Report of

Chip Characterization on pixtest10

Semester Arbeit SS 2004

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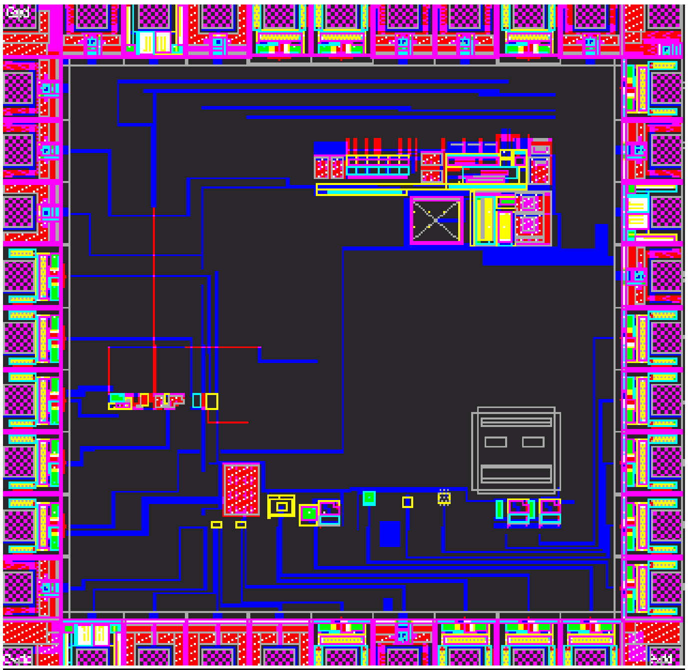

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Table of Contents

1 Project Objectives

This project is to measure and characterize some of the devices and circuits on the chip "pixtest10". The chip "pixtest10" is manufactured in AMI 1.50 micron CMOS process through MOSIS services, and packaged in a standard DIP40. The chip is tested with a pot-box, and the results are presented and discussed in this report.

The devices and circuits measured include: 3 source-follower n-p photodiodes, 2 connected p-n and n-p photodiodes, 1 p-n photodiode in the feedback loop of an opamp, and

2 Three Source-Follower n-p Photodiodes

These three photodiodes are all of n-p type, but with different implementations as n+ (source/drain) to p-substrate, n-well plus n+ (source/drain) to p-substrate, and n-well to p-substrate respectively. Figure 1 shows the schematic and Figure 2 shows the layout. It is worth mentioning that the third photodiode, marked as *pin38: nwellscr*, has only n-well as the source of the n-FET device.

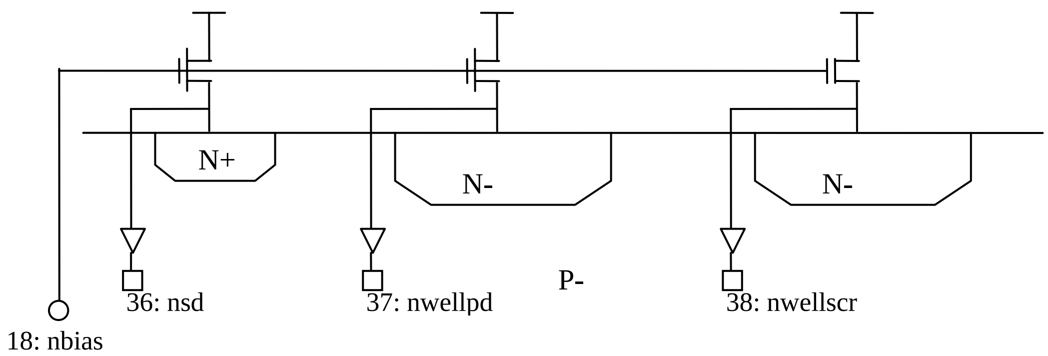


Figure 1 Schematic of 3 n-p Source-Follower Photodiodes

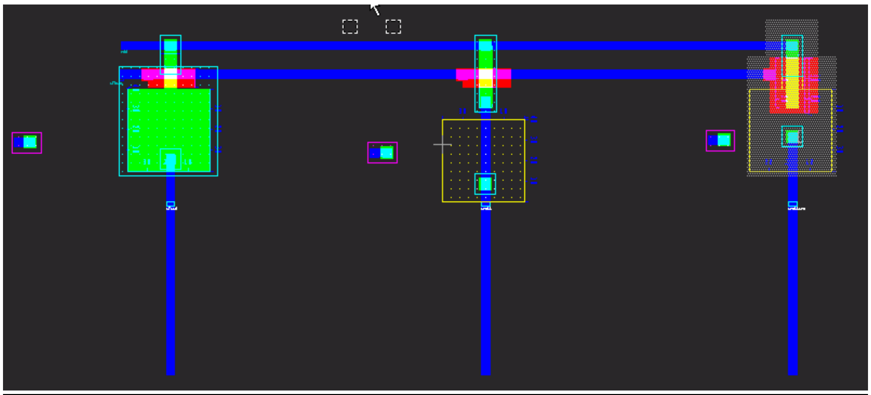


Figure 2 Layout of 3 n-p Source-Follower Photodiodes

Three diodes all have the same drawn size of 40um x 40um for the ease of comparison of measurement results.

2.1 Dark Current Measurements

2.1.1 Setup

The chip is shielded from light. The gate of the source follower transistors (*pin18: nbias*) is connected to a square wave input alternating between 0V and 5V. The frequency is set at 20mHz so that the period is long enough to measure the diode voltage drop caused by the leakage current.

The diode voltages (*pin36: nsd, pin37: nwellpd, pin38: nwellscr*) are probed and recorded by the oscilloscope.

2.1.2 Results

The photodiodes are reset when the gate is at 5V, and when the gate is switched to 0V, the diodes capacitors are discharged by the leakage currents. Therefore, voltages drop linearly with time as observed in Figure 3. The slopes are measured as nsd=132mV/20s, nwellpd=216mV/20s, and nwellscr=212mv/20s.

The dark current can be calculated by the equation, $I = C\frac{dV}{dt}$. The capacitance is calculated with the drawn size and the process parameter. The following table summarized the calculation.

