Homework # 5 Solutions

EE482
Fall '02

2 (a) $N_d >> N_a$, so diode current is primarily electrons injected into p-side $J \cong J_{np}$ (ignoring recomb. in depletion region)

$$J = 100\,\frac{A}{cm^2} = J_{np} = \frac{Q_n}{\tau_n} \qquad Q_n = 100\,\frac{A}{cm^2}(10^{-6}\,s) = 10^{-4}\,C/cm^2$$

(b) $Q_d = \sqrt{2K_s\epsilon_0 q N_a(\phi_i - V_a)}$

$D_n \cong 21\,\frac{cm^2}{s}$

$$J_{np} = q\frac{n_i^2}{N_a}\left(\frac{D_n}{L_n}\right)\exp\left(\frac{qV_a}{kT}\right) \qquad L_n = (D_n\tau_n)^{1/2} = 4.6\times10^{-3}\,cm = 46\,\mu m$$

$$= (1.6\times10^{-19}\,C)\left(\frac{2\times10^{20}\,cm^{-6}}{10^{17}\,cm^{-3}}\right)\left(\frac{21\,cm^2/s}{4.6\times10^{-3}\,cm}\right)\exp\left(\frac{qV_a}{kT}\right)$$

$$= 1.46\times10^{-12}\,\frac{A}{cm^2}\exp\left(\frac{qV_a}{kT}\right) = 100\,\frac{A}{cm^2} \Rightarrow V_a = 0.83\,V$$

Assume $E_f \cong E_c$ on n-side, so $\phi_i = \frac{kT}{q}\ln\left(\frac{(3\times10^{19})(10^{17})}{2\times10^{20}}\right) = 0.96\,V$

$$Q_d = \begin{cases} 1.79\times10^{-7}\,\frac{C}{cm^2} & V_a = 0 \\ 0.66\times10^{-7}\,\frac{C}{cm^2} & V_a = 0.83\,V \quad (\phi_i - V_a) = 0.13\,V \end{cases}$$

(c) Divide switching into two parts:

As V_{diode} rises from 0, first only depletion charge is changing significantly, then at end Q_n increases exponentially with V_{diode}. Also, until Q_n rises to within a few kT of final value, very little current is required to compensate for recombination of injected minority carriers $\left(\frac{Q_n}{\tau_n}\right)$

$$\Delta t_1 = \frac{\Delta Q_d}{I_{avg}} = \frac{1.13\times10^{-7}\,C/cm^2}{100\,A/cm^2} = 1.13\times10^{-9}\,s = 1.13\,ns$$

For second stage Q_n and thus $\frac{Q_n}{\tau_n}$ becomes significant
Can neglect ΔQ_{depl} since ΔV is small and we have already accounted for it in full.

$$I_f = \frac{Q_n}{\tau_n} + \frac{dQ_n}{dt}$$

$$Q_n = I_f \tau_n \left[1 - \exp\left(-\frac{t}{\tau_n}\right)\right]$$

$$= 10^{-4} \frac{C}{cm^2} \left[1 - \exp\left(-\frac{t}{\tau_n}\right)\right]$$

(i) 63% of final value: $\left[1 - \exp\left(-\frac{t_2}{\tau_n}\right)\right] = 0.63$

$$\Delta t_2 = \tau_n = 10^{-6}\,s$$

$$t_{turn\text{-}on} = \Delta t_1 + \Delta t_2 = 1.13 \times 10^{-9}\,s + 10^{-6}\,s = 10^{-6}\,s$$

