$\boxed{\text{CHAPTER 8}}$

8.1

(a) It is the time period (t_s) during which the observed current associated with the turn-off transient remains constant at a large negative value.—See Fig. 8.1(b). The excess minority carriers stored in the quasineutral region are being removed during this time period.

(b) With reference to the turn-off transient pictured in Fig. 8.1(b), $t_r = t_{rr} - t_s$, where t_{rr} is the total time for the reverse current to decay to 10% of its maximum magnitude and t_s is the storage delay time.

(c) $\boxed{\text{Yes}}$. This is precisely what happens during the t_s portion of the turn-off transient. Even though there is an excess of carriers at the edges of the depletion region making $\upsilon_A >$ 0, the external circuitry enables a reverse current flow that acts to eliminate the excess.

(d) A delay in switching from the on- to the off-state arises because a finite amount of time is required to remove the excess minority carriers stored in the quasineutral regions on the two sides of the junction.

(e) The excess carriers are removed by *recombination* and *reverse injection.*

(f) $\boxed{\text{True}}$. $\Delta p_n(x,t) > 0$ implies $\Delta p_n(x_n,t) > 0$, the necessary condition making $\upsilon_A > 0$.

(g) $\boxed{\text{False}}$. Referring to Eq. (8.2), if $i > 0$, the slope of a $p_n(x,t)$ versus x plot must be *negative* at $x = x_n$.

(h) The electrical response of the step-recovery diode is special in that the t_r portion of the transient is very short compared to the storage delay time. Physically, step recovery diodes are actually a P-I-N type structure with very abrupt junctions.

(i) $\boxed{\text{True}}$. Both the approximate expression (Eq. 8.8) and the more exacting expression (Eq. 8.9) for t_s vary only as the ratio of I_F and I_R. Thus, increasing both I_F and I_R by the same amount will have no effect.

(j) $\boxed{\text{True}}$. During turn-on recombination obviously dominates over generation because there is a carrier excess. Thus, the inevitable loss of carriers via recombination will indeed retard the build-up of stored carriers. (This fact is confirmed mathematically by Eq. 8.10.)

8.2

(a) $\boxed{\text{Reverse biased}}$. $\Delta p_n(x_n,t) = p_n(x_n,t) - p_{n0} < 0$. A carrier deficit at the edge of the depletion region indicates the junction is reverse biased.

(b) Invoking the law of the junction,

$$n(x_n)p(x_n) = N_D p_{n0}/2 = n_i^2/2 = n_i^2\, e^{q\upsilon_A/kT}$$

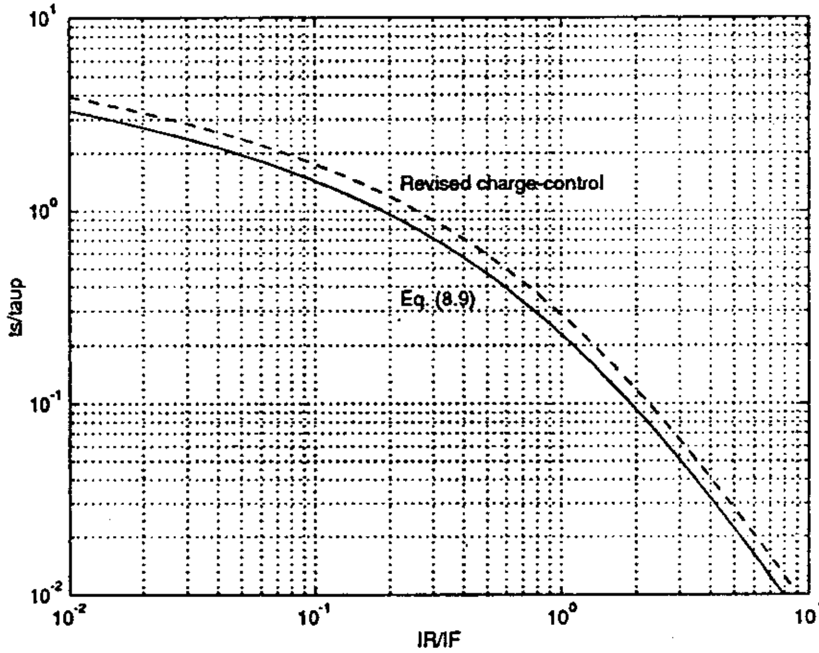
or

$$\upsilon_A = (kT/q)\ln(1/2) = -0.0259\ln 2 = -0.018\ \text{V}$$

(c) $\boxed{\text{Reverse}}$. Since $d\Delta p_n/dx|_{x=x_n} = dp_n/dx|_{x=x_n} > 0$, it follows from Eq. (8.2) that $i < 0$.

