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ECE606: Solid State Devices
Lecture 24: Large Signal Response

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Topic Map

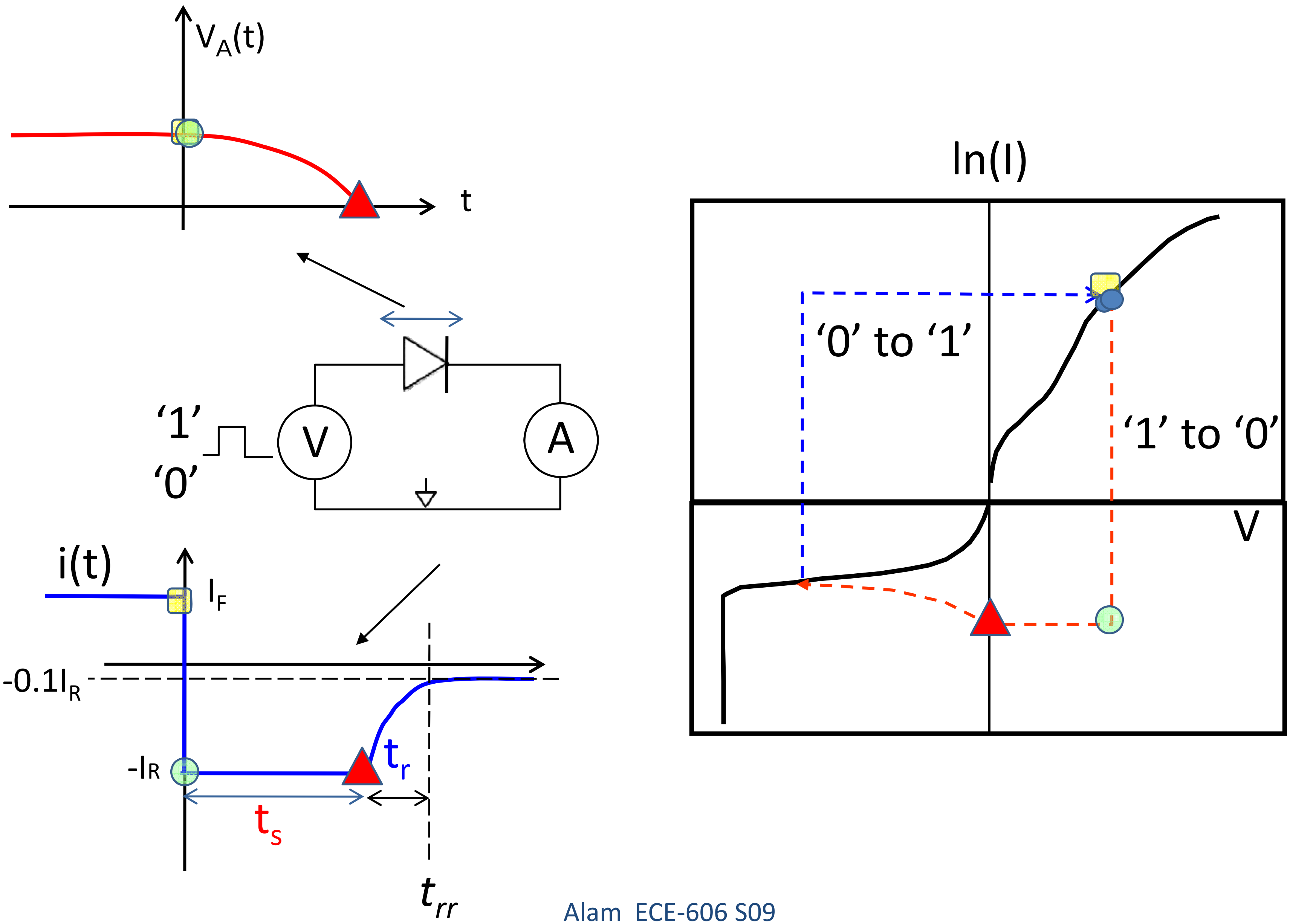
	Equilibrium	**DC**	Small signal	**Large Signal**	Circuits
Diode			◆		
Schottky					
BJT/HBT					
MOSFET					

Outline

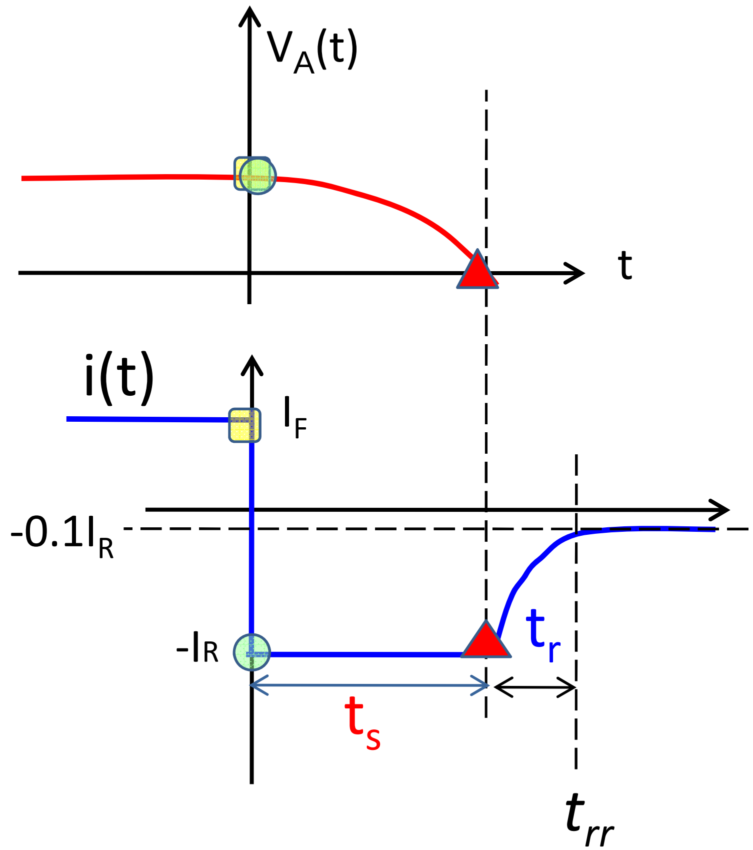
1) **Large signal response and charge control model**
2) Turn-off characteristics
3) Turn-on characteristics
4) Other applications
5) Conclusion

Ref. SDF, Chapter 8

Digital, Large Signal Applications



Definitions



t_s … Charge storage time

t_r … Recovery time

t_{rr} .. Reverse recovery time

Continuity Equations

Full analytical solution impossible for large signal....

