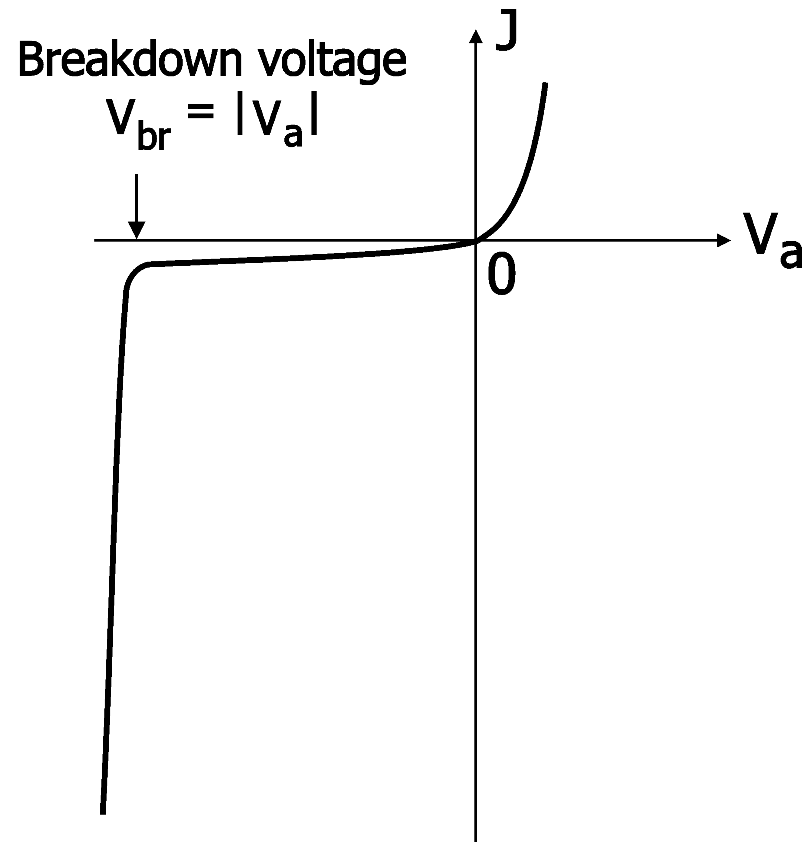
# EE2003 Semiconductor Fundamentals

## Reverse Breakdown of the P-N Junction

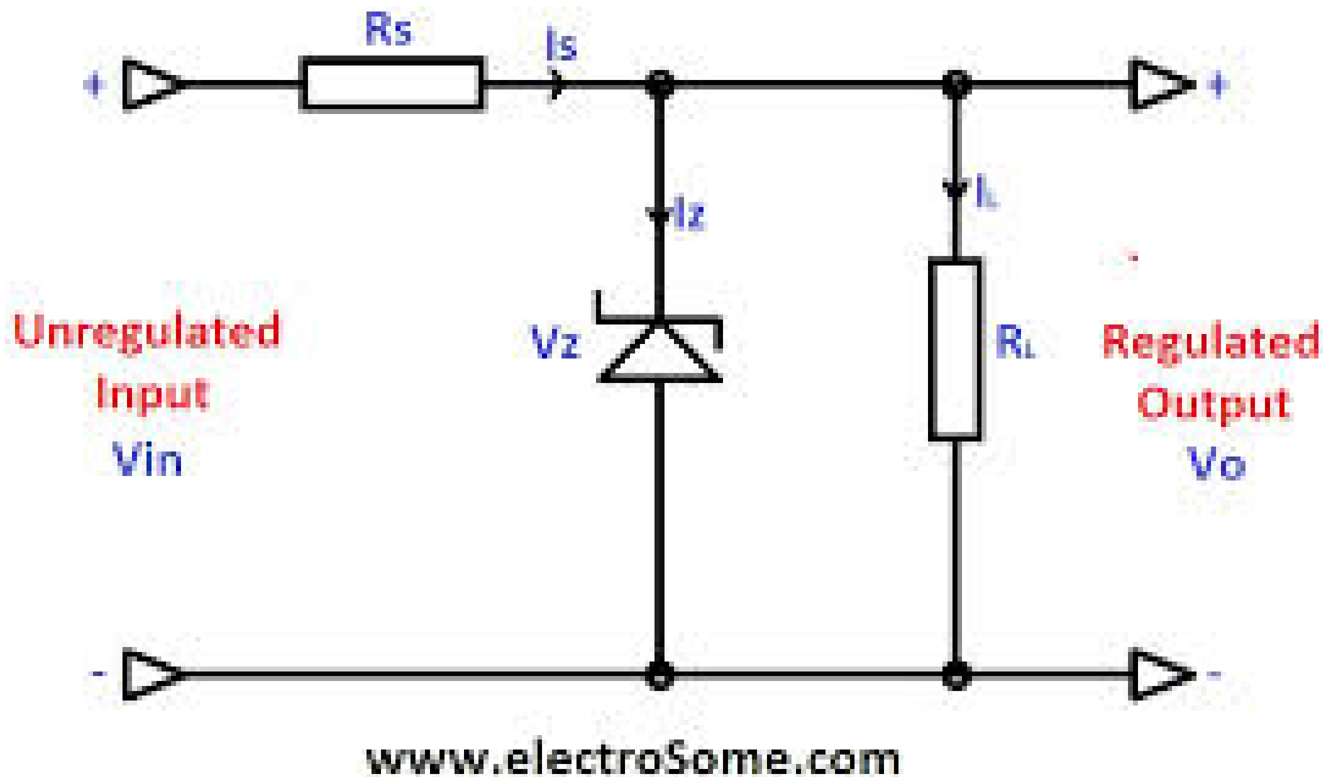
# Reverse Breakdown

- The reverse leakage current of a practical diode remains small only for a limited range of applied voltage.