8.3

A comparison of the plot displayed below and Fig. 8.6 indicates the revised charge-control expression is indeed a significant improvement. The improvement is clearly greatest at the largest I_R/I_F values.

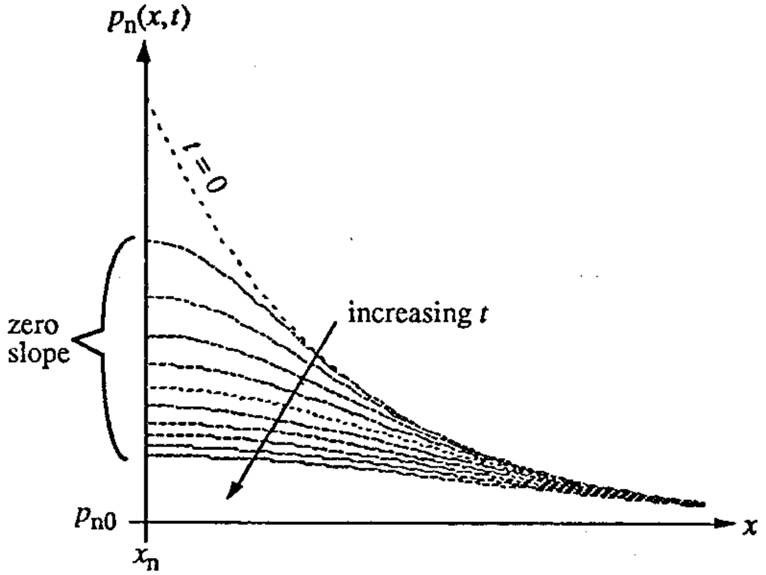


MATLAB program script...

```
% Comparison of the ts/taup versus IR/IF computed
% using Eq.(8.9) and the revised charge control expression

%Initialization
clear; close

%ts/taup calculation
Iratio=logspace(-2,1); %Iratio=IR/IF
 %Revised charge control expression
 x=1./Iratio;
 ts1=log((1+x).^2./(1+2.*x));
 %Equation (8.9)
 ts2=erfinv(1./(1+Iratio)).^2;

%Plotting results
loglog(Iratio,ts1,'--g')
axis([1.0e-2,10,1.0e-2,10]); grid
hold on
loglog(Iratio,ts2)
xlabel('IR/IF'); ylabel('ts/taup')
text(0.22,1.4,'Revised charge-control');
text(0.22,0.35,'Eq. (8.9)')
hold off
```

8.4

(a) Because the diode is open circuited, $i = 0$. Thus, based on Eq. (8.2), the slope of all the $p_n(x,t)$ versus x curves evaluated at $x = x_n$ should be zero.



(b) With $i = 0$, the general equation for the stored hole charge reduces to

$$\frac{dQ_P}{dt} = -\frac{Q_P}{\tau_p}$$

The general solution is

$$Q_P(t) = Q_P(0^+)\, e^{-t/\tau_p}$$

where paralleling the analysis in the text

$$Q_P(0^+) = I_F \tau_p$$

Thus

$$Q_P(t) = I_F \tau_p\, e^{-t/\tau_p}$$

(c) If the charge is assumed to decay quasistatically, then, referring to Eq. (8.15),

$$Q_P(t) = I_0\tau_p\left(e^{qv_A/kT} - 1\right) \cong I_0\tau_p\, e^{qv_A/kT}$$

Equating the part (b) and (c) expressions for $Q_P(t)$ gives

$$I_F\tau_p\, e^{-t/\tau_p} = I_0\tau_p\, e^{qv_A/kT}$$

or

$$e^{qv_A/kT} = (I_F/I_0)\, e^{-t/\tau_p}$$

But from the statement of the problem

$$I_F/I_0 \cong e^{qV_{ON}/kT}$$

Therefore

$$e^{qv_A/kT} = e^{qV_{ON}/kT}\, e^{-t/\tau_p}$$

or

$$\boxed{v_A(t) = V_{ON} - \frac{kT}{q}\frac{t}{\tau_p}}$$

(d) The part (c) result suggests a very simple way of determining τ_p (known as the Open-Circuit Decay Method). After forward biasing the diode, one open-circuits the device and monitors the voltage drop across the diode as a function of time. Provided the decay follows the ideal form, τ_p is readily determined from the slope of the data.