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N \mathcal{E} + qD_N \nabla n$$

$$\frac{\partial Q_n}{\partial t} = i_{n,diff} - \frac{Q_n}{\tau_n}$$

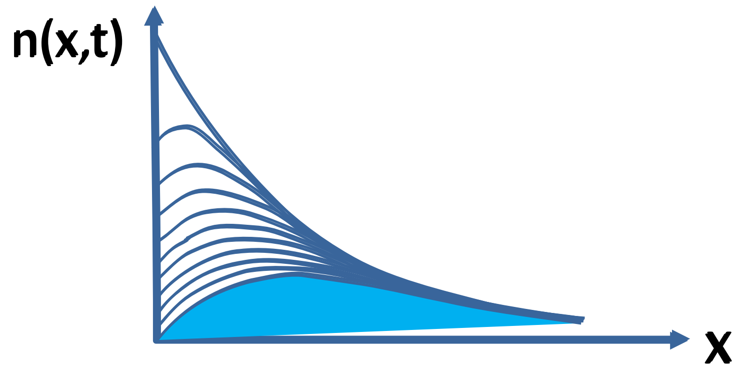
$$\frac{\partial p}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

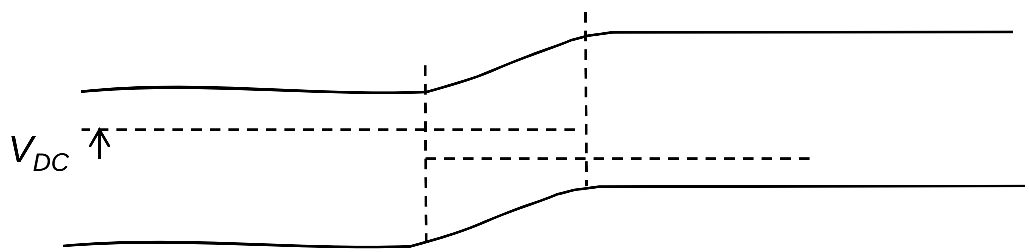
$$\mathbf{J}_P = qp\mu_P \mathcal{E} - qD_P \nabla p$$

$$\frac{\partial Q_p}{\partial t} = i_{p,diff} - \frac{Q_p}{\tau_n}$$

Charge control equations ...

Large Signal Charge Control Model





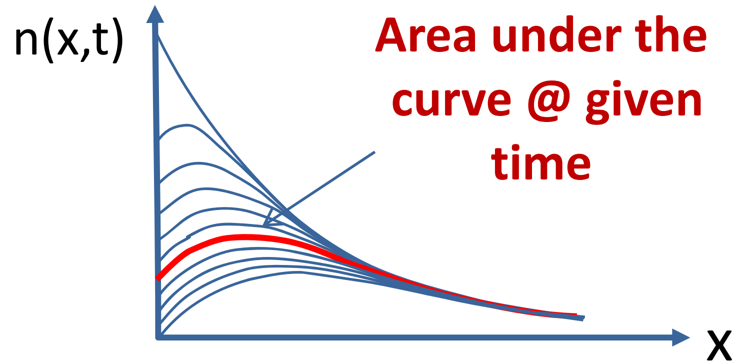
$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{dJ_n}{dx} - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N \mathcal{E} + qD_N \frac{dn}{dx}$$

$$\frac{\partial(\Delta n)}{\partial t} = D_N \frac{d^2(\Delta n)}{dx^2} - \frac{\Delta n}{\tau_n}$$

Large Signal Charge Control Model

$$\frac{\partial(\Delta n)}{\partial t} = D_N \frac{d^2(\Delta n)}{dx^2} - \frac{\Delta n}{\tau_n}$$



$$\int_0^{W_p} \frac{\partial(qA\Delta n)}{\partial t} dx = \int_0^{W_n} D_N \frac{d}{dx} \frac{d(qA\Delta n)}{dx} dx - \int_0^{W_n} \frac{qA\Delta n}{\tau_n} dx$$

$$Q \equiv \int_0^{W_p} (qA\Delta n)\, dx$$

$$\frac{\partial Q}{\partial t} = D_N \left.\frac{d(qA\Delta n)}{dx}\right|_{x=W_p} - D_N \left.\frac{d(qA\Delta n)}{dx}\right|_{x=0} - \frac{Q}{\tau_n}$$

