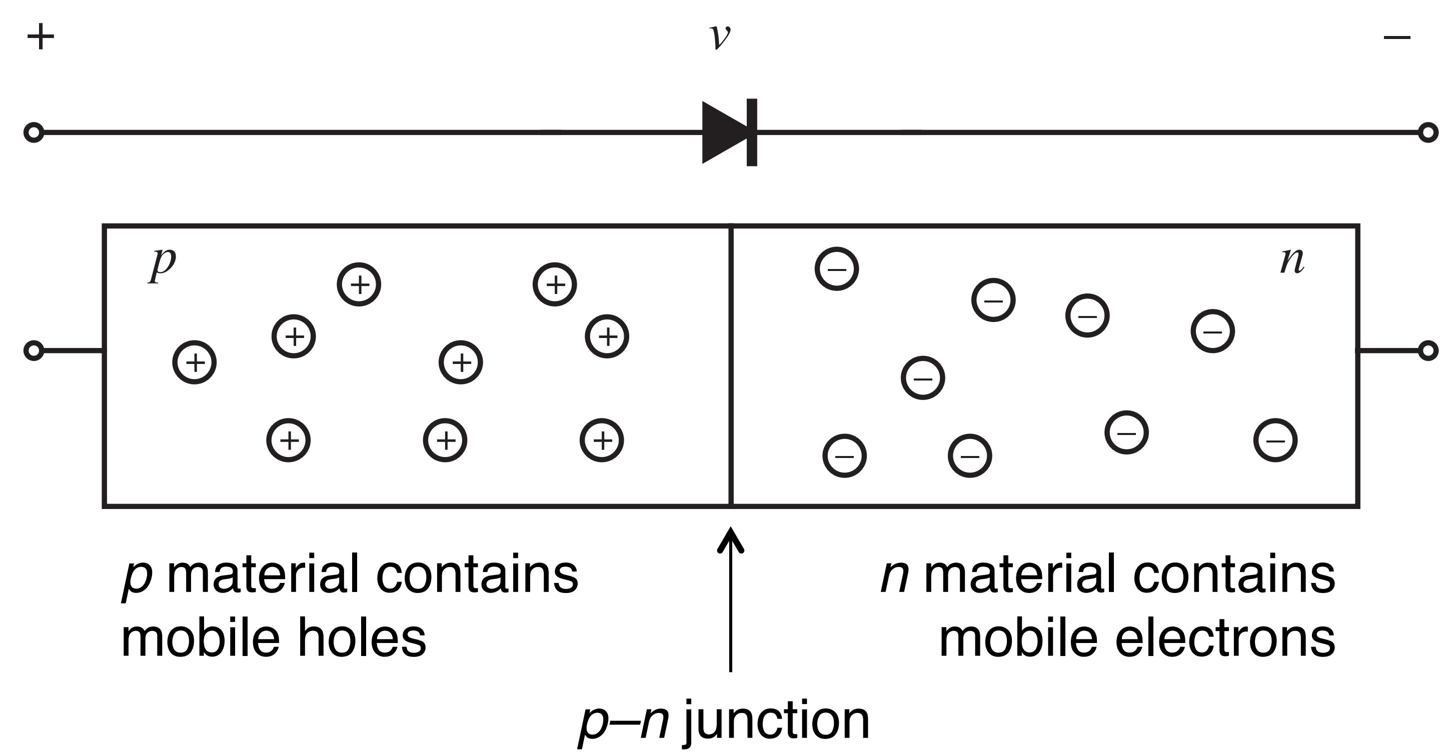
p–n junction

Junction diode consisting of

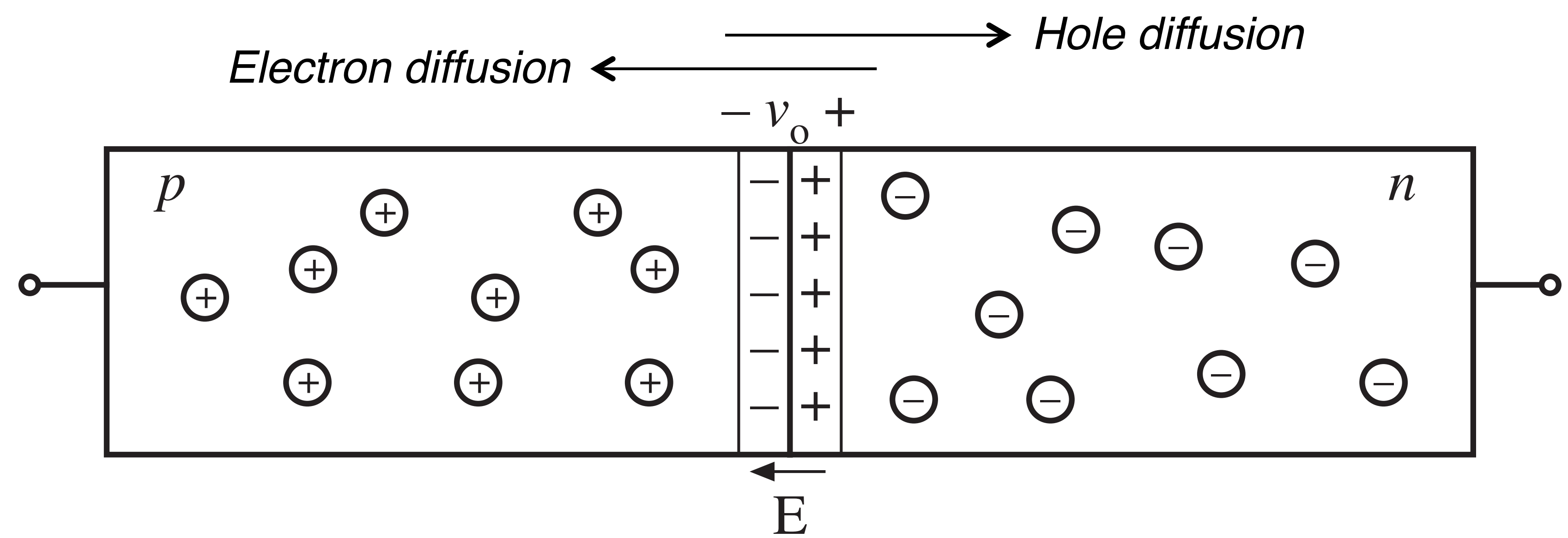
- *p*-doped silicon
- *n*-doped silicon
- A *p-n* junction where the *p*- and *n*-material meet



Formation of depletion region

