ENG262 Principles of Electronic Instrumentation

Project No.1 2014: Schmitt Trigger

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Executive Summary

The purpose of this project is to design a Schmitt trigger that reconstructs a square wave (logic pulse) from a degraded form such as a blurred optical pulse train in to a logical High/Low output with hysteresis between two trigger points (in this case trigger currents) where beyond which the output will always be a logical High or logical Low.

This design primarily uses two transistors which alternate between saturation and cut-off in a bistable multivibrator manner with three carefully chosen resistor values determining all output values.

The elements of particular interest in this design are the output voltage swing from high to low, the tolerance in the trigger points and the amount of current passing through the transistors from collector to emitter.

Introduction

The objective of this project is to design a Schmitt trigger using a photodiode as the input to reconstruct a square wave from a blurred input signal.

For success of this project we require the output high voltage to be > 85% of the voltage source (V_{cc}), the low output voltage to be < 3.4% of V_{cc} and cover 95% of the range of the set trigger currents.

Output Voltage swing (%Vcc)	85
%Tolerance in trigger currents	5%
Maximum Transistor CE current	800mA

Background

A Schmitt trigger is a digital comparator with hysteresis, that is, the input must cross a set point (trigger points) in order to change the output.

A Schmitt trigger can be used anywhere a binary out is desired from a continuous input, such as from an optical pulse train, as in this case, or from sensor to a circuit requiring a high/low logic input. Its hysteresis makes a Schmitt Trigger more suited for noisier signals when using a simple comparator would produce very rapid changes in output, due to the noise.

A Schmitt trigger is implemented as a current controlled voltage source with a very high gain, but limited output. For this reason it can be built typically using a bi-stable multivibrator circuit, as in this project, or an opAMP with positive feedback.

Final Schematic

VCC = 6.00 V	I_PD = PhotoDiode Current (A)	Q1/Q1 = 2N2222 Transistor
RC_1 = 18,000 Ω Resistor	RF_1 = 180,000 Ω Resistor	RB_a = 12,000 Ω Resistor
RC_2 = 18,000 Ω Resistor	RF_2 = 180,000 Ω Resistor	RB_b = 560 Ω Resistor

Circuit Schematic in typical Low output state (≤ 20 μA PhotoDiode Current)

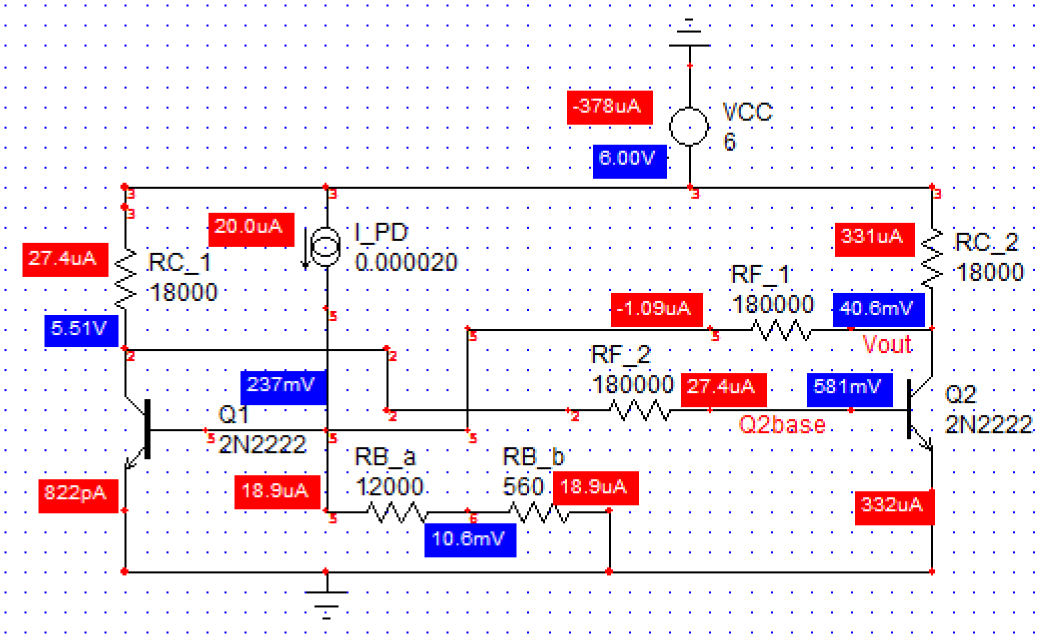

Figure 4.1

Circuit Schematic in typical High output state (≥ 50 μA PhotoDiode Current)

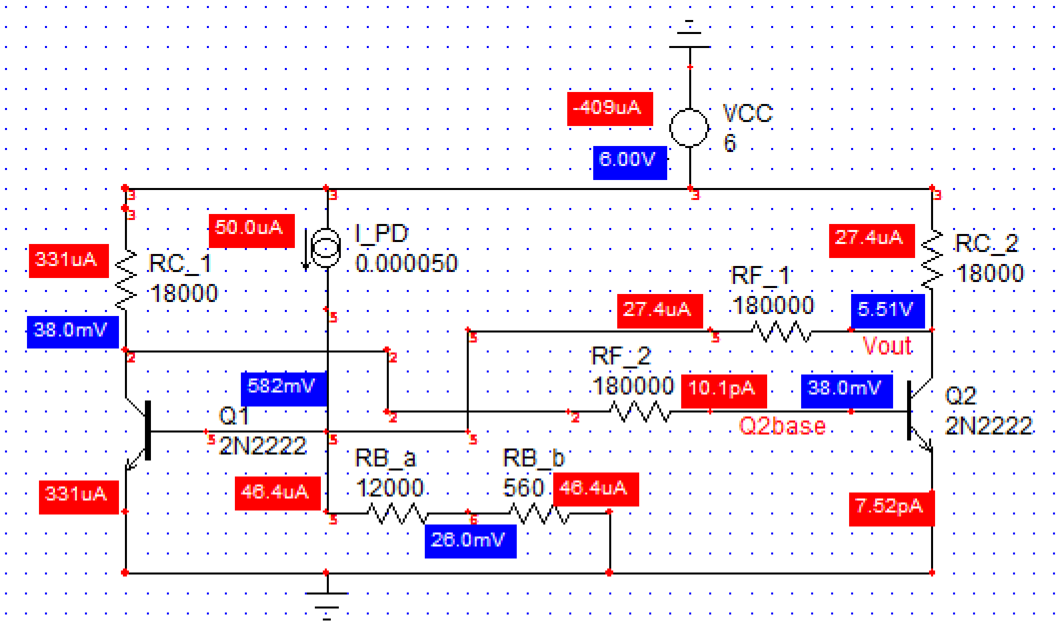

Figure 4.2

Results

Using the resistor values as seen in Figure 4.1 and which were derived as per the derivation procedure in the following section the below hysteresis chart was produced by the circuit as seen in figure 5.1 which is better elaborated upon in the following derivation and design equations section.

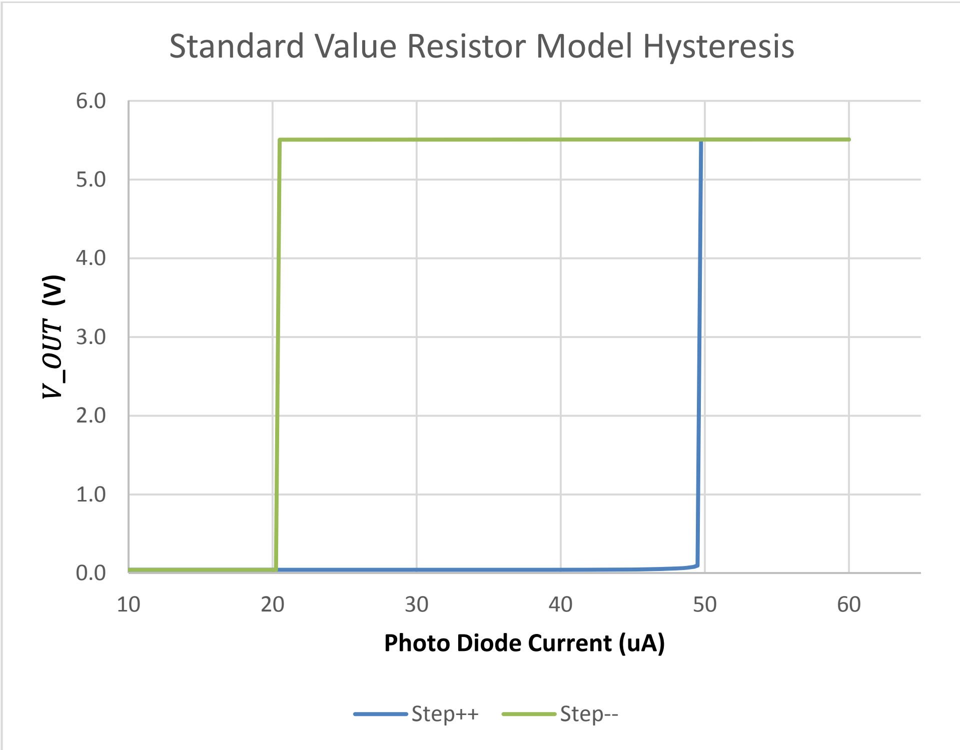

Figure 5.1 – Standard Value Resistor Model Hysteresis

Using this circuit with a simulated time varying sinusoidal current input at 1Hz is included below in figure 5.2. This circuit can be seen triggering at the intended transitions of 20 µA High to Low and 50 µA Low to High as intended.

