Lecture 5  Diodes

Resistors, capacitors, inductors all linear
Current is linear function of voltage
Very important elements are nonlinear.
Simplest: diode = semiconductor junction
Start by describing physics of silicon

\[ \begin{align*}
\text{Energy levels:} & \quad E \\
\text{Conduction band} & \quad \uparrow \\
\text{Gap} = 1.1 \text{ eV} & \quad \text{(no states)} \\
\text{Valence band} & \quad \uparrow \\
\end{align*} \]

Valence band normally full of electrons
Conduction band empty

\Rightarrow \text{ Si is an insulator (poor one, because gap is small) }

Interesting effects when doped with impurities:

Two types: \( p \): captures \( e^- \) from valence band,
leaves hole
\( n \): donates \( e^- \) to conduction band

Donated holes/electrons provide conduction

Picture:

\[ \begin{align*}
\text{Step} & \\
\text{holes (+)} & \\
\text{electrons (-)} & \\
\end{align*} \]

Note, captured charges aren't shown. Total system is neutral charge.
Diode = pn junction

\[ \text{wire} \begin{array}{c}
\text{p} \\
\text{n} \\
\text{wire}
\end{array} \]

At junction, electrons from n-type fill holes in p-type

\[ \text{capture charges} \]

Leave captured charges behind, build up static charge

Resulting electric field keeps carriers near junction

Think about using electric potential

Total picture:

\[ \text{p-type} \quad \text{\hspace{1cm} v-type} \]

\[ \text{Energy} \quad \text{gap} \quad \text{trapped charges} \]

\[ \text{dep} \quad \text{AE} \quad \text{gap} \]

\[ \text{filled holes} \]

In junction area, no carriers, insulating layer

But two effects do allow current:

1) Thermal excitation in p-type: electrons excited from V to C

Then roll down hill into n-type

\[ \Rightarrow \text{current from n to p} \]

"thermal current"

2) Electrons in n-type might have enough thermal energy to overcome barrier, drift into p-type

Then recombine with holes

\[ \Rightarrow \text{current from p to n} \]

"recombination current"
In equilibrium, currents cancel \( \Rightarrow I_{\text{tot}} = 0 \)

Now, say we apply voltage \( V \) to junction:

Changes barrier height \( \Delta E = \Delta E_0 - eV \)

\( I_{\text{thermal}} \propto e^{-E_{\text{sep}}/kT} \) doesn’t change

\( I_{\text{recomb}} \propto e^{-\Delta E/kT} \) does change

\[ I_r \propto e^{-\frac{\Delta E_0}{kT} + \frac{eV}{kT}} = e^{-\frac{\Delta E_0}{kT}} e^{rac{eV}{kT}} \]

\[ I_r = I_s e^{eV/kT} \]

\( I_s \) = "scale current"

So \( I_{\text{tot}} = I_s e^{eV/kT} - I_{\text{therm}} \)

At \( V = 0 \), know \( I_{\text{tot}} = 0 \) \( \Rightarrow I_{\text{therm}} = I_s \)

All together, \( I_{\text{tot}} = I_s (e^{eV/kT} - 1) \)

Really, \( I = I_s (e^{uV_0/kT} - 1) \) \( U_0 = \frac{kT}{e} \), varies by a factor of 2

For typical diode, \( I_s \) is very small, \( \approx nA \)
So on mA scale, looks like

\[ \text{I vs. } V \]

\[ I = 0 \text{ unless } V \geq V_0 \]

Then I grows really fast

Simple approx:

\[ \text{I vs. } V_0 \]

Take \( I = 0 \text{ for } V \leq V_0 \)

\( I = \infty \text{ for } V > V_0 \)

\( \Rightarrow \) no current if \( V \leq V_0 \)

Then \( V \) "clamped" at \( V_0 \)

Call \( V_0 \) = diode drop

Typ: \( \sim 0.6\text{V} \)

Effect: think of diode as one-way valve

\[ \text{\rightarrow} \]

\(-\text{N}^{-} \) : only current \( \rightarrow \)

Takes small forward voltage \( V_0 \) to "open" valve

Very nonlinear behavior, useful in many situations