also called "space charge layer"

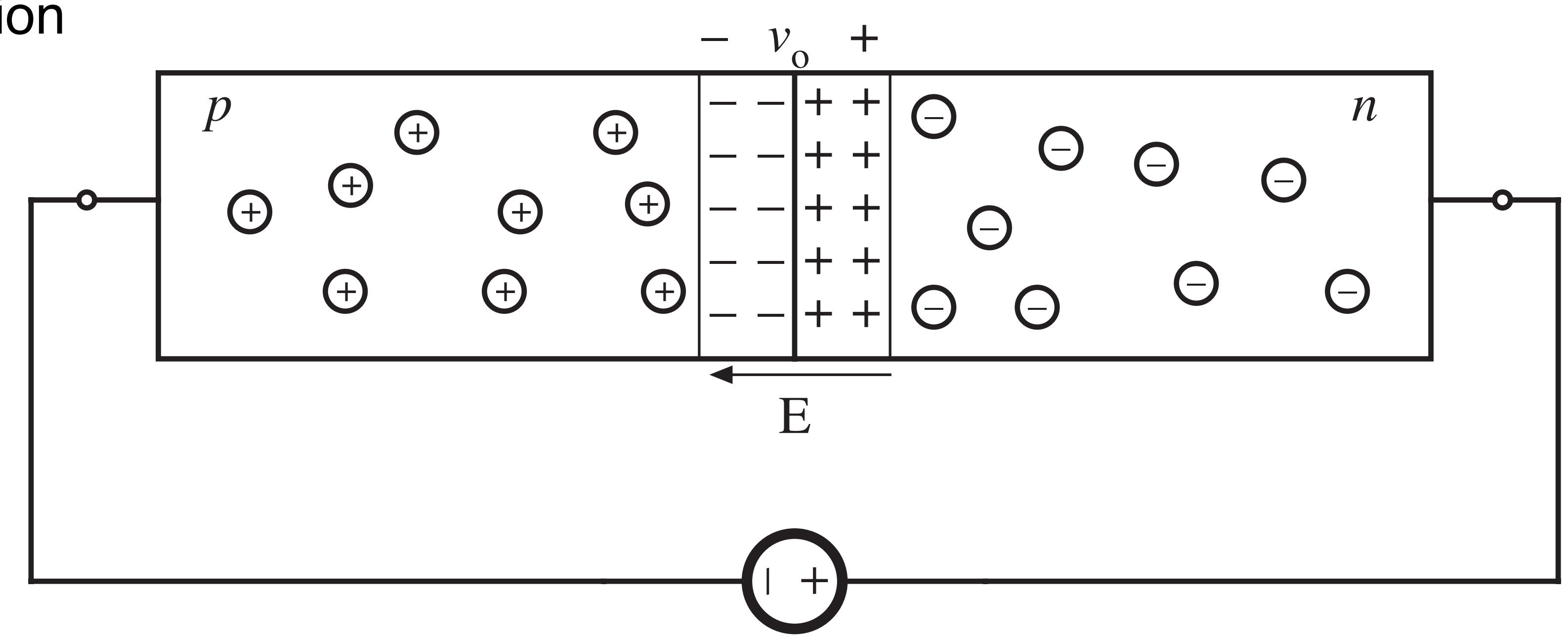
- At the junction, the concentrations of holes and electrons changes abruptly
- The holes and electrons diffuse in the direction of reducing concentration