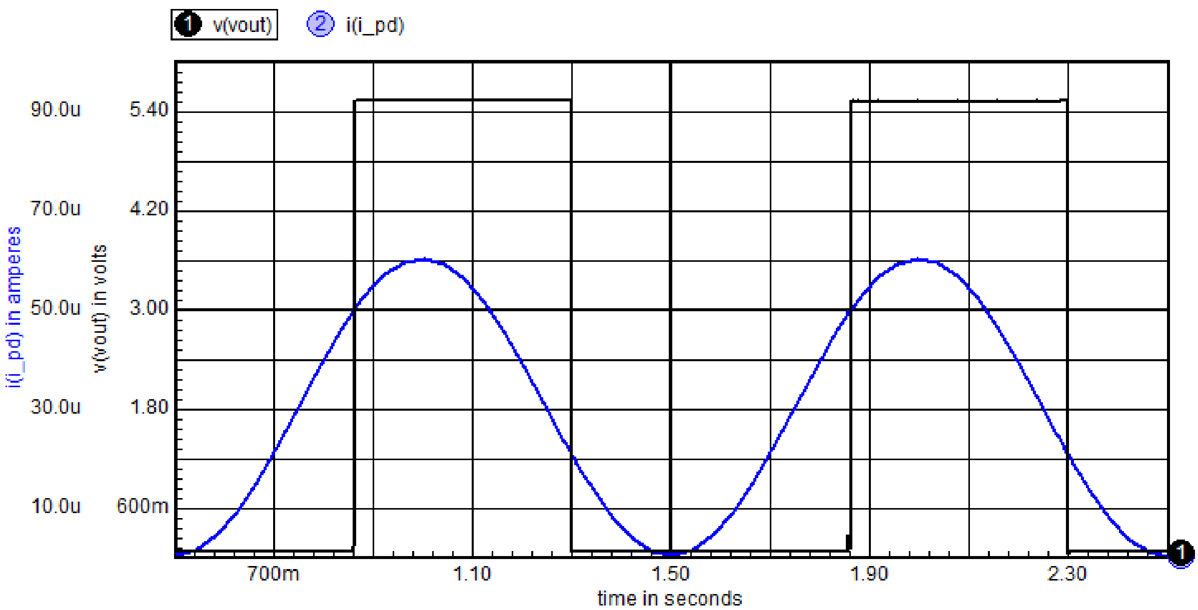

Figure 5.2 –Sinusoidal Photodiode

Additional Steady State Simulation Results with $I_{PD} = 0$ & $I_{PD} = 2 * I_{PD,L-H}$

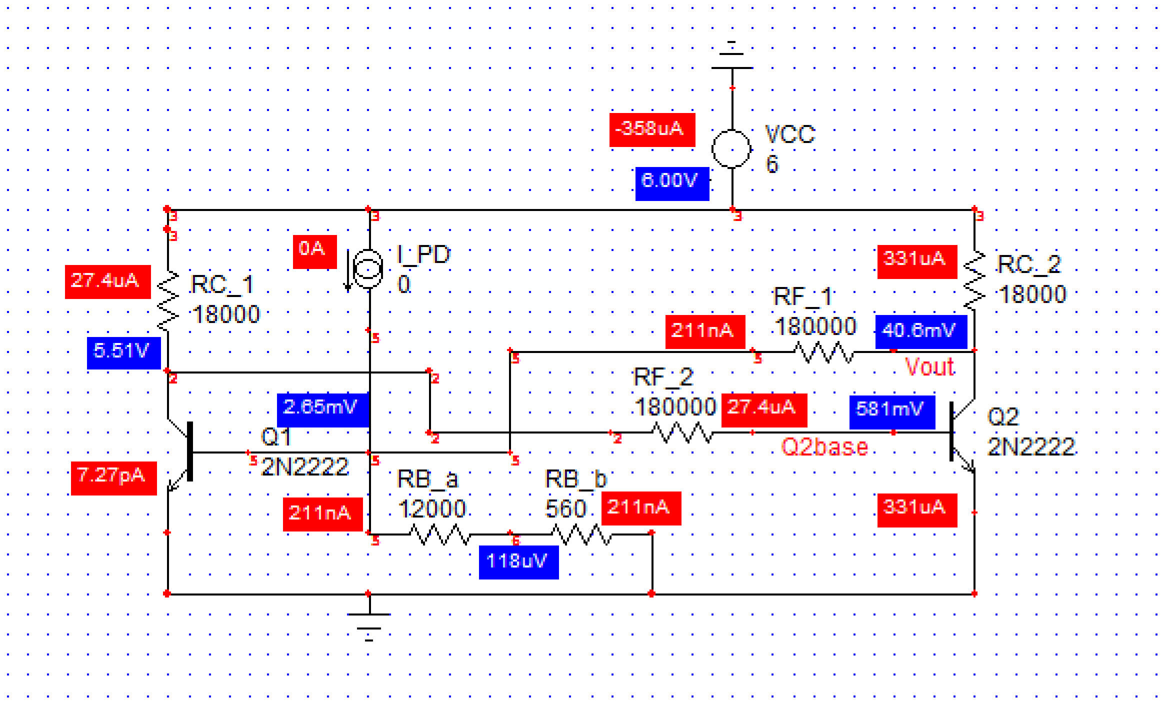

Figure 5.3 – Steady State Simulation with I_PD = 0 µA

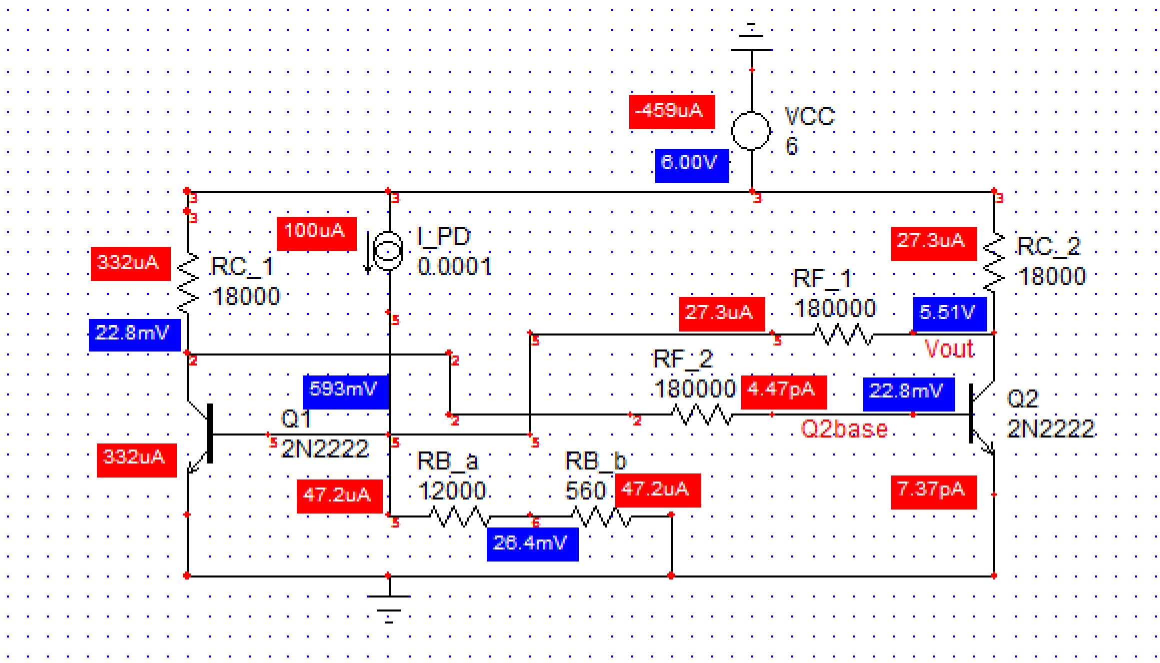

Figure 5.4 - Steady State Simulation with I_PD = 100 µA

The above figures 5.3 and 5.4 further illustrate the output switching of the final circuit in two states beyond the scope of the sweeping simulations which have previously been shown (10 µA -60 µA range).