- Beyond a particular critical voltage, the reverse current increases rapidly as shown. The voltage at this point is known as the **breakdown voltage**.
- Mechanisms::
  - **Zener effect**
  - **Avalanche effect**



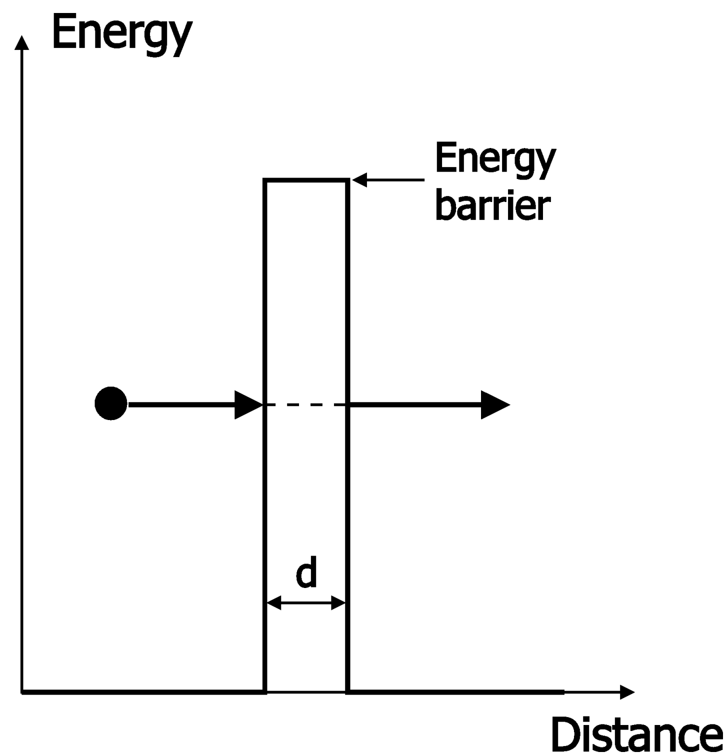
# Voltage Regulator

An example of a practical application where a p-n junction diode is operated in the reverse breakdown mode.