- These holes and electrons leave behind charged atoms—a "depletion region"
- An electric field forms in the vicinity of the junction
- This electric field constitutes an energy barrier that opposes diffusion
- The device comes to equilibrium when the voltage v_o across the depletion region is enough to stop further diffusion of charges across the junction

The diode under reverse bias conditions

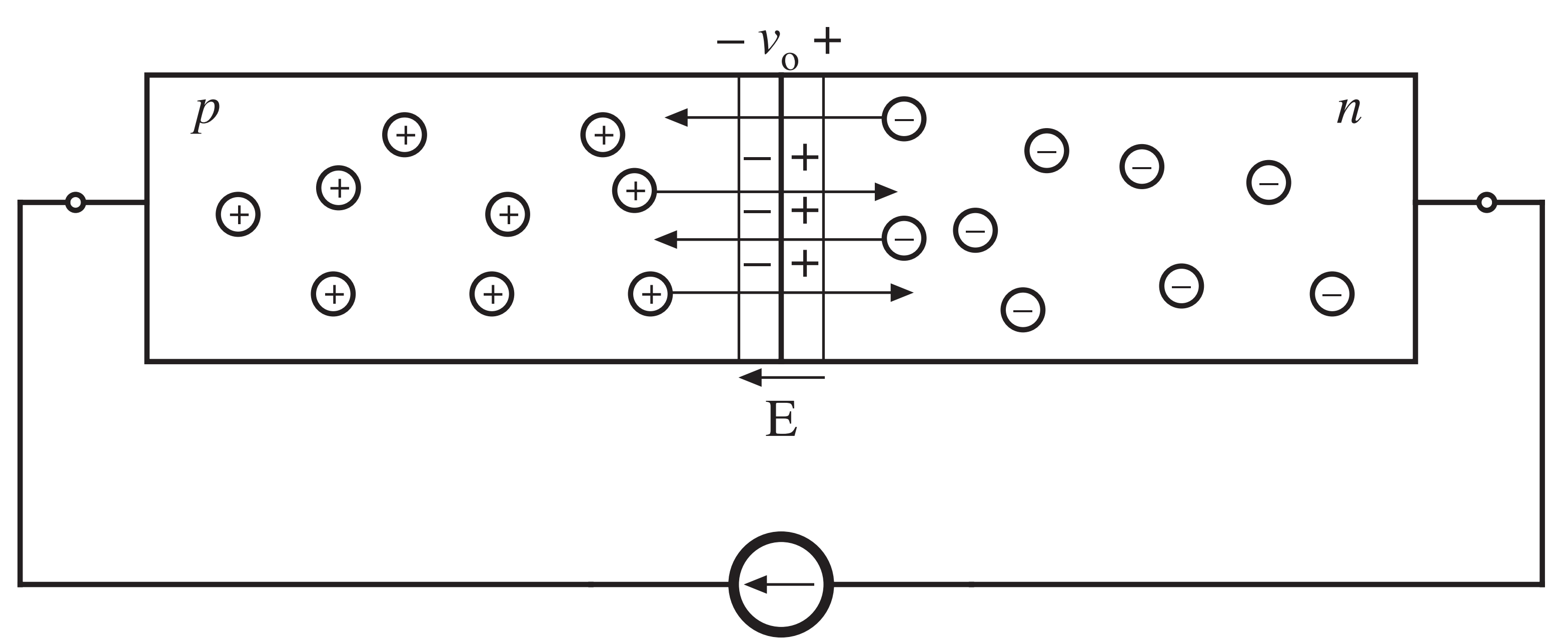
- Application of an external reverse voltage to the diode causes the depletion region to increase
- The external voltage is blocked by the depletion region
- Increasing the reverse voltage requires that charge is added to the depletion region



