5.4 Reverse Biased Breakdown

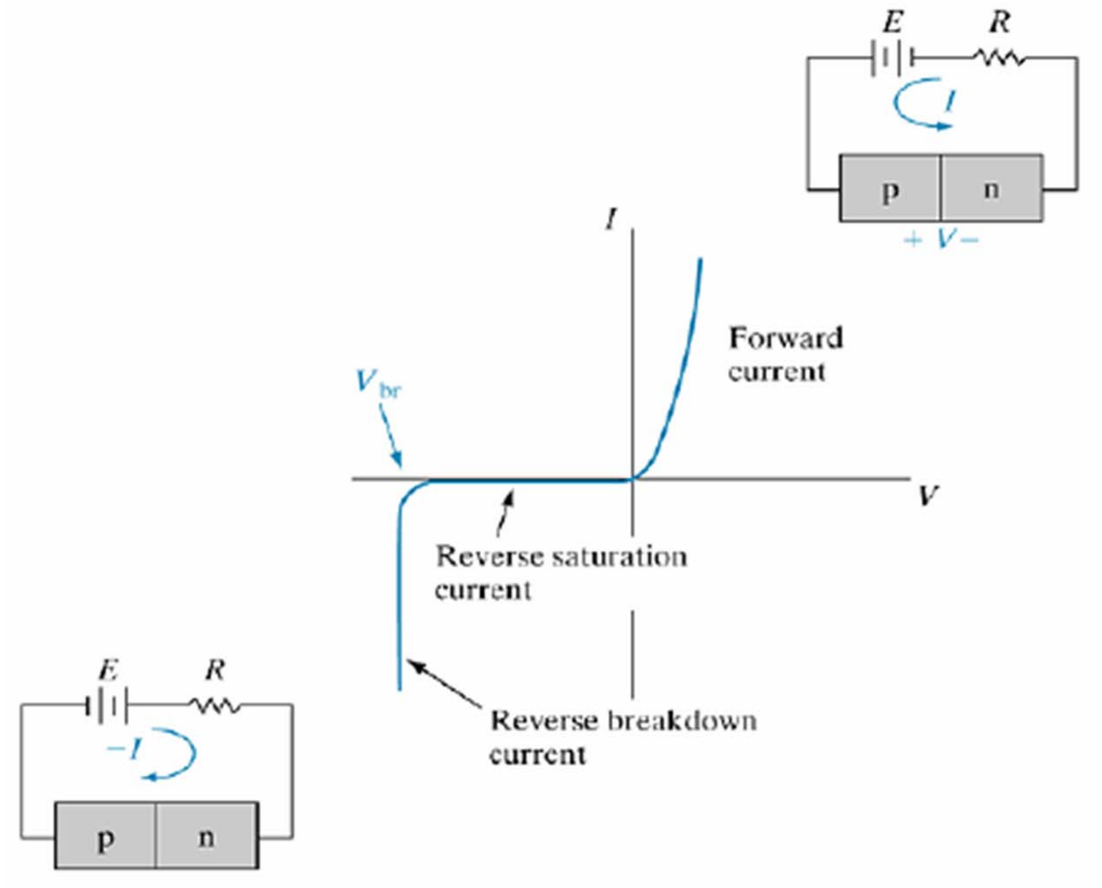
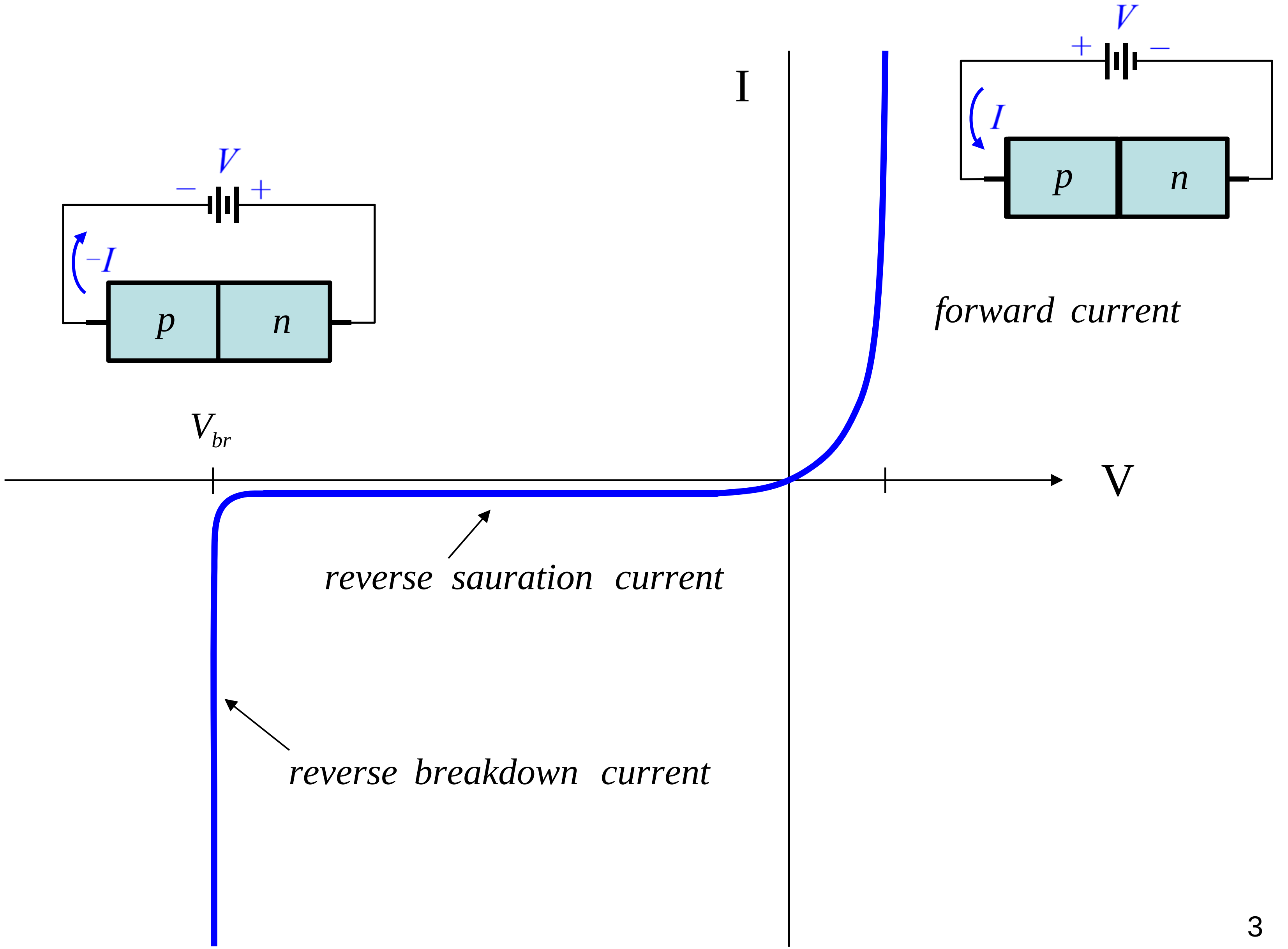


Figure 5—19
Reverse breakdown in a p-n junction.

