• Free electron-hole pairs are generated by thermal agitation in an intrinsic material.
• Crystal is space-charge neutral.
  \[ \bar{n} = \bar{p} = \eta_i \]
• \( \eta_i \) is produced by a dynamic process.
• At thermal equilibrium, rate of generation = rate of recombination.
• The value of \( \eta_i \) is only about a trillionth \( (10^{-12} - 10^{-13}) \) of a free-electron concentration in a metal.
$10^{20}$ in $10^{22}$ cm$^{-3}$ is certainly known as 'impurity'.

$$\bar{n} \bar{p} = n_i^2$$

why?

Free-electron concentration in the p-type crystal decreases below $n_i$ and hole concentration increases.
Si $\rightarrow 10^{22}$ cm$^{-3}$ intrinsic

make every millionth, i.e., $10^6$ of the site an impurity site of let's say group III element intrinsic

Hence, the local concentration of holes, i.e., $10^{10}$ cm$^{-3}$ will get changed to impurity hole concentration $\approx 10^{16}$.

This certainly changes the conductivity by six orders of magnitude.
Excess Carriers

$\bar{n}, \bar{p}$ are thermal eqn$^m$ concentrations of carriers at a given temp.

A device does operate using an external energy source.

This upset the eqn$^m$ concentration.

A new eqn$^m$ will be achieved.

It may be smaller $\rightarrow$ carrier depletion larger $\rightarrow$ excess carrier
Hence carrier concentrations increase till light is turned on.

Something else starts at this point. Recombination!

Like a heavy steel ball is kept on a stretched rubber sheet. It finds out its equilibrium position on the sheet. If it is pushed up by some force, it would again come back to equilibrium.
Recombination lets the concentrations to return to the thermal equilibrium levels.

Finally

\[ \text{Generation} = \text{Recombination} \]

\[ \Rightarrow \text{a steady state.} \]

Diagram:
- Holes or free electrons
- Equilibrium with light
- Thermal equ. level (initial)
- Time \( t \)
Let's introduce $\hat{\beta}$ and $\hat{n}$ for excess concentrations:

\[ \beta = \bar{\beta} + \hat{\beta} \]
\[ n = \bar{n} + \hat{n} \]

Initially, when generation rate is not very high, i.e., $\hat{\beta}$ or $\hat{n}$ is not very high, the recombination rate is proportional to the concentration itself.

\[ \hat{\beta} \] let's say.

where $\tau$ is some time constant.

Hence we can write:

\[ \frac{d\hat{\beta}}{dt} = g - \frac{\hat{\beta}}{\tau} \]
at steady state
\[
\frac{d\bar{p}}{dt} = 0
\]

\[\Rightarrow \bar{p} = \gamma \tau\]

So excess hole concentration depends on the generation rate and the time in which it would disappear by recombination process.

What happens when light is turned off?

\[\gamma = 0\]
\[
\Rightarrow \frac{d\hat{p}}{dt} = -\frac{\hat{p}}{\tau}
\]

\[
\Rightarrow \frac{d\hat{p}}{\hat{p}} = -\frac{dt}{\tau}
\]

Integrate on both sides

\[
\int_{\hat{p}(0)}^{\hat{p}(t)} \frac{1}{\hat{p}} \, d\hat{p} = -\int_0^t \frac{1}{\tau} \, dt
\]

\[
\Rightarrow \ln\left(\frac{\hat{p}(t)}{\hat{p}(0)}\right) = \frac{-t}{\tau}
\]

\[
\Rightarrow \ln\hat{p} = -\frac{t}{\tau}
\]

\[
\Rightarrow \hat{p}(t) = \hat{p}(0) e^{-\frac{t}{\tau}}
\]

\[
\hat{p} = g \tau e^{-\frac{t}{\tau}}
\]

Decays exponentially with \(\tau\).