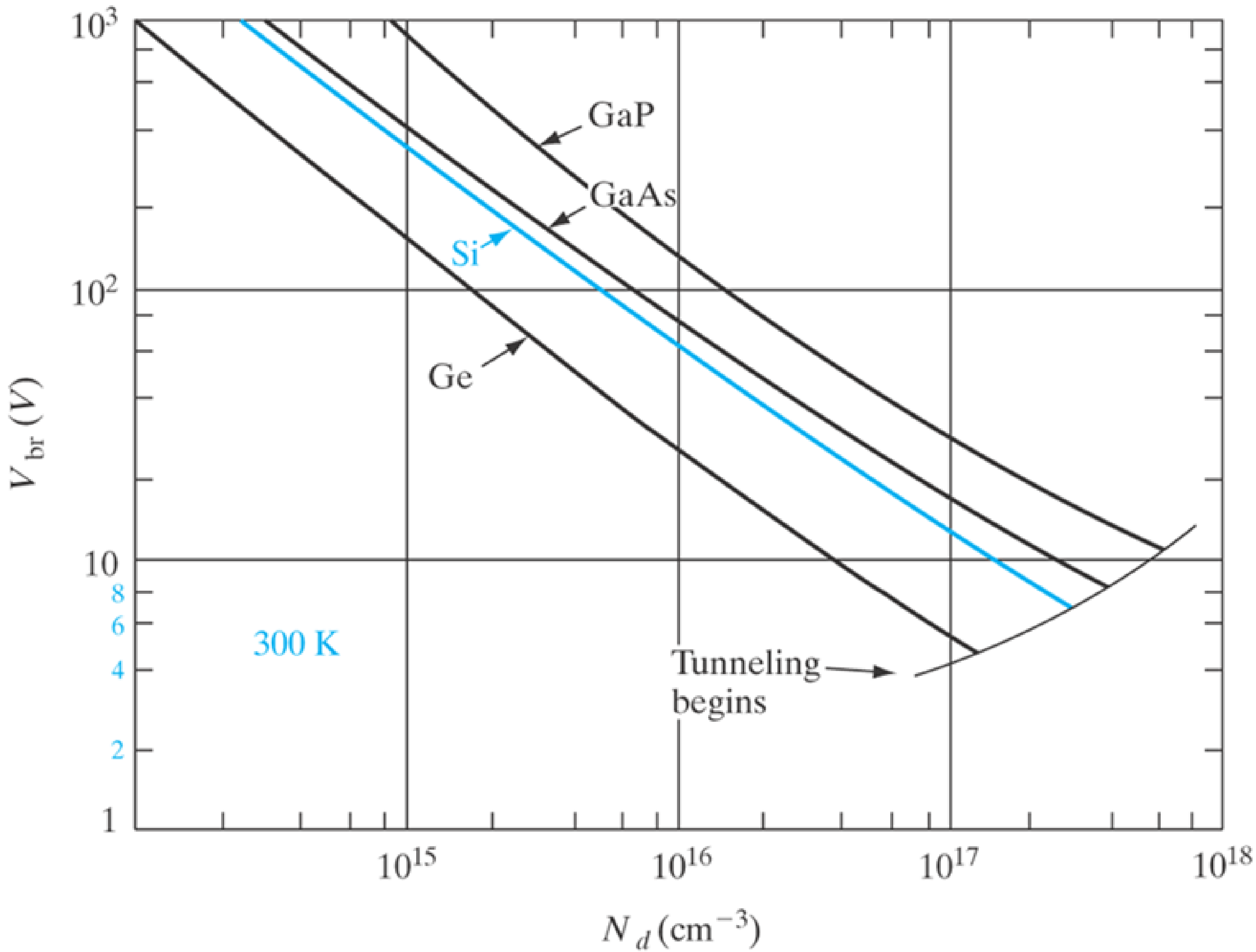
$$M_n = \frac{n_{out}}{n_{in}} = \frac{1}{1 - P}$$

In this simple model, since P is close to unity, carrier multiplication essentially could grow without limit. The external circuit, as seen earlier, actually limits the current and there should also be a dependence on bias.