It can be noted that the circuit continues to act as desired when I_PD = 0 µA and when I_PD = 100 µA.

Derivation and design equations

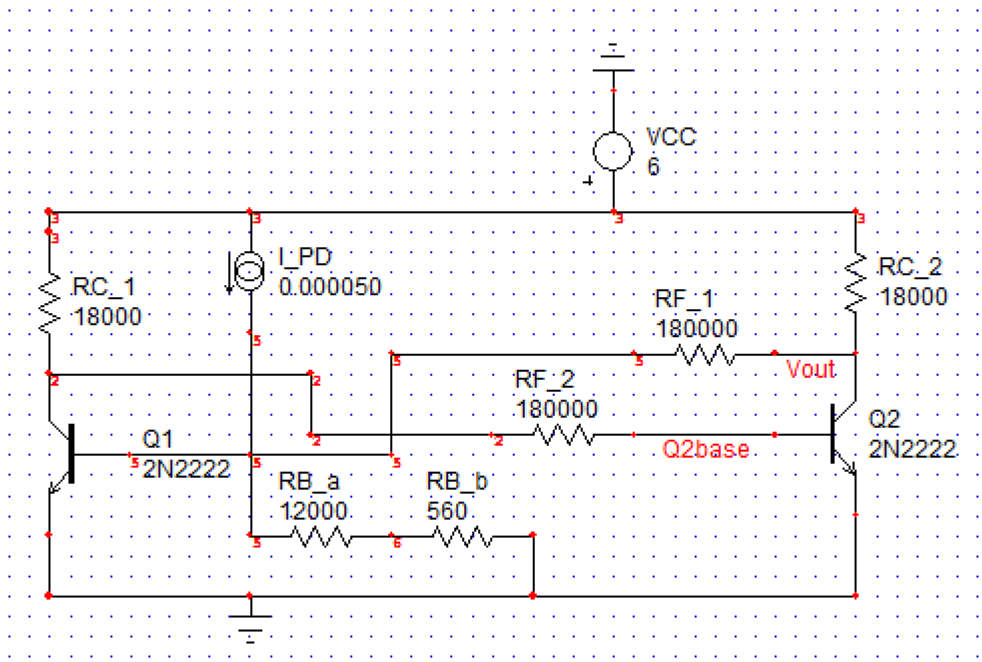

Figure 6.1 – ICAPS Circuit

In approaching this circuit there were three angles which had to be considered.

The first two are likely the most obvious which were to take into consideration the two points in time where the state of the output would be forced high or forced low. One of these points is where Q2 is saturated and the base-emitter voltage of transistor Q1 rises to reach $V_{BE,ON}$ where any current at all flowing into the base quickly forces Q2 into cut-off, saturates Q2 and results in a High output which was aligned with the I_{PDLH} trigger point. The second is when Q1 is saturated and the circuit is no longer able to provide any current to the base of Q1 at $V_{BE,ON}$ (i.e., the node drops below $V_{BE,ON}$) and was aligned with the I_{PDHL} trigger point.

Detailed derivation equations relating to these two situations is done in appendix A where Kirchhoff's Current Law is applied at the base of Q1 (node 5 of figure 6.1) in each situation.

The third angle which needed to be considered was the amount of current the circuit should draw and how much current should be passed through each transistor. The variable of interest here was the RC resistor where a resistor to small would be a waste of current and possibly exceed the current rating of the transistor, a resistor to large would lower the voltage of a High V_{OUT} which could cause the same issues that a Schmitt Trigger is designed to overcome.

To find a suitable RC value many bi-stable multivibrator circuits were examined and a typical value for the equivalent of RC appeared to be around 5-10% of the equivalent RF resistor. As the output of this circuit is essentially a digital voltage signal there is no need for a large amount of current to be passing through the transistors so a relatively large RC was favoured. Some tentative calculations have been shown in appendix A where 10% of the RF resistor appeared to be a reasonable value for RC resistor.

By applying the derived equations for the values of RB, RF and RC (see appendix A for derivation and reasoning) to the ideal transistor model with $V_{BE,ON} = 0.7\,V$ and $V_{CE,Sat} = 0.2\,V$, the following parameters and equations calculated the values shown.

VCC = 6 V	$V_{BE,ON}$ = 0.7 V	$V_{CE,Sat}$ = 0.2 V	$I_{PD,L-H}$ = 50 µA	$I_{PD,H-L}$ = 50 µA

$$\mathrm{RB} = \frac{\frac{(\mathrm{V_{BE,ON}}-\mathrm{V_{CE,Sat}})*1.1*\mathrm{V_{BE,ON}}}{\mathrm{V_{BE,ON}}-\mathrm{VCC}}-\mathrm{V_{BE,ON}}}{\frac{(\mathrm{V_{BE,ON}}-\mathrm{V_{CE,Sat}})*1.1*\mathrm{I_{PD,H-L}}}{\mathrm{V_{BE,ON}}-\mathrm{VCC}}-\mathrm{I_{PD,L-H}}}\ \Omega \cong 14{,}837\ \Omega$$

$$\mathrm{RF} = \frac{\frac{10}{11}*(\mathrm{V_{BE,ON}}-\mathrm{VCC})+\mathrm{V_{CE,Sat}}-\mathrm{V_{BE,ON}}}{\mathrm{I_{PD,H-L}}-\mathrm{I_{PD,L-H}}}\ \Omega \cong 177{,}273\ \Omega$$

$$\mathrm{RC} = \frac{\mathrm{RF}}{10} \cong 17{,}727\ \Omega$$

This model was simulated using a sweeping simulation within with the ICAPS software package. Within the simulation, the photodiode current was varied in 1 µA increments from 0 to 80 µA and then again with -1 µA increments from 80 µA to 0, each data point from each simulation was exported to a spreadsheet. The results of these simulations can be found in appendix B and are shown plotted against V_{OUT} in figure 6.2

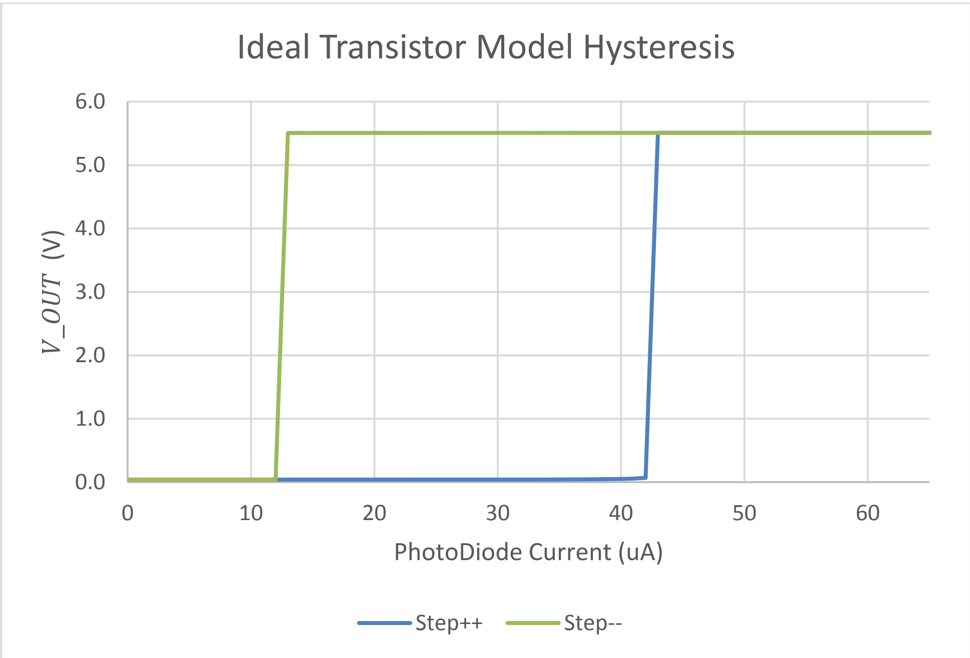

Figure 6.2 – Ideal Transistor Model Hysteresis

This model produced hysteresis somewhat similar to that anticipated, however, the timing of the High --> Low and Low --> High transitions was substantially misaligned. Based on these results more specific values of $V_{BE,ON}$ and $V_{CE,Sat}$ were sought by using the scope and cursor features within ICAPS and focusing on Q1 (transistor one) at the Low to High V_{OUT} transition where Q1 saturates.