$$\frac{\partial Q}{\partial t} = i_{diff} - \frac{Q}{\tau_n}$$

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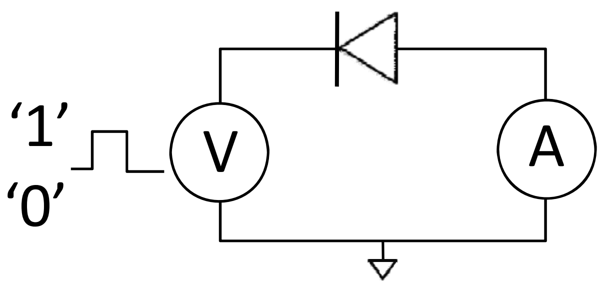
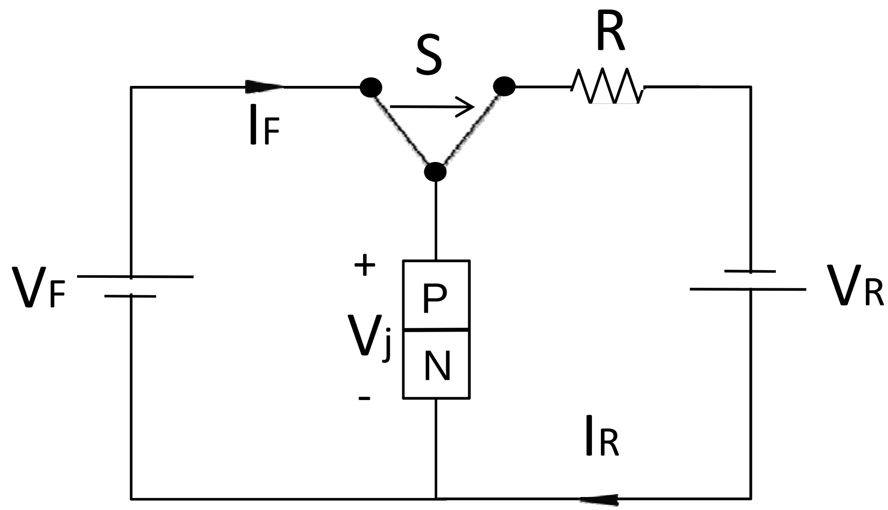
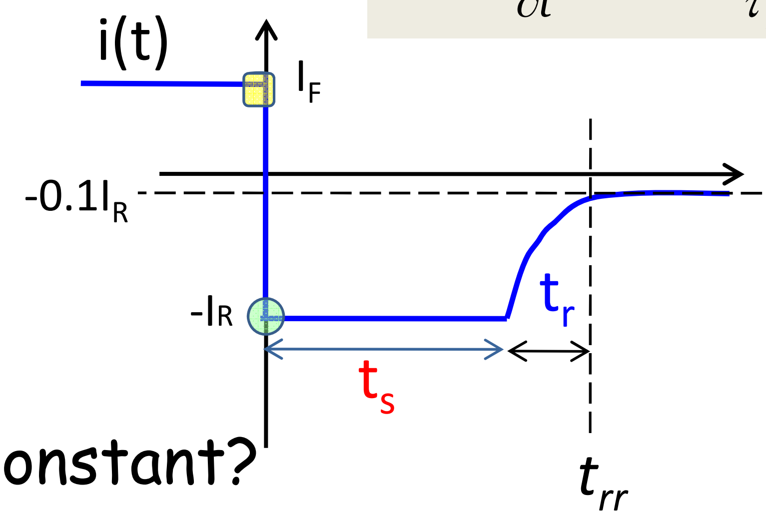
Turn-off Characteristics: Determine (t_s)





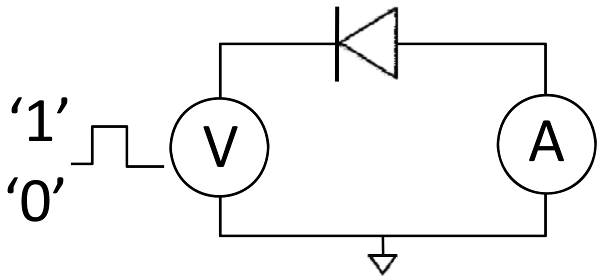
$$t < 0 \quad \frac{\partial Q}{\partial t} = I_F - \frac{Q(0^-)}{\tau_n}$$

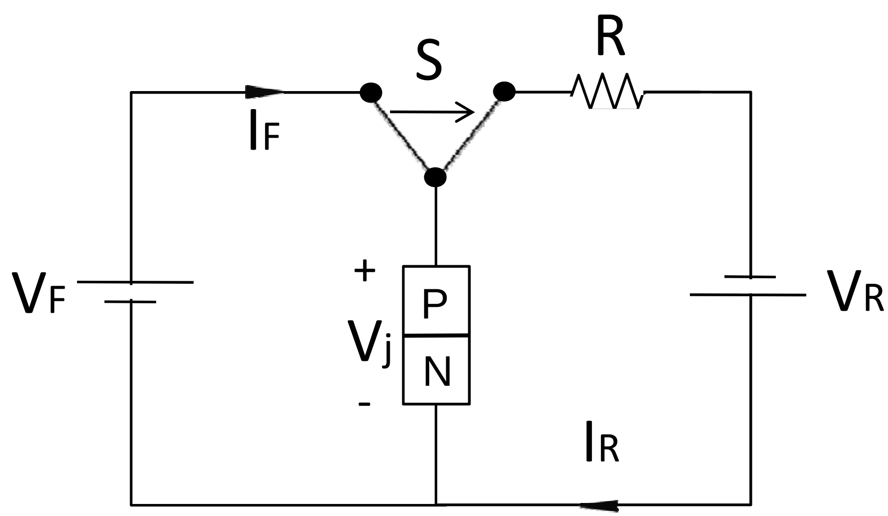
$$\frac{\partial Q}{\partial t} = i_{diff} - \frac{Q}{\tau_n}$$



Why does the current remain constant?