8.5

Since under steady state conditions

$$I_F = I_0\left(e^{qV_{ON}/kT} - 1\right) \cong I_0\, e^{qV_{ON}/kT}$$

$$V_{ON} \cong \frac{kT}{q}\ln\left(\frac{I_F}{I_0}\right) = 0.0259\ln\left(\frac{10^{-3}}{10^{-15}}\right) = 0.716\text{ V}$$

Next, solving Eq. (8.16) for t, one obtains in general

$$t = -\tau_p \ln\left[1 - (I_0/I_F)(e^{qv_A/kT} - 1)\right] \cong -\tau_p \ln\left[1 - e^{qv_A/kT}/e^{qV_{ON}/kT}\right]$$

or

$$t = -\tau_p \ln\left[1 - e^{q(v_A - V_{ON})/kT}\right]$$

Corresponding to $v_A = 0.9V_{ON}$,

$$t_{90\%} = -(10^{-6})\ln\left[1 - e^{-(0.1)(0.716)/(0.0259)}\right] = \mathbf{65.1\ nsec}$$

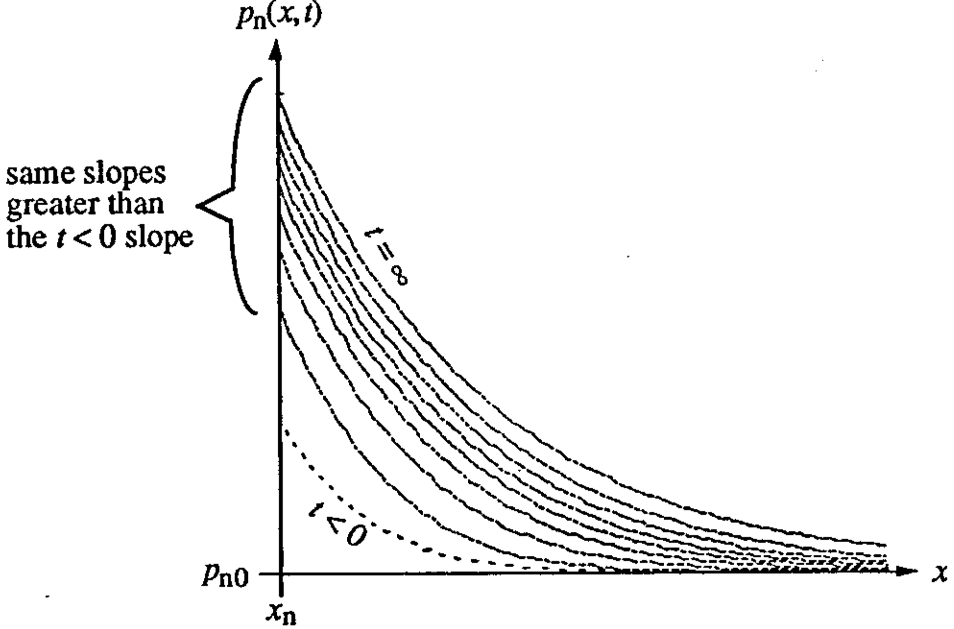
To reach $v_A = 0.95V_{ON}$,

$$t_{95\%} = -(10^{-6})\ln\left[1 - e^{-(0.05)(0.716)/(0.0259)}\right] = \mathbf{289\ nsec}$$

Note that the 90%–95% portion of the transient takes much longer than the 0–90% portion of the transient. this property of the turn-on transient was noted at the end of Section 8.2.

8.6

(a)



(b) Here for $t > 0$,

$$\frac{dQ_P}{dt} = I_{F2} - \frac{Q_P}{\tau_p}$$

$$\int_{Q_P(0^+)}^{Q_P(t)} \frac{dQ_P}{I_{F2} - Q_P/\tau_p} = t$$

$$t = -\tau_p \ln\left(I_{F2} - \frac{Q_P}{\tau_p}\right)\Bigg|_{Q_P(0^+)=I_{F1}\tau_p}^{Q_P(t)} = -\tau_p \ln\left(\frac{I_{F2} - Q_P/\tau_p}{I_{F2} - I_{F1}}\right)$$

Thus

$$I_{F2} - \frac{Q_P}{\tau_p} = (I_{F2} - I_{F1})\, e^{-t/\tau_p}$$

and

$$Q_P(t) = I_{F2}\tau_p - (I_{F2} - I_{F1})\tau_p\, e^{-t/\tau_p}$$

Invoking the quasistatic assumption (Eq. 8.15), we can also write

$$Q_P(t) = I_0\tau_p\,(e^{qv_A/kT} - 1)$$

Therefore, equating the $Q_P(t)$ relationships,

$$e^{qv_A/kT} - 1 = \frac{I_{F2}}{I_0} - \frac{(I_{F2}-I_{F1})}{I_0}\,e^{-t/\tau_p}$$