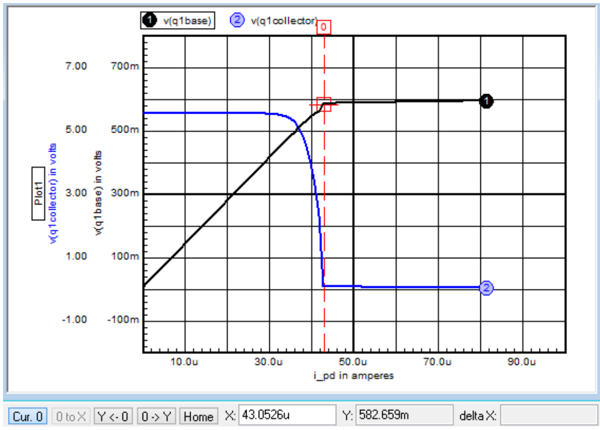

Figure 6.3 - $V_{BE,ON}$ from Scope

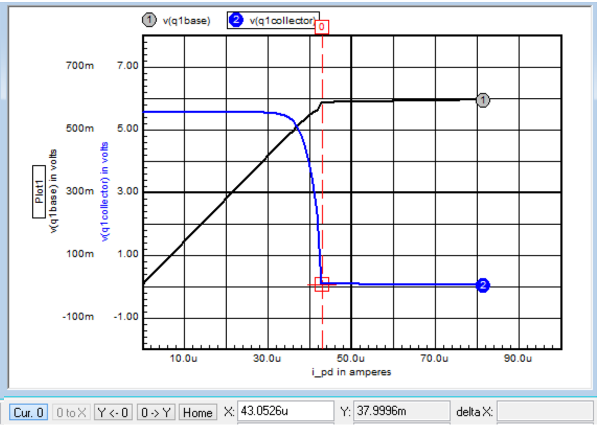

Figure 6.4 - $V_{CE,Sat}$ from Scope

From this investigation $V_{BE,ON}$ can be seen to be ≈ 0.583 V (Figure 6.3) and $V_{CE,Sat}$ ≈ 0.038 V (Figure 6.4) for this particular model.

With this change in parameters, the values of RC, RF and RB needed recalculating based on the derived formulas (appendix A).

Model Parameters:

VCC = 6 V	$V_{BE,ON}$ = 0.583 V	$V_{CE,Sat}$ = 0.038 V	$I_{PD,L-H}$ = 50 µA	$I_{PD,H-L}$ = 50 µA

Re-Calculated Resistor Values:

RB = 12,401 Ω	RF = 182,318 Ω	RC = 18,232 Ω

With the model now updated, the sweeping simulation was run again with the same 1 µA steps between 0 and 80 µA in each direction. The results of this simulation are in appendix C and are plotted against V_{OUT} below in figure 6.5

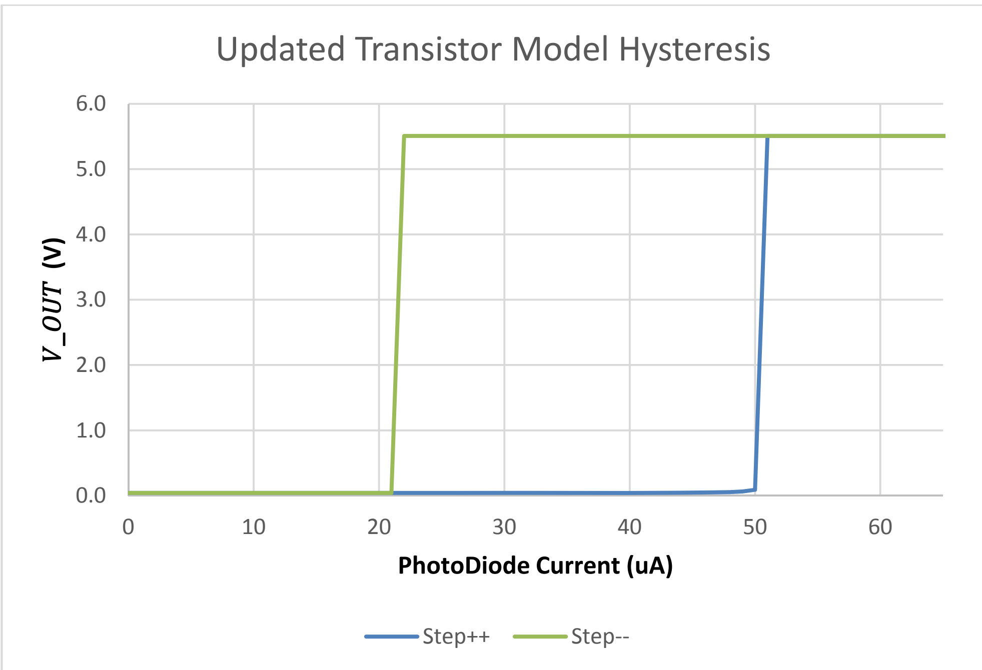

Figure 6.5 – Updated Transistor Model Hysteresis

This model produced hysteresis with the desired shape and range with only a small error in the timing of ~+/- 1 µA which is also the resolution of the plot.

With the model now very close to the desired functionality, the resistors were substituted for standard value resistors where within only a few iterations of slightly varying the RB resistor the model converged to a suitable result with the following resistor values:

RB = 12,000 Ω in series with 560 Ω	RF = 180,000 Ω	RC = 18,000 Ω

This time a simulation was run with photodiode current steps of 0.25 µA in each direction over a range of 10 µA to 60 µA with the logged results included as appendix D and plotted earlier in figure 5.1

From this figure, it is evident that when the photodiode current is below 20 µA the output will always be low, when the photodiode current is above 50 µA the output will always be high and when between these two values the output will keep its current state until it approaches the next threshold. This hysteresis shows that the circuit is operating precisely in the intended manner.

Conclusions

Comparing this circuit with a general purpose IC Schmitt Trigger 74LVC2G17 shows our design has a higher output voltage swing (≈5.1 to >0.8 V in the IC compared with 5.5 to 0.038 V) and much less current drawn from the supply, 0.5 mA at high current input of 100 µA compared to 100 mA for the NXP 74LVC2G17.

In addition to outperforming a commercial general purpose IC, we exceeded the success criteria of the project.

Output Voltage swing (%Vcc)	85%	91.1%
%Tolerance in trigger currents	5%	1.7% (0.5 µA)
Maximum Transistor CE current	800 mA	0.332 mA (I_PD = 100uA)

Possible improvements to this design may include using an opAMP instead of transistors, which although likely easier to implement this solution will have a higher cost per unit, greater power consumption and likely a smaller output voltage swing (unless using “rail-to-rail” opAMPs).