Reverse Biased Breakdown



5.4.1 Zener Breakdown

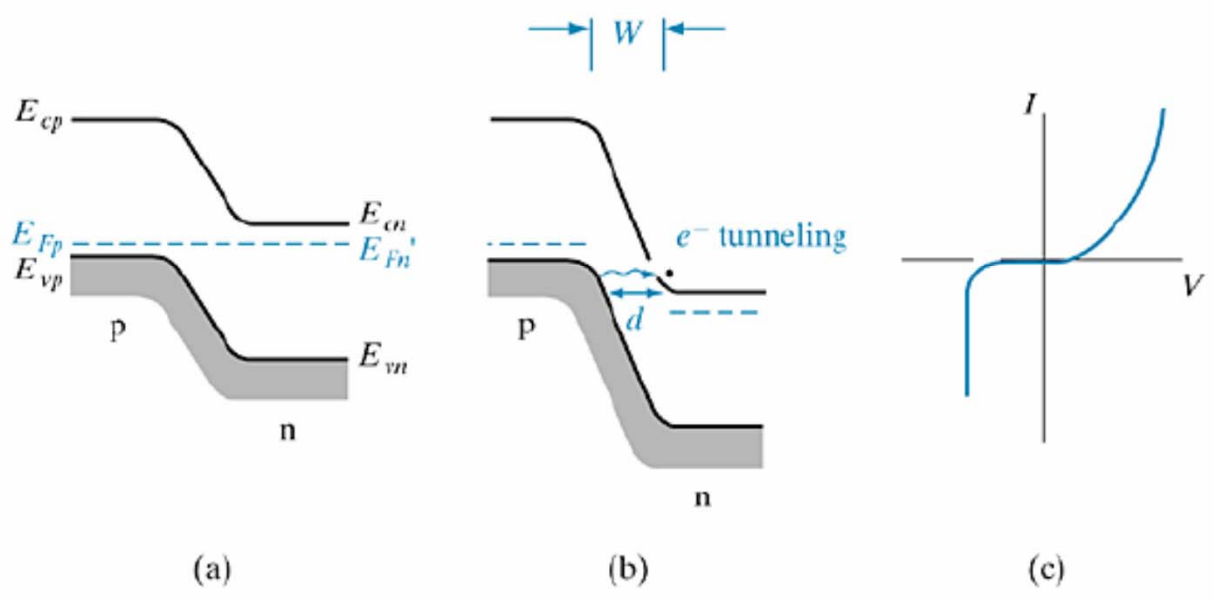
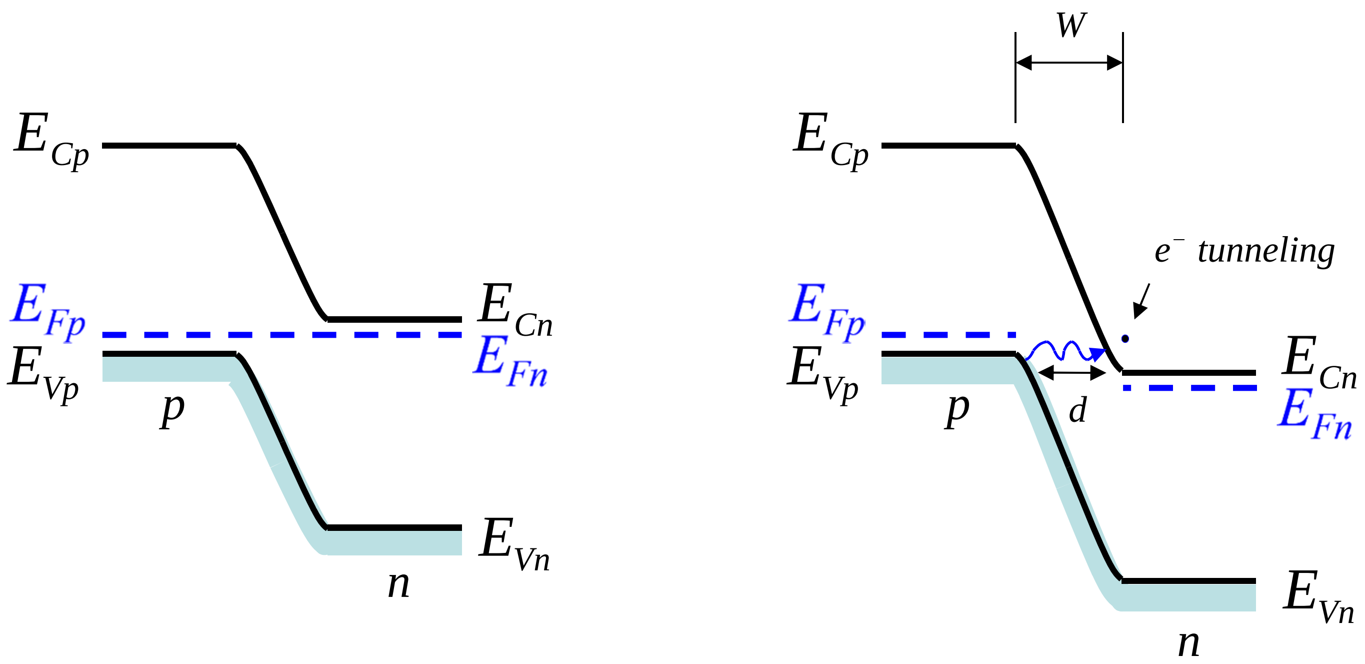


Figure 5—20
The Zener effect: (a) heavily doped junction at equilibrium; (b) reverse bias with electron tunneling from p to n; (c) *I–V* characteristic.

