1. The pn junction diode

- start with an n-type Si wafer with donor impurity doping: \( N_d \)

- selectively dope the wafer with acceptor impurity atoms where \( N_A > N_d \) makes substrate portion p-type

- appropriately metallize both sides to make electrical contacts

\[ \text{Schematic symbol} \]

\[ \text{anode} \quad \text{p} \quad \text{n} \quad \text{cathode} \]

Typical charge carrier concentrations:

- **p-type side**
  - \( P_p = 10^{17} \text{ holes/cm}^2 \)
  - \( n_p = 10^3 \text{ } \text{e}^-/\text{cm}^2 \)

- **n-type side**
  - \( \rho_n = 10^4 \text{ holes/cm}^2 \)
  - \( n_n = 10^6 \text{ } \text{e}^-/\text{cm}^2 \)
- Large concentration of holes on p-type side of MJ
- Large " " e's " n-type " " "

Some mobile holes will diffuse across the MJ to the n-type side
" e's " " " p-type side

On p-type side of MJ \(\rightarrow\) immobile negative charged acceptor atoms remain

On n-type side of MJ \(\rightarrow\) immobile ionized donor atoms with a localized positive charge remain

\(-\) This results in the development of a Space Charge Region (SCR), depleted of mobile charge carriers around the MJ \(\rightarrow\) also called a Depletion Region or Depletion Layer

\(-\) The SCR results in an electric field that limits additional charge carrier diffusion across the MJ

\(\rightarrow\) "Electric Field" \(\rightarrow\) results in a built-in potential across the pn junction

\[ \phi_j = -\int E(x) dx, \quad [\phi_j] = V \]

\[ = V_T \ln \left( \frac{N_A N_D}{n_i^2} \right) \]

\[ W_{d_0} = \text{depletion-layer width (in x-direction)} \]

\[ = (x_n + x_p) \]

\[ \sqrt{\frac{2 \varepsilon_S}{q} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) \phi_j} \]

\[ [W_{d_0}] = m \]
The SCR E-field results in drift currents in opposite direction to diffusion currents, so that they balance out.

a. Applying a voltage across the pn junction

1. **Reverse Bias Operation**

- Applied negative voltage increases the potential barrier to a net of charge carriers moving across the MJ: \( i_0 \ll OA \)

2. **Forward Bias Operation**

- A positive applied voltage reduces the potential barrier

\[
i_0 = \frac{I_s}{e^{\left(\frac{V_D}{nV_T}\right)} - 1}
\]

where: \( I_s \) = Reverse Saturation Current: typically \( 10^{-18} A \leq I_s \leq 10^{-9} A \)

\( n \) = nonideality factor: typically \( n = 1 \) to 1.1

\( V_T \) = thermal voltage = \( \frac{kT}{q} \)

Note: if \( T \uparrow \), \( V_D \uparrow \) for same \( i_0 \)
b. Reverse Breakdown

1. Avalanche Breakdown $\Rightarrow$ impact-ionization process: depletion layer increases under reverse bias until E-field is strong enough to accelerate e's to a velocity fast enough to break covalent bonds upon impact $\Rightarrow$ impact-ionization, i.e. creating electron-hole pairs.

2. Zener Breakdown $\Rightarrow$ reverse bias induced carrier tunneling directly between conduction and valence energy bands in heavily doped diodes.

2. Schottky Barrier Diode

p-type Si side is replaced with a metal conductor: "contact"

- Anode $\Rightarrow$ n-type $\Rightarrow$ n$^+$ cathode
- n$^+$ region added to ensure that the cathode contact is ohmic
- non-ohmic rectifying metal contact
- has a much lower turn on voltage than a p-n junction.

3. The amazing p-n junction

1. Rectifier
2. Photovoltaic device
3. LED
4. TEC - solid state heat pump or power generator - Peltier effect
5. Photodiode $\Rightarrow$ camera
6. Temp sensor
7. 2 p-n junctions $\Rightarrow$ BJT transistor