Appendix A

Derivation of Resistor Value Formulas

Low to High Transition Nodal Analysis @ Q1 Base using Kirchhoff's Current Law:

$$-I_{PD,L-H} + \frac{V_{BE,ON} - V_{CE,Sat}}{RF} + \frac{V_{BE,ON}}{RB} = I_{Q1B} = 0$$

High to Low Transition Node Analysis @ Q1 Base using Kirchhoff's Current Law:

$$\frac{V_{BE,ON} - VCC}{RC + RF} - I_{PD,H-L} + \frac{V_{BE,ON}}{RB} = I_{Q1B} = 0$$

Considerations for RC Resistor Value

Low Output = $V_{CE,Sat}$

High Output = $V_{BE,ON} + \left(VCC - V_{BE,ON}\right) * \frac{RF}{RF+RC}$

Maximum Transistor Collector-Emitter Current $I_{Q,CE|MAX} = \frac{VCC - V_{CE,Sat}}{RC}$

Tentative values based on ideal model values $V_{BE,ON} = 0.7\ V$, $V_{CE,Sat}$ = 0.2 V and using $RC = \frac{RF}{10}$

Low Output = $V_{CE,Sat} = 0.2\ V$

High Output = $V_{BE,ON} + \left(VCC - V_{BE,ON}\right) * \frac{RF}{RF+RC} = \ 0.7 + (6.00 - 0.7) * \frac{10}{11} \cong 5.52\ V$

Output swing as % of VCC = $\frac{5.52-0.2}{6.00} * 100 = 88.67\% \ \therefore Acceptable$

Given the 2N2222 Maximum Transistor Collector-Emitter Current is 0.800 A

$I_{Q,CE|MAX} < \frac{VCC - V_{CE,Sat}}{RC}$ $\quad 0.800 < \frac{6.00-0.2}{RC}$ $\quad RC > \frac{6.00-0.2}{0.8\ 00}$ $\quad RC > 7.25\ \Omega$ (Very Likely)

∴ Design Decision: $RC = \frac{RF}{10}$ (Restrict Transistor Current and allow large Low/High Output swing)

High to Low Transition in terms of RF:

$$\frac{V_{BE,ON} - VCC}{1.1 * RF} = I_{PD,H-L} - \frac{V_{BE,ON}}{RB}$$

$$\frac{V_{BE,ON} - VCC}{1.1} = RF * \left(I_{PD,H-L} - \frac{V_{BE,ON}}{RB}\right)$$

$$RF = \frac{V_{BE,ON} - VCC}{1.1 * (I_{PD,H-L} - \frac{V_{BE,ON}}{RB})}\ \Omega$$

Substituting High to Low into Low to High to find RB:

$$-I_{PD,L-H} + \frac{V_{BE,ON} - V_{CE,Sat}}{RF} + \frac{V_{BE,ON}}{RB} = 0$$

$$-I_{PD,L-H} + \frac{\left(V_{BE,ON} - V_{CE,Sat}\right) * 1.1 * (I_{PD,H-L} - \frac{V_{BE,ON}}{RB})}{V_{BE,ON} - VCC} + \frac{V_{BE,ON}}{RB} = 0$$

$$-I_{PD,L-H} + \frac{\left(V_{BE,ON} - V_{CE,Sat}\right) * 1.1 * I_{PD,H-L}}{V_{BE,ON} - VCC} - \frac{\left(V_{BE,ON} - V_{CE,Sat}\right) * 1.1 * V_{BE,ON}}{RB * \left(V_{BE,ON} - VCC\right)} + \frac{V_{BE,ON}}{RB} = 0$$

$$RB * \left(\frac{\left(V_{BE,ON} - V_{CE,Sat}\right) * 1.1 * I_{PD,H-L}}{V_{BE,ON} - VCC} - I_{PD,L-H}\right) = \frac{\left(V_{BE,ON} - V_{CE,Sat}\right) * 1.1 * V_{BE,ON}}{V_{BE,ON} - VCC} - V_{BE,ON}$$

$$\boldsymbol{RB = \frac{\frac{\left(V_{BE,ON} - V_{CE,Sat}\right) * 1.1 * V_{BE,ON}}{V_{BE,ON} - VCC} - V_{BE,ON}}{\frac{\left(V_{BE,ON} - V_{CE,Sat}\right) * 1.1 * I_{PD,H-L}}{V_{BE,ON} - VCC} - I_{PD,L-H}}\ \Omega}$$

High to Low Transition in terms of RB:

$$\frac{V_{BE,ON}}{RB} = I_{PD,H-L} - \frac{V_{BE,ON} - VCC}{1.1 * RF}$$

$$V_{BE,ON} = RB * (I_{PD,H-L} - \frac{V_{BE,ON} - VCC}{1.1 * RF})$$

$$RB = \frac{V_{BE,ON}}{I_{PD,H-L} - \frac{V_{BE,ON} - VCC}{1.1 * RF}} \quad \Omega$$

Substituting High to Low into Low to High to find RF:

$$-I_{PD,L-H} + \frac{V_{BE,ON} - V_{CE,Sat}}{RF} + \frac{V_{BE,ON}}{RB} = 0$$

$$-I_{PD,L-H} + \frac{V_{BE,ON} - V_{CE,Sat}}{RF} + V_{BE,ON} * \frac{1}{\frac{V_{BE,ON}}{I_{PD,H-L} - \frac{V_{BE,ON} - VCC}{1.1 * RF}}} = 0$$

$$-I_{PD,L-H} + \frac{V_{BE,ON} - V_{CE,Sat}}{RF} + V_{BE,ON} * \frac{I_{PD,H-L} - \frac{V_{BE,ON} - VCC}{1.1 * RF}}{V_{BE,ON}} = 0$$

$$-I_{PD,L-H} + \frac{V_{BE,ON} - V_{CE,Sat}}{RF} + I_{PD,H-L} - \frac{V_{BE,ON} - VCC}{1.1 * RF} = 0$$

$$RF * \left(I_{PD,H-L} - I_{PD,L-H}\right) = \frac{V_{BE,ON} - VCC}{1.1} - \left(V_{BE,ON} - V_{CE,Sat}\right) = 0$$

$$\boldsymbol{RF = \frac{\frac{10}{11} * \left(V_{BE,ON} - VCC\right) + V_{CE,Sat} - V_{BE,ON}}{I_{PD,H-L} - I_{PD,L-H}} \ \Omega}$$

Ideal Transistor Model Results					
I_PhotoDiode		V_Out	I_PhotoDiode		V_Out
Amps	uAmps	Step++	Amps	uAmps	Step--
0	0	0.04056	8.00E-05	80	5.50826
1.00E-06	1	0.04057	7.90E-05	79	5.50824
2.00E-06	2	0.04057	7.80E-05	78	5.50823
3.00E-06	3	0.04058	7.70E-05	77	5.50821
4.00E-06	4	0.04058	7.60E-05	76	5.50819
5.00E-06	5	0.04059	7.50E-05	75	5.50817
6.00E-06	6	0.04059	7.40E-05	74	5.50816
7.00E-06	7	0.04060	7.30E-05	73	5.50814
8.00E-06	8	0.04060	7.20E-05	72	5.50812
9.00E-06	9	0.04061	7.10E-05	71	5.50810
1.00E-05	10	0.04061	7.00E-05	70	5.50808
1.10E-05	11	0.04062	6.90E-05	69	5.50806
1.20E-05	12	0.04062	6.80E-05	68	5.50805
1.30E-05	13	0.04063	6.70E-05	67	5.50803
1.40E-05	14	0.04063	6.60E-05	66	5.50801
1.50E-05	15	0.04064	6.50E-05	65	5.50799
1.60E-05	16	0.04064	6.40E-05	64	5.50797
1.70E-05	17	0.04065	6.30E-05	63	5.50795
1.80E-05	18	0.04065	6.20E-05	62	5.50793
1.90E-05	19	0.04065	6.10E-05	61	5.50791
2.00E-05	20	0.04066	6.00E-05	60	5.50789
2.10E-05	21	0.04066	5.90E-05	59	5.50787
2.20E-05	22	0.04067	5.80E-05	58	5.50785
2.30E-05	23	0.04067	5.70E-05	57	5.50783
2.40E-05	24	0.04068	5.60E-05	56	5.50781
2.50E-05	25	0.04069	5.50E-05	55	5.50779
2.60E-05	26	0.04069	5.40E-05	54	5.50777
2.70E-05	27	0.04070	5.30E-05	53	5.50774
2.80E-05	28	0.04071	5.20E-05	52	5.50772
2.90E-05	29	0.04073	5.10E-05	51	5.50770
3.00E-05	30	0.04076	5.00E-05	50	5.50768
3.10E-05	31	0.04079	4.90E-05	49	5.50766
3.20E-05	32	0.04086	4.80E-05	48	5.50764
3.30E-05	33	0.04096	4.70E-05	47	5.50761
3.40E-05	34	0.04112	4.60E-05	46	5.50759
3.50E-05	35	0.04140	4.50E-05	45	5.50757
3.60E-05	36	0.04184	4.40E-05	44	5.50754
3.70E-05	37	0.04258	4.30E-05	43	5.50752
3.80E-05	38	0.04379	4.20E-05	42	5.50750
3.90E-05	39	0.04577	4.10E-05	41	5.50747
4.00E-05	40	0.04910	4.00E-05	40	5.50745
4.10E-05	41	0.05503	3.90E-05	39	5.50743
4.20E-05	42	0.06757	3.80E-05	38	5.50740
4.30E-05	43	5.50752	3.70E-05	37	5.50738
4.40E-05	44	5.50754	3.60E-05	36	5.50735
4.50E-05	45	5.50757	3.50E-05	35	5.50733
4.60E-05	46	5.50759	3.40E-05	34	5.50730
4.70E-05	47	5.50761	3.30E-05	33	5.50727