Zener Breakdown



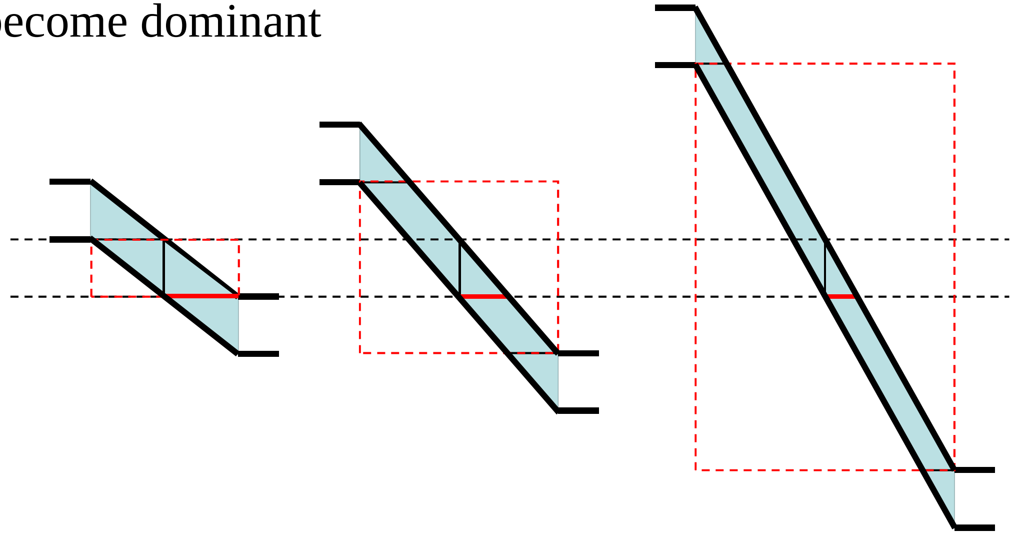
The Zener effect:

(1) Heavily doped junction at equilibrium,

(2) Reverse bias with electron tunneling from p to n.

For Zener breakdown (tunneling)

- Extends only a very short distance W from each side of the junction
    - The metallurgical junction be sharp
    - The doping high
- The tunneling distance d may be too large for appreciable tunneling. However,
    - d becomes smaller as the reverse bias is increased, because the higher electric fields result in steeper slopes for the band edges
        - This assumes that the transition region width W does not increase appreciably with reverse bias
            - For low voltages and heavy doping on each side of the junction, this is a good assumption
- If Zener breakdown does not occur with reverse bias of a few volts, avalanche breakdown will become dominant



5.4.2 Avalanche Breakdown

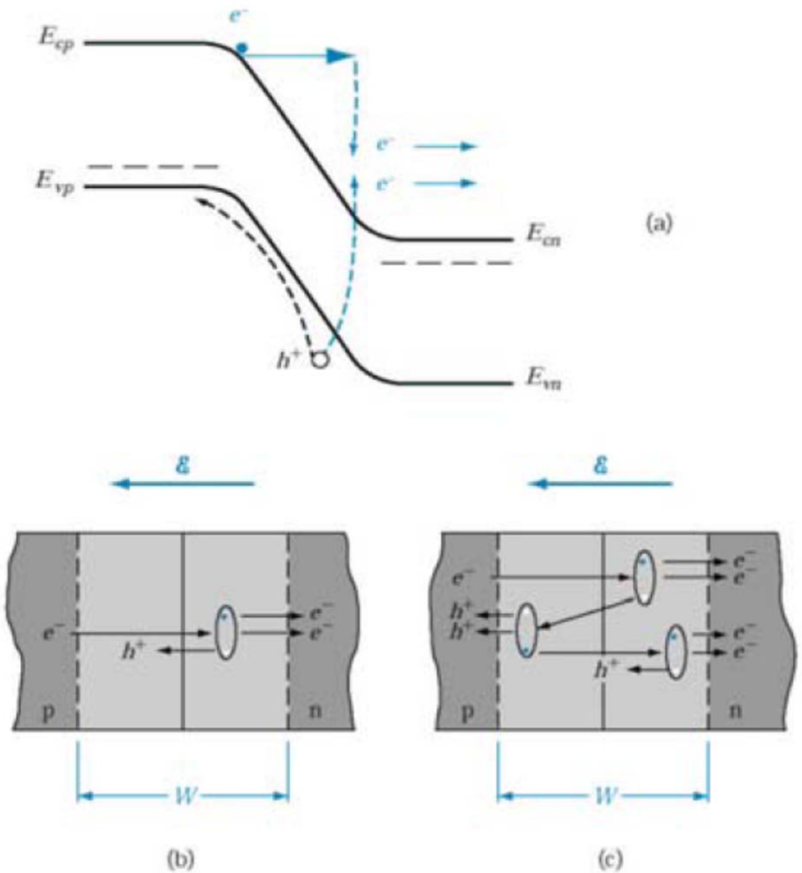
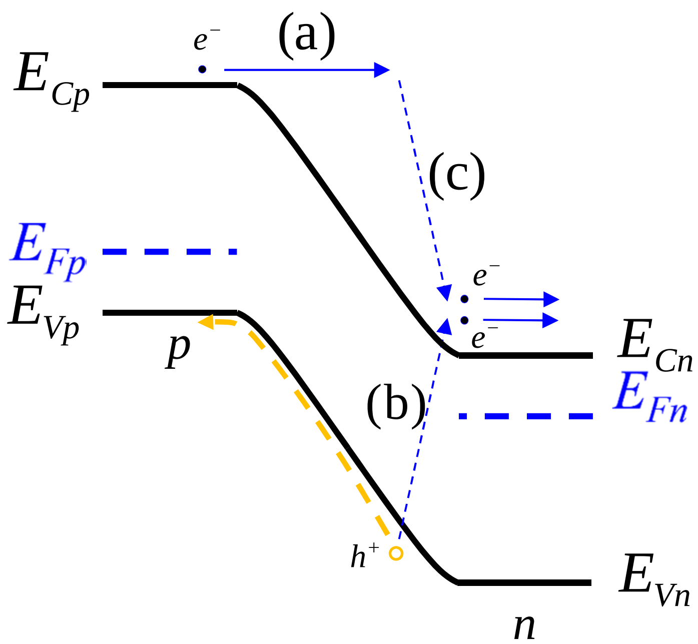