Device	Capacitance	Voltage slope	Dark Current	Dark Current Density
nsd	495.5fF	132mV/20s	3.27fA	204.4pA/cm^2
nwellpd	212.5fF	216mV/20s	2.29fA	143.1pA/cm^2
nwellscr	192.0fF	212mV/20s	2.03fA	126.9pA/cm^2

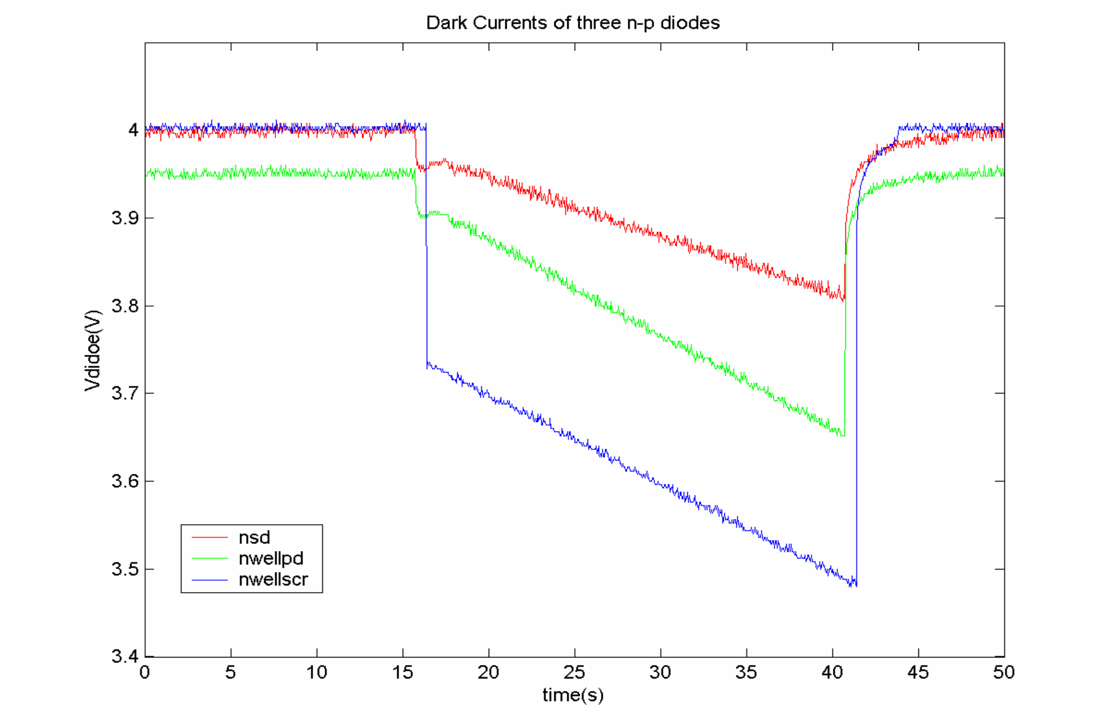


Figure 3 Dark Currents of 3 n-p Source Follower Photodiodes

As the nsd diffusion has a higher concentration than n-well, the smaller depletion width results in a larger diode capacitance. Therefore, the dark current of nsd-psub diode is larger than that of nwell-psub diodes, although the voltage drops faster for the nwell-psub diodes.

The dark currents of two different implementations of nwell-psub diodes are slightly different. The one without n+ diffusion has slightly better performance.

It is also noted that the nwell-psub diode without n+diffusion has a much larger step change compared to the other two diodes which are comparable to each other. As the n-well has a lower concentration than n+ diffusion, the channel charge tends to go to the n-well side (source) instead of n+ diffusion (drain).

2.2 Responsivity Measurements

2.2.1 Setup

The gate of the source follower transistors (*pin18: nbias*) is connected to a square wave input alternating between 0V and 5V. A green LED and a red LED are shinning on the die respectively. The diode voltages (*pin36: nsd, pin37: nwellpd, pin38: nwellscr*) are probed and recorded by the oscilloscope.

Then the gate of the source follower transistors (*pin18: nbias*) is connected to a fixed supply of 5V. A red LED shines on the die with 4 decades of filtering, and the diode voltages are recorded.

2.2.2 Results

The voltage drops after the reset switch is turned off, the slope is measured as nsd=360mV/800us, nwellpd=460mV/800us, nwellscr=500mV/800us for the green LED and nsd=112mV/800us, nwellpd=150mV/800us, nwellscr=164mV/800us for the red LED.

Device	Capacitance	Voltage slope	Photocurrent
nsd	495.5fF	Green: 360mV/800us	Green: 223.98pA
		Red: 112mV/800us	Red: 69.37pA
nwellpd	212.5fF	Green: 460mV/800us	Green: 112.19pA
		Red: 150mV/800us	Red: 39.84pA
nwellscr	192.0fF	Green: 500mV/800us	Green: 120pA
		Red: 164mV/800us	Red: 39.36pA

The photocurrents in response to the green LED are generally larger than those in response to the red LED, which is in accordance with the known optical property of silicon, i.e. the absorption coefficient drops as wavelength increases. The nsd-psub diode shows a larger reponsivity than nwell-psub diodes. This can be a result of the shallow depletion depth and wide depletion region of the nsd-psub diode. However, the difference in responsivities of two types of photodiodes at red is much smaller than the difference at green. This is because that the red photons penetrate deeper than the green, and the nwell has a larger depletion depth than n+ diffusion.