4.80E-05	48	5.50764	3.20E-05	32	5.50725
4.90E-05	49	5.50766	3.10E-05	31	5.50722
5.00E-05	50	5.50768	3.00E-05	30	5.50719
5.10E-05	51	5.50770	2.90E-05	29	5.50717
5.20E-05	52	5.50772	2.80E-05	28	5.50714
5.30E-05	53	5.50774	2.70E-05	27	5.50711
5.40E-05	54	5.50777	2.60E-05	26	5.50708
5.50E-05	55	5.50779	2.50E-05	25	5.50705
5.60E-05	56	5.50781	2.40E-05	24	5.50703
5.70E-05	57	5.50783	2.30E-05	23	5.50700
5.80E-05	58	5.50785	2.20E-05	22	5.50697
5.90E-05	59	5.50787	2.10E-05	21	5.50694
6.00E-05	60	5.50789	2.00E-05	20	5.50690
6.10E-05	61	5.50791	1.90E-05	19	5.50687
6.20E-05	62	5.50793	1.80E-05	18	5.50684
6.30E-05	63	5.50795	1.70E-05	17	5.50681
6.40E-05	64	5.50797	1.60E-05	16	5.50677
6.50E-05	65	5.50799	1.50E-05	15	5.50674
6.60E-05	66	5.50801	1.40E-05	14	5.50670
6.70E-05	67	5.50803	1.30E-05	13	5.50496
6.80E-05	68	5.50805	1.20E-05	12	0.04062
6.90E-05	69	5.50806	1.10E-05	11	0.04062
7.00E-05	70	5.50808	1.00E-05	10	0.04061
7.10E-05	71	5.50810	9.00E-06	9	0.04061
7.20E-05	72	5.50812	8.00E-06	8	0.04060
7.30E-05	73	5.50814	7.00E-06	7	0.04060
7.40E-05	74	5.50816	6.00E-06	6	0.04059
7.50E-05	75	5.50817	5.00E-06	5	0.04059
7.60E-05	76	5.50819	4.00E-06	4	0.04058
7.70E-05	77	5.50821	3.00E-06	3	0.04058
7.80E-05	78	5.50823	2.00E-06	2	0.04057
7.90E-05	79	5.50824	1.00E-06	1	0.04057
8.00E-05	80	5.50826	1.32E-19	1.32E-13	0.04056

Updated Transistor Model Results					
I_PhotoDiode		V_Out	I_PhotoDiode		V_Out
Amps	uAmps	Step++	Amps	uAmps	Step--
0	0	0.04056	8.00E-05	80	5.50808
1.00E-06	1	0.04057	7.90E-05	79	5.50806
2.00E-06	2	0.04057	7.80E-05	78	5.50804
3.00E-06	3	0.04058	7.70E-05	77	5.50802
4.00E-06	4	0.04058	7.60E-05	76	5.50800
5.00E-06	5	0.04058	7.50E-05	75	5.50798
6.00E-06	6	0.04059	7.40E-05	74	5.50796
7.00E-06	7	0.04059	7.30E-05	73	5.50794
8.00E-06	8	0.04060	7.20E-05	72	5.50792
9.00E-06	9	0.04060	7.10E-05	71	5.50790
1.00E-05	10	0.04060	7.00E-05	70	5.50788
1.10E-05	11	0.04061	6.90E-05	69	5.50786
1.20E-05	12	0.04061	6.80E-05	68	5.50784
1.30E-05	13	0.04062	6.70E-05	67	5.50782
1.40E-05	14	0.04062	6.60E-05	66	5.50780
1.50E-05	15	0.04062	6.50E-05	65	5.50778
1.60E-05	16	0.04063	6.40E-05	64	5.50776
1.70E-05	17	0.04063	6.30E-05	63	5.50774
1.80E-05	18	0.04064	6.20E-05	62	5.50772
1.90E-05	19	0.04064	6.10E-05	61	5.50770
2.00E-05	20	0.04064	6.00E-05	60	5.50767
2.10E-05	21	0.04065	5.90E-05	59	5.50765
2.20E-05	22	0.04065	5.80E-05	58	5.50763
2.30E-05	23	0.04066	5.70E-05	57	5.50761
2.40E-05	24	0.04066	5.60E-05	56	5.50758
2.50E-05	25	0.04066	5.50E-05	55	5.50756
2.60E-05	26	0.04067	5.40E-05	54	5.50754
2.70E-05	27	0.04067	5.30E-05	53	5.50751
2.80E-05	28	0.04068	5.20E-05	52	5.50749
2.90E-05	29	0.04068	5.10E-05	51	5.50747
3.00E-05	30	0.04069	5.00E-05	50	5.50744
3.10E-05	31	0.04070	4.90E-05	49	5.50742
3.20E-05	32	0.04070	4.80E-05	48	5.50739
3.30E-05	33	0.04071	4.70E-05	47	5.50737
3.40E-05	34	0.04073	4.60E-05	46	5.50734
3.50E-05	35	0.04075	4.50E-05	45	5.50732
3.60E-05	36	0.04077	4.40E-05	44	5.50729
3.70E-05	37	0.04081	4.30E-05	43	5.50727
3.80E-05	38	0.04087	4.20E-05	42	5.50724
3.90E-05	39	0.04096	4.10E-05	41	5.50721
4.00E-05	40	0.04110	4.00E-05	40	5.50719
4.10E-05	41	0.04131	3.90E-05	39	5.50716
4.20E-05	42	0.04164	3.80E-05	38	5.50713
4.30E-05	43	0.04214	3.70E-05	37	5.50711
4.40E-05	44	0.04291	3.60E-05	36	5.50708
4.50E-05	45	0.04409	3.50E-05	35	5.50705
4.60E-05	46	0.04593	3.40E-05	34	5.50702
4.70E-05	47	0.04884	3.30E-05	33	5.50699

4.80E-05	48	0.05370	3.20E-05	32	5.50696
4.90E-05	49	0.06278	3.10E-05	31	5.50693
5.00E-05	50	0.09007	3.00E-05	30	5.50690
5.10E-05	51	5.50747	2.90E-05	29	5.50687
5.20E-05	52	5.50749	2.80E-05	28	5.50684
5.30E-05	53	5.50751	2.70E-05	27	5.50680
5.40E-05	54	5.50754	2.60E-05	26	5.50677
5.50E-05	55	5.50756	2.50E-05	25	5.50674
5.60E-05	56	5.50758	2.40E-05	24	5.50670
5.70E-05	57	5.50761	2.30E-05	23	5.50666
5.80E-05	58	5.50763	2.20E-05	22	5.50662
5.90E-05	59	5.50765	2.10E-05	21	0.04065
6.00E-05	60	5.50767	2.00E-05	20	0.04064
6.10E-05	61	5.50770	1.90E-05	19	0.04064
6.20E-05	62	5.50772	1.80E-05	18	0.04064
6.30E-05	63	5.50774	1.70E-05	17	0.04063
6.40E-05	64	5.50776	1.60E-05	16	0.04063
6.50E-05	65	5.50778	1.50E-05	15	0.04062
6.60E-05	66	5.50780	1.40E-05	14	0.04062
6.70E-05	67	5.50782	1.30E-05	13	0.04062
6.80E-05	68	5.50784	1.20E-05	12	0.04061
6.90E-05	69	5.50786	1.10E-05	11	0.04061
7.00E-05	70	5.50788	1.00E-05	10	0.04060
7.10E-05	71	5.50790	9.00E-06	9	0.04060
7.20E-05	72	5.50792	8.00E-06	8	0.04060
7.30E-05	73	5.50794	7.00E-06	7	0.04059
7.40E-05	74	5.50796	6.00E-06	6	0.04059
7.50E-05	75	5.50798	5.00E-06	5	0.04058
7.60E-05	76	5.50800	4.00E-06	4	0.04058
7.70E-05	77	5.50802	3.00E-06	3	0.04058
7.80E-05	78	5.50804	2.00E-06	2	0.04057
7.90E-05	79	5.50806	1.00E-06	1	0.04057
8.00E-05	80	5.50808	1.32E-19	1.3E-13	0.04056