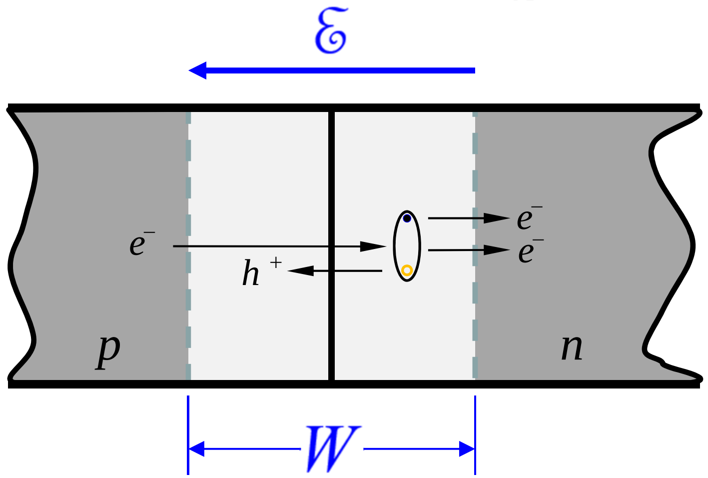
Figure 5–21
Electron-hole pairs created by impact ionization: (a) band diagram of a p-n junciton in reverse bias showing (primary) electron gaining kinetic energy in the field of the depletion region, and creating a (secondary) electron-hole pair by impact ionization, the primary electron losing most of its kinetic energy in the process; (b) a single ionizing collision by an incoming electron in the depletion region of the junction; (c) primary, secondary and tertiary collisions.

Avalanche Breakdown

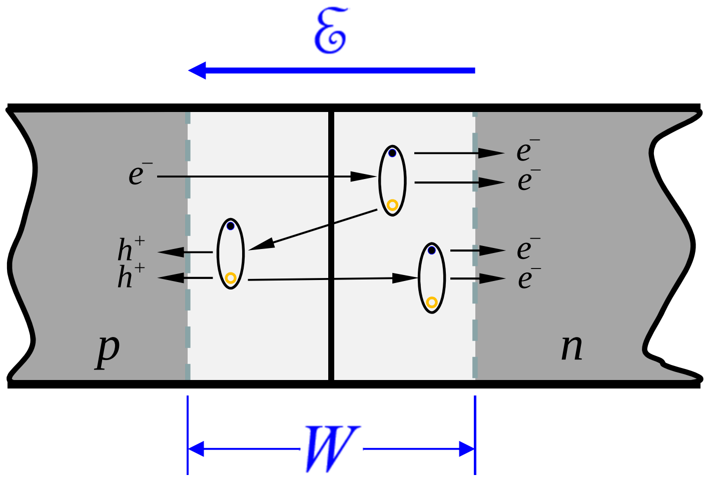


Electron-hole pairs created by impact ionization.

(a) Electron (primary) gaining kinetic energy in the field of the depletion region.
(b) An electron-hole pair (secondary) is created by impact ionization.
(c) The primary electron losing most of its kinetic energy in the process.



A single ionization collision event



Primary, secondary, and tertiary collisions.

Avalanche Breakdown

- **In lightly doped junctions electron tunneling is negligible, the breakdown mechanism involves the *impact ionization* of host atoms by energetic carriers.**
- **A single such interaction results in *carrier multiplication.***

Approximate analysis result:

$$n_{out} = n_{in}(1 + P + P^2 + P^3 + \ldots)$$ Assume no recombination

Electron multiplication $$M_n = \frac{n_{out}}{n_{in}} = 1 + P + P^2 + P^3 + \ldots = \frac{1}{1-P}$$

An empirical relation

$$M = \frac{1}{1-(V/V_{br})^n}$$ n = 3~6

Avalanche Multiplication

Avalanche breakdown

- In lightly doped junctions electron tunneling is negligible, the breakdown mechanism involves the ***impact ionization*** of host atoms by energetic carriers.
- A single such interaction results in ***carrier multiplication***.

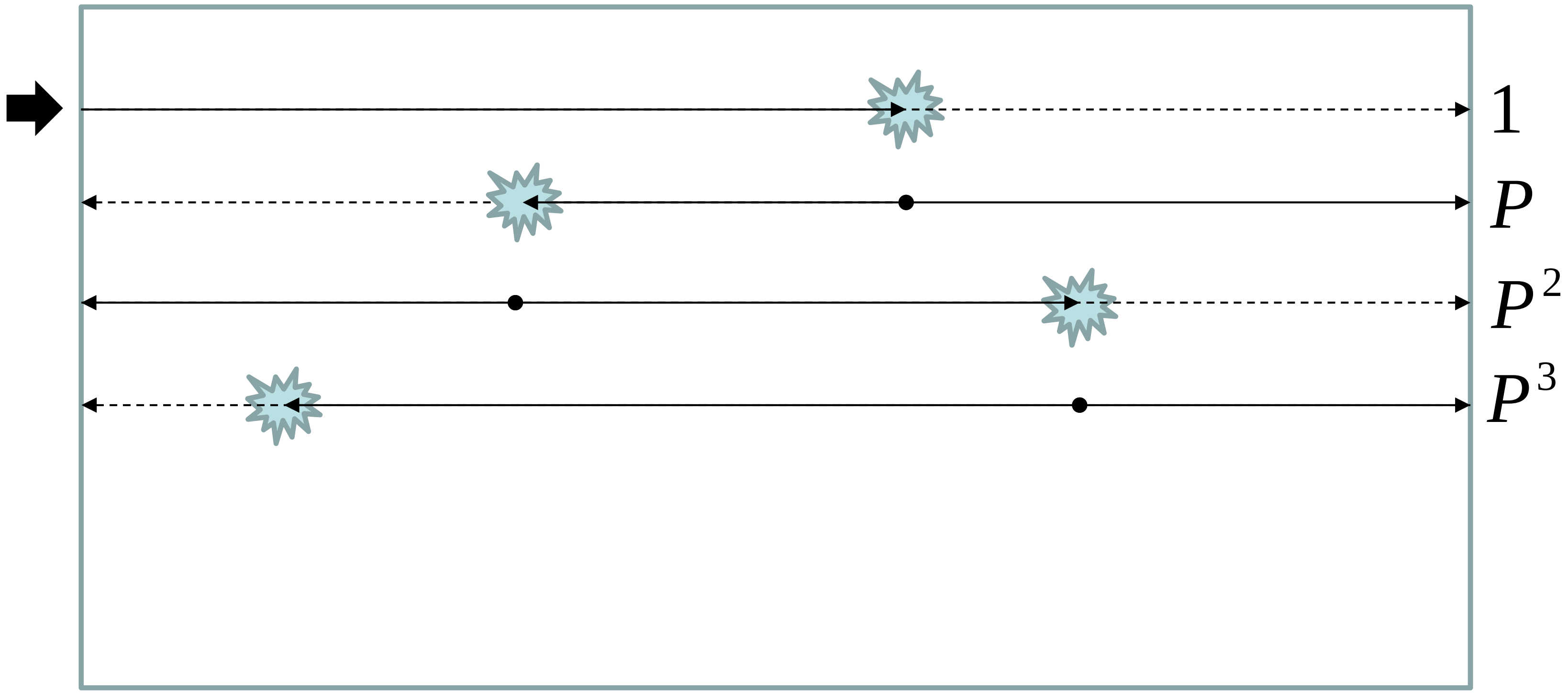
Approximate analysis result:

$$n_{out} = n_{in}(1 + P + P^2 + P^3 + \cdots) \quad \text{(Assume no recombination)}$$