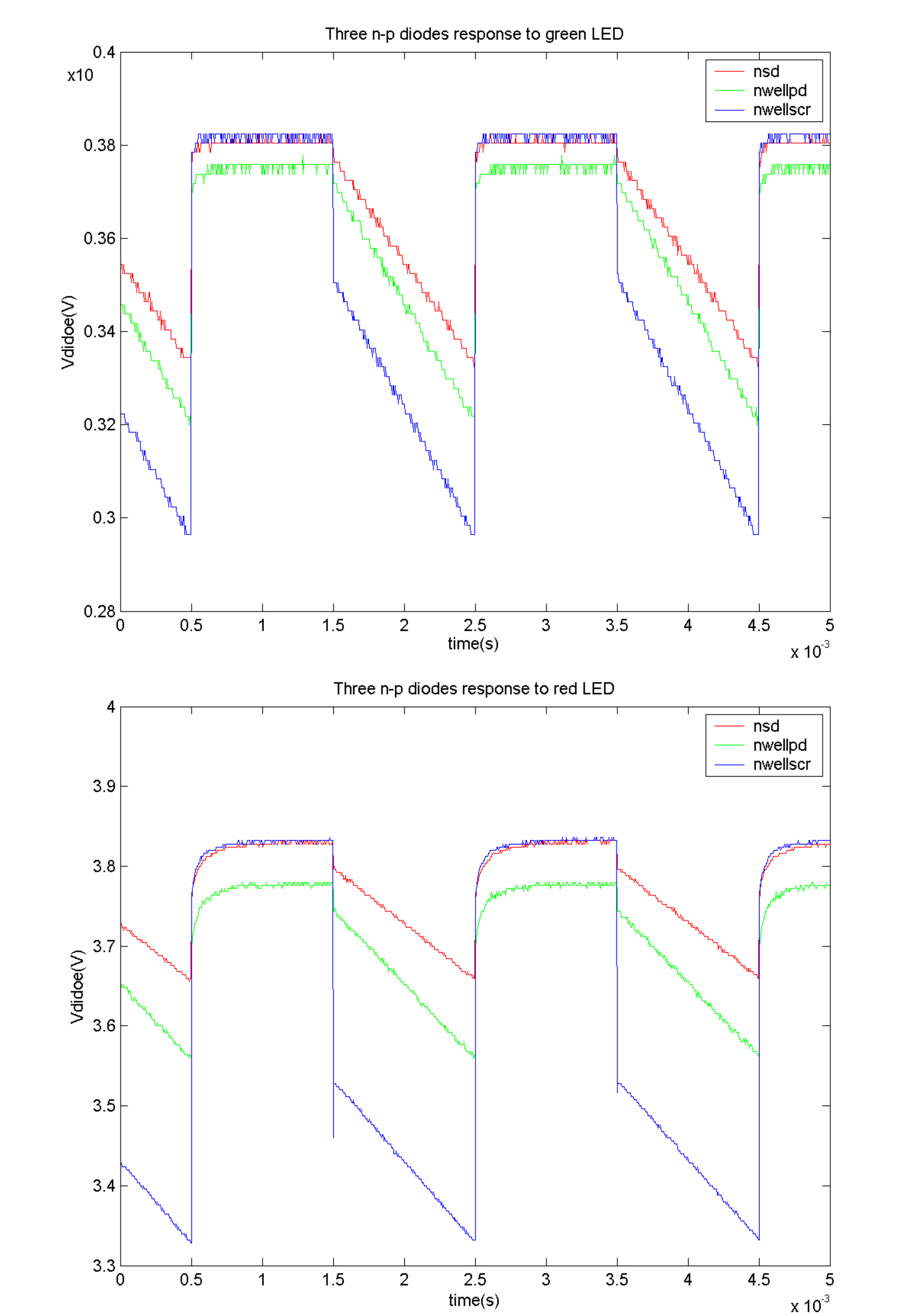


Figure 4 Voltages of 3 n-p Diodes in Response to Green and Red LEDs

Figure 5 shows the diodes' voltages with a red LED shining on the die through 4-decade filters. The measured voltages are summarized as follows:

nsd =	3.795V,	3.854V,	3.914V,	3.918V
nwellpd =	3.75V,	3.811V,	3.871V,	3.879V
nwellscr =	3.801V,	3.862V,	3.923V,	3.93V

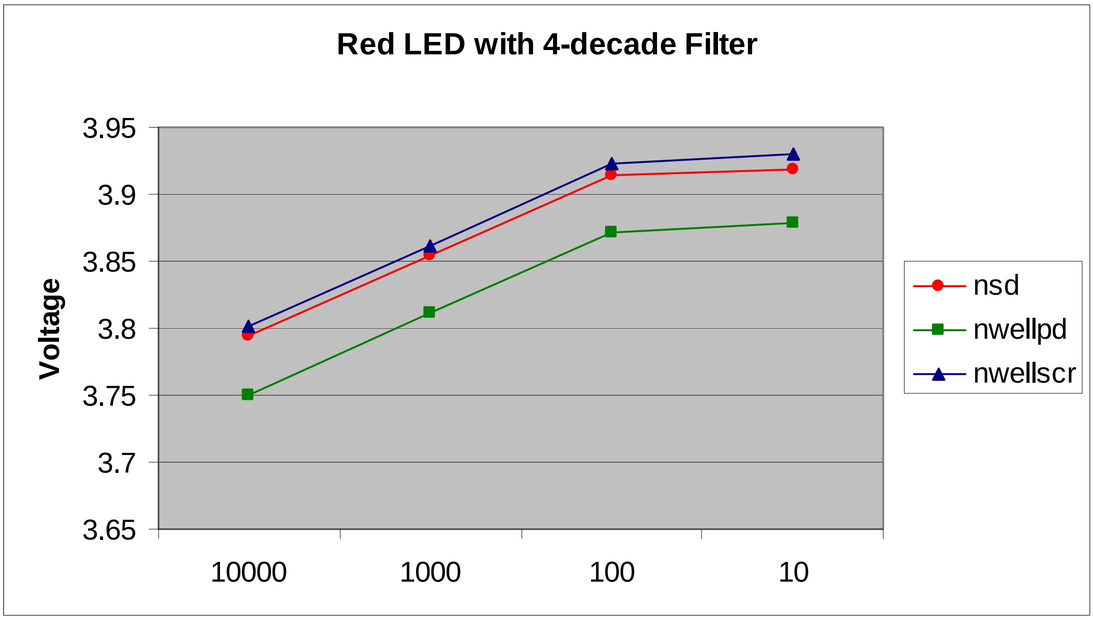


Figure 5 Voltages of 3 n-p Diodes in Response to Red LED with 4-decade Filtering

As expected, the voltages change linearly with the logarithmic of light intensity except for the last filter. This is probably due to the strong light filtering results in a very small photocurrent that is already comparable to the dark current.