- “Junction capacitance”: depletion region charge vs. voltage characteristic

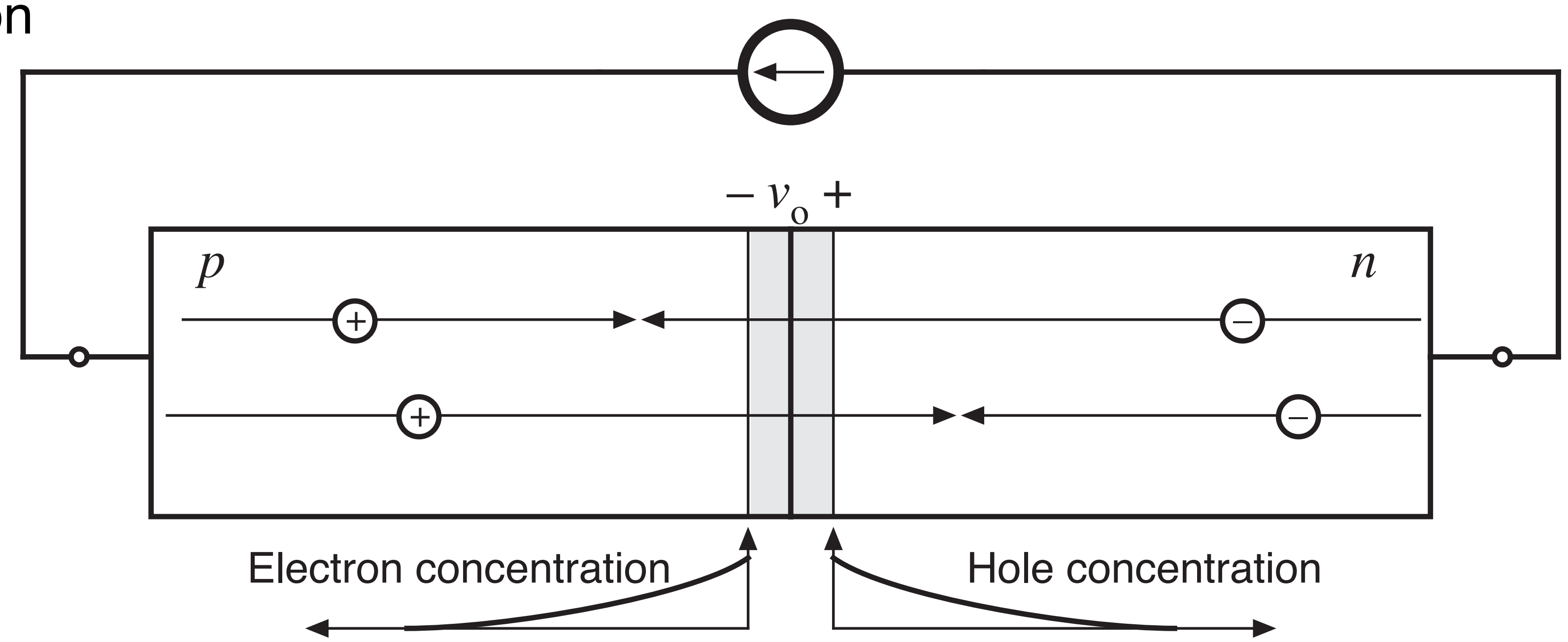
The diode under forward bias conditions

- When the diode voltage is positive, the depletion region voltage is not large enough to prevent diffusion of charge across the junction
- Holes from the *p*-region diffuse across the junction, and become minority carriers in the *n*-region, whose energy state is high enough to enable them to conduct
- Similarly, electrons from *n*-region diffuse across the junction and become minority carriers in the *p*-region



Minority-carrier stored charge in forward-biased diode

Under forward-biased conditions, a hole enters the p-material from the external circuit. It then either (a) diffuses across junction, then recombines with an electron in the n-region, or (b) recombines in the p-region with a minority-carrier electron



The forward current of the diode consists entirely of recombination, either in the p- or n-region. The forward current continues as long as there is minority charge. To turn off the diode, the minority charge must be eliminated.

