Physics 111A Lab 3

Pre-Lab Questions:

1) $I_D(V_D) = I_s\left[\exp\left(\frac{eV_D}{nkT}\right) - 1\right] = I_s \exp\left(\frac{eV_D}{nkT}\right)\left[1 - \exp\left(-\frac{eV_D}{nkT}\right)\right]$

$V_D > 0.1\,V, \quad \frac{kT}{e} \approx 25.7\,mV, \; n \approx 2$

$$I_D(V_D) = I_s \exp\left(\frac{V_D}{2(25.7mV)}\right)\left[1 - \exp\left(-\frac{V_D}{2(25.7mV)}\right)\right]$$

$$= I_s \exp\left(\frac{V_D}{51.4mV}\right)\left[1 - \exp\left(-\frac{V_D}{51.4mV}\right)\right], \quad \exp\left(-\frac{V_D}{51.4mV}\right) < \exp\left(-\frac{0.1V}{51.4mV}\right) = 0.143$$

so for $V_D > 0.1V$, $\exp\left(-\frac{V_D}{51.4mV}\right) \approx 0$

so then, $I_D(V_D) = I_s \exp\left(\frac{eV_D}{nkT}\right)$

2) Zener diodes are special diodes that have a low and precise reverse breakdown voltage. Zener diodes are typically used in reverse bias and can act as voltage regulators.

3) $n = 2$, room temp., $\Delta T \approx 9°C$, $T_2 - T_1 = \Delta T$, $T_1 = 20°C$, $E_G = 1.14\,eV$, $k = 1.38\times10^{-23}\,J/K$

$$I_s \propto T^3 \exp\left(-\frac{E_G}{nkT}\right)$$

$$\frac{I_{s2}}{I_{s1}} = \frac{T_2^3 \exp\left(-\frac{E_G}{nkT_2}\right)}{T_1^3 \exp\left(-\frac{E_G}{nkT_1}\right)} = \frac{T_2^3}{T_1^3}\exp\left(-\frac{E_G}{nkT_2} + \frac{E_G}{nkT_1}\right) = \frac{T_2^3}{T_1^3}\exp\left(\frac{E_G}{nkT_1T_2}(T_2 - T_1)\right) = \left(\frac{T_2}{T_1}\right)^3 \exp\left(\frac{E_G}{nkT_1T_2}\Delta T\right)$$

$$= \left(\frac{\Delta T}{T_1} + 1\right)^3 \exp\left(\frac{E_G}{nkT_1T_2}\Delta T\right) = \left(\frac{9K}{293.15K} + 1\right)^3 \exp\left(\frac{1.14eV \times 1.6\times10^{-19}\frac{J}{eV}}{2(1.38\times10^{-23}\frac{J}{K})(293K)(302K)}(9K)\right)$$

$$= 2.07919 \approx 2$$

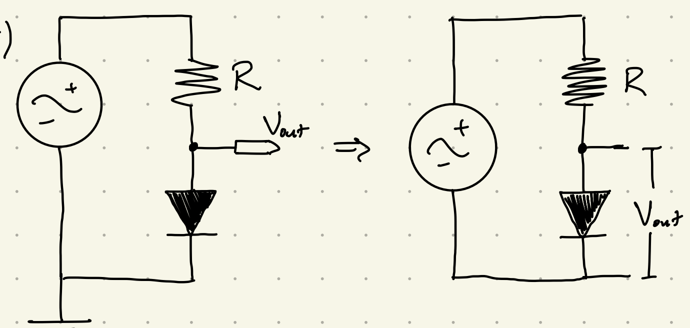
4) $n = 2$, $\Delta V \approx 35\,mV$, $e = 1.6\times10^{-19}\,C$, $k = 1.38\times10^{-23}\,\frac{J}{K}$, $T = 293.15K$

$$I_D(V_D) = I_s \exp\left(\frac{eV_D}{nkT}\right)$$

$$\frac{I_{D2}}{I_{D1}} = \frac{I_s \exp\left(\frac{eV_{D2}}{nkT}\right)}{I_s \exp\left(\frac{eV_{D1}}{nkT}\right)} = \exp\left(\frac{eV_{D2}}{nkT} - \frac{eV_{D2}}{nkT}\right) = \exp\left(\frac{e}{nkT}\Delta V\right) = \exp\left(\frac{1.6\times10^{-19}C}{2(1.38\times10^{-23})(293.15K)}(35mV)\right)$$

$$= 1.99797 \approx 2$$

5)