2.3 Spectral Response Measurements

2.3.1 Setup

The gate of the source follower transistors (*pin18: nbias*) is connected to a fixed supply of 5V. A series of colors are displayed on the LCD screen in front of the die with a dark cloth shielding the stray light. The diode voltages (*pin36: nsd, pin37: nwellpd, pin38: nwellscr*) are recorded.

2.3.2 Results

The diode voltages are shown on the left three columns of the following table. The voltage differences to the reset levels are then calibrated, and shown on the right three column

Measured Voltages			Normalized Response		
nsd	Nwellpd	nwellscr	nsd	nwellpd	nwellscr
3.903	3.865	3.918	6.889E-01	6.148E-01	6.074E-01
3.893	3.8555	3.908	7.630E-01	6.852E-01	6.815E-01
3.891	3.8535	3.906	7.778E-01	7.000E-01	6.963E-01
3.891	3.8535	3.906	7.778E-01	7.000E-01	6.963E-01
3.892	3.854	3.906	7.704E-01	6.963E-01	6.963E-01
3.884	3.8465	3.899	8.296E-01	7.519E-01	7.481E-01
3.88	3.8425	3.895	8.593E-01	7.815E-01	7.778E-01
3.88	3.8425	3.895	8.593E-01	7.815E-01	7.778E-01
3.877	3.8385	3.89	8.815E-01	8.111E-01	8.148E-01
3.872	3.8315	3.88	9.185E-01	8.630E-01	8.889E-01
3.872	3.8315	3.88	9.185E-01	8.630E-01	8.889E-01
3.872	3.8315	3.88	9.185E-01	8.630E-01	8.889E-01
3.877	3.836	3.885	8.815E-01	8.296E-01	8.519E-01
3.875	3.8345	3.883	8.963E-01	8.407E-01	8.667E-01
3.875	3.833	3.881	8.963E-01	8.519E-01	8.815E-01
3.868	3.83	3.881	9.481E-01	8.741E-01	8.815E-01
3.868	3.8295	3.88	9.481E-01	8.778E-01	8.889E-01
3.865	3.8275	3.878	9.704E-01	8.926E-01	9.037E-01
3.861	3.8235	3.875	1.000E+00	9.222E-01	9.259E-01
3.861	3.8235	3.875	1.000E+00	9.222E-01	9.259E-01
3.864	3.827	3.878	9.778E-01	8.963E-01	9.037E-01
3.867	3.83	3.881	9.556E-01	8.741E-01	8.815E-01
3.871	3.833	3.884	9.259E-01	8.519E-01	8.593E-01
3.871	3.833	3.884	9.259E-01	8.519E-01	8.593E-01
3.873	3.837	3.887	9.111E-01	8.222E-01	8.370E-01
3.878	3.84	3.891	8.741E-01	8.000E-01	8.074E-01
3.88	3.8425	3.893	8.593E-01	7.815E-01	7.926E-01
3.881	3.843	3.893	8.519E-01	7.778E-01	7.926E-01
3.886	3.848	3.898	8.148E-01	7.407E-01	7.556E-01
3.893	3.854	3.905	7.630E-01	6.963E-01	7.037E-01
3.901	3.862	3.913	7.037E-01	6.370E-01	6.444E-01
3.943	3.903	3.953	3.926E-01	3.333E-01	3.481E-01

Figure 6 plots the measured diode voltages, and Figure 7 shows the calculated relative spectral response of three different n-p photodiodes.

As the plots shown, the response peaks around the green wavelength, and drops quickly at the red region. The response at blue region is small mainly due to the interface states. One can easily observe that the two nwell-psub diodes have similar response curves, and the nsd-psub diode has a larger response generally until into the deep red region. This is in line with what has been measured with green and red LEDs.