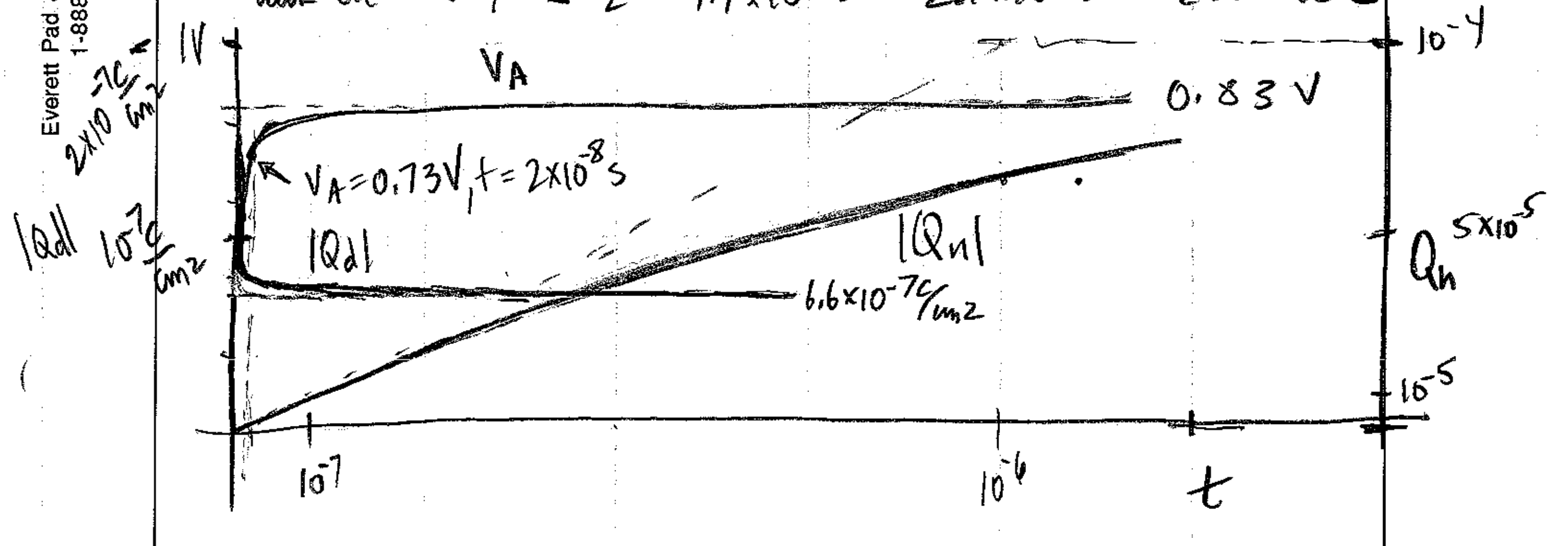
(ii) $V_a = 0.83 - 0.1 = 0.73\,V$ $\quad Q_n = 10^{-4} \frac{C}{cm^2} \exp\left(-\frac{0.1\,V}{0.025\,V}\right)$

$$= 2.1 \times 10^{-6}\ C/cm^2$$

$\left[1 - \exp\left(\frac{\Delta t_2}{\tau_n}\right)\right] = 2.1 \times 10^{-2}$ $\quad \Delta t_2 = 2.1 \times 10^{-2}\,\tau_n$

$$= 2.1 \times 10^{-8}\,s$$

$$t_{turn\text{-}on} = \Delta t_1 + \Delta t_2 = 1.1 \times 10^{-9}\,s + 2.1 \times 10^{-8}\,s = 2.2 \times 10^{-8}\,s$$



(d) Storage time

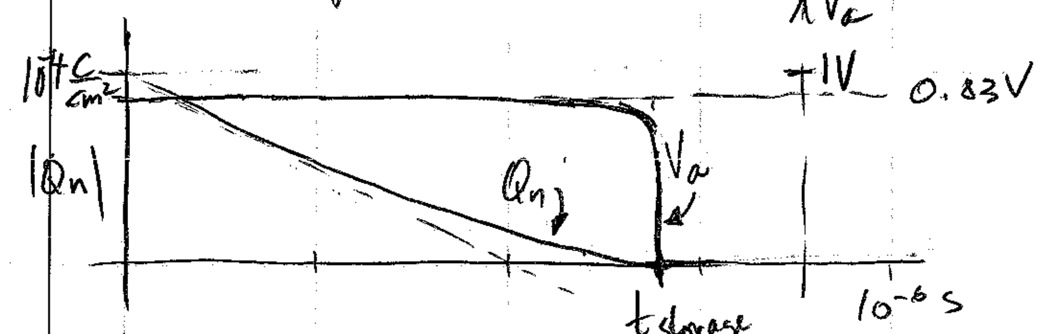
$$I_R = \frac{Q_n}{\tau_n} + \frac{dQ_n}{dt} = -100\,\frac{A}{cm^2}$$

$$Q_n(t=0) = I_f \tau_n = 10^{-4}\,\frac{C}{cm^2}$$

$$Q_n = A + B e^{-t/\tau_n} \qquad A + B = Q_n(t=0) = 10^{-4}\,\frac{C}{cm^2}$$

$$= 10^{-4}\frac{C}{cm^2}\left(2e^{-t/\tau_n} - 1\right) \qquad A = I_R \tau_n = -10^{-4}\frac{C}{cm^2}$$

$t_{storage}$ defined for $Q_n = 0$ $\quad 2e^{-t/\tau_n} = 1 \quad \underline{t_{storage} = 6.9\times10^{-7}\,s}$



(e) For short base, $\quad J_{np} = \frac{q n_i^2}{N_a}\left(\frac{D_n}{W_p}\right)\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]$

$$Q_n = \frac{1}{2} W_p \frac{q n_i^2}{N_a}\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]$$

$$= J_{np}\left(\frac{W_p^2}{2D_n}\right) = J_{np}\left(6\times10^{-11}\,s\right)$$

transit time: average time for minority carriers to cross neutral region, which is average lifetime due to fast recomb. at contact

$Q_n = 6\times10^{-9}\,\frac{C}{cm^2} \qquad V_a = 0.71\,V$

$Q_{deple}(0.71V) = 0.91\times10^{-7}\,C/cm^2$

ΔQ MUCH smaller, switching MUCH faster.