For Si (Ge, GaAs similar) there is a bandgap \( \gtrsim kT \):

- **Conduction band**
- **Valence band**

\[
\frac{kT}{e} \approx 0.025 \text{ V at room temp.}
\]

There are just a few thermal conduction electrons, \( \approx 10^{16} \text{ m}^{-3} \) at room temp.

**Things change drastically if trace impurities are added:**

**n-type**: Add P, As, or Sb dopant, Valence 5

- little energy is required to liberate the extra electron
- \( \text{immobile} + \text{ion, "donor"}, \text{fixed in lattice} \)

**p-type**: Add B, Valence 3, or similar

- The "hole" can move freely if the electron is attached to the Immobile (-) ion, or "acceptor"

So in effect, p-type charge carriers are (+).

**Diode junction**

- Holes and electrons recombine at boundary until the potential inhibits further net motion.
- For Si, \( V_0 \approx 0.5 \text{ V} \) (on the order of the bandgap)
Equilibrium: Let \( N_p \) = hole density, \( N_e \) = electron density. For holes on n side, no barrier, but very few holes are available. For holes on p side, fraction able to cross is given by a Boltzmann factor:
\[
e^{-eV_0/k_BT}
\]
where \( k_B T \approx 40 \text{ ev at } 300 \text{K} \).
So in equilibrium:
\[
N_p (\text{n side}) = N_p (\text{p side}) e^{-eV_0/k_BT}
\]
Likewise, \( N_e (\text{p side}) = N_e (\text{n side}) e^{-eV_0/k_BT} \)

**Externally biased diode**

V will appear across depletion region, reducing potential to \( V_0 - V \) (or increasing, if \( V \) is negative).

**Net flow of e\(^-\) from n side is now**
\[
I_e \propto N_e (\text{n side}) e^{-e(V_0-V)/k_BT} - N_e (\text{p side}) e^{eV_0/k_BT}
\]
\[
= C N_e (\text{p side}) (e^{eV/k_BT} - 1)
\]
\[
\equiv I_{po}, \text{ electron saturation current}
\]
So \( I_e = I_{po} (e^{eV/k_BT} - 1) \)

Similarly, \( I_p = I_{po} (e^{eV/k_BT} - 1) \), so altogether:
\[
I \propto I_0 (e^{eV/k_BT} - 1). \text{ Also OK for reverse bias!}
\]

A slightly modified version works better,
\[
I_{diodo} \sim I_0 \left( e^{\frac{eV}{nk_BT}} - 1 \right)
\]

Here \( n \) is between 1 and 2, and accounts for recombination and other device-dependent effects.

This works well unless \( V \) is so negative that reverse avalanche breakdown occurs (failure) or, in special "Zener diodes," a sharp breakdown is reached due to quantum tunneling. These are used as voltage references.
Where \( \frac{e}{lT} = 1000 \)V as before assuming T=300K.
and \( I_o = \text{reverse saturation current} \), typ. \( \sim 1 \)mA or less.
and \( n \) contains device physics; it's about 1-2.

\( I_o \) is set by flow of "minority" carriers.

Reverse breakdown occurs by
1) Avalanche breakdown

or 2) Zero breakdown - direct breakage
of covalent bonds by E field at junction.

Normally causes destruction, but used intentionally for "zener diode".

**Ratings:**

Important ones are --
1) \( PIV \) (peak inverse voltage)
or \( VR \) (max)
2) \( I_F \) (max.

3) \( I_R \) (max)

(goes up 6.2% /°C !)