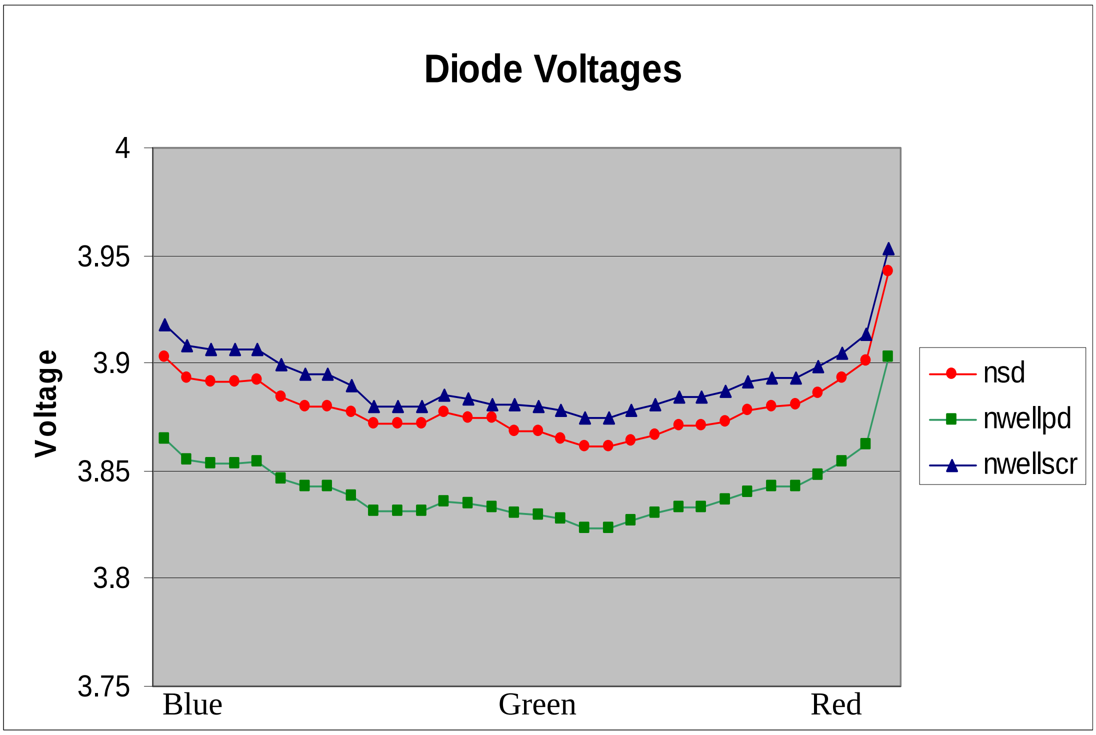


Figure 6 Voltages of 3 n-p Diodes at Different Wavelengths

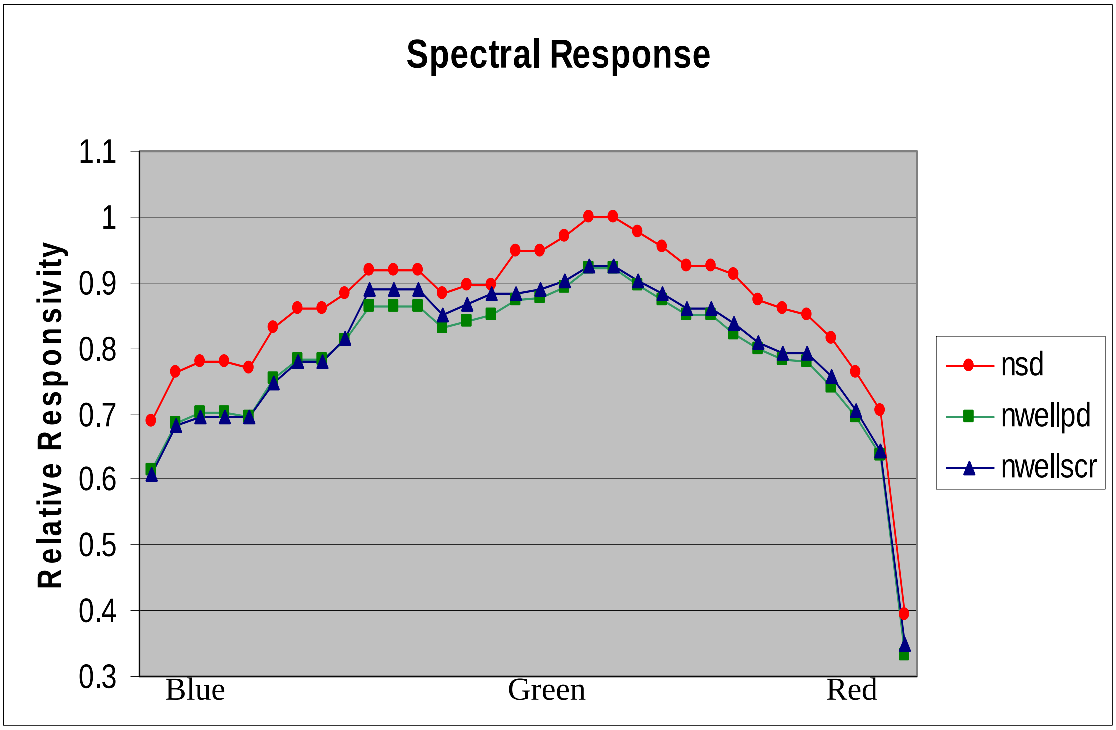


Figure 7 Relative Spectral Responses of 3 n-p Diodes

3 Two Connected p-n and n-p Photodiodes

Two different types of photodiodes are built on a common n-well. The n-well diffusion on p-sub forms the n-p diode, while a p+ diffusion sitting inside the n-well forms a p-n diode.

An n-FET is implemented with its source tied to ground, and drain connected to the p+ diffusion. A p-FET is implemented with its source tied to power supply, and drain connected to the n-well. They are used to reset the diode nodes: *pin33: psd*, and *pin32: nwell*.

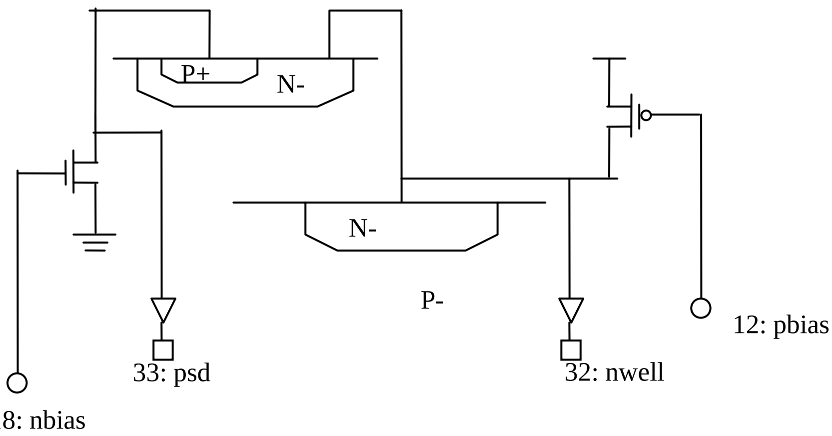


Figure 8 Schematic of 2 Connected p-n and n-p Photodiodes

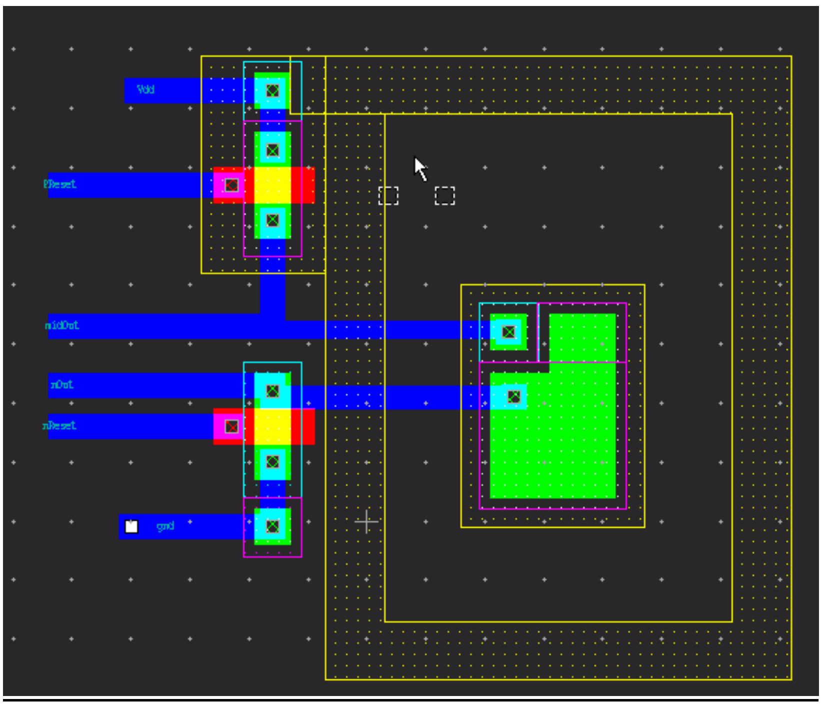


Figure 9 Layout of 2 Connected p-n and n-p Photodiodes

The n-well has a drawn size of 31um x 41um. The p+ diffusion consists of two rectangular shapes of 21um x 21um and 11um x 10um.