$$V_{out} = \frac{nkT}{e} = nV_T \quad \text{where } V_T = \frac{kT}{e}$$

$$V_{in} = V_{tot} = V_R + V_D = IR + \frac{nkT}{e} = IR + nV_T$$

$$G = \frac{V_{out}}{V_{in}} = \frac{nV_T}{IR + nV_T}$$

6) $\frac{eV_D - E_G}{T} \simeq$ constant

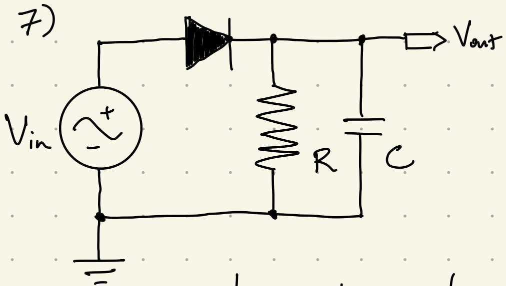
$$\frac{eV_1 - E_G}{T_1} = \frac{eV_2 - E_G}{T_2}$$

$$\frac{eV_1}{T_1} - \frac{eV_2}{T_2} = \frac{E_G}{T_1} - \frac{E_G}{T_2}$$

$$\frac{e(V_1T_2 - V_2T_1)}{T_1T_2} = \frac{E_G(T_2 - T_1)}{T_1T_2}$$

$$E_G = \frac{e(V_1T_2 - V_2T_1)}{T_2 - T_1}$$

7)



$$V = V_0 e^{-t/\tau}$$

$$\Delta V = V_0\left(1 - e^{-\frac{1}{f\tau}}\right)$$

$$\frac{\Delta V}{V_0} = \frac{V_0\left(1 - e^{-\frac{1}{f\tau}}\right)}{V_0} = 1 - e^{-1/f\tau}$$

$$1 - e^{-\frac{1}{f\tau}} = \frac{1}{f\tau} - \frac{1}{2(f\tau)^2} + \frac{1}{6(f\tau)^3} + \cdots$$

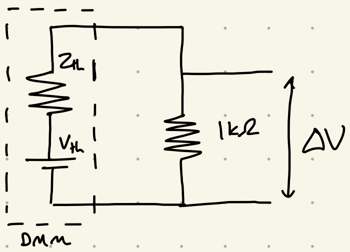
since $f \gg \frac{1}{RC} = \frac{1}{\tau} \Rightarrow f\tau \gg 1$

so then $1 - e^{-\frac{1}{f\tau}} \approx \frac{1}{f\tau}$

$$\frac{\Delta V}{V_0} \approx \frac{1}{f\tau}$$

Lab Exercises:

Problem R3.1



a) $V_{th} = 2.994\ V$

$\Delta V = 882\ mV$

$$\Delta V = \frac{R}{R + Z_{th}} V_{th} \Rightarrow \frac{\Delta V}{V_{th}}(R + Z_{th}) = R \Rightarrow Z_{th} = \frac{V_{th}}{\Delta V}\left(1 - \frac{\Delta V}{V_{th}}\right) R = \frac{2.994}{0.882}\left(1 - \frac{0.882}{2.994}\right)(1000)$$

$$= 2394.6\ \Omega \approx 2.4\ k\Omega$$

$$\Delta V = \frac{(2\ k\Omega)}{(2\ k\Omega) + (2.4\ k\Omega)}(2.994\ V) = 1.36\ V$$

actual ΔV for $R = 2k\Omega$ was recorded to be $\approx 1.368\ V$

b) DMM Readings:

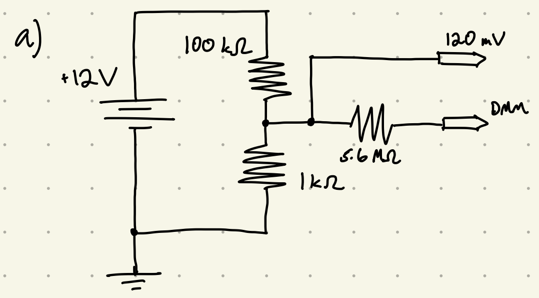
forward-bias: $V = 0.610\ V$

reverse-bias: $V = 1$ (registered as an overload)

In reverse-bias the diode doesn't let current through so it can be said to have a very high impedence and therefore high voltage drop reading causing the DMM to read it as an overload.