Boundary Condition





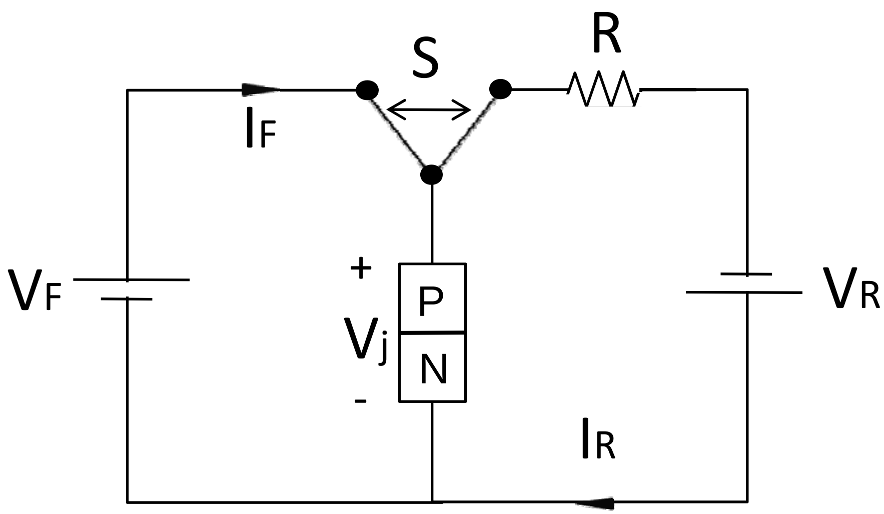
$$\frac{\partial Q}{\partial t} = i_{diff} - \frac{Q}{\tau_n}$$

$$t < 0 \quad \frac{\partial Q}{\partial t} = I_F - \frac{Q(0^-)}{\tau_n}$$

$$Q(0^-) = I_F \tau_n = Q(0^+)$$

Note. For a capacitor, charge can not change instantly ....

Turn-off *Current* Transient



constant!

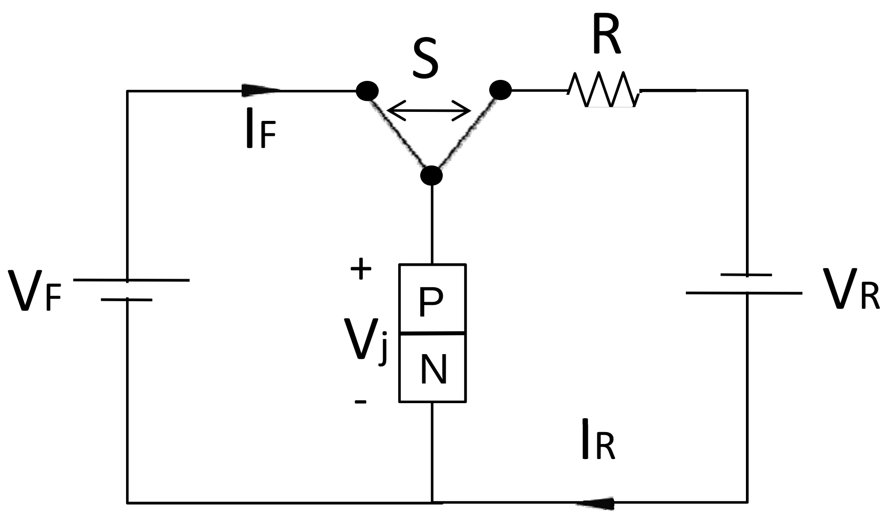
$$\frac{\partial Q}{\partial t} = i_{diff} - \frac{Q}{\tau_n}$$

$$t > 0 \quad \frac{\partial Q}{\partial t} = -I_R - \frac{Q}{\tau_n}$$

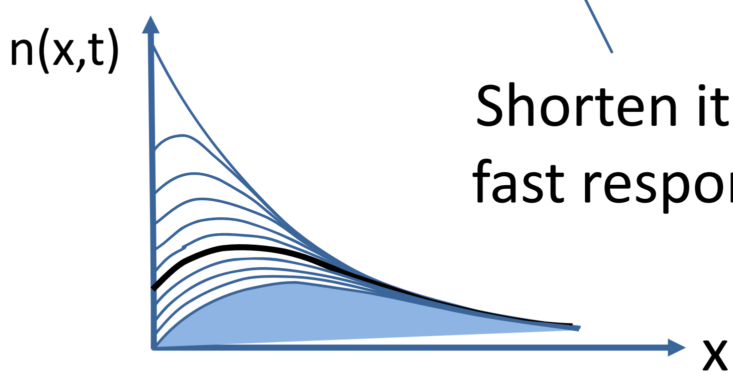
$$\int_{Q(0+)}^{Q(t_s)} \frac{dQ}{-\left(I_R + \frac{Q}{\tau_n}\right)} = \int_0^{t_s} dt$$

