Name *Master*

ECE 321 Electronics I
Test #1 Winter 2008

Time allowed: 2 hours (including the first 5 minutes for exam review.... no writing.) Calculator permitted.

Closed book; one-side 8½x11in "crib-sheet" permitted; (turn in the crib sheet with the test paper.)

Answer questions on these pages. If you need more space, use the back of the page.

There are eleven questions at 10 points each. Answer any ten or all eleven. Maximum score 100 points.

In all your answers, <u>state all approximations</u> clearly, and <u>explain each step</u> succinctly.

1 [2.19] InP is composed of equal atoms of In and P in a lattice similar to that of Si. If a Ge atom replaces an In atom in the lattice, Will it act as an acceptor or donor? Explain.

In is group III, Ge is group IV
∴ Ge will provide one electron more than needed to replace the In bonding electrons. ∴ Donor

2. [2.47] A 5μm-long block of p-type Si has an acceptor doping profile given by:
$N_A(x) = 10^{14} + 10^{18}\exp(-10^{14}x)$ where x is in cm.

(a) Show that the material must have a non-zero internal electric field, E.
(b) Find E at (i) x=0 and (ii) x=5μm.

Total hole current density $J_p = q\mu_p p E - qD_p \frac{dp}{dx}$
$= 0$ at equilibrium

$\therefore q\mu_p p E = q D_p \frac{dp}{dx}$

and equilibrium field E is established

$E = \frac{D_p}{\mu_p}\frac{1}{p}\frac{dp}{dx} = \frac{kT}{q}\frac{1}{p}\frac{dp}{dx}$ using Einstein's equation

For $p \approx N_A$ $\frac{dp}{dx} = \frac{dN_A}{dx} = 10^{18}(\exp -10^{14}x)(-10^{14})$
$= -10^{32}\exp -10^{14}x$

so $E = \frac{-0.025 \times 10^{32}\exp -10^{14}x}{10^{14}+10^{18}\exp -10^{14}x} = -\frac{1}{40(10^{-18}\exp -10^{14}x + 10^{-32})} = \frac{2.5\times 10^{16}}{1+10^{+4}\exp -10^{14}x}$

E(0) ≈ -2.5×10^{12} V/cm   E(5μm) ≈ -2.5×10^{16} V/cm

Note: There was a typo error on this problem — should have been $\exp -10^4x$
Doesn't affect the method, but the results are not practical values.

3. Given the diode equation $i_D = I_S[\exp(v_D/nV_T) - 1)$, with reverse saturation current I_S, derive an expression for the temperature coefficient of v_D in terms of i_D, V_T, n, energy band-gap E_G, & temperature T.

$$i_D = I_S\left(\exp\frac{v_D}{nV_T} - 1\right) \approx I_S \exp\frac{v_D}{nV_T} \quad \text{for } v_D \gtrsim 4nV_T \ (\sim 0.1v)$$

$$\text{so } v_D = nV_T \ln\frac{i_D}{I_S}$$

For constant i_D (defined by external circuit)

$$\frac{dv_D}{dT} = nV_T \cdot \frac{I_S}{i_D} \cdot \frac{i_D}{I_S^2}(-1)\frac{dI_S}{dT} + n\frac{dV_T}{dT}\ln\frac{i_D}{I_S}$$

$$= -nV_T\frac{1}{I_S}\frac{dI_S}{dT} + \frac{v_D}{V_T}\frac{dV_T}{dT}$$

$$V_T = \frac{kT}{q} \quad \text{so} \quad \frac{dV_T}{dT} = \frac{k}{q}$$

$I_S \propto n_i^2$ since I_S due to minority carriers

$$= BT^3\exp - E_g/kT \quad \text{where } B = \text{constant}$$

$$\therefore \frac{dI_S}{dT} = (BT^3\exp - E_g/kT)\left(-\frac{E_g}{k}\right)\left(-\frac{1}{T^2}\right) + 3BT^2\exp - E_g/kT$$

$$= I_S \cdot \frac{E_g}{kT^2} + \frac{3}{T}I_S$$

$$\text{So } \frac{dv_D}{dT} = \frac{v_D}{V_T}\frac{k}{q} - nV_T\left(\frac{3}{T} + \frac{E_g}{kT^2}\right)$$

$$= \frac{v_D - 3nV_T - nE_g/q}{T}$$

$$\frac{dv_D}{dT} = \frac{v_D - 3nV_T - nE_g/q}{T}$$

4. [3.39] A diode has $w_{d0} = 1\mu m$ and $\varphi_j = 0.6V$. If the diode breaks down when the internal field exceeds 300kV/cm, what is the diode breakdown voltage?