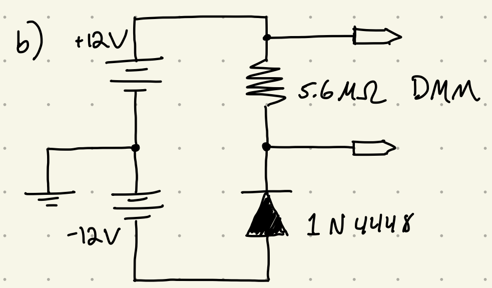
Problem R3.2

a)



without 5.6 MΩ resistor: V = 119.9 mV
with 5.6 MΩ resistor: V = 77.0 mV

b)



V = 32.1 mV

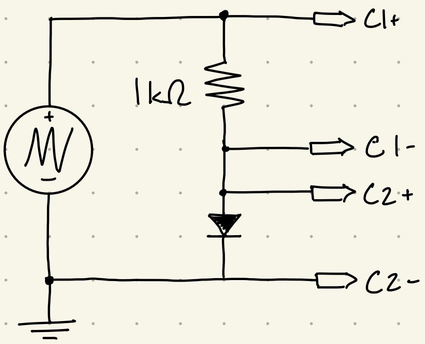
The voltage accross the resistor was higher after warming up the diode for a short-time.

V = -149 mV with the -3.3 and -12V reverse voltages

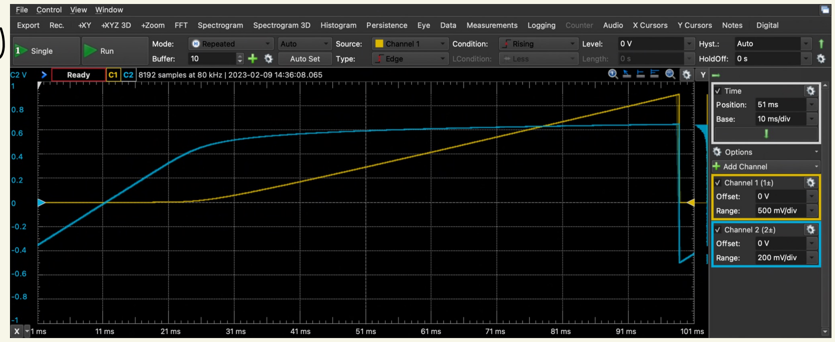
Increasing the diodes temperature makes it less effective at stopping current in reverse bias, causing the total current in the circuit to increase, and in turn increasing the voltage drop accross the resistor.

The leakage current is not dependent on reverse voltage.

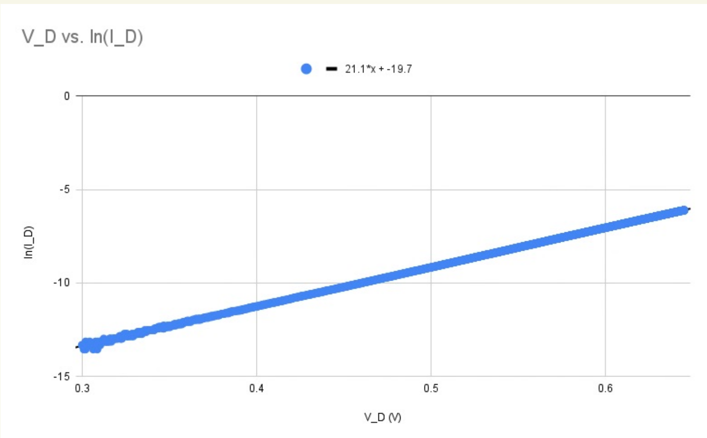
Problem R3.3



a)



b)



slope: $21.1 = \frac{1}{nV_T}$, $V_T = \frac{kT}{e} \Rightarrow 21.1 = \frac{e}{nkT} \Rightarrow n = \frac{e}{21.1\,kT} = \frac{1.6\times10^{-19}}{21.1\,(1.38\times10^{-23})(293)} = 1.88$

intercept: $-19.7 = \ln(I_s) \Rightarrow I_s = e^{-19.7} = 2.78$ nA

c) $I_D(V_D) = I_s \exp\left(\frac{eV_D}{nkT}\right)$, $n = 1.88$, $I_s = 2.78$ nA