$$t_s = \tau_n \ln \frac{I_R + Q(0^+)/\tau_n}{I_R + Q(t_s)/\tau_n}$$

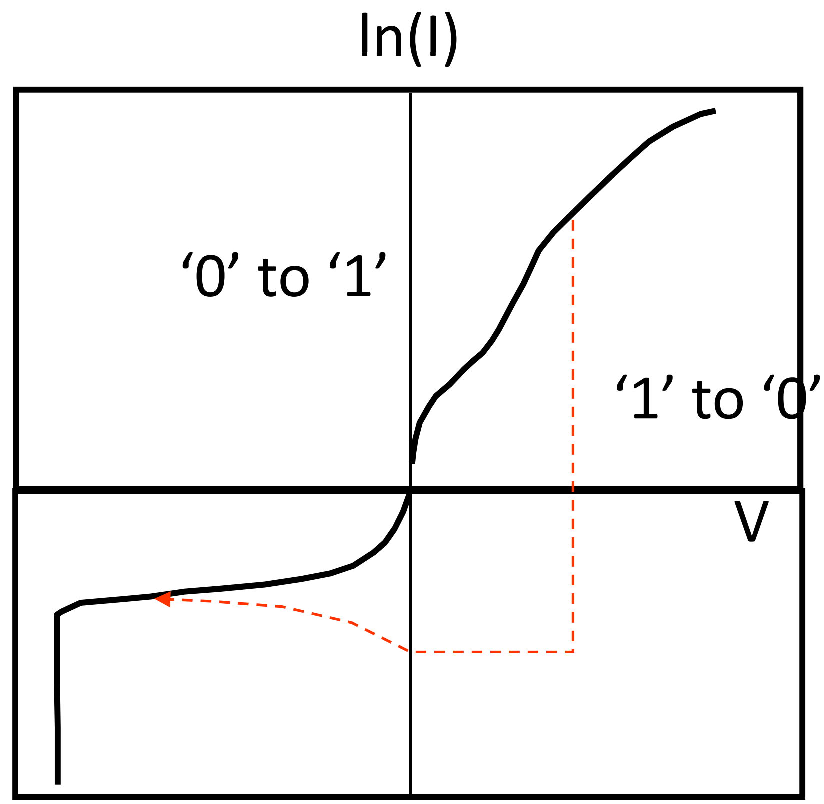
Storage Time



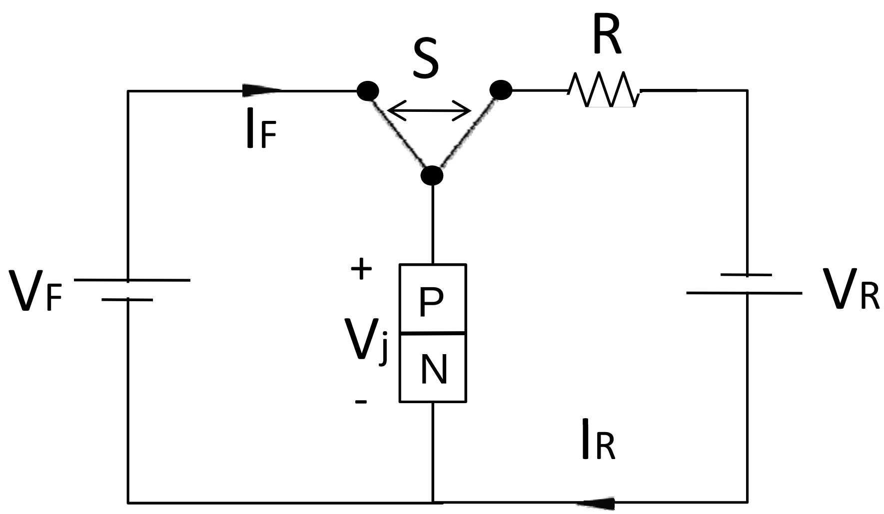
$$t_s = \tau_n \ln \frac{I_R + Q(0^+)/\tau_n}{I_R + Q(t_s)/\tau_n} = \tau_n \ln \frac{I_R + I_F}{I_R}$$

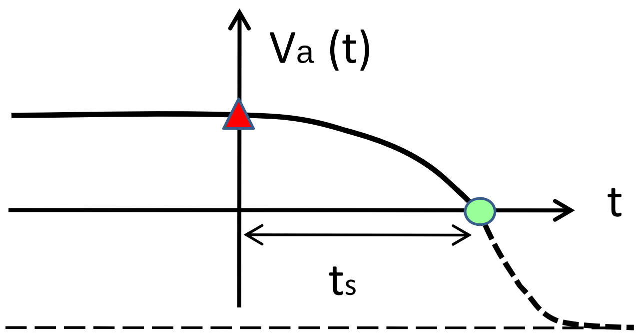


Shorten it for fast response!