# Reverse Breakdown

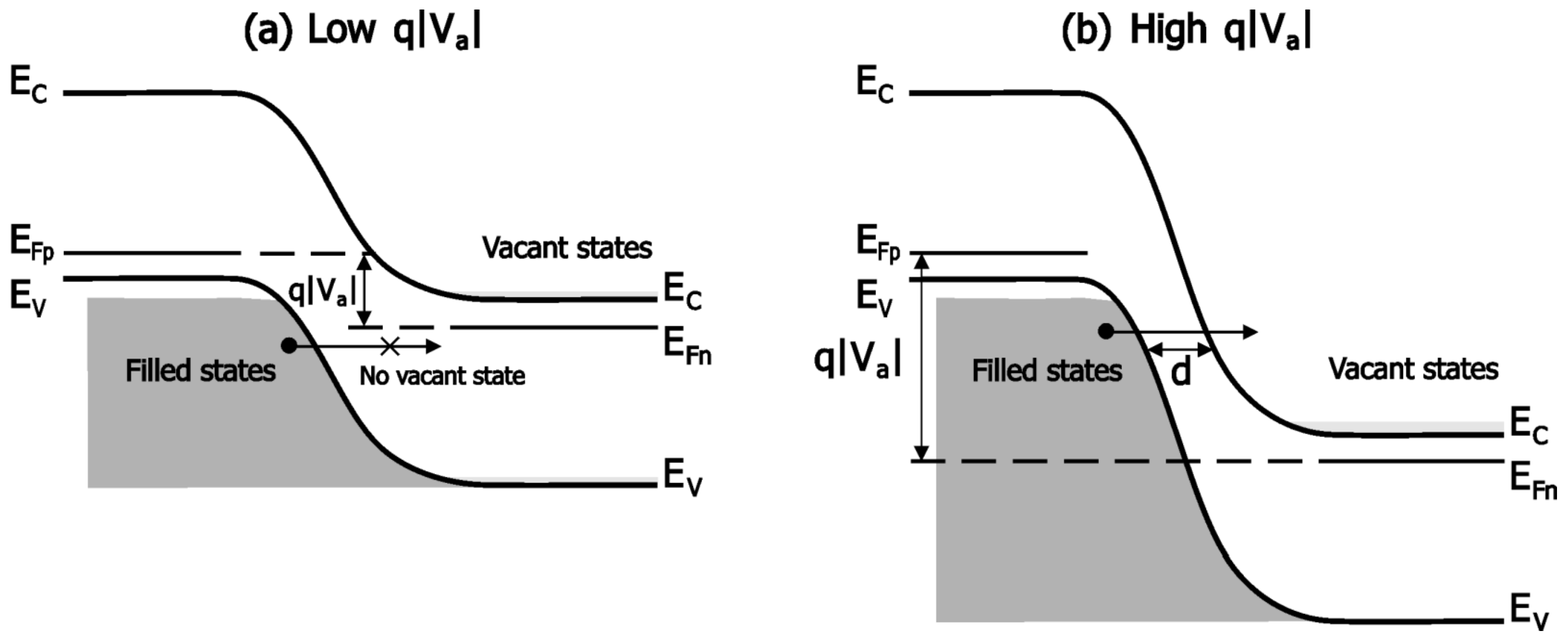
- **Zener breakdown** occurs in a highly doped p-n junction, via **quantum mechanical tunneling**.
  - Even when the potential energy of an electron is less than that of the barrier, there exists a non-zero probability that the electron will penetrate (**tunnel through**) the barrier, and continue its motion on the other side as shown.
  - An analogy is the passage of a bullet through a thin wall.



# Reverse Breakdown

- The **tunneling probability** depends on:
  - Thickness of the barrier
    - The thicker the barrier, the smaller the probability.
  - Magnitude of the applied electric field
    - The electric field provides a force that tends to "pull" the electron across the barrier.
  - The presence of an **empty** energy state at the other side of the barrier.
    - After passing through the barrier, the electron must have a place to "reside" in.

# Reverse Breakdown




Energy band diagrams of a p-n junction. In (a), because the applied reverse voltage is relatively low, no tunneling can occur since there is no vacant state to which the electron can tunnel to. In (b), the applied reverse voltage causes $E_C$ in the n region to be lower than $E_V$ in the p region. Electrons in the valence band of the p region can easily tunnel to the empty states in the conduction band of the n region.

# Reverse Breakdown

- Zener breakdown occurs when the applied reverse bias is such that it lowers the conduction band edge of the n region **below** the valence band edge of the p region.
- When this happens, electrons in the valence band of the p region could tunnel to the empty states in the conduction band of the n region.
- At relatively low reverse bias, this tunneling cannot occur since there are no empty states to which the electrons could tunnel to.

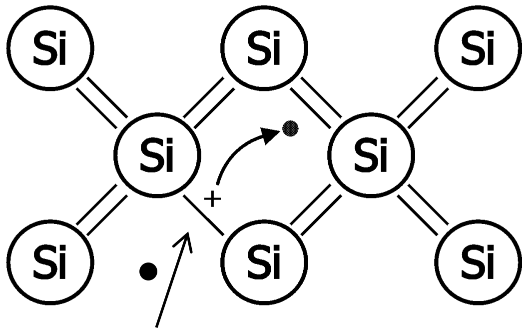
$$|E_m| = |E(x=0)| = \frac{qN_A x_{p0}}{\varepsilon_r \varepsilon_0} = \frac{qN_D x_{n0}}{\varepsilon_r \varepsilon_0}$$

# Reverse Breakdown

$$W_0 = \left[\frac{2\varepsilon_r \varepsilon_0 V_{bi}}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right]^{1/2}$$

- Heavily doped n and p regions:
  - Narrower depletion width
  - Higher electric field for a given applied reverse bias voltage
- The above factors make it easier for an electron to tunnel through the energy barrier (see diagram) at a given applied reverse bias voltage.
  - More tunneling $\Rightarrow$ higher reverse leakage current
- In practice, the desired breakdown voltage can be achieved through varying the doping concentrations of the n and p regions.