Electron multiplication $$M_n = \frac{n_{out}}{n_{in}} = 1 + P + P^2 + P^3 + \cdots = \frac{1}{1 - P}$$

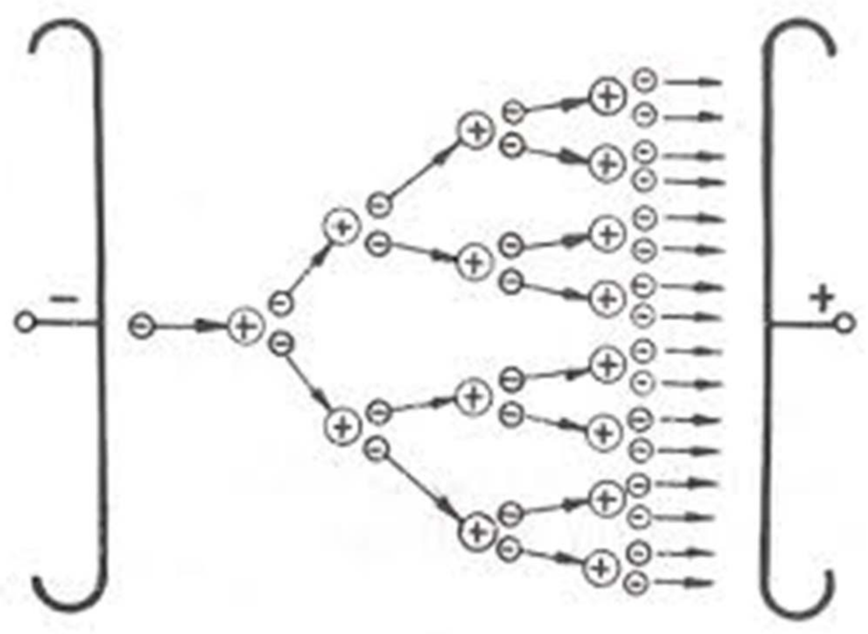
An empirical relation $$M = \frac{1}{1 - (\frac{V}{V_{br}})^n} \qquad n = 3 \sim 6$$

Probability of Ionization P



For Avalanche breakdown

• Impact ionization rather than field ionization (Zener)
• Carrier multiplication
• The peak electric field within W increases with increased doping on the more lightly doped side of the junction (from Eq. 5-23b and Eq. 5-17)



For Avalanche breakdown

• Impact ionization rather than field ionization (Zener)
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• The peak electric field within W increases with increased doping on the more lightly doped side of the junction (from Eq. 5-23b and Eq. 5-17)

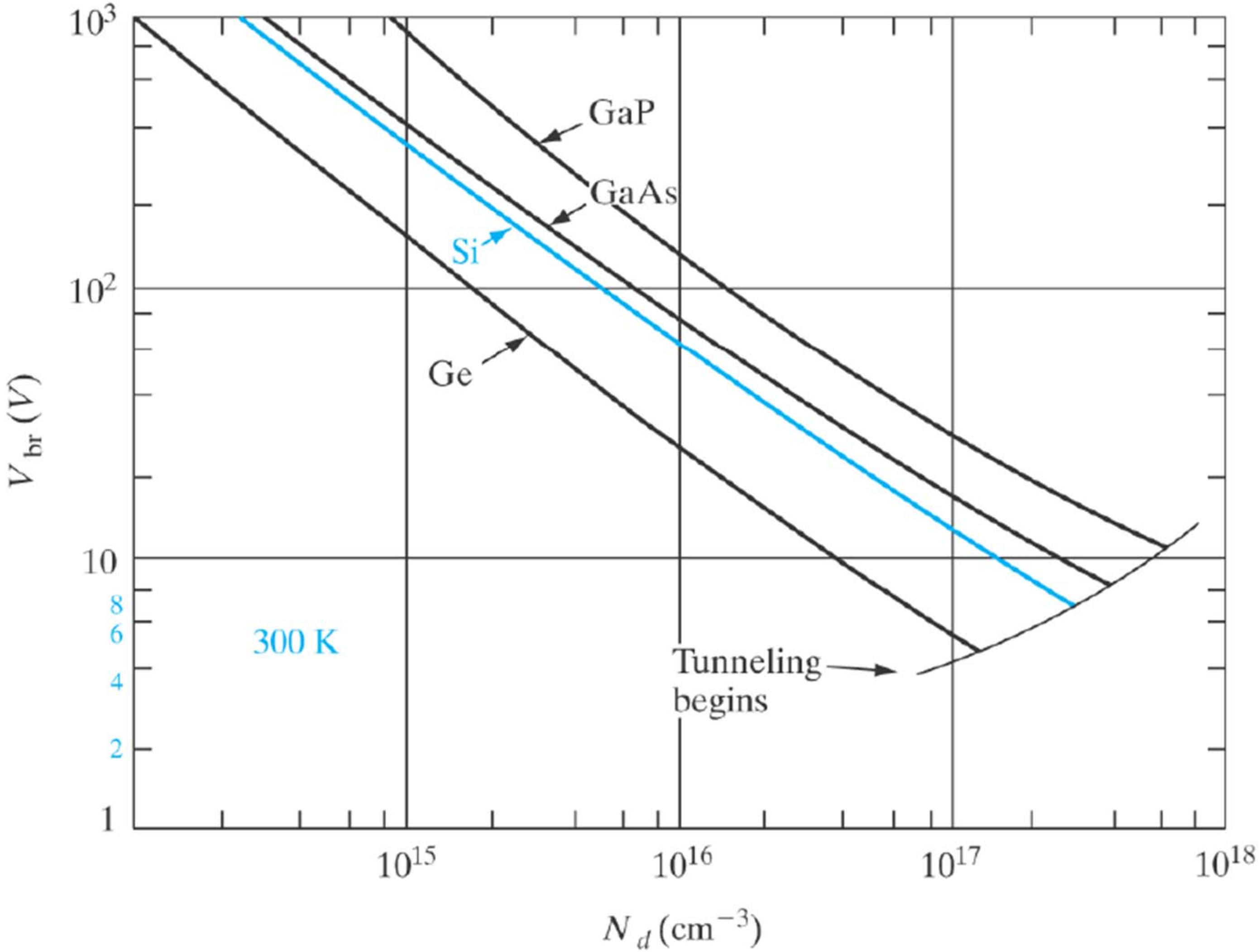


Figure 5—22

Variation of avalanche breakdown voltage in abrupt p+-n junctions, as a function of donor concentration on the n side, for several semiconductors. [After S. M. Sze and G. Gibbons, *Applied Physics Letters*, vol. 8, p. 111 (1966).]