**Small-signal:**

<table>
<thead>
<tr>
<th>Device</th>
<th>( VR ) (max)</th>
<th>( I_F ) (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN914</td>
<td>75 V</td>
<td>10 mA (cont.)</td>
</tr>
<tr>
<td>(or IN4478)</td>
<td></td>
<td>( 0.75V )</td>
</tr>
<tr>
<td></td>
<td>( 5 )μA at 100°C and ( VR )</td>
<td></td>
</tr>
</tbody>
</table>

**Typ. Rectifier:**

<table>
<thead>
<tr>
<th>Device</th>
<th>( VR ) (max)</th>
<th>( I_F ) (max)</th>
<th>( I_R ) (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN4007</td>
<td>1000 V</td>
<td>1000 mA (cont.)</td>
<td>50 μA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 0.9V )</td>
<td></td>
</tr>
</tbody>
</table>

Note: IN400x is much slower than IN914.

General rule: use "conduction" \( AV \sim 0.6V \)
(of thumb) for Si diodes.
Still OK: Kirchhoff's laws

Not OK: Ohm's law (assumes linearity)
       Thévenin Theorem (assumes both linearity & superposition principles)

Applications:

1) Rectification:

   a) half-wave

   b) full-wave

Simple power supply:
Estimate ripple: look at limit of small ripple.

Assume \( I_{\text{load}} \) constant, and that \( C \) discharges for full half-cycle \( \Delta t = \frac{1}{2f} \).

Then

\[
\Delta V = \frac{Q}{C} = \frac{I_{\text{load}} \Delta t}{C} = \frac{I_{\text{load}}}{2fC}
\]

(This overestimates real ripple.)

Example: \( 100 \mu F, I = 100 \text{ mA}, 60 \text{ Hz} \)

\[
\Rightarrow \frac{1}{2(60)(10^{-4})} = 8.3 \text{ V (!!)}
\]

So we need at least \( 1000 \mu F \) to do at all well here.

Apart from using huge capacitors (and transformers), a good solution is to add regulators and series inductors, called "chokes." Increasing \( f \) also an option -- used by switching power supplies.

2) Variant: Voltage doubler:

\[
V_{\text{out}} = V_{\text{in}} \text{ (aver)}
\]

like 2 half-wave rectifiers in series.

Can extend for tripler, etc.
Basic clamp:

\[ V_n \quad V_c \quad V_a \]

\[ V_n \quad V_c \quad V_a \]

Want a perfect clamp? Use an op amp!

Uses:
1) protection (e.g., in IC's)
2) prevent overmodulation (e.g., radio, etc.)
3) limit swing in servo, etc., prevent latching.

Symmetric limiter:

Also good for ampl. protection!

Variation -- ac restoration/shifting

\[ V_{out} \]

When diode conducts, C changes. So its voltage builds up until conduction stops:

\[ V_{out} \]

Zero is shifted by \( \frac{A}{2} \) (-.6 V)
Protection from back-emf:

- Solenoid or relay coil → Protection diode
- Transistor switching circuit such as emitter follower (next)

For detectors with small signals, can even use

\[ -0.6 < V < +0.6 \]
Diode Mixers & such:

Can explicitly exploit nonlinearities as a log converter.
Or can exploit it to generate new freqs --
see lab!

\[ w_1 \quad \text{or} \quad \text{dum: just } \cos(w_1 t) + \cos(w_2 t) \]

\[ w_2 \]

Has beat note --

\[ \text{waveform} \]

Yes

But replace \( \oplus \) with

\[ \text{expression} \]

\[ V_{out} = IR = I_0 (e^{\frac{V}{A}} - 1) R, \]

where \( V = V_1 \cos(w_1 t) + V_2 \cos(w_2 t) \)

To get

\[ \text{Has new freqs} \]

\[ e^{\frac{V}{A}} = \frac{1}{2} \left( e \frac{V}{A} + \frac{1}{2} \left( \frac{V}{A} \right)^2 \right) + \cdots \]

gives \( w_1, w_2, 2w_1, \ldots \)

Can see \( w_1, w_2 \) here in arg.

To reduce distortion, bias diode into conduction.

IF \( w_1 \ll w_2 \), this is an amplitude modulator;
if comparable, it's a mixer.