Standard Value Resistor Model Results					
I_PhotoDiode		V_Out	I_PhotoDiode		V_Out
Amps	uAmps	Step++	Amps	uAmps	Step--
1.00E-05	10.000	0.04060	6.00E-05	60.000	5.50770
1.03E-05	10.250	0.04061	5.98E-05	59.750	5.50770
1.05E-05	10.500	0.04061	5.95E-05	59.500	5.50769
1.07E-05	10.750	0.04061	5.93E-05	59.250	5.50769
1.10E-05	11.000	0.04061	5.90E-05	59.000	5.50768
1.12E-05	11.250	0.04061	5.88E-05	58.750	5.50768
1.15E-05	11.500	0.04061	5.85E-05	58.500	5.50767
1.17E-05	11.750	0.04061	5.83E-05	58.250	5.50766
1.20E-05	12.000	0.04061	5.80E-05	58.000	5.50766
1.22E-05	12.250	0.04061	5.78E-05	57.750	5.50765
1.25E-05	12.500	0.04061	5.75E-05	57.500	5.50765
1.27E-05	12.750	0.04062	5.73E-05	57.250	5.50764
1.30E-05	13.000	0.04062	5.70E-05	57.000	5.50764
1.32E-05	13.250	0.04062	5.68E-05	56.750	5.50763
1.35E-05	13.500	0.04062	5.65E-05	56.500	5.50763
1.37E-05	13.750	0.04062	5.63E-05	56.250	5.50762
1.40E-05	14.000	0.04062	5.60E-05	56.000	5.50761
1.42E-05	14.250	0.04062	5.58E-05	55.750	5.50761
1.45E-05	14.500	0.04062	5.55E-05	55.500	5.50760
1.47E-05	14.750	0.04062	5.53E-05	55.250	5.50760
1.50E-05	15.000	0.04062	5.50E-05	55.000	5.50759
1.52E-05	15.250	0.04063	5.48E-05	54.750	5.50759
1.55E-05	15.500	0.04063	5.45E-05	54.500	5.50758
1.57E-05	15.750	0.04063	5.43E-05	54.250	5.50757
1.60E-05	16.000	0.04063	5.40E-05	54.000	5.50757
1.62E-05	16.250	0.04063	5.38E-05	53.750	5.50756
1.65E-05	16.500	0.04063	5.35E-05	53.500	5.50756
1.67E-05	16.750	0.04063	5.33E-05	53.250	5.50755
1.70E-05	17.000	0.04063	5.30E-05	53.000	5.50755
1.72E-05	17.250	0.04063	5.28E-05	52.750	5.50754
1.75E-05	17.500	0.04063	5.25E-05	52.500	5.50753
1.77E-05	17.750	0.04064	5.23E-05	52.250	5.50753
1.80E-05	18.000	0.04064	5.20E-05	52.000	5.50752
1.82E-05	18.250	0.04064	5.18E-05	51.750	5.50752
1.85E-05	18.500	0.04064	5.15E-05	51.500	5.50751
1.87E-05	18.750	0.04064	5.13E-05	51.250	5.50751
1.90E-05	19.000	0.04064	5.10E-05	51.000	5.50750
1.92E-05	19.250	0.04064	5.08E-05	50.750	5.50749
1.95E-05	19.500	0.04064	5.05E-05	50.500	5.50749
1.97E-05	19.750	0.04064	5.03E-05	50.250	5.50748
2.00E-05	20.000	0.04064	5.00E-05	50.000	5.50748
2.02E-05	20.250	0.04065	4.98E-05	49.750	5.50747
2.05E-05	20.500	0.04065	4.95E-05	49.500	5.50746
2.07E-05	20.750	0.04065	4.93E-05	49.250	5.50746
2.10E-05	21.000	0.04065	4.90E-05	49.000	5.50745
2.12E-05	21.250	0.04065	4.88E-05	48.750	5.50745
2.15E-05	21.500	0.04065	4.85E-05	48.500	5.50744
2.17E-05	21.750	0.04065	4.83E-05	48.250	5.50743

2.20E-05	22.000	0.04065	4.80E-05	48.000	5.50743
2.22E-05	22.250	0.04065	4.78E-05	47.750	5.50742
2.25E-05	22.500	0.04066	4.75E-05	47.500	5.50742
2.27E-05	22.750	0.04066	4.73E-05	47.250	5.50741
2.30E-05	23.000	0.04066	4.70E-05	47.000	5.50740
2.32E-05	23.250	0.04066	4.68E-05	46.750	5.50740
2.35E-05	23.500	0.04066	4.65E-05	46.500	5.50739
2.37E-05	23.750	0.04066	4.63E-05	46.250	5.50739
2.40E-05	24.000	0.04066	4.60E-05	46.000	5.50738
2.42E-05	24.250	0.04066	4.58E-05	45.750	5.50737
2.45E-05	24.500	0.04066	4.55E-05	45.500	5.50737
2.47E-05	24.750	0.04066	4.53E-05	45.250	5.50736
2.50E-05	25.000	0.04067	4.50E-05	45.000	5.50735
2.52E-05	25.250	0.04067	4.48E-05	44.750	5.50735
2.55E-05	25.500	0.04067	4.45E-05	44.500	5.50734
2.57E-05	25.750	0.04067	4.43E-05	44.250	5.50734
2.60E-05	26.000	0.04067	4.40E-05	44.000	5.50733
2.62E-05	26.250	0.04067	4.38E-05	43.750	5.50732
2.65E-05	26.500	0.04067	4.35E-05	43.500	5.50732
2.67E-05	26.750	0.04067	4.33E-05	43.250	5.50731
2.70E-05	27.000	0.04067	4.30E-05	43.000	5.50730
2.72E-05	27.250	0.04068	4.28E-05	42.750	5.50730
2.75E-05	27.500	0.04068	4.25E-05	42.500	5.50729
2.77E-05	27.750	0.04068	4.23E-05	42.250	5.50728
2.80E-05	28.000	0.04068	4.20E-05	42.000	5.50728
2.82E-05	28.250	0.04068	4.18E-05	41.750	5.50727
2.85E-05	28.500	0.04068	4.15E-05	41.500	5.50727
2.87E-05	28.750	0.04068	4.13E-05	41.250	5.50726
2.90E-05	29.000	0.04068	4.10E-05	41.000	5.50725
2.92E-05	29.250	0.04069	4.08E-05	40.750	5.50725
2.95E-05	29.500	0.04069	4.05E-05	40.500	5.50724
2.97E-05	29.750	0.04069	4.03E-05	40.250	5.50723
3.00E-05	30.000	0.04069	4.00E-05	40.000	5.50723
3.02E-05	30.250	0.04069	3.98E-05	39.750	5.50722
3.05E-05	30.500	0.04069	3.95E-05	39.500	5.50721
3.07E-05	30.750	0.04070	3.93E-05	39.250	5.50721
3.10E-05	31.000	0.04070	3.90E-05	39.000	5.50720
3.12E-05	31.250	0.04070	3.88E-05	38.750	5.50719
3.15E-05	31.500	0.04070	3.85E-05	38.500	5.50719
3.17E-05	31.750	0.04070	3.83E-05	38.250	5.50718
3.20E-05	32.000	0.04071	3.80E-05	38.000	5.50717
3.22E-05	32.250	0.04071	3.78E-05	37.750	5.50717
3.25E-05	32.500	0.04071	3.75E-05	37.500	5.50716
3.27E-05	32.750	0.04071	3.73E-05	37.250	5.50715
3.30E-05	33.000	0.04072	3.70E-05	37.000	5.50714
3.32E-05	33.250	0.04072	3.68E-05	36.750	5.50714
3.35E-05	33.500	0.04073	3.65E-05	36.500	5.50713
3.37E-05	33.750	0.04073	3.63E-05	36.250	5.50712
3.40E-05	34.000	0.04073	3.60E-05	36.000	5.50712
3.42E-05	34.250	0.04074	3.58E-05	35.750	5.50711
3.45E-05	34.500	0.04074	3.55E-05	35.500	5.50710