# Reverse Breakdown

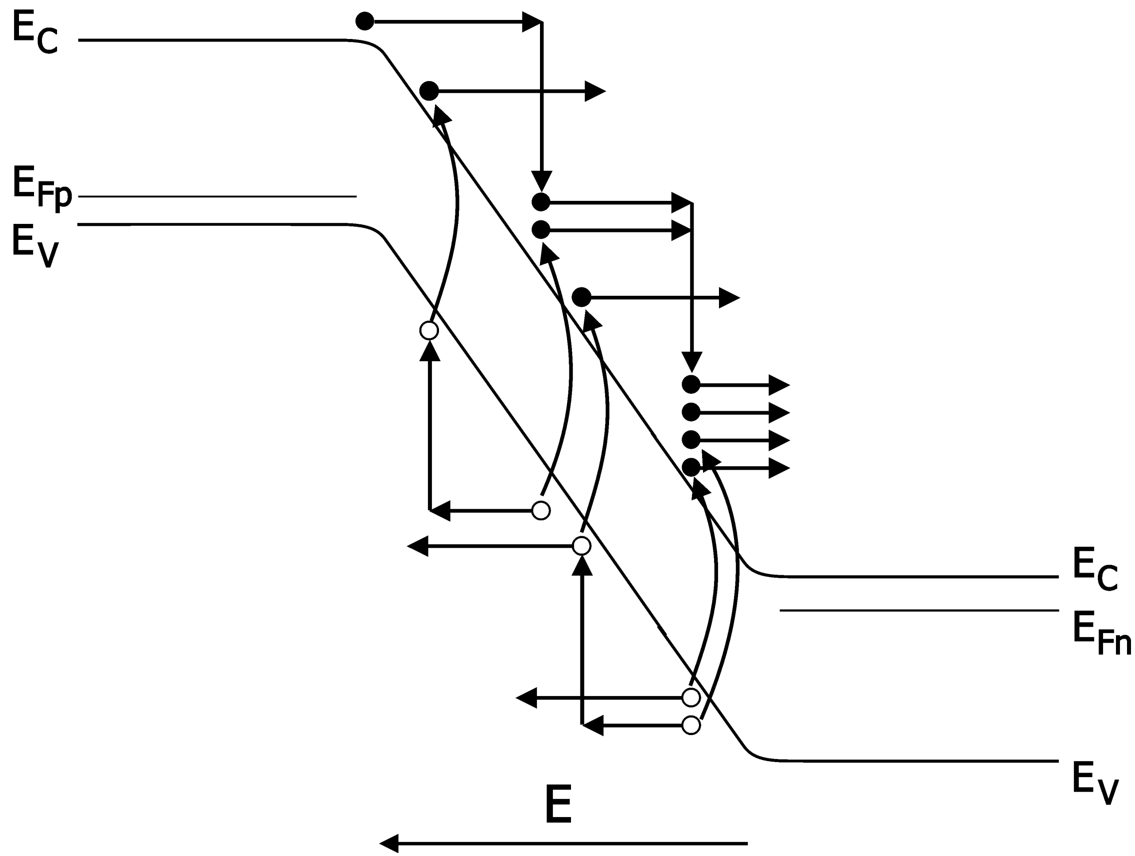



- **Avalanche breakdown**:
  - Mobile charges in the space charge region are accelerated to high speed by the high electric field.
  - When these energetic carriers collide with the lattice atoms, electrons which are involved in the covalent bonding could receive appropriate amount of energy from the colliding electrons/holes and be ‘freed’.
    - Bonds are broken $\Rightarrow$ electrons are promoted from the valence band to the conduction band (electron-hole pair generation).
    - This process through which electron-hole pairs are created via the collision of energetic carriers is known as **impact ionization**.

# Reverse Breakdown

- **Avalanche breakdown:**
  - The newly generated carriers are in turn accelerated by the same field, leading to the generation of more 'free' carriers in the semiconductor.
  - A chain reaction (**positive feedback** path) is thus set-up, leading to a rapid increase in the diode reverse current $\Rightarrow$ diode breaks down.
  - **Snow ball analogy**

# Reverse Breakdown




An illustration of the avalanche multiplication of carriers.