$$E_{max} = \frac{2(\phi_j + V_R)}{W_d} = \frac{2(\phi_j + V_R)}{W_{do}\sqrt{1 + \frac{V_R}{\phi_j}}} = \frac{2\phi_j}{W_{do}}\sqrt{1 + \frac{V_R}{\phi_j}}$$

$$\therefore V_R\Big)_{breakdown} = \phi_j\left[\left(\frac{E_{max}W_{do}}{2\phi_j}\right)^2 - 1\right] = 0.6v\left[\left(\frac{300\times10^3 \text{ v/cm} \times 10^{-4}\text{ cm}}{2\times 0.6v}\right)^2 - 1\right]$$

$$= 0.6 \times 624 \text{ v} = 374.4 \text{ v}$$

V_{BR} = 374.4 v

5. [3.46/47] A pn junction diode with $N_A=10^{19}/cm^3$ on the p-side and $N_D=10^{17}/cm^3$ on the n-side, has cross-sectional area $10^4 \mu m^2$.

(a) What is the junction capacitance at a reverse bias of 5V?

(b) What is the diffusion capacitance at a forward bias current of 100mA for a 10ns diode transit time, and how much charge is stored in the diode?

(a) $C_j = \dfrac{C_{jo}}{\sqrt{1 + V_R/\phi_j}}$, $C_{jo} = \dfrac{\varepsilon_{Si} A}{w_{do}}$, $w_{do} = \sqrt{\dfrac{2\varepsilon_s}{q}\left(\dfrac{1}{N_A}+\dfrac{1}{N_D}\right)\phi_j}$, $\phi_j = V_T \ln \dfrac{N_A N_D}{n_i^2}$

$\phi_j = 0.025 \ln \dfrac{10^{19} \times 10^{17}}{10^{20}} = 0.9786v$, $w_{do} = \left[\dfrac{2 \times 11.7 \times 8.85 \times 10^{-14}}{1.6 \times 10^{-19}}(10^{-19} + 10^{-17})\, 0.9786\right]^{1/2}$

assuming $V_T \approx .025v$

$n_i^2 \approx 10^{20}/cm^6$

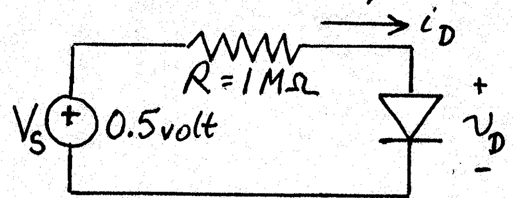
$= 11.3 \times 10^{-6}$ cm

$C_{jo} = \dfrac{(11.7 \times 8.85 \times 10^{-14}) \times (10^4 \times 10^{-8})}{11.3 \times 10^{-6}} = 9.16\,pF$, $C_j = \dfrac{9.16\,pF}{(1 + 5/0.9786)^{1/2}} = 3.71\,pF$

(b) $C_D = \dfrac{I_D \tau_T}{V_T} = \dfrac{.1 \times 10^{-8}}{.025} = 40 \times 10^{-9} F = 40nF$, $Q = I_D \tau_T = 0.1 \times 10^{-8} = 1nC$

(a) C_j = 3.71 pF (b) Q = 1nC C_D = 0.04 μF

6. Find the diode operating point (i_D, v_D) by iteration, for a diode with $I_S=10^{-12}$A and n=2.



$0.5 = 10^6\, 10^{-12}[\exp(80 V_D) - 1] + V_D$

$\therefore f = 0.5 - 10^{-6}(\exp(80V_D) - 1) - V_D$

$f' = -8 \times 10^{-5} \exp(80V_D) - 1$

Assuming $\dfrac{V_D}{nV_T} = \dfrac{V_D}{2 \cdot \frac{1}{40}} = 80V_D$

Note $V_D)_{n+1} = V_D)_n - \dfrac{f_n}{f'_n}$

First guess $V_D < 0.5v$ say $V_D)_1 = 0.4v$

	V_D	f_n	f'_n	f_n/f'_n
1.	0.4v	-7.9×10^7	-6.3×10^9	1.25×10^{-2}
2.	0.3875	-2.9×10^7	-2.3×10^9	1.26×10^{-2}
3.	0.3749	-1.06×10^7	-8.48×10^8	1.25×10^{-2}
4	0.3624	-3.9×10^6	-3.12×10^8	1.25×10^{-2}