3.1 Dark Current Measurements

3.1.1 Setup

The chip is shielded from light. The gate of the n-FET transistor (*pin18: nbias*) is connected to a square wave input alternating between 0V and 5V while the gate of p-FET transistor (*pin12: pbias*) is tied to 0V. The frequency is set at 20mHz so that the period is long enough to measure the diode voltage drop caused by the leakage current. The diode voltage of p+ diffusion diode (*pin33: psd*) is probed and recorded by the oscilloscope.

Then the gate of the n-FET transistor (*pin18: nbias*) is tied to 5V, while the gate of the p-FET transistor (*pin12: pbias*) is connected to a square wave input alternating between 0V and 5V at 20mHz. The diode voltage of n-well diode (*pin32: nwell)* is recorded.

3.1.2 Results

As shown in Figure 10, diode voltages drop linearly with time as the reset switches are open. The slopes are measured as nwell=168mV/20s, and psd=28mv/20s.

The dark current can be calculated by the equation, $I = C\frac{dV}{dt}$. The capacitance is calculated with the drawn size and the process parameter. The following table summarized the calculation. Note that the p+ diffusion to n-well capacitance parameter is not provided by the foundry, only p+ diffusion to substrate parameter is used as an estimate.

Device	Capacitance	Voltage slope	Dark Current	Dark Current Density
Nwell	152.5fF	168mV/20s	1.28fA	100.8pA/cm^2
psd	191.3fF	28mV/20s	0.27fA	49pA/cm^2

The dark current density of nwell-psub diode is similar to the result presented in section 2. The difference could be due to the fact that the sidewall capacitance is ignored as there is no process parameter available.

It is also noted that psd-nwell has a much lower dark current density than nwell-psub diode.

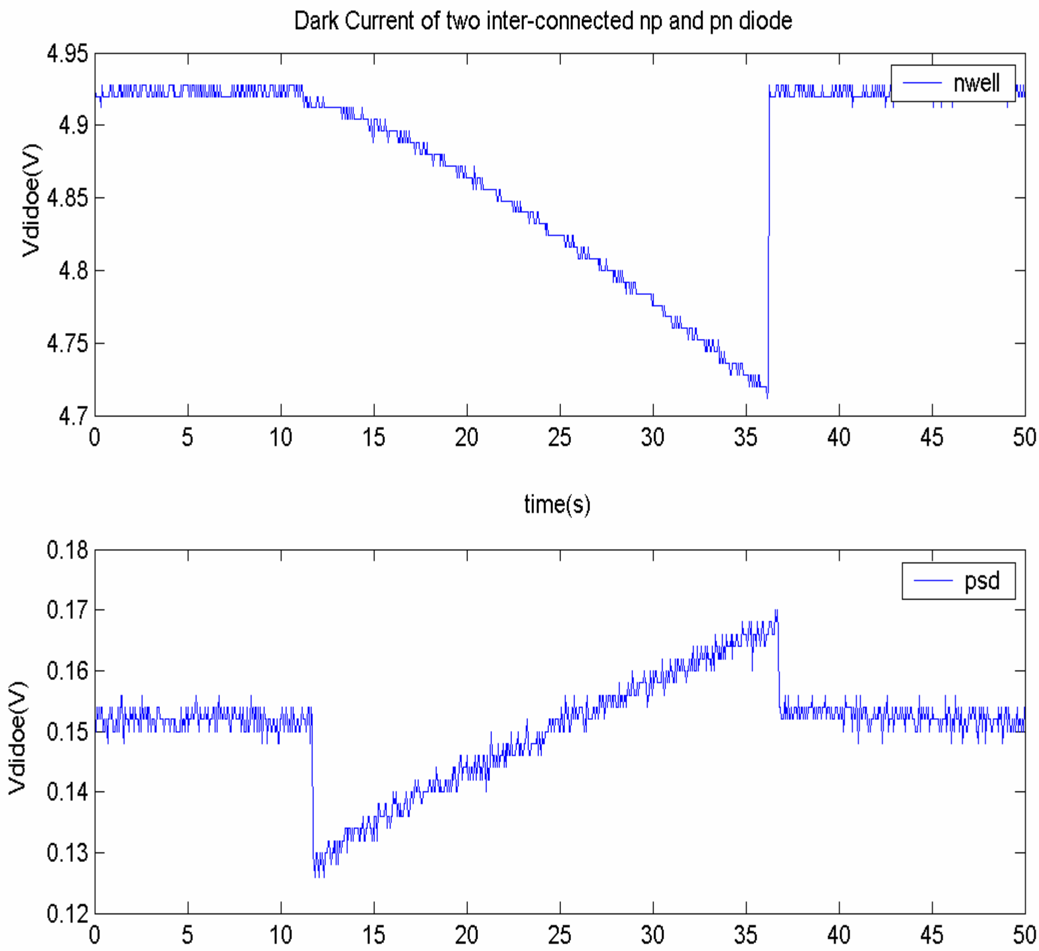


Figure 10 Dark Currents of 2 Connected p-n and n-p Photodiodes

3.2 Responsivity Measurements

3.2.1 Setup

The gate of the n-FET transistor (*pin18: nbias*) is connected to a square wave input alternating between 0V and 5V while the gate of p-FET transistor (*pin12: pbias*) is tied to 0V. A green LED and a red LED are shinning on the die respectively. The diode voltage of p+ diffusion diode (*pin33: psd*) is probed and recorded by the oscilloscope. Then a filter strip with 4-decade densities is used to filter the red LED and the diode voltages are measured.