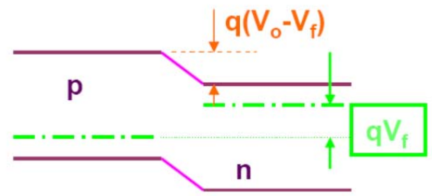
Example 5-4

An abrupt Si p-n junction (A=10^{-4} cm^2) has the following properties at 300 K:

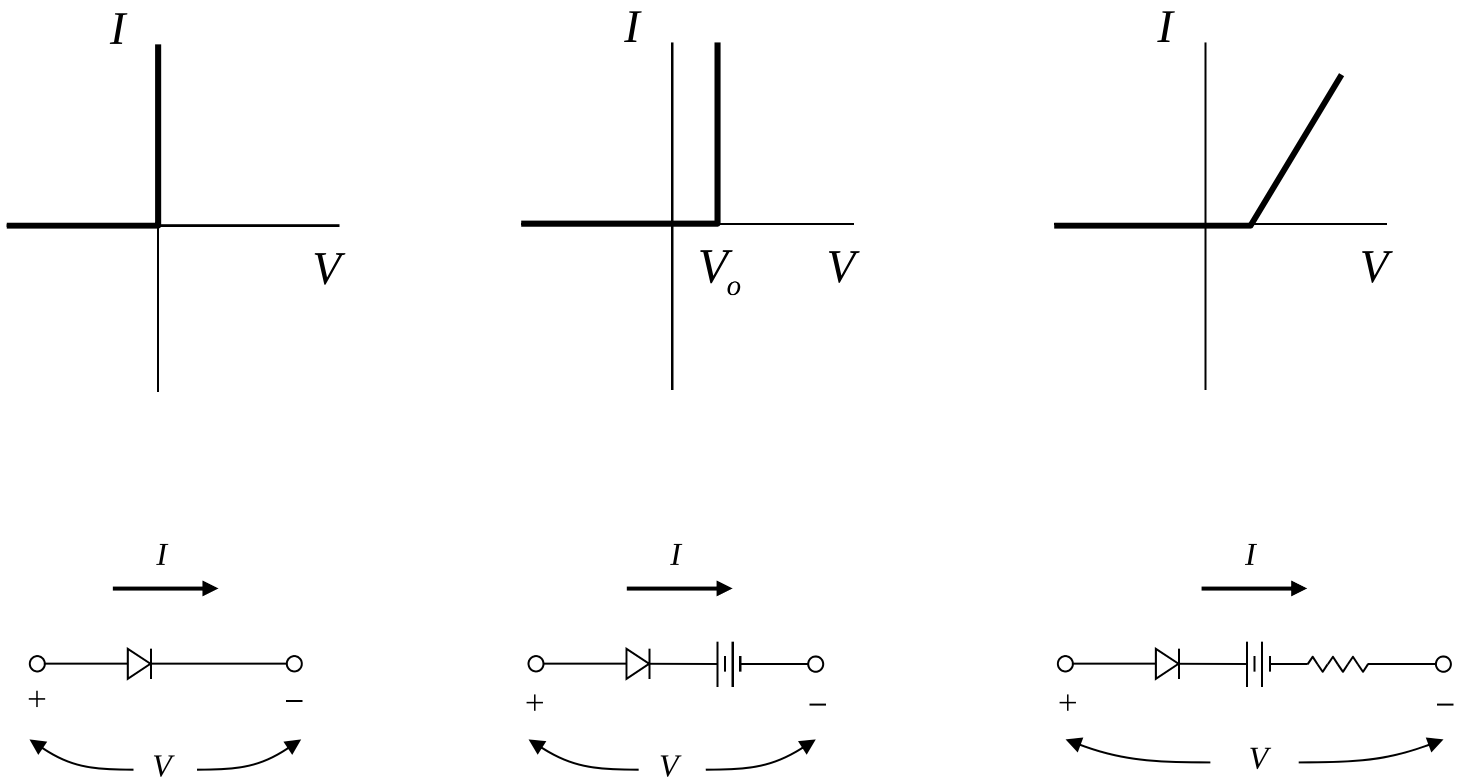
$p\ side$	$n\ side$
$N_a = 10^{17} cm^{-3}$	$N_d = 10^{15} cm^{-3}$
$\tau_n = 0.1 \mu s$	$\tau_p = 10 \mu s$
$\mu_p = 200 cm^2 / V-s$	$\mu_n = 1300 cm^2 / V-s$
$\mu_n = 700$	$\mu_p = 450$

The junction is forward biased by 0.5 v. What is the forward current? What is the current at a reverse bias of -0.5 V?

5.4.3 Rectifiers



$$V_f \le V_o \quad always$$



Consideration for rectifier

Junction diodes designed for use as rectifiers should have I-V characteristics as close as possible to that of the ideal diode.

- The reverse current should be negligible
- The forward current should exhibit little voltage dependence (negligible forward resistance R)
- The reverse breakdown voltage should be large
- The offset voltage E_o in the forward direction should be small.

Large bandgap

- small n_i
  - Small reverse saturation current
- Operable at high temperature
  - Reduced thermal excited EHPs
- Increased contact potential
  - Increased offset voltage E_o

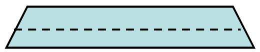
Consideration of doping concentration

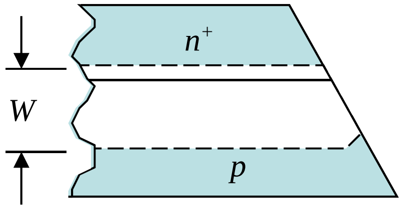
The doping concentration on each side of the junction influences *the avalanche breakdown voltage*, *the contact potential*, and *the series resistance* of the diode.