Taking $V_D = 0.15924v$ $I_D = 10^{-12}(\exp(80V_D) - 1) = 0.34085\,\mu A$

i_D = 0.341 μA v_D = 0.159 v

Note: $0.34085\mu A \times 1M\Omega$
$= 0.34085v$

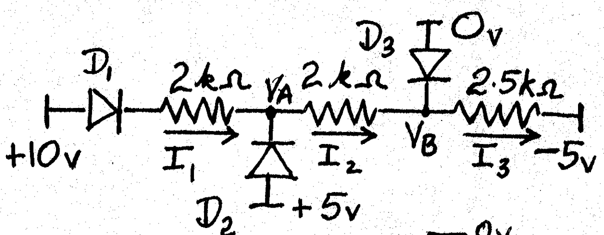
$0.34085 + 0.15924v$
$= 0.50009v$ indicating degree of accuracy

$$f_n = 0.5 - V_D - 10^{-6}(\exp(80V_D) - 1)$$
$$f_n' = -8\times10^{-5}\exp(80V_D) - 1$$

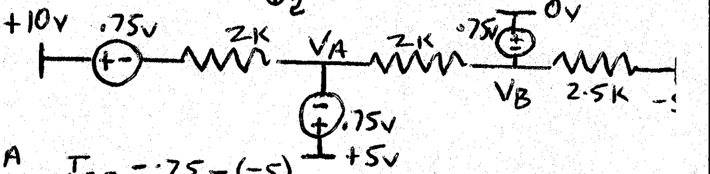
Q6 iteration table continued

	V_D	f_n	f_n'	f_n/f_n'
5	0.3499	-1.435×10^{6}	-1.15×10^{8}	1.25×10^{-2}
6	0.3374	-5.3×10^{5}	-4.2×10^{7}	1.26×10^{-2}
7	0.3248	-1.93×10^{5}	-1.54×10^{7}	1.25×10^{-2}
8	0.3123	-7.1×10^{4}	-5.7×10^{6}	1.25×10^{-2}
9	0.2998	-2.6×10^{4}	-2.1×10^{6}	1.24×10^{-2}
10	0.2874	-9.7×10^{3}	-7.7×10^{5}	1.26×10^{-2}
11	0.2748	-3.53×10^{3}	-2.82×10^{5}	1.25×10^{-2}
12	0.2623	-1.3×10^{3}	-1.04×10^{5}	1.25×10^{-2}
13	0.2498	-4.8×10^{2}	-3.8×10^{4}	1.26×10^{-2}
14	0.2372	-174	-1.4×10^{4}	1.24×10^{-2}
15	0.2248	-64.37	-5.2×10^{3}	1.24×10^{-2}
16	0.2124	-24.25	-1.9×10^{3}	1.28×10^{-2}
17	0.1996	-8.907	-688.5	1.29×10^{-2}
18	0.1867	-3.38	-246.3	.0137
19	0.1730	-0.6978	-82.98	.0084
20	0.1646	$+.28305$	-42.86	$-.0066$
21	0.1712	$-.55495$	-72	$+.0077$
22	0.1635	$-.14276$	-39.34	$+.0036$
23	0.1599	$-.0192$	-29.75	$+.00065$
24	0.15925	$-.00037$	-28.3	$+.000013$
25	0.15924	ie. close enough		

7. (a) Determine which diodes are "on" and which are "off" in the circuit shown, if V_{on} for a conducting diode is 0.75V.
(b) Calculate the voltages V_A, V_B, and currents I_1, I_2, I_3.
(c) Verify your answer, and comment on your result.



1. Assume all diodes ON →

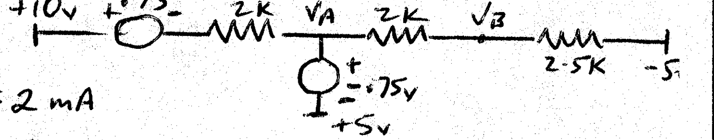


Hence $V_A = 4.25v$, $V_B = -0.75v$

$I_1 = \frac{9.25-4.25}{2} mA = 2.5mA$ $\quad I_2 = \frac{4.25+.75}{2} mA = 2.5mA$ $\quad I_3 = \frac{-.75-(-5)}{2.5} mA = 1.7mA$

Note $I_3 < I_2$, so D_3 cannot be ON, $I_1 = I_2$ ∴ D_2 just on the ON/OFF edge.