$I_D(V_D) = (2.78\text{ nA}) \exp\left(\frac{eV_D}{1.88\,kT}\right)$

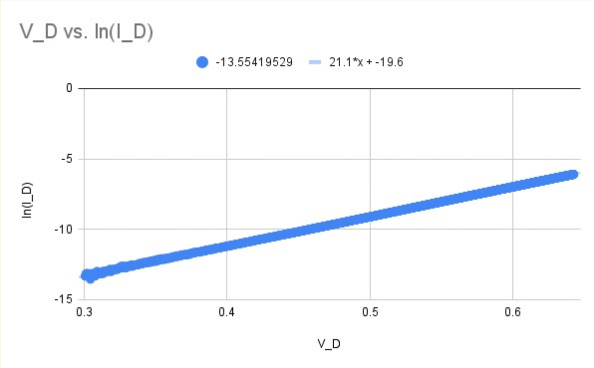
$V_D = 0.4$ V, $I_D = 12.6\ \mu A$ measured $I_D = 12.68\ \mu A$ % diff = 0.63%

$V_D = 0.5$ V, $I_D = 103.4\ \mu A$ measured $I_D = 104.4\ \mu A$ % diff = 0.97%

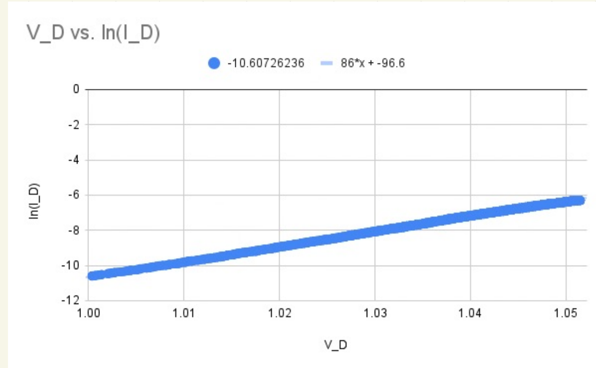
$V_D = 0.6$ V, $I_D = 848.6\ \mu A$ measured $I_D = 869.1\ \mu A$ % diff = 2.4%

The predicted values are all very close the measured ones.

d)



warm diode

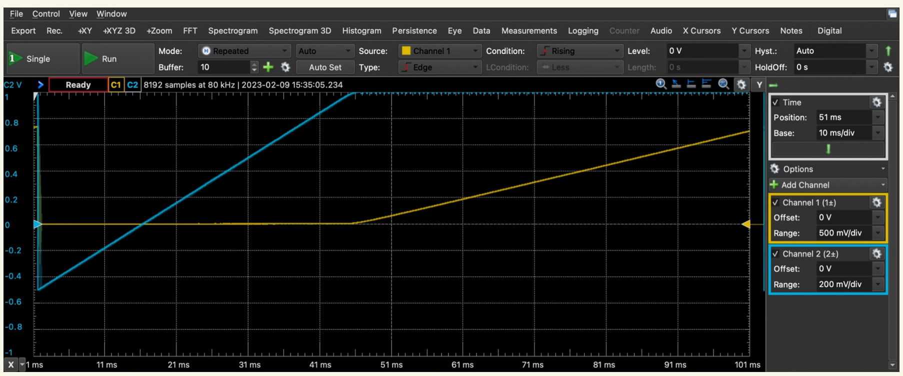


cold diode

slope: $21.1 = \frac{1}{nV_T}$, $V_T = \frac{kT}{e} \Rightarrow 21.1 = \frac{e}{nkT} \Rightarrow n = \frac{e}{21.1\,kT} = \frac{1.6\times10^{-19}}{21.1\,(1.38\times10^{-23})(293)} = 1.88$

intercept: $-19.6 = \ln(I_s) \Rightarrow I_s = e^{-19.6} = 3.07\,nA$

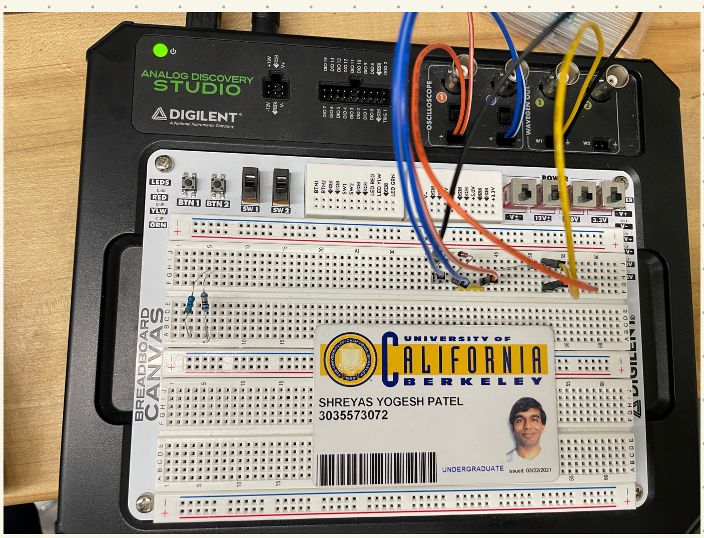
Cold Diode ($T = 77K$)