Charge-controlled behavior of the diode

The diode equation:

$$q(t) = Q_0\left(e^{\lambda v(t)} - 1\right)$$

Charge control equation:

$$\frac{dq(t)}{dt} = i(t) - \frac{q(t)}{\tau_L}$$

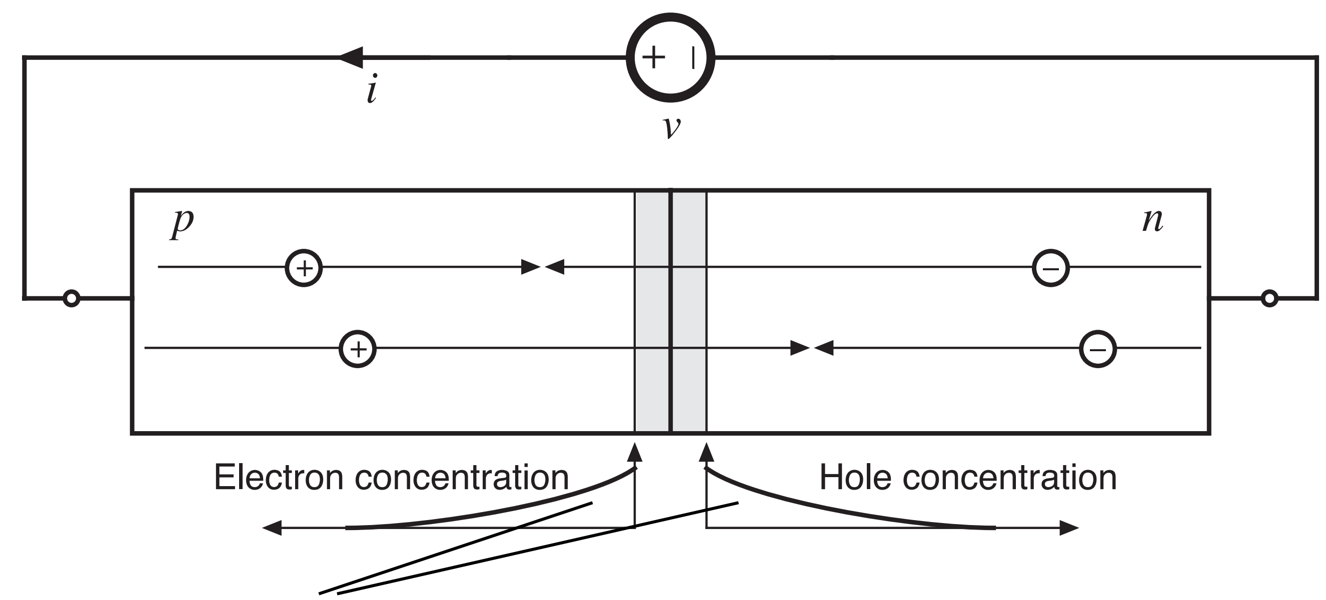
with:

λ = 1/(26 mV) at 300 K

τ_L = minority carrier lifetime

(above equations don' t include current that charges depletion region capacitance)

(lumped-element charge control model with 1 lump)