2. Assume D_1, D_2 ON D_3 OFF

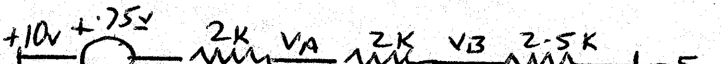


∴ $V_A = 4.25v$ $\quad I_1 = 2.5mA$

$I_2 = I_3 = \frac{4.25-(-5)}{4.5K} \approx 2 mA$

∴ D_2 cannot be ON, Also $V_B = -5 + \frac{2.5}{4.5} 9.25 = 0.14v$ i.e. D_1 off

3. Assume D_1 ON, D_2, D_3 OFF



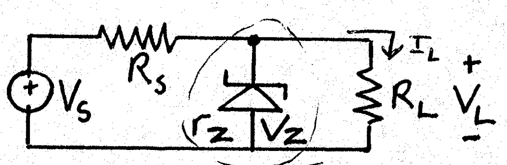
$I_1 = I_2 = I_3 = (14.25/6.5) mA = 2.19mA$ $\quad$ ∴ $V_A = 9.25 - 2(2.19) = 4.87v$ & D_2 off & $V_B = -5 + 2.5(2.19) = 0.475$ & D_3 off

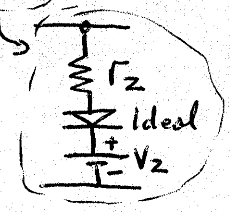
Note: D2 forward biased < Von

D_1 ON $\quad D_2$ OFF $\quad D_3$ OFF

I_1 = 2.19mA $\quad I_2$ = 2.19mA $\quad I_3$ = 2.19mA $\quad V_A$ = 4.87v $\quad V_B$ = 0.475v

8. For the Zener regulator circuit shown,
(a) Express V_L in terms of the circuit parameters, and hence
(b) Identify expressions for the line and load regulation.





At the node: $\frac{V_S - V_L}{R_S} = \frac{V_L - V_Z}{r_Z} + \frac{V_L}{R_L}$

Rearrange: $V_L = \frac{V_S/R_S + V_Z/r_Z}{1/R_S + 1/r_Z + 1/R_L} = \frac{V_S R_L r_Z + V_Z R_L R_S}{R_L R_S + R_S r_Z + r_Z R_L}$

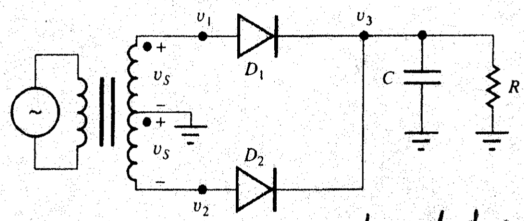
For load regulation, $\frac{dV_L}{dI_L}$, need I_L as the variable parameter, rather than $R_L = \frac{V_L}{I_L}$

∴ $\frac{V_S - V_L}{R_S} = \frac{V_L - V_Z}{r_Z} + I_L$ $\quad V_L = \frac{V_S/R_S + V_Z/r_Z - I_L}{1/R_S + 1/r_Z} = V_S \frac{r_Z}{R_S + r_Z} + V_Z \frac{R_S}{R_S + r_Z} - I_L \frac{R_S r_Z}{R_S + r_Z}$

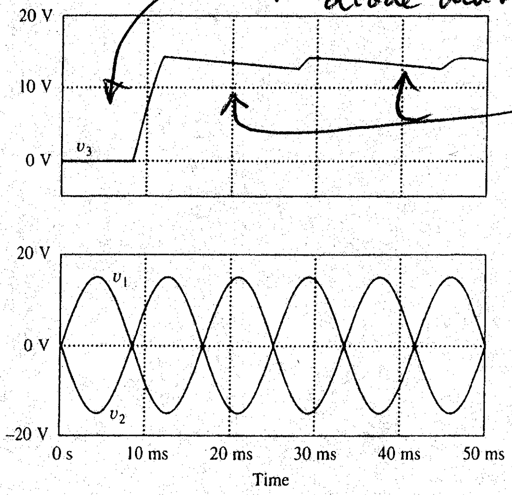
(a) V_L = either of equations shown

(b) Line regulation = $\frac{dV_L}{dV_S} = \frac{r_Z}{R_S + r_Z}$ $\quad$ Load regulation = $\frac{dV_L}{dI_L} = -(r_Z // R_S)$

9. [3.105] The full-wave rectifier circuit was designed to have a maximum ripple of approximately 1V, but is not operating properly. The measured waveforms at the 3 nodes identified are shown. What is wrong with the circuit?