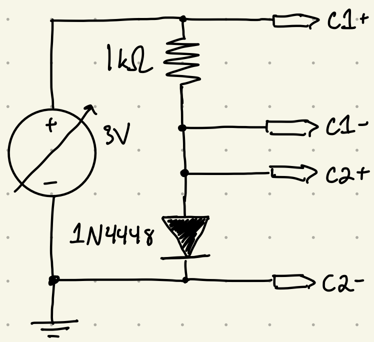
slope: $86 = \frac{1}{nV_T}$, $V_T = \frac{kT}{e} \Rightarrow 86 = \frac{e}{nkT} \Rightarrow n = \frac{e}{86\,kT} = \frac{1.6\times10^{-19}}{86\,(1.38\times10^{-23})(77)} = 1.75$

intercept: $-96.6 = \ln(I_s) \Rightarrow I_s = e^{-96.6} = 1.11\times10^{-42}\,A$

The data shifts by having a greater slope and much lower intercept.



Problem R3.4



a) $V_D = 586$ mV
$V_R = 390$ mV

$V_D + V_R = 976$ mV $= 0.976$ V

$I_D = \frac{V_R}{R} = \frac{390 \text{ mV}}{1 \text{ k}\Omega} = 390\ \mu A$

Wavegen V (V)	V_D (V)	V_R (V)	V_D+V_R (V)	I_D (mA)
0.6	0.512	0.078	0.580	0.078
1	0.586	0.39	0.976	0.39
3	0.658	2.228	2.886	2.228
5	0.688	4.108	4.796	4.796

b)

Wavegen V (V)	V_D (V)	V_R (V)	V_D+V_R (V)	I_D (μA)
1	0.478	0.514	0.992	51.4
3	0.552	2.436	2.988	243.6
5	0.582	4.4	4.982	440

c) $n = 1.88$, $I_s = 2.78$ nA, $T = 293.15$ K, $V_D = 2.886$ V, $k = 1.38 \times 10^{-23}$ J K^{-1}

i) $\frac{V_0 - V}{R} = I_D \Rightarrow \frac{V_0 - V}{R} = I_s \exp\left(\frac{eV_D}{nkT}\right) \Rightarrow \exp\left(\frac{eV_D}{nkT}\right) = \frac{V_0 - V}{I_s R} \Rightarrow V_D = \frac{nkT}{e} \ln\left(\frac{V_0 - V}{I_s R}\right)$

$$V_D = \frac{(1.88)(1.38 \times 10^{-23})(293.15)}{1.6 \times 10^{-19}} \ln\left(\frac{0.114 \text{ V}}{(2.78 \times 10^{-9})(10\,000)}\right) = 1.49 \text{ V}$$

ii) $I_D = \frac{3 \text{ V}}{1 \text{ k}\Omega} = 3$ mA

$$V_D = \left(\frac{nkT}{e}\right) \ln\left(1 + \frac{I_D}{I_s}\right) \Rightarrow \frac{1.88(1.38 \times 10^{-23})(293.15)}{1.6 \times 10^{-19}} \ln\left(1 + \frac{3 \text{ mA}}{2.78 \text{ nA}}\right) = 0.66 \text{ V}$$

$I_D = \frac{V_0 - V}{R} = \frac{3 - 0.66 \text{ V}}{1 \text{ k}\Omega} = 2.34$ mA

$V_D = 0.649$ V

$I_D = \frac{3 - 0.649 \text{ V}}{1 \text{ k}\Omega} = 2.351$ mA

$V_D = 0.649$ V

iii) $V_0 - V_D - RI_s\left[\exp\left(\frac{eV_D}{nkT}\right) - 1\right] = 0$

$V_D = 0.649$ V

Problem R3.5

a) $R = 1\,k\Omega$

$V_{D0} = 0.663\ V$

$v_d = 14.9\ mV$

$V_{R0} = 3.17\ V \Rightarrow I_{D0} = 3.17\ mV$

$v_R = 0.93\ V \Rightarrow i_d = 930\ \mu A$

$r_d = \frac{v_d}{i_d} = \frac{14.9\,mV}{0.251\,mA} = 16.02\ \Omega$

b) $R = 10\ k\Omega$

$V_{D_0} = 0.557\ V$

$v_d = 13.4\ mV$

$V_{R0} = 3.42\ V \Rightarrow I_{D_0} = 0.342\ mA$

$v_R = 0.97\ V \Rightarrow i_d = 97\ \mu A$

$r_d = \frac{v_d}{i_d} = \frac{13.4\,mV}{0.097\,mA} = 138.14\ \Omega$

c) $R = 1\,k\Omega, \quad \frac{v_d}{V_{in}} = \frac{14.9\,mV}{1\,V} = 14.9 \times 10^{-3}$