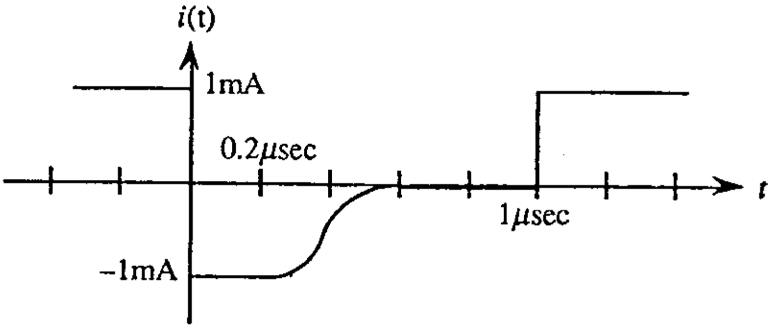
or

$$\boxed{v_A(t) = \frac{kT}{q}\ln\left[1 + \frac{I_{F2}}{I_0} - \frac{(I_{F2}-I_{F1})}{I_0}\,e^{-t/\tau_p}\right]}$$

Note as a check that the foregoing expression reduces to Eq. (8.16) if $I_{F1} \to 0$ and $I_{F2} \to I_F$.

8.7

(a) We note using Fig. 8.6 that $t_s/\tau_p \cong 0.22$ when $I_R/I_F = 1$. Thus $t_s = 0.22\mu$sec, or the diode becomes reverse biased before it is pulsed back to the ON condition. Based on the above information, we conclude



(b) Since pulsing is occurring from reverse bias, we can assume by analogy with the text turn-on development that the pulsing effectively occurs from $i = 0$ with $Q_P(1\mu\text{sec}) = 0$. The situation here is completely analogous—all but identical—to the turn-on situation considered in Section 8.2, except t is replaced by $t - 1\mu$sec. Consequently, the required expression is just Eq. (8.16) with the t in $\exp(-t/\tau_p)$ replaced by $t - 1\mu$sec

8.8

(a) In the CPG program

$$\text{yon}(1) = \Delta p_n(0,t)/\Delta p_{n\max}$$

Thus

$$\text{yon}(1) = \frac{e^{qv_A/kT} - 1}{e^{qV_{ON}/kT} - 1}$$

and

$$\frac{v_A}{V_{ON}} = \left(\frac{kT/q}{V_{ON}}\right)\ln\left[1 + \text{yon}(1)\left(e^{qV_{ON}/kT} - 1\right)\right]$$

The desired v_A/V_{ON} values can be obtained by inserting the following five lines into the last segment of the CPG program.

Place before `for i=1:j,`

```
VON=0.5;
vrel=[];  %vrel=vA/VON
kT=0.0259;
```

Place after `yon=(A-B)/2;`

```
vj=(kT/VON)*log(1+yon(1)*(exp(VON/kT)-1));
vrel=[vrel,vj];
```

After the program is run, `vrel` is read out from the Command window.

(b) Appropriately modifying Eq. (8.16),

$$\frac{v_A}{V_{ON}} = \left(\frac{kT/q}{V_{ON}}\right)\ln\left[1 + \left(1 - e^{-t/\tau_p}\right)\left(e^{qV_{ON}/kT} - 1\right)\right]$$

The computational results based on the above relationship are recorded along with the exact results in the table below. Note in all cases that v_A/V_{ON}(exact) > v_A/V_{ON}(quasistatic).

t/τ_p	exact v_A/V_{ON}	quasistatic v_A/V_{ON}	t/τ_p	exact v_A/V_{ON}	quasistatic v_A/V_{ON}
0.1	0.9449	0.8782	1.1	0.9923	0.9790
0.2	0.9612	0.9115	1.2	0.9933	0.9814
0.3	0.9701	0.9301	1.3	0.9941	0.9835
0.4	0.9760	0.9425	1.4	0.9949	0.9853
0.5	0.9802	0.9517	1.5	0.9955	0.9869
0.6	0.9835	0.9588	1.6	0.9960	0.9883
0.7	0.9860	0.9644	1.7	0.9965	0.9896
0.8	0.9881	0.9691	1.8	0.9969	0.9906
0.9	0.9897	0.9730	1.9	0.9973	0.9916
1.0	0.9911	0.9762	2.0	0.9976	0.9925