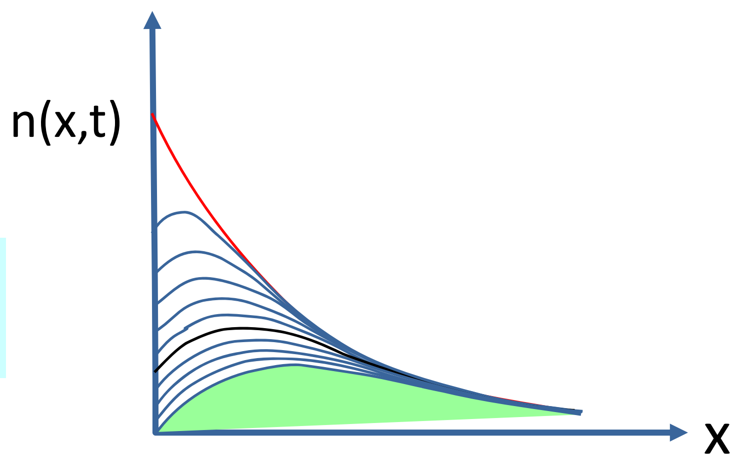


Turn-off *Voltage* Transient





$$\upsilon_A(t) = \frac{kT}{q} \ln \frac{n_p(0,t)}{n_{po}}$$

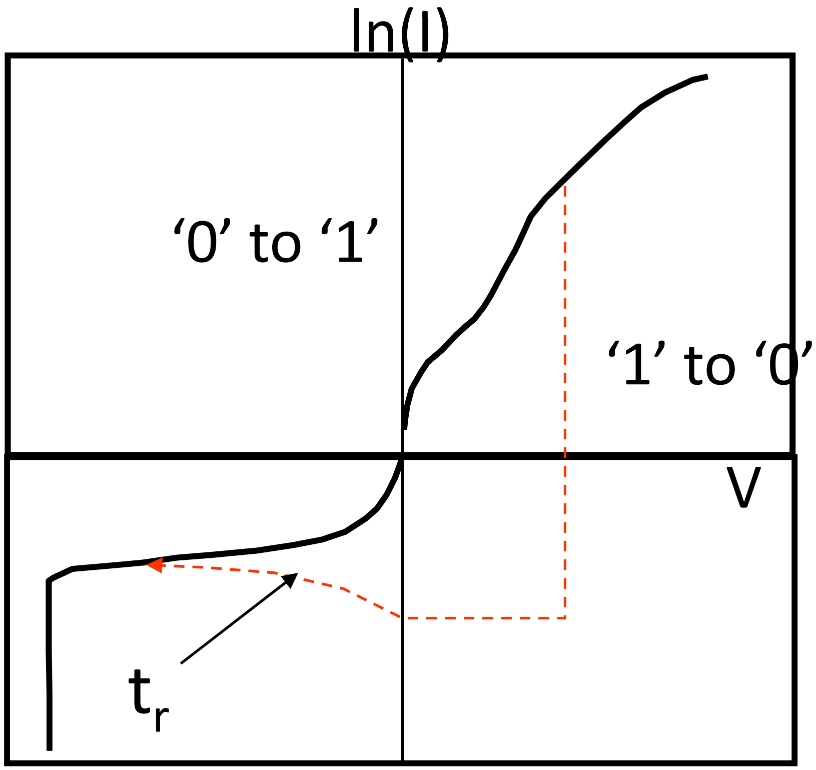


$$Q_n(t) = \tau_p \ln\left(-I_R + (I_R + I_F)e^{-t/\tau_p}\right)$$

Allows easy calculation of $n_p(0,t)$.

Recovery Time

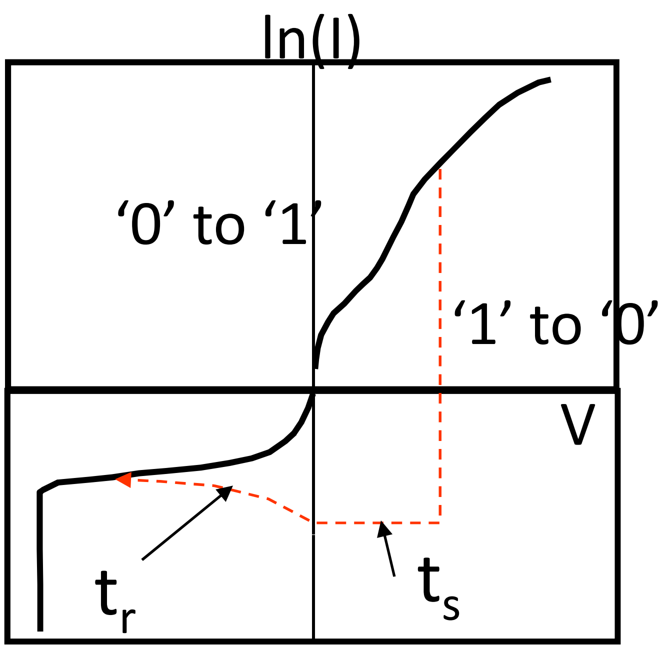
$$erf\sqrt{\frac{t_r}{\tau_p}}+\frac{e^{-\frac{t_r}{\tau_p}}}{\sqrt{\pi\frac{t_r}{\tau_p}}}=1+0.1\frac{I_F}{I_R}$$



Useful formula …

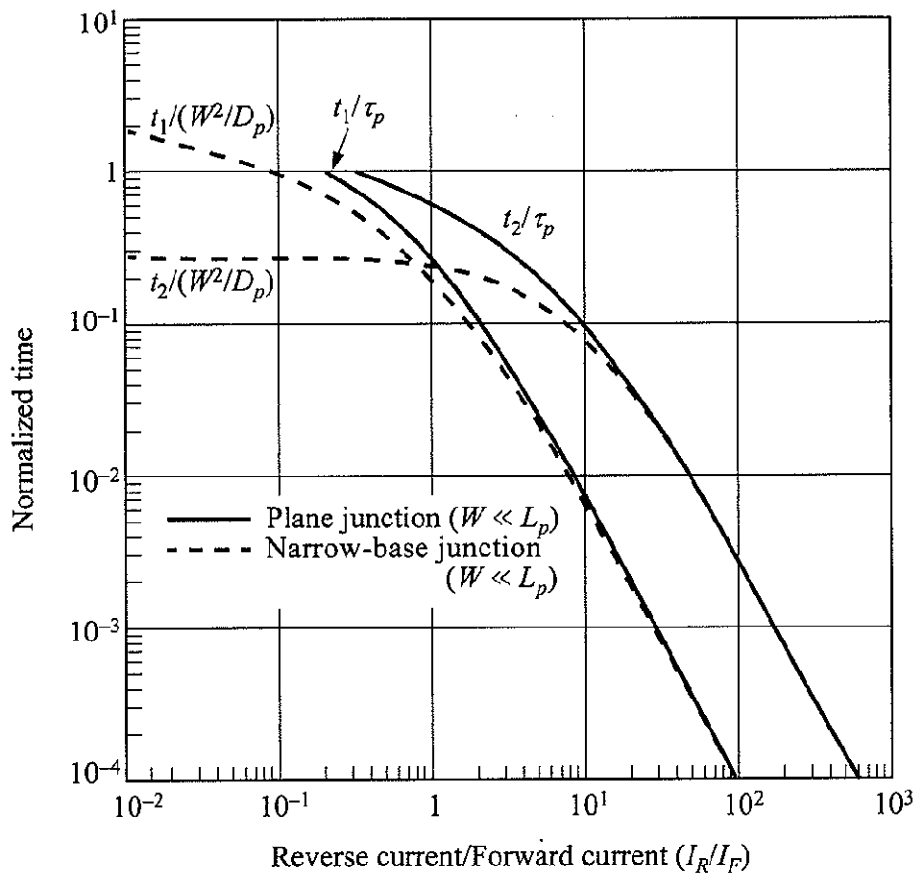
$$erf(\sqrt{x})=\left[1-\mathrm{e}^{-x\frac{1.27+0.15x}{1+0.15x}}\right]^{0.5}$$

