Switching Time of a Diode

- Switching Time of a diode is the time it takes to switch the diode between two states (ON and OFF states).

Assume $R_S$ is large enough that all current flows through diode in forward bias conditions.

Switching Time of a Diode

For Forward Bias:
- Current source $I_D$ is an ideal diode current source: $I_D = I_S \left( e^{V_D / \Phi_T} - 1 \right)$
- $C_j$ represents the space-charge (junction capacitance).
- $C_d$ represents the excess minority carrier charge (diffusion capacitance).
  (Note that both of these are small-signal capacitances; to be applicable large-signal analysis, average capacitance values must be used).

For Reverse Bias:
- Eliminate the current source $I_D$ and the diffusion capacitance $C_d$.

Transient response requires finding a solution to:

$$I_{in} = I_D(t) + \left( C_d + C_j \right) \frac{dV_D(t)}{dt}$$

$$I_{in} = I_S \left( e^{V_D(t) / \Phi_T} - 1 \right) + \left( C_d + C_j \right) \frac{dV_D(t)}{dt}$$
Switching Time of a Diode

- **Transient response:**
  - The exponential and the non-linear dependence of \( C_d \) and \( C_j \) on \( V_D \) make this difficult to do by hand.

  - Consider the simulated response:

![Switching Time of a Diode](image)

Switching Time of a Diode
- **Turn-off Transient.**

  - The turn-off transient, has two operation intervals.

  - **Region 1:**
    - Diode is on.
    - \( I_2 \) removes excess minority charge.
    - Voltage drop is small allowing \( C_j \) to be ignored since space-charge remains \( \sim \)constant.

  - **Region 2:**
    - \( I_D \sim 0 \) (diode off).
    - Space-charge changes while building a reverse-bias over the diode.
    - Therefore, \( C_j \) dominates performance.
Derivation of Turn-off Transient.

- **Region 1**: Removal of excess minority charge.
  - **Charge-control expression**:

\[
I_{in} = \frac{Q_D(t)}{\tau_T} + \frac{dQ_D(t)}{dt}
\]

Current splits into 2 fractions.

\[
\text{Component that adds and removes excess charge. Goes to 0 under steady state.}
\]

\[
Q_S/\tau_T
\]

Component that sustains the normal diffusion current.

The term \(dQ_D(t)/dt\) represents the current due to the removal of injected carriers from the base region and the term \(Q_D(t)/\tau_T\) represents the normal diffusion current where \(\tau_T\) is the Base transit time.

- **Solving this differential equation assuming that**: \(Q_D = I_1\tau_T\) at time \(t = 0\) or the initial value of \(Q_D\) and \(I_{in} = I_2\)

Where \(I_1 = \frac{(V_D - V_B)}{R_S}\) is the current under forward bias and \(I_2 = \frac{V_2}{R_S}\)

- **Yields**:

\[
Q_D(t) = \tau_T[I_2 + (I_1 - I_2)e^{-t/\tau_T}]
\]

- **The turn-off time is derived by solving for the time \(t = t_1\)** (\(Q_D\) evaluates to 0):

\[
t_1 = \tau_T \ln \left[ \frac{I_1 - I_2}{-I_2} \right]
\]

- **Region 2**: Changing the Space Charge.
  - Diode is off, circuit evolves toward steady state.

\[
V_D(t = \infty) = V_2 = I_2 R_S
\]

- During this time, a reverse voltage is built over the diode.
- Therefore, space charge has to be provided.
• The change in excess minority charge can be ignored as well as the reverse bias diode current $I_d$.
• This leaves us with a simple RC circuit (red capacitor model shown earlier).

$$I_2 = V_D(t) + C_j \frac{dV_D}{dt}$$

$C_j$ is the average junction capacitance over the voltage range of interest.

- Assuming the value of $V_D$ at time $t = t_1$ is 0, the solution is the well-known exponential:

$$V_D(t) = I_2 R_S \left[ 1 - e^{-\frac{(t-t_1)}{R_S C_j}} \right]$$

- The 90% point is reached after 2.2 time-constants of $R_S C_j$:

$$t_2 - t_1 = 2.2 R_S C_j$$

• Derivation of Turn-on Transient.

- Similar considerations hold for the turn-on transient.

- Space Charge:

  - The transient waveform for the diode voltage (assume $t = 0$):

$$V_D(t) = R_S \left[ I_1 - (I_2 - I_1) e^{-\frac{1}{R_S C_j}} \right]$$

$$t_3 = R_S C_j \ln \left[ \frac{I_1 - I_2}{I_1} \right] \quad \text{Assuming } V_D = 0$$

- Excess charge:

$$Q_D(t) = I_1 \tau_T \left[ 1 - e^{-\frac{(t-t_3)}{\tau_T}} \right]$$

- It takes 2.2 time constants for $Q_D$ to reach 90% of its final value.

$$t_4 - t_3 = 2.2 \tau_T$$