$\frac{v_d}{V_{in}} = \frac{r_d}{R + r_d} = \frac{16.02\,\Omega}{1000\,\Omega + 16.02\,\Omega} = 15.77 \times 10^{-3}$

$R = 10\,k\Omega, \quad \frac{v_d}{V_{in}} = \frac{13.4\,mV}{1V} = 13.4 \times 10^{-3}$

$\frac{v_d}{V_{in}} = \frac{r_d}{R + r_d} = \frac{138.14\,\Omega}{10000\,\Omega + 138.14\,\Omega} = 13.6 \times 10^{-3}$

The expected ratios are consistant with the measured ones.

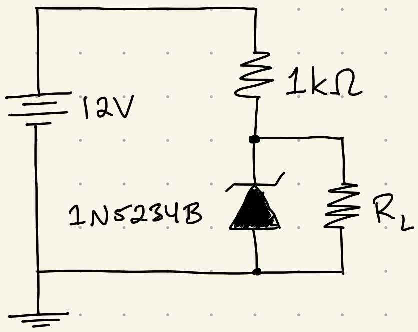
d) $r_d = \frac{nV_T}{I_{D_0}} = \frac{nkT}{eI_{D_0}}$

$R = 1\,k\Omega, \quad r_d = \frac{(1.88)(1.38 \times 10^{-23})(293)}{(1.6 \times 10^{-19})(3.17 \times 10^{-3})} = 14.99\ \Omega$

$R = 10\,k\Omega, \quad r_d = \frac{(1.88)(1.38 \times 10^{-23})(293)}{(1.6 \times 10^{-19})(0.342 \times 10^{-3})} = 138.92\ \Omega$

The measured diode dynamic impedences are very close and consitant with the expected values.

Problem R3.6



a) V_{BD} for 1N4448 = 6.2V

$V_R = 5.8\,V \Rightarrow I_R = \frac{V_R}{R} = 5.8\,mA$

For the minimum load, I_D is negligible in comparison to I_R, so

$I_R = I_{R_L} \Rightarrow R_L = \frac{V_{R_L}}{I_{R_L}} = \frac{6.2V}{5.8mA} = 1.069\,k\Omega$

b) before R_L: $V_z = 6.252\,V$, $V_R = 5.766\,V \Rightarrow I_z = \frac{V_R}{R} = 5.766\,mA$

after R_L: $V_z = 6.248\,V$, $V_R = 5.77\,V \Rightarrow I_z = \frac{V_R}{R} = 5.77\,mA$; $I_{R_L} = \frac{V_z}{R_L} = \frac{6.248}{10\,000} = 0.62\,mA$

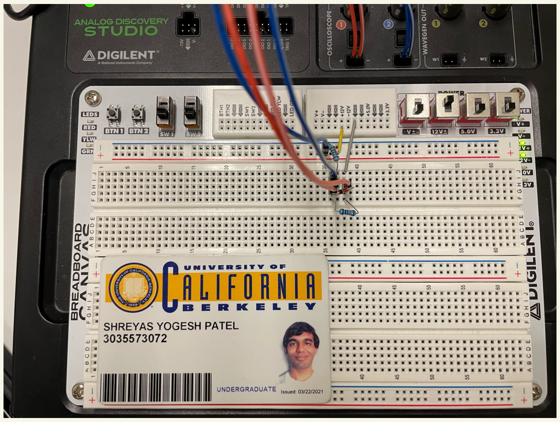
$\Delta V_z = -0.004\,V$, $\Delta I_z = (5.77 - 5.766 - 0.62)\,mA = -0.616\,mA$

$r_z = \frac{\partial V_z}{\partial I_z} = \frac{0.004\,V}{0.616\,m\Omega} = 0.00649\,k\Omega = 6.49\,\Omega$

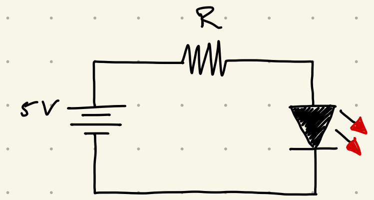
c) $V_{out} \approx 6.25\,V$, $r_z = 6.49\,\Omega \Rightarrow I = 0.963\,A$

$P = IV = (6.25)(0.963) = 6.01875\,W$

The circuit wouldn't work because the power dissipated by the resistor would exceed its rating.