Empirical relation from experimental observations where n depends on the material and is between 3 and 6

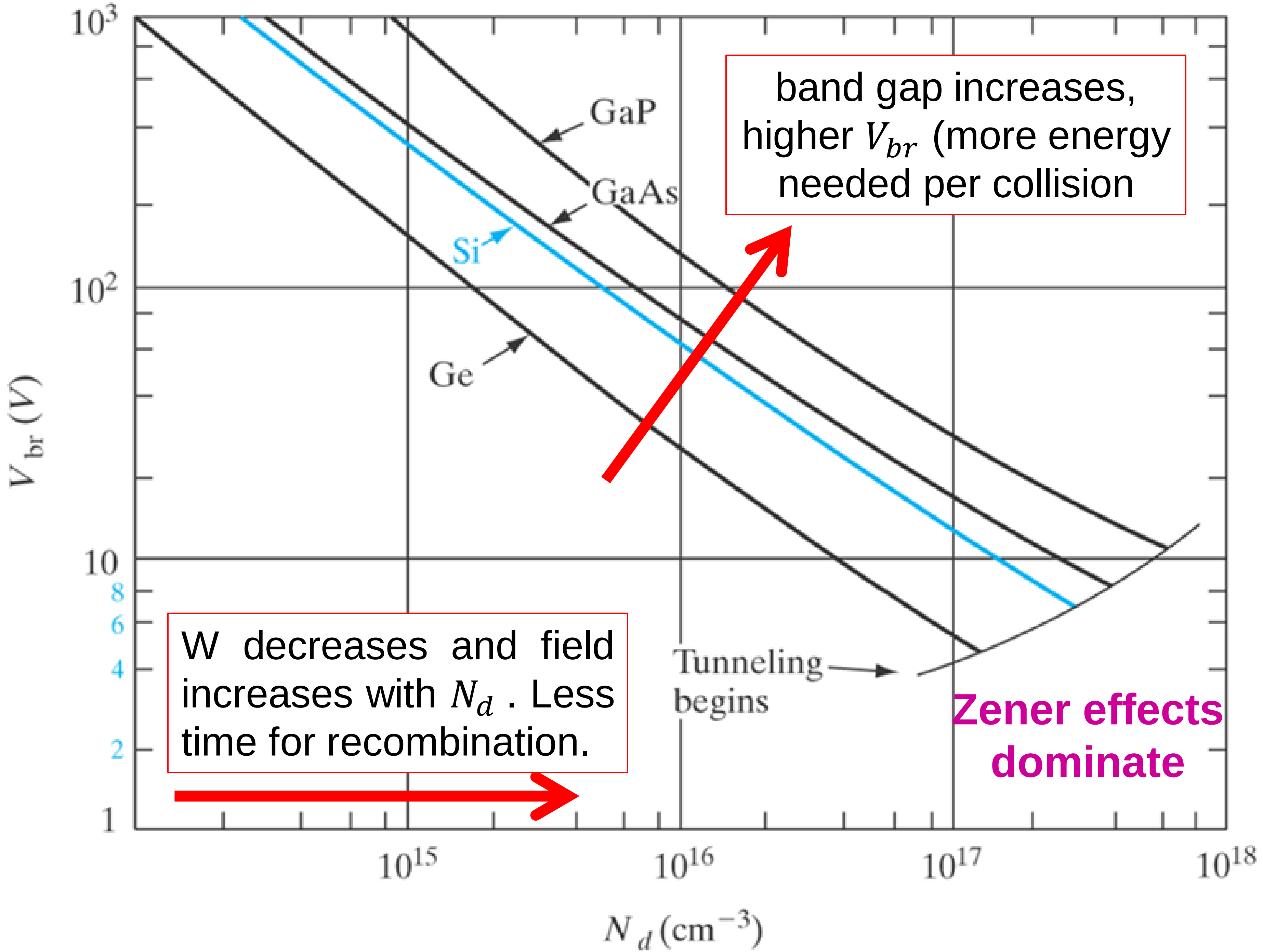
$$M_{exp} = \frac{1}{1 - \left(\frac{V}{V_{br}}\right)^n}$$