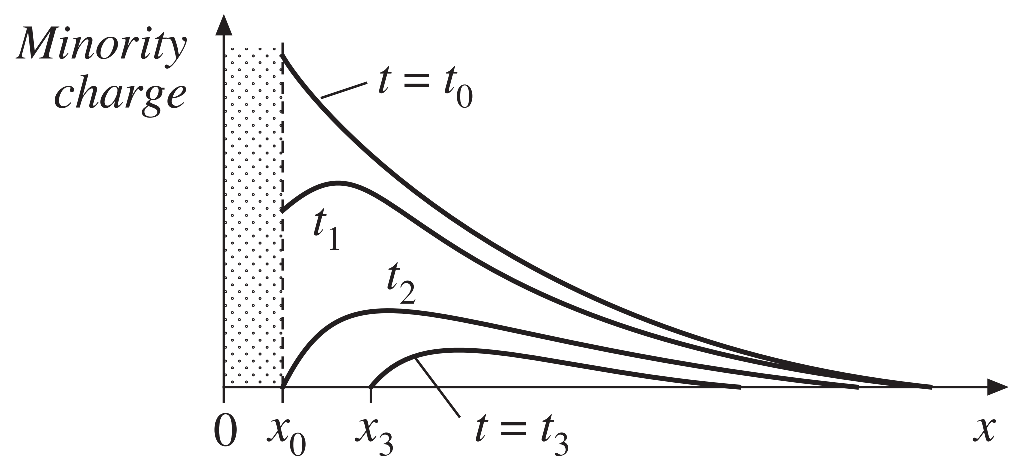


In equilibrium: $dq/dt = 0$, and hence

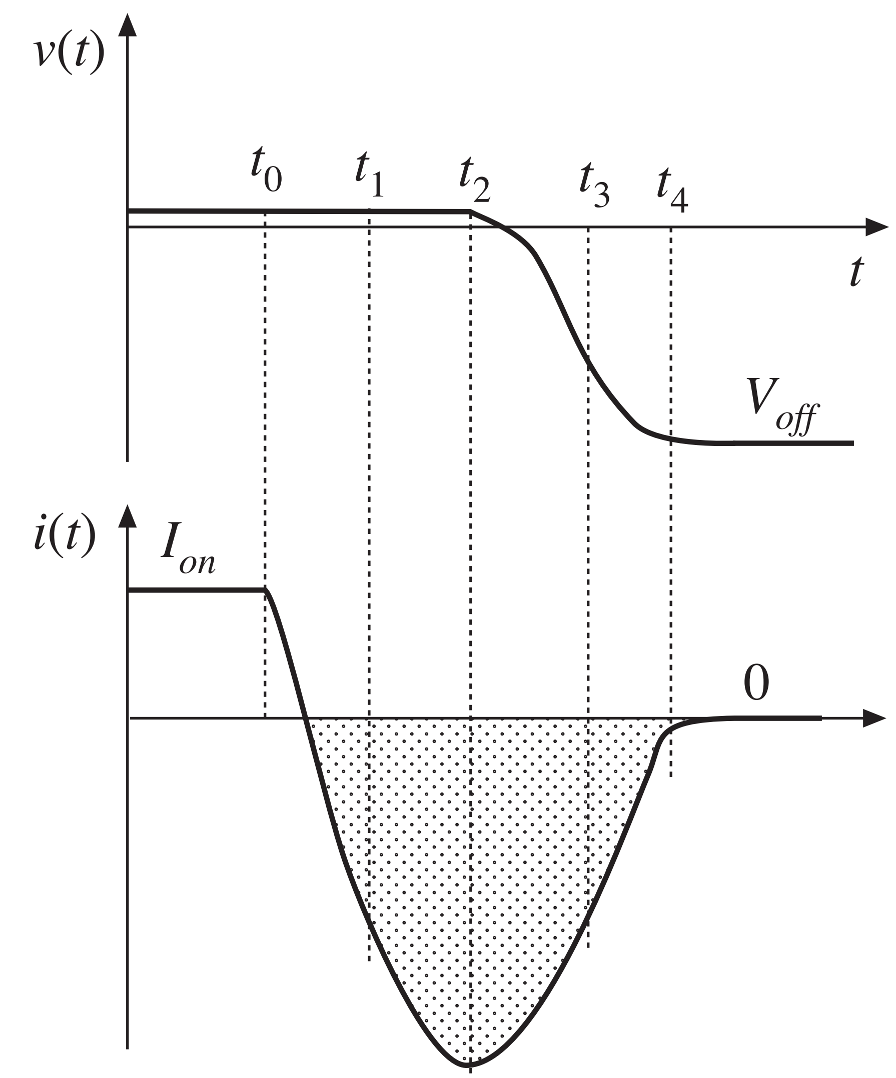
$$i(t) = \frac{q(t)}{\tau_L} = \frac{Q_0}{\tau_L}\left(e^{\lambda v(t)} - 1\right) = I_0\left(e^{\lambda v(t)} - 1\right)$$

Removal of stored charge during reverse recovery

Distribution of minority charge on one side of p-n junction during reverse recovery



Slope determines diffusion rate and hence current



Charge-control in the diode: Discussion

- The familiar i–v curve of the diode is an equilibrium relationship that can be violated during transient conditions
- During the turn-on and turn-off switching transients, the current deviates substantially from the equilibrium i–v curve, because of change in the stored charge and change in the charge within the reverse-bias depletion region
- The reverse-recovery time t_r is the time required to remove the stored charge in the diode and enable it to block the full applied negative voltage. The area of the negative diode current during reverse recovery is the recovered charge Q_r