Problem R3.7



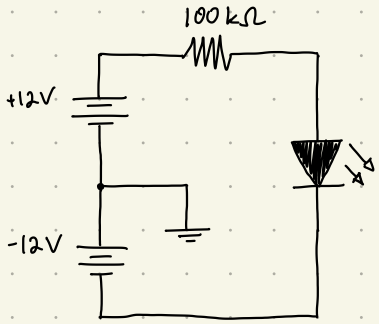
a) $V_D = 1.5\,V$

$V_R = 3.5\,V$, $I_D = 10\,mA$

$R = \frac{V_R}{I_D} = \frac{3.5\,V}{10\,mA} = 0.35\,k\Omega = 350\,\Omega$

actual: $V_D = 1.618\,V \rightarrow V_R = 3.382\,V \rightarrow R = \frac{3.382\,V}{10\,mA} = 338.2\,\Omega$

$V_R = 3.41\,V$, $R = 337.5\,\Omega \Rightarrow I_D = \frac{V_R}{R} = \frac{3.41\,V}{337.5\,\Omega} = 10.1\,mA$



b) $V_D = 1.5\,V \rightarrow V_R = 22.5\,V \Rightarrow I_D = \frac{V_R}{R} = \frac{22.5\,V}{100\,k\Omega} = 0.225\,mA$

actual $V_D = 1.751\,V$, $h = \frac{E_G \lambda}{c}$, $E_G = \frac{e(V_1 T_2 - V_2 T_1)}{T_2 - T_1} = \frac{e(V_1 T_2 - V_2 T_1)}{T_2 - T_1} \frac{\lambda}{c}$

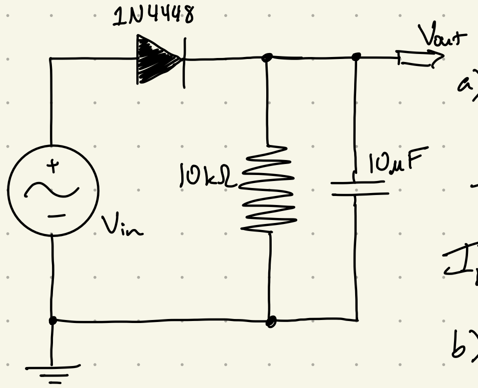
Red: $T_1 = 22^\circ C = 293.15\,K$, $V_1 = 1.754\,V$; $E_G = \frac{(1.6\times10^{-19})(1.754(260.15) - 1.766(293.15))}{260.15 - 293.15} = 2.98\times10^{-19}$

$T_2 = -13^\circ C = 260.15\,K$, $V_2 = 1.766\,V$; $h = E_G \frac{\lambda}{c} = (2.98\times10^{-19})\left(\frac{650\times10^{-9}}{3\times10^{8}}\right) = \underline{6.45\times10^{-34}\,J\cdot s}$

Green: $T_1 = 22^\circ C = 293.15\,K$, $V_1 = 1.792\,V$; $E_G = \frac{(1.6\times10^{-19})(1.792(260.15) - 1.827(293.15))}{260.15 - 293.15} = 3.36\times10^{-19}$

$T_2 = -13^\circ C = 260.15\,K$, $V_2 = 1.827\,V$; $h = E_G \frac{\lambda}{c} = (3.36\times10^{-19})\left(\frac{565\times10^{-9}}{3\times10^{8}}\right) = \underline{6.34\times10^{-34}\,J\cdot s}$

Problem R3.8



a) $\Delta V = V_{in} - V_{out} = 2.4895\,V - 1.9495\,V = 0.54\,V$

$I_D = I_S \exp\left(\frac{eV_D}{nkT}\right) \Leftrightarrow \frac{eV_D}{nkT} = \ln\left(\frac{I_D}{I_S}\right) \Rightarrow V_D = \frac{nkT}{e} \ln\left(\frac{I_D}{I_S}\right)$