Then the gate of the n-FET transistor (*pin18: nbias*) is tied to 5V, while the gate of the p-FET transistor (*pin12: pbias*) is connected to a square wave input alternating between 0V and 5V. The same experiments are carried out and the diode voltage of n-well diode (*pin32: nwell)* is recorded.

3.2.2 Results

The voltages drop after the reset switch is turned off, the slopes are measured as nwell=1.80V/50ms, psd=260mV/50ms for the red LED, and nwell=3.2V/20ms=8V/50ms, psd=1.42V/50ms for the green LED.

Device	Capacitance	Voltage slope	Photocurrent
psd	152.5fF	Green: 1.42V/50ms	Green: 4.33pA
		Red: 260mV/50ms	Red: 0.8pA
nwell	191.3fF	Green: 8V/50ms	Green: 30.61pA
		Red: 1.8V/50ms	Red: 6.89pA

The psd-nwell diode has a considerably smaller photocurrent than what nwell-psub diode has. This can be explained by the shallow diffusion depth of p+ diffusion inside n-well, and green and red photons are typically generated outside the depletion region and there is great opportunity for recombination before collected by psd.

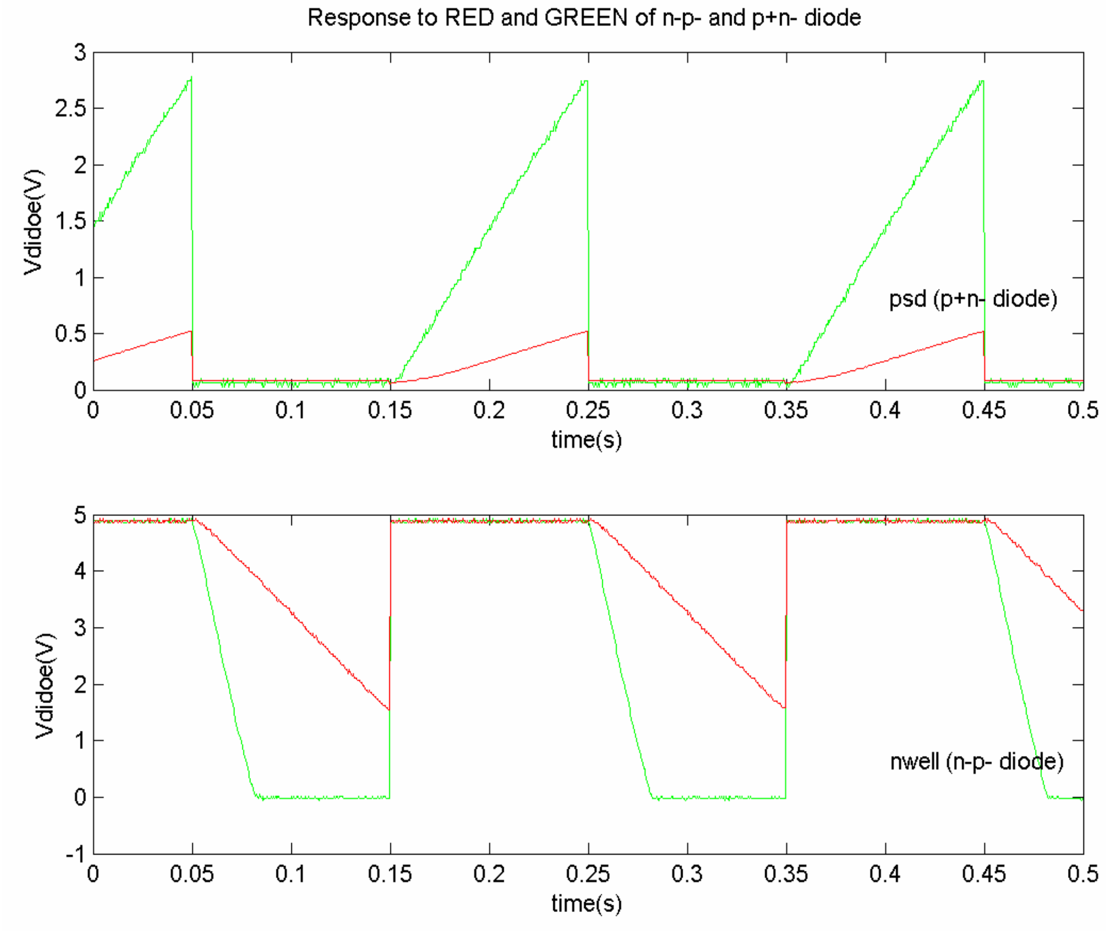
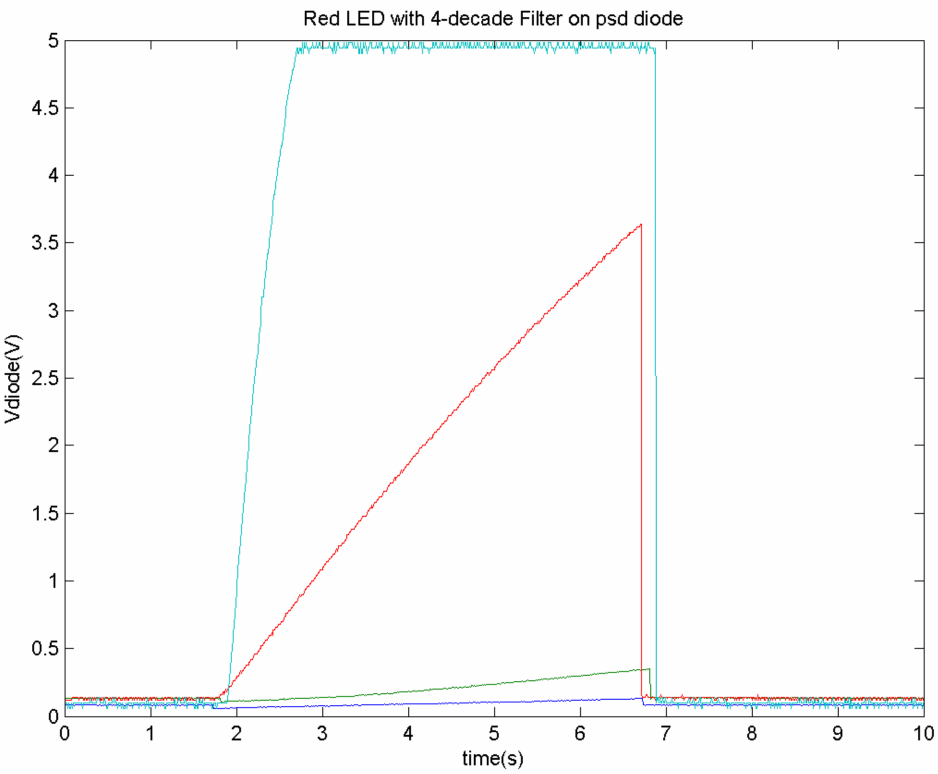