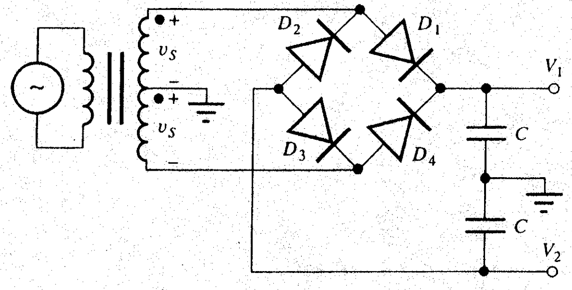
Capacitor did not charge during first 1/2 cycle when diode did not conduct $v_1 > 0$.



Capacitor does not re-charge during the positive half cycles when $v_1 > 0$

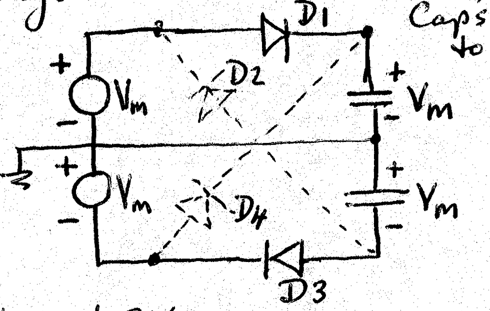
∴ D_1 is open circuit (or connections to D_1 bad)

10.[3.109] What are the dc output voltages V_1 and V_2 for this circuit with v_S=35sin377t and C=10,000μF?



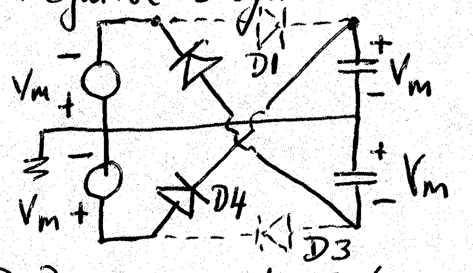
Assume ideal diodes.
Consider each ½ cycle in turn, and re-draw showing the sources at maximum amplitudes $\pm V_m$
Note: No RC ripple — peak detectors

Positive ½ cycle



Caps charge to V_m

Negative ½ cycle



D_2, D_4 rev biased $2V_m$

D_1, D_3 rev biased $2V_m$

V_1 = ___+35 V___

V_2 = ___−35 V___

11. [3.107] A3000V, 1A dc power supply is to be designed with a ripple voltage $\leq 1\%$ at 60Hz input, using a full-wave bridge rectification circuit with capacitor filter.

(a) What is the size of the filter capacitor C?
(b) What is the minimum PIV rating for the diodes?
(c) What is the rms value of the transformer voltage?
(d) What is the peak value of the repetitive current in the diode?
(e) What is the surge current at $t=0^+$?

(a) $V_r \approx V_m \frac{T/2}{RC}$ assuming: ripple small (linear approx^n)
conduction angle small
ripple small (DC voltage ≈ peak voltage)

$\therefore C = \frac{V_m/R}{V_r} \cdot \frac{T}{2} = \frac{I_m}{V_r} \frac{T}{2}$

$= \frac{1A}{0.01 \times 3000} \frac{1}{120} = 277.8\mu F$

(b) Bridge $\longrightarrow$ $PIV = V_m = 3000V$

(c) $V_{RMS} = \frac{V_m}{\sqrt{2}} = \frac{3000}{\sqrt{2}} = 2121.3v$

(d) $I_p = I_{dc} \frac{T}{\Delta T}$ where $\Delta T = \frac{1}{\omega}\sqrt{\frac{2V_r}{V_p}}$ $\therefore I_p = I_{dc} T \omega \sqrt{V_p/2V_r}$

$= 1A \; 2\pi \; (100/2)^{1/2}$

(since $2\pi f T = 2\pi$ and $V_p/V_r = 100$)

$= 44.42 A$

(e) $I_{surge} = \omega C V_M = (2\pi 60) 277.8 \times 10^{-6} \times 3000 = 314.2 A$

(a) C 277.8μF (b)PIV = 3000V (c) V_{rms} = 2121.3v

(d) I_P = 44.42 A I_{SC} = 314.2A