- For p^+-n junction, the lightly doped region determines many of the properties of the junction.
    - High-resistivity region should be used for at least one side of the junction to increase the breakdown voltage V_{br}.
    - However, this approach tends to increase the forward resistance R
        - Contribute to resistant heating
    - Countermeasure
        - make large area of the lightly doped region
    - The lightly doped region of the junction cannot be made arbitrarily short for punch-through.

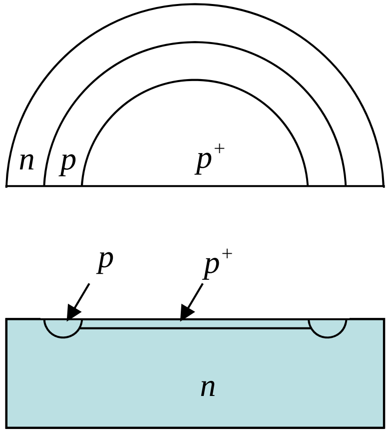
Avoid premature breakdown across the edge

•Beveling





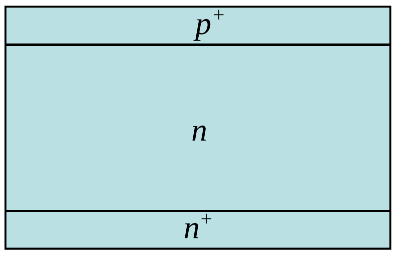
•Guard ring

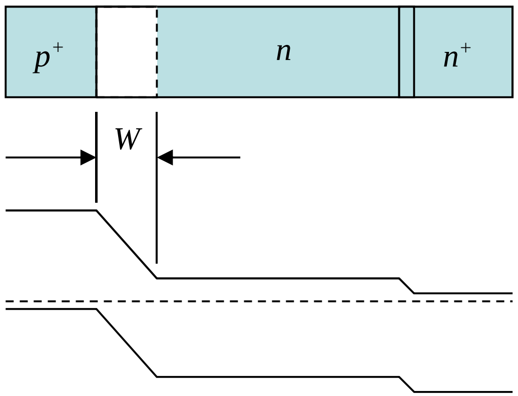


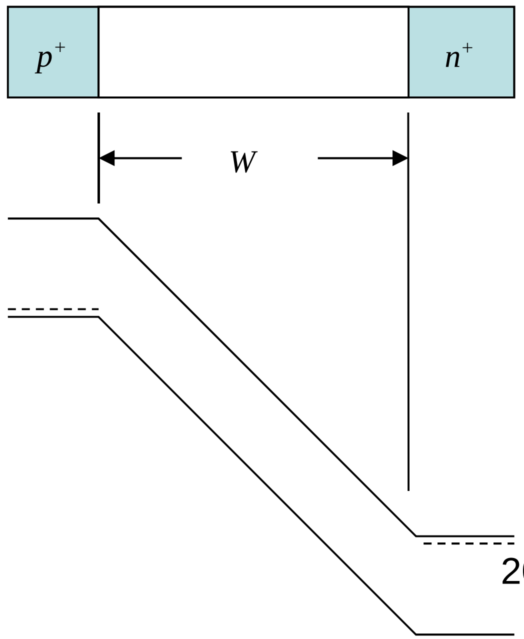
Consideration of p$^+$-n-n$^+$ structure

In fabricating a p$^+$-n or p$^+$-n junction,

- It is common to terminate the lightly doped region with a heavily doped layer of the same type for ohmic contact to the device
- The result is a p$^+$-n-n$^+$ structure with the p$^+$-n layer serving as the active junction
  - The lightly doped center region determines the avalanche breakdown voltage
    - If this region is short compared with the minority carrier diffusion length, the excess carrier injection for large forward currents can increase the conductivity of the region significantly
      - This type of *conductivity modulation*, which reduces the forward resistance R, can be very useful for high-current devices
      - On the other hand, a short, lightly doped center region can also lead to punch-through under reverse bias.





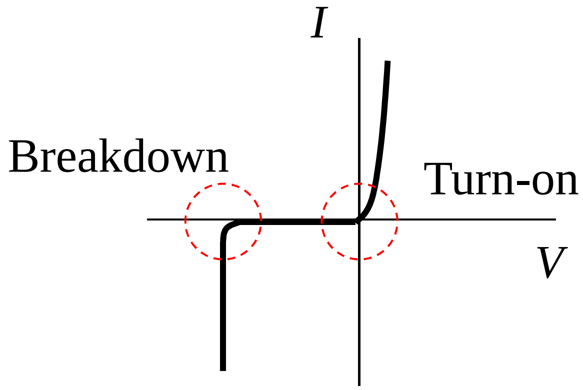


Consideration of Mounting of Rectifier Junction

The mounting of a rectifier junction is critical to its ability to handle power.

• For diodes used in low-power circuits, glass or plastic encapsulation or a simple header mounting is adequate.
• For high current devices, special mountings to transfer thermal energy away from the junction I s required.
  • A typical Si power rectifier is mounted on a molybdenum or tungsten disk to match the thermal expansion properties of the Si.
  • This disk is fastened to a large stud of copper or other thermally conductive material that can be bolted to a heat sink.