# Reverse Breakdown

- **Breakdown voltage:**
  - The diode breaks down when the applied reverse voltage is such that the electric field established reaches or exceeds the **critical electric field**.
  - The critical electric field is at which significant impact ionization starts to take place.
  - For silicon, the critical electric field, $E_c \approx 3\text{x}10^5$ V/cm, and is dependent on the doping concentration.

# Reverse Breakdown

- **Breakdown voltage:**
  - Maximum electric field:

$$\left|E_{max}\right| = \frac{qN_D}{\varepsilon_r \varepsilon_o} x_n = \frac{qN_A}{\varepsilon_r \varepsilon_o} x_p$$

  - $x_n$ and $x_p$ are the widths of the depletion regions in the n and p regions respectively:

$$x_n = \left[ \frac{2\varepsilon_r \varepsilon_o \left(V_{bi} - V_a\right)}{q} \cdot \frac{N_A}{N_D\left(N_A + N_D\right)} \right]^{1/2}$$

$$x_p = \left[ \frac{2\varepsilon_r \varepsilon_o \left(V_{bi} - V_a\right)}{q} \cdot \frac{N_D}{N_A\left(N_A + N_D\right)} \right]^{1/2}$$

# Reverse Breakdown

- **Breakdown voltage:**
  - Substituting the expression for $x_n$ or $x_p$ into that of $E_{max}$ gives:

$$E_{max}^{2} = \frac{2q(V_{bi} - V_a)}{\varepsilon_r \varepsilon_o} \cdot \frac{N_A N_D}{(N_A + N_D)}$$

$$V_{bi} - V_a = \frac{\varepsilon_r \varepsilon_o (N_A + N_D)}{2q N_A N_D} E_{max}^{2}$$

  - For reverse bias, $V_r = -V_a >> V_{bi}$, $V_{bi} - V_a \approx V_r$.

$$V_r \approx \frac{\varepsilon_r \varepsilon_o (N_A + N_D)}{2q N_A N_D} E_{max}^{2}$$

# Reverse Breakdown

- **Breakdown voltage:**
  - Breakdown occurs when the maximum field in the space charge region reaches the critical field. Equating $E_{max}$ to $E_c$ thus allows us to determine the reverse breakdown voltage $V_{br}$ according to

$$\boldsymbol{V_{br} \approx \frac{\varepsilon_r \varepsilon_o (N_A + N_D)}{2qN_A N_D} E_c^{\,2}}$$

# Example 1

- An abrupt p-n junction has a uniform doping concentration of $10^{16}$ cm$^{-3}$ for the n and p regions. Calculate the avalanche breakdown voltage. The critical field is $3.5\text{x}10^5$ V/cm.

- The breakdown voltage is

$$V_{br} \approx \frac{\varepsilon_r \varepsilon_o (N_A + N_D)}{2qN_A N_D} E_c^{\;2}$$

$$= \frac{(11.7)(8.85\times10^{-14})(10^{16}+10^{16})}{2(1.6\times10^{-19})(10^{16})(10^{16})}(3.5\times10^{5})^2$$

$$= 79.3 \text{ V}$$

# Example 1

- Comments:
  - The avalanche breakdown voltage is typically in the range of several tens to hundreds of volts. In comparison, the Zener breakdown voltage is much lower (in the range of 5-20V).

# Example 2

- Design an $n^+p$ abrupt junction to achieve a breakdown voltage of 100 V. The critical field is $3.5 \times 10^5$ V/cm.
- For an $n^+p$ junction, $N_D >> N_A$. The breakdown voltage is given by

$$V_{br} \approx \frac{\varepsilon_r \varepsilon_o (N_A + N_D)}{2qN_A N_D} E_c^{\,2} \approx \frac{\varepsilon_r \varepsilon_o}{2qN_A} E_c^{\,2}$$

- The required doping for the p region is therefore

$$N_A \approx \frac{\varepsilon_r \varepsilon_o}{2qV_r} E_c^{\,2}$$
$$= \frac{(11.7)(8.85 \times 10^{-14})}{2(1.6 \times 10^{-19})(100)} (3.5 \times 10^5)^2$$
$$= 3.96 \times 10^{15} \text{ cm}^{-3}$$

# Example 2

- Comments:
  - The avalanche breakdown voltage of a one-sided pn junction is controlled by the doping concentration of the lowly doped side.
  - In this example, we see that the breakdown voltage is inversely proportional to the doping concentration of the lowly doped p region, i.e.

$$V_{br} \propto \frac{1}{N_A}$$