3.47E-05	34.750	0.04075	3.53E-05	35.250	5.50710
3.50E-05	35.000	0.04076	3.50E-05	35.000	5.50709
3.52E-05	35.250	0.04076	3.48E-05	34.750	5.50708
3.55E-05	35.500	0.04077	3.45E-05	34.500	5.50708
3.57E-05	35.750	0.04078	3.43E-05	34.250	5.50707
3.60E-05	36.000	0.04079	3.40E-05	34.000	5.50706
3.62E-05	36.250	0.04080	3.38E-05	33.750	5.50705
3.65E-05	36.500	0.04081	3.35E-05	33.500	5.50705
3.67E-05	36.750	0.04082	3.33E-05	33.250	5.50704
3.70E-05	37.000	0.04084	3.30E-05	33.000	5.50703
3.72E-05	37.250	0.04085	3.28E-05	32.750	5.50703
3.75E-05	37.500	0.04087	3.25E-05	32.500	5.50702
3.77E-05	37.750	0.04089	3.23E-05	32.250	5.50701
3.80E-05	38.000	0.04091	3.20E-05	32.000	5.50700
3.82E-05	38.250	0.04093	3.18E-05	31.750	5.50700
3.85E-05	38.500	0.04096	3.15E-05	31.500	5.50699
3.87E-05	38.750	0.04099	3.13E-05	31.250	5.50698
3.90E-05	39.000	0.04102	3.10E-05	31.000	5.50697
3.92E-05	39.250	0.04106	3.08E-05	30.750	5.50697
3.95E-05	39.500	0.04110	3.05E-05	30.500	5.50696
3.97E-05	39.750	0.04114	3.03E-05	30.250	5.50695
4.00E-05	40.000	0.04119	3.00E-05	30.000	5.50694
4.02E-05	40.250	0.04125	2.98E-05	29.750	5.50694
4.05E-05	40.500	0.04131	2.95E-05	29.500	5.50693
4.07E-05	40.750	0.04138	2.93E-05	29.250	5.50692
4.10E-05	41.000	0.04146	2.90E-05	29.000	5.50691
4.12E-05	41.250	0.04155	2.88E-05	28.750	5.50691
4.15E-05	41.500	0.04164	2.85E-05	28.500	5.50690
4.17E-05	41.750	0.04175	2.83E-05	28.250	5.50689
4.20E-05	42.000	0.04187	2.80E-05	28.000	5.50688
4.22E-05	42.250	0.04200	2.78E-05	27.750	5.50687
4.25E-05	42.500	0.04215	2.75E-05	27.500	5.50687
4.27E-05	42.750	0.04231	2.73E-05	27.250	5.50686
4.30E-05	43.000	0.04250	2.70E-05	27.000	5.50685
4.32E-05	43.250	0.04270	2.68E-05	26.750	5.50684
4.35E-05	43.500	0.04293	2.65E-05	26.500	5.50684
4.37E-05	43.750	0.04319	2.63E-05	26.250	5.50683
4.40E-05	44.000	0.04347	2.60E-05	26.000	5.50682
4.42E-05	44.250	0.04379	2.58E-05	25.750	5.50681
4.45E-05	44.500	0.04415	2.55E-05	25.500	5.50680
4.47E-05	44.750	0.04454	2.53E-05	25.250	5.50679
4.50E-05	45.000	0.04499	2.50E-05	25.000	5.50679
4.52E-05	45.250	0.04548	2.48E-05	24.750	5.50678
4.55E-05	45.500	0.04604	2.45E-05	24.500	5.50677
4.57E-05	45.750	0.04667	2.43E-05	24.250	5.50676
4.60E-05	46.000	0.04737	2.40E-05	24.000	5.50675
4.62E-05	46.250	0.04816	2.38E-05	23.750	5.50674
4.65E-05	46.500	0.04906	2.35E-05	23.500	5.50674
4.67E-05	46.750	0.05008	2.33E-05	23.250	5.50673
4.70E-05	47.000	0.05124	2.30E-05	23.000	5.50672
4.72E-05	47.250	0.05257	2.28E-05	22.750	5.50671

4.75E-05	47.500	0.05412	2.25E-05	22.500	5.50670
4.77E-05	47.750	0.05592	2.23E-05	22.250	5.50669
4.80E-05	48.000	0.05804	2.20E-05	22.000	5.50668
4.82E-05	48.250	0.06059	2.18E-05	21.750	5.50667
4.85E-05	48.500	0.06373	2.15E-05	21.500	5.50666
4.87E-05	48.750	0.06771	2.13E-05	21.250	5.50665
4.90E-05	49.000	0.07305	2.10E-05	21.000	5.50664
4.92E-05	49.250	0.08098	2.08E-05	20.750	5.50662
4.95E-05	49.500	0.09653	2.05E-05	20.500	5.50659
4.97E-05	49.750	5.50747	2.03E-05	20.250	0.04065
5.00E-05	50.000	5.50748	2.00E-05	20.000	0.04064
5.02E-05	50.250	5.50748	1.98E-05	19.750	0.04064
5.05E-05	50.500	5.50749	1.95E-05	19.500	0.04064
5.07E-05	50.750	5.50749	1.93E-05	19.250	0.04064
5.10E-05	51.000	5.50750	1.90E-05	19.000	0.04064
5.12E-05	51.250	5.50751	1.88E-05	18.750	0.04064
5.15E-05	51.500	5.50751	1.85E-05	18.500	0.04064
5.17E-05	51.750	5.50752	1.83E-05	18.250	0.04064
5.20E-05	52.000	5.50752	1.80E-05	18.000	0.04064
5.22E-05	52.250	5.50753	1.78E-05	17.750	0.04064
5.25E-05	52.500	5.50753	1.75E-05	17.500	0.04063
5.27E-05	52.750	5.50754	1.73E-05	17.250	0.04063
5.30E-05	53.000	5.50755	1.70E-05	17.000	0.04063
5.32E-05	53.250	5.50755	1.68E-05	16.750	0.04063
5.35E-05	53.500	5.50756	1.65E-05	16.500	0.04063
5.37E-05	53.750	5.50756	1.63E-05	16.250	0.04063
5.40E-05	54.000	5.50757	1.60E-05	16.000	0.04063
5.42E-05	54.250	5.50757	1.58E-05	15.750	0.04063
5.45E-05	54.500	5.50758	1.55E-05	15.500	0.04063
5.47E-05	54.750	5.50759	1.53E-05	15.250	0.04063
5.50E-05	55.000	5.50759	1.50E-05	15.000	0.04062
5.52E-05	55.250	5.50760	1.48E-05	14.750	0.04062
5.55E-05	55.500	5.50760	1.45E-05	14.500	0.04062
5.57E-05	55.750	5.50761	1.43E-05	14.250	0.04062
5.60E-05	56.000	5.50761	1.40E-05	14.000	0.04062
5.62E-05	56.250	5.50762	1.38E-05	13.750	0.04062
5.65E-05	56.500	5.50763	1.35E-05	13.500	0.04062
5.67E-05	56.750	5.50763	1.33E-05	13.250	0.04062
5.70E-05	57.000	5.50764	1.30E-05	13.000	0.04062
5.72E-05	57.250	5.50764	1.28E-05	12.750	0.04062
5.75E-05	57.500	5.50765	1.25E-05	12.500	0.04061
5.77E-05	57.750	5.50765	1.23E-05	12.250	0.04061
5.80E-05	58.000	5.50766	1.20E-05	12.000	0.04061
5.82E-05	58.250	5.50766	1.18E-05	11.750	0.04061
5.85E-05	58.500	5.50767	1.15E-05	11.500	0.04061
5.87E-05	58.750	5.50768	1.13E-05	11.250	0.04061
5.90E-05	59.000	5.50768	1.10E-05	11.000	0.04061
5.92E-05	59.250	5.50769	1.08E-05	10.750	0.04061
5.95E-05	59.500	5.50769	1.05E-05	10.500	0.04061
5.97E-05	59.750	5.50770	1.03E-05	10.250	0.04061
6.00E-05	60.000	5.50770	1.00E-05	10.000	0.04060