Reverse breakdown (B): p^+-*n junction*



These results were calculated numerically by Sze and Gibbons, Applied Phys Lett, vol. 8, p.111, 1996

Values should be intended as upper limits for V_{br}

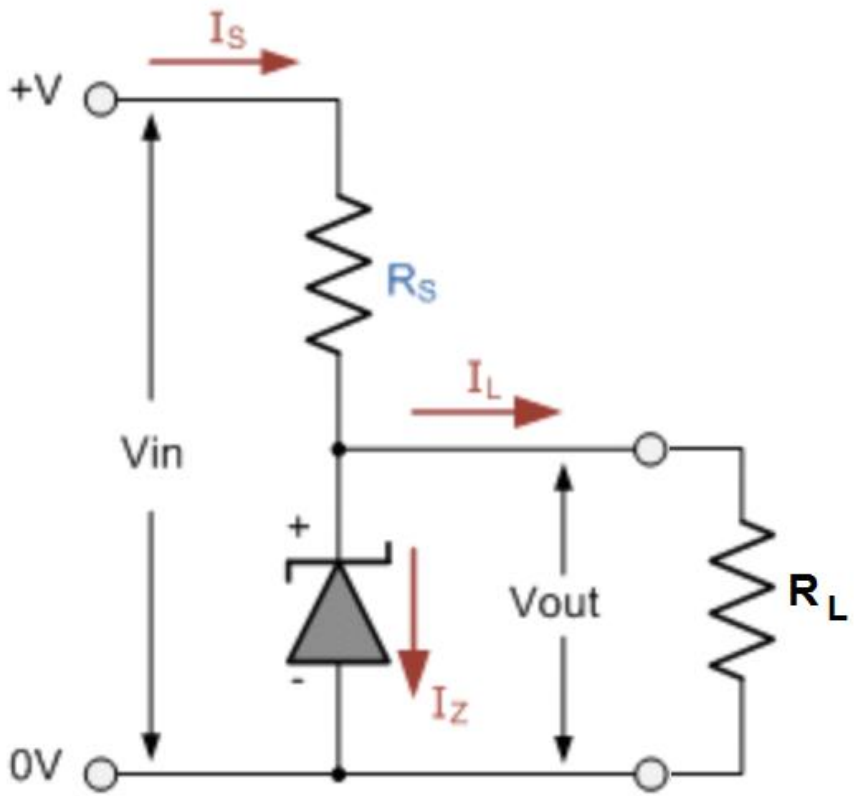

GaP
GaAs
Si
Ge
band gap increases, higher V_{br} (more energy needed per collision
W decreases and field increases with N_d . Less time for recombination.
Tunneling begins
Zener effects dominate
V_{br} (V)
10^3
10^2
10
8
6
4
2
1
10^{15}
10^{16}
10^{17}
10^{18}
N_d (cm^{-3})

Breakdown diodes

Breakdown diodes are largely based on avalanche generation effects, although these devices are often referred to an Zener diodes. This is historical, due to misinterpretations in early observations of breakdown in p-n junctions.

Zener tunnelling is only effective up to several volts in highly doped junctions. Diodes which are rated for breakdown at tens to hundreds of volts, experience primarily avalanche generation.

EXTRA – voltage reference in circuits



Example:

$V_{in} = 12\text{ V}$ (available)

$V_{out} = 5\text{ V}$ (wanted)

Maximum power rating of the breakdown diode $P_{max} = 2\text{ W}$.