5.4.4 The breakdown diode



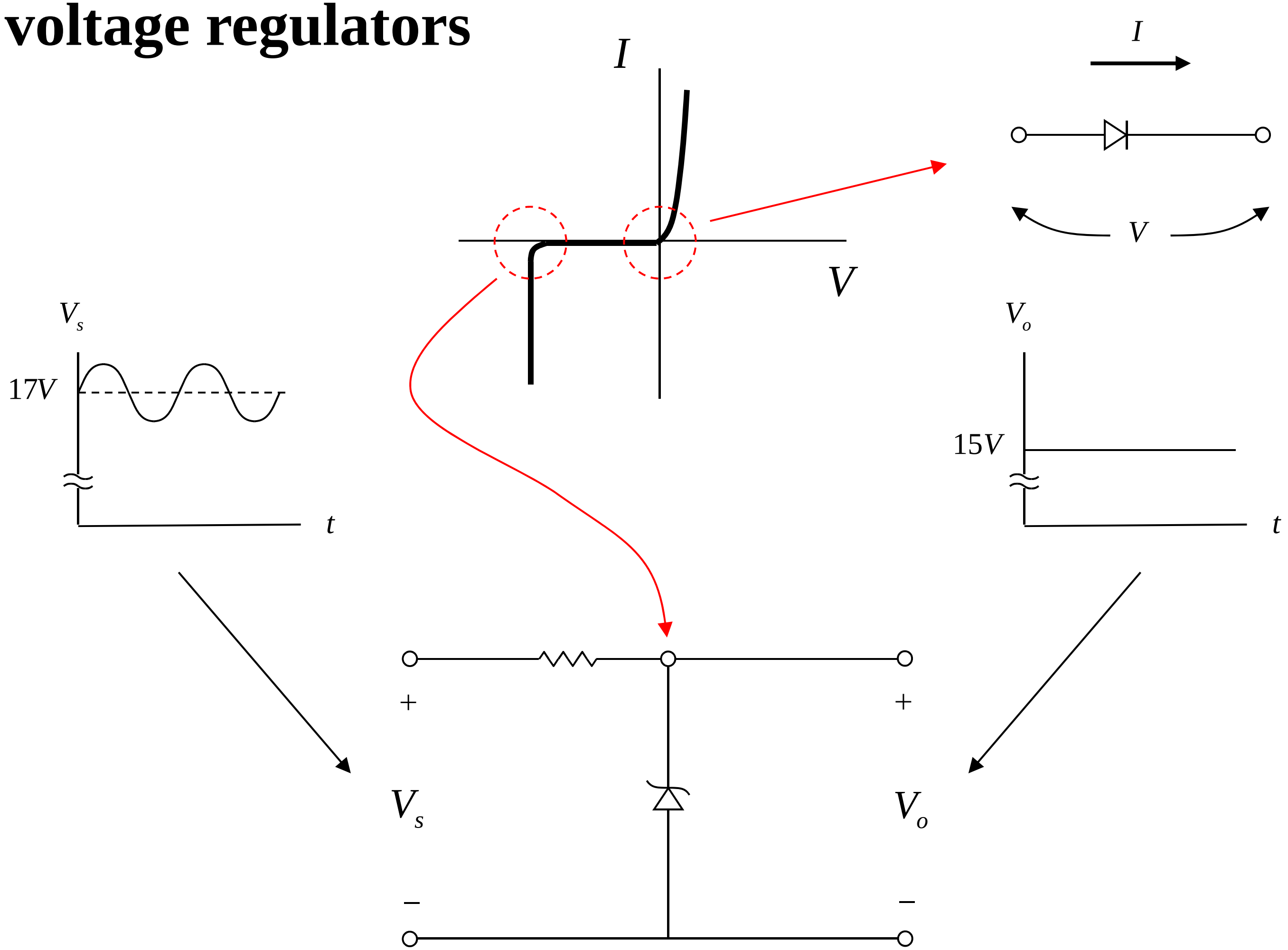
Mechanisms for breakdown

• The Zener effect (tunneling) breakdown mechanism (field ionization) is for abrupt junctions with extremely heavy doping.
• The more common breakdown is avalanche (impact ionization), typically of more lightly doped or graded junctions.

Breakdown ≠ material destruction

• There is nothing inherently destructive about reverse breakdown.
• If current is not limited externally, the junction can be damaged by excess reverse current, through overheat.
    • the destruction of the device is not necessarily due to mechanisms unique to reverse breakdown.

The voltage regulators

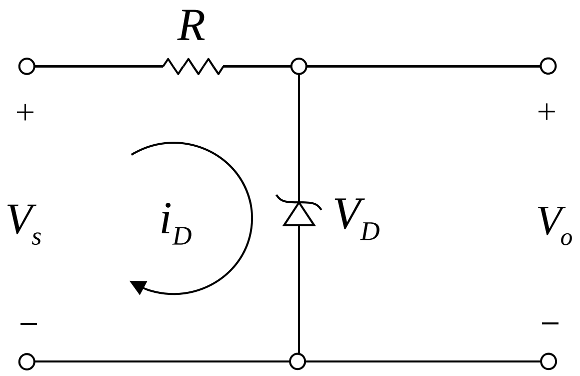


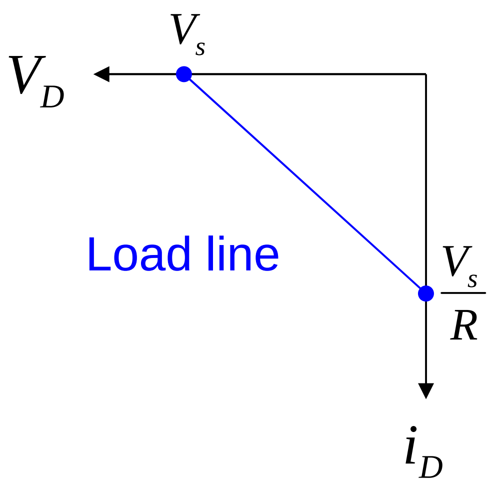
• When a diode is designed for a specific breakdown voltage, it is called a *breakdown diode*.
• Such diodes are also called *Zener diodes*, despite the fact that the actual breakdown mechanism is usually the avalanche effect.
• Breakdown diodes can be used as *voltage regulators* in circuits with varying inputs.

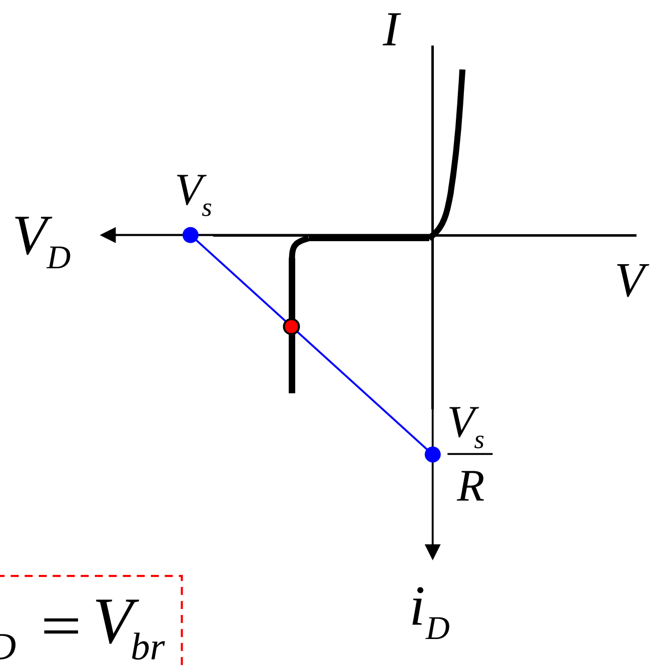
Voltage Drop across the Diode

$$V_s = i_D R + V_D$$

$$i_D = \frac{V_s - V_D}{R}$$







$$\boxed{V_D = V_{br}}$$