Recovery Time



$$t_{rr} = t_r + t_f \approx \begin{cases} \dfrac{W_p^2}{2D_n}\left(\dfrac{I_R}{I_F}\right)^{-2} & (W_p \ll L_n) \\ \dfrac{\tau_p}{2}\left(\dfrac{I_R}{I_F}\right)^{-2} & (W_p \gg L_n) \end{cases}$$

Ref. Sze/Ng, p. 117



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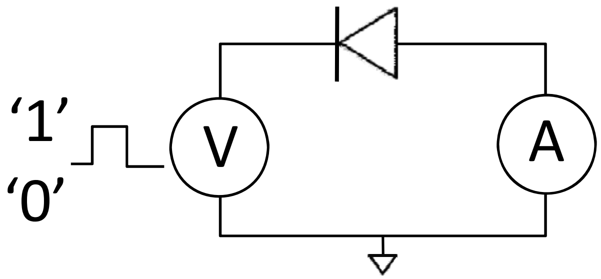
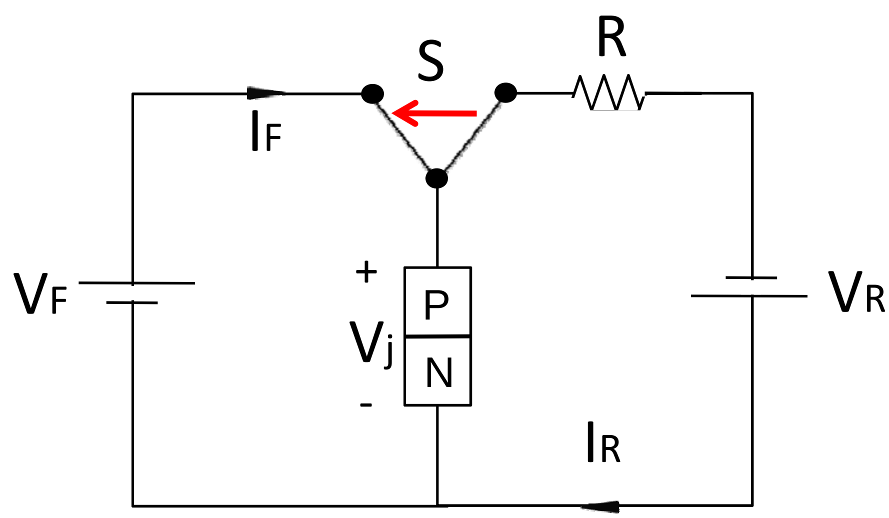
Turn-on Characteristics: Boundary Condition



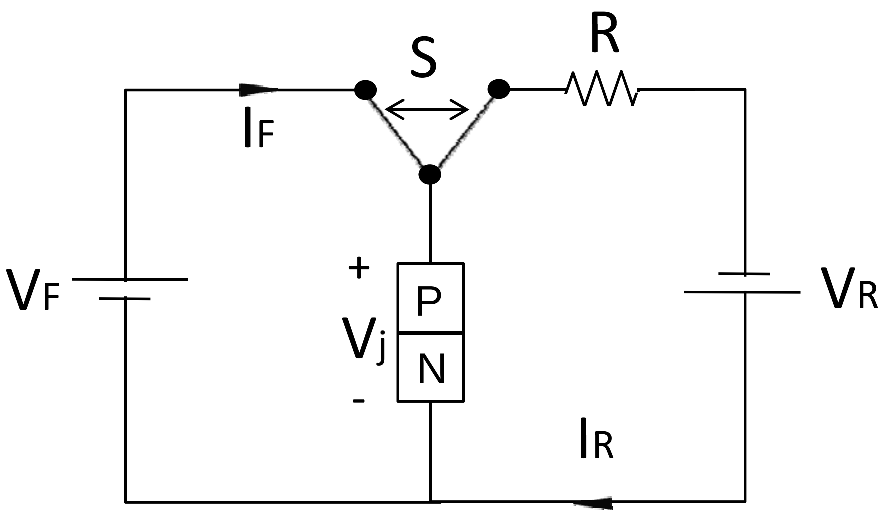


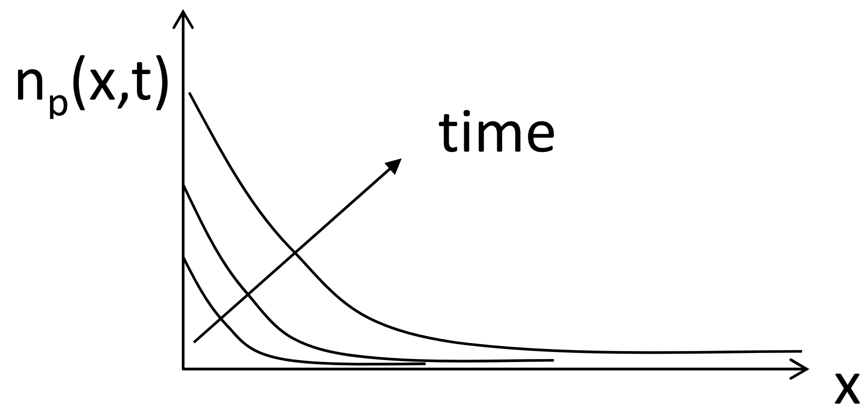
$$\frac{\partial Q}{\partial t} = i_{diff} - \frac{Q}{\tau_n}$$

$$t \to \infty \quad \frac{\partial Q}{\partial t} = I_F - \frac{Q(t=\infty)}{\tau_n}$$

$$Q(t=\infty) = I_F \tau_n$$

Turn-on Characteristics





$$\frac{\partial Q}{\partial t} = i_{diff} - \frac{Q}{\tau_n}$$

$$t > 0 \quad \frac{\partial Q}{\partial t} = I_F - \frac{Q}{\tau_n}$$

$$Q(t) = Q(t \to \infty)\left(1 - e^{-\frac{t}{\tau_n}}\right) = I_F \tau_n \left(1 - e^{-\frac{t}{\tau_n}}\right)$$