Calculate:

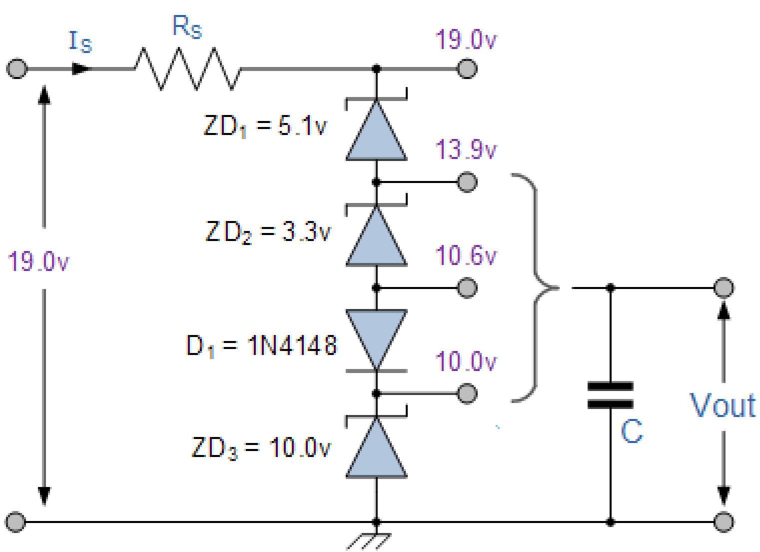
(a) maximum breakdown current
(b) Minimum value of R_S
(c) Current I_L with load $R_L = 1\,k\Omega$
(d) Diode current I_Z with load & R_{Smin}

(a) $I_{Zmax} = 2\text{W}/5\text{V} = 400\text{ mA}$
(b) $R_{Smin} = (V_{in} - V_{out})/I_{Zmax} = (12 - 5)/0.4 = 17.5\ \Omega$
(c) $I_L = (V_{out}/R_L) = 5/1000 = 5\text{mA}$
(d) $I_Z = I_S - I_L = 400\text{mA} - 5\text{mA} = 395\text{mA}$

EXTRA – Breakdown Diodes in series

More voltage options with diodes in series.

Standard forward biased Si diodes may be included to add ~ 0.6 to 0.7 V increments

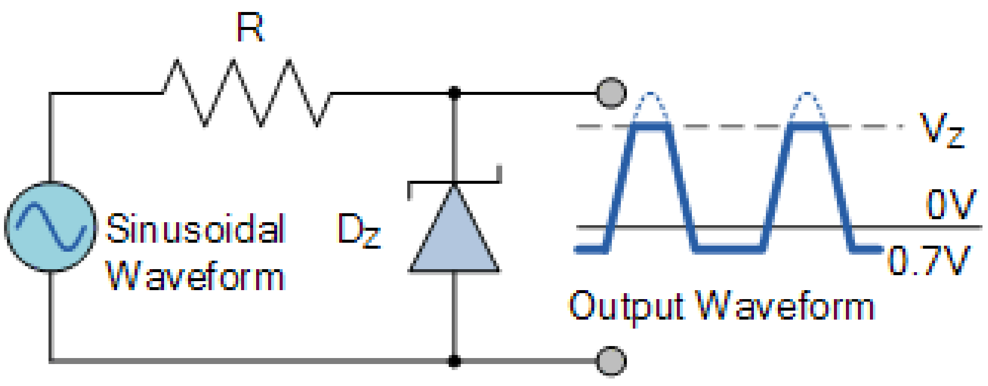


Example - Commercial diodes

BZX55 Zener Diode Power Rating 500mW							
2.4V	2.7V	3.0V	3.3V	3.6V	3.9V	4.3V	4.7V
5.1V	5.6V	6.2V	6.8V	7.5V	8.2V	9.1V	10V
11V	12V	13V	15V	16V	18V	20V	22V
24V	27V	30V	33V	36V	39V	43V	47V
BZX85 Zener Diode Power Rating 1.3W							
3.3V	3.6V	3.9V	4.3V	4.7V	5.1V	5.6	6.2V
6.8V	7.5V	8.2V	9.1V	10V	11V	12V	13V
15V	16V	18V	20V	22V	24V	27V	30V
33V	36V	39V	43V	47V	51V	56V	62V

EXTRA - More options for voltage clippers

Single breakdown diode clipper (in forward bias it behaves like a regular diode)



Double breakdown diode clipper (for each half wave one diode is at beakdown, the other one is a forward biased diode adding 0.6 to 0.7 V)