$I_D = \frac{V_R}{R} = \frac{1.9495V}{10k\Omega} = 0.195\,mA$, $V_D = \frac{(1.88)(1.38\times10^{-23})(293)}{(1.6\times10^{-19})} \ln\left(\frac{0.195\times10^{-3}}{2.78\times10^{-9}}\right) = 0.53$

b) $V_D = 0.39\,V$

The diode voltage is a little less than the voltage difference from part a.

c) $V_{p2p} = 218.60\,mV$

$\frac{\Delta V}{V_0} = \frac{1}{fRC}$, $R = 10k\Omega$, $C = 10\mu F$, $f = 100Hz$

exp $V_{p2p} = \frac{V_0}{fRC} = \frac{2.5}{(100)(10k\Omega)(10\mu F)} = 0.25\,V = 250\,mV$

% diff $= 12.56\%$

i) $f = 200\,Hz$

$V_{p2p} = 118.5\,mV$

exp $V_{p2p} = \frac{2.5}{(200)(10k\Omega)(10\mu F)} = 0.125\,V = 125\,mV$

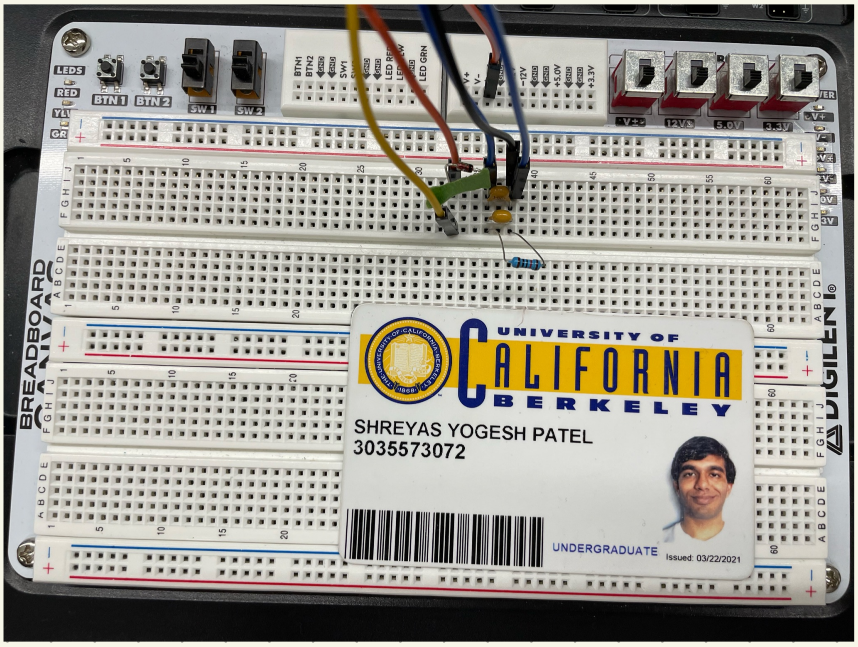
% diff $= 5.2\%$

ii) $C = 20\mu F$

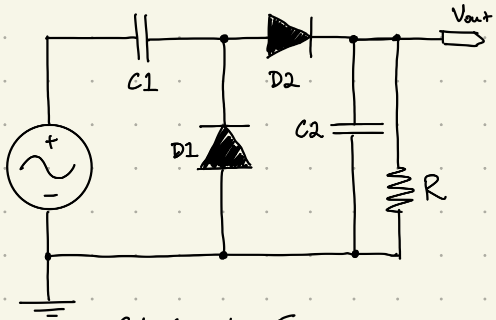
$V_{p2p} = 118.5\,mV$

exp $V_{p2p} = \frac{2.5}{(100)(10k\Omega)(20\mu F)} = 125\,mV$

% diff $= 5.2\%$



Problem R3.9



C1 = C2 = 10 μF
D1 = D2 = 1N4448
R = 3 kΩ

a) expected $V_{out} \cong 2V_0 - 1.2V = 10V - 1.2V = 8.8V$

measured $V_{out} \cong 8.87\ V$

b) $I_{peak} = \frac{V}{R} = \frac{6.6\ V}{3k\Omega} = 2.2\ mA$

$V_{RMS} = 76.62\ mV$

c) $V_{RMS} = 4.76\ mV$

The ripple is reduced by a factor of 16

$r_z = 6.49\Omega \Rightarrow I_z = \frac{V}{r_z} = \frac{4.76mV}{6.49\Omega} = 0.733\ mA$

$I_{max} = 2.2mA - 0.733mA = 1.467\ mA$