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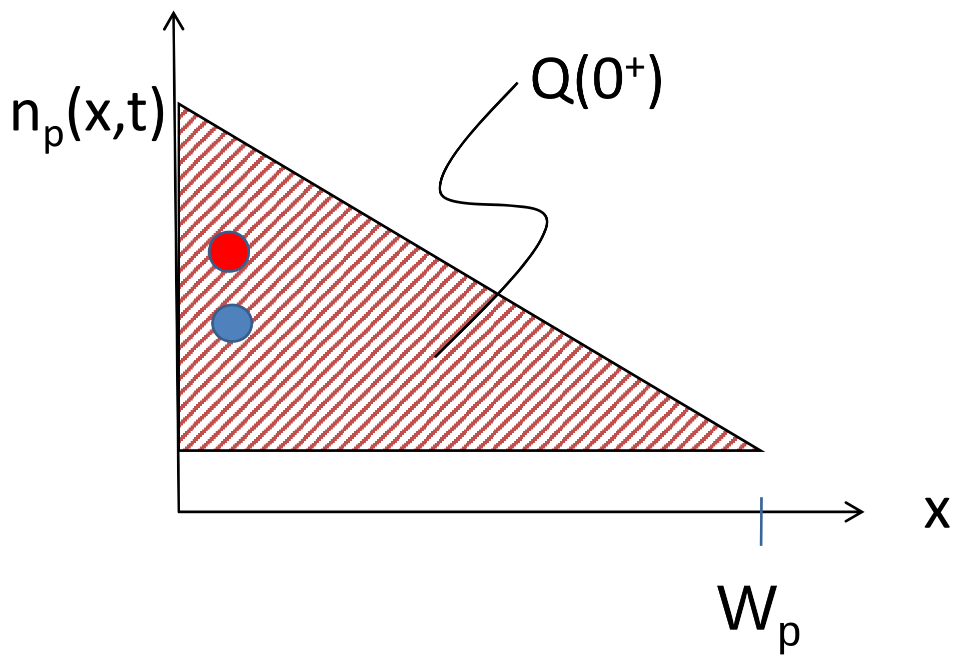
Calculating Diffusion Time by Charge Control

$$\frac{\partial Q}{\partial t} = i_{diff} - \frac{Q}{\tau_n}$$

$$\frac{Q(0^+) - Q(t=\infty)}{\tau_{diff}} = i_{diff}$$



$$\tau_{diff} = \frac{Q(0^+)}{i_{diff}} = \frac{q\left[\frac{\Delta n_p(0)}{2}\right]W_p}{qD_n\frac{\Delta n_p(0)}{W_p}} = \frac{W_p^2}{2D_n} \sim \frac{1}{2}\times\frac{W_p}{\left(D_n/W_p\right)}$$

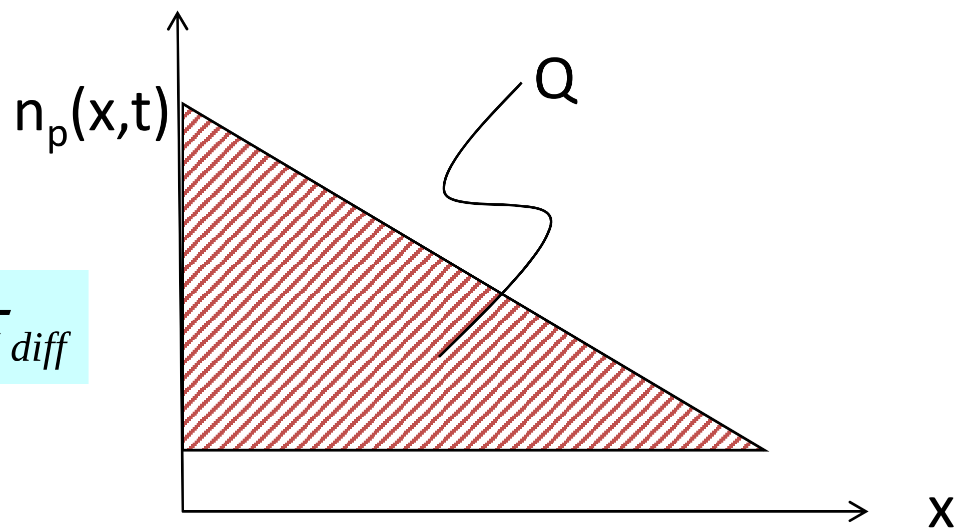
Diffusion velocity

Two line derivation of Steady State Diode Current

$$\frac{\partial Q}{\partial t} = i_{diff} - \frac{Q}{\tau_n}$$

$$\tau_n \rightarrow \tau_{diff}$$

$$i_{diff} = \frac{Q}{\tau_{diff}}$$



$$i_{diff} = \frac{Q}{\tau_{diff}} = \frac{q \times \frac{1}{2}\frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right) \times W_p}{\frac{W_p^2}{2D_n}} = q\frac{D_n}{W_p}\frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right)$$

Exact Expression!

Conclusion

Large signal response of devices of great importance for digital applications.

Analytical solution of partial differential equation often difficult (if not impossible), therefore approximate methods like Charge-control approximation often help simplify the solution and still provide a great deal of insight into the dynamics of switching operation.

Be careful in using the boundary condition which is often dictated by external circuit conditions.