Figure 11 Voltages of 2 Connected p-n and n-p diodes in Response to Green and Red LEDs

The voltages are also measured with a red LED shining through 4-decade filters. Figure 12 shows the recorded voltage curves for both diodes at four different filter settings. The measured voltage slopes are summarized as follows:

psd =	2.56V/400ms,	1.4V/2s,	116mV/2s,	28mV/2s
nwell =	1.36V/20ms,	2.64V/400ms,	1.12V/2s,	400mV/2s

As the voltage slope is proportional to the photocurrent, it decreases exponentially with each increase of the filter density. The plot in Figure 12 therefore exhibits linear curves with semi-log scale. Again, the strongest filter results in the weakest optical power, and the dark current starts to be non-negligible which results in the change of the linear slope at the last step.



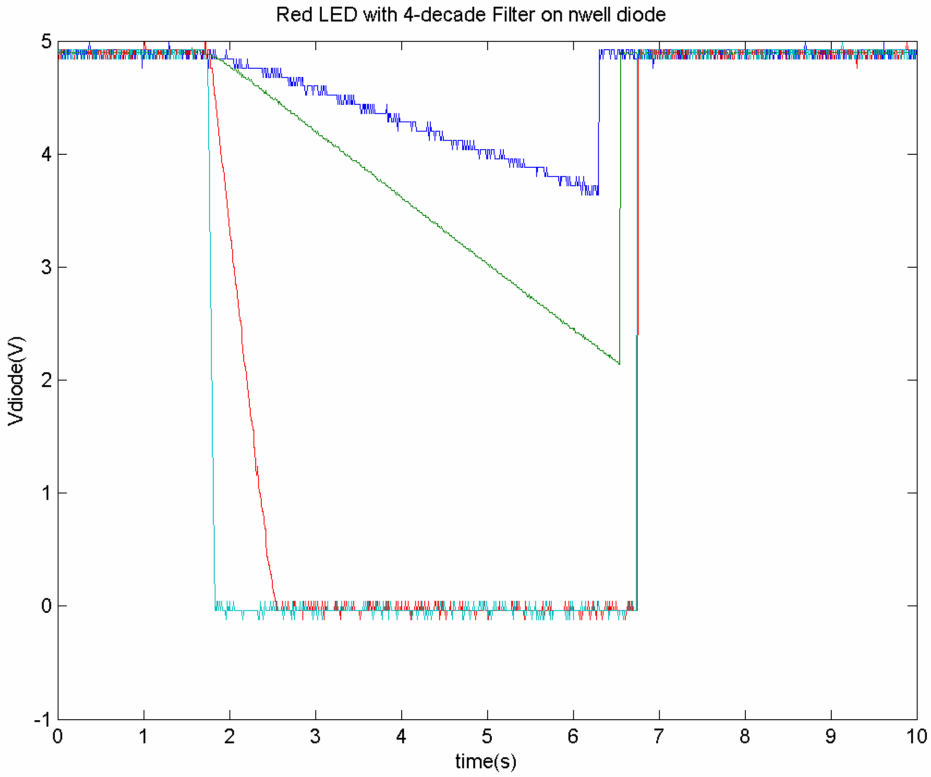


Figure 12 Voltages of 2 Connected p-n and n-p Diodes with 4-decade Filtering

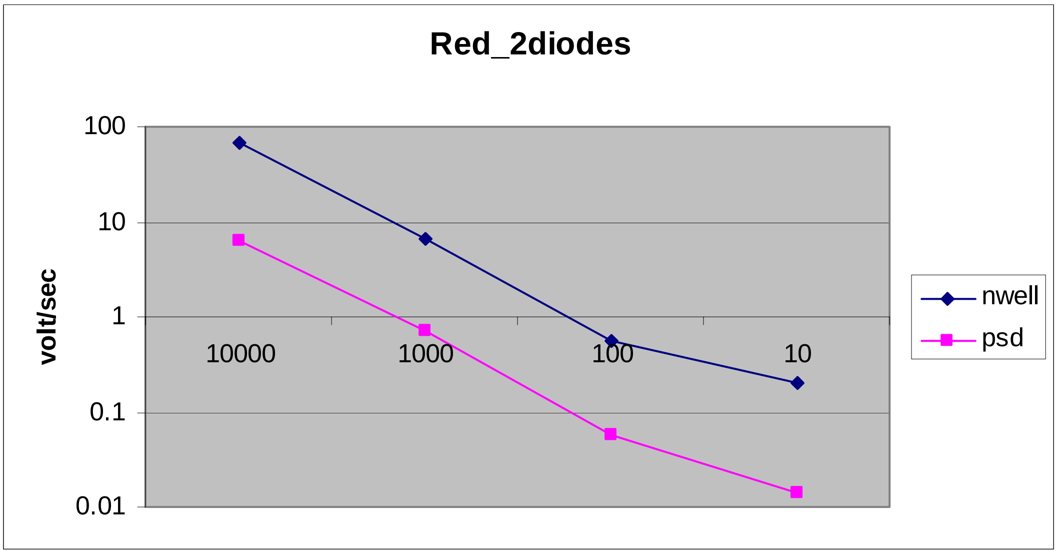


Figure 13 Voltage Slopes of 2 Connected p-n and n-p Diodes with 4-decade Filtering

4 One p-n Photodiode in the Feedback Loop of an OTA

A psd-nwell photodiode is connected in the feedback loop of an OTA (Operational Transconductance Amplifier) as shown in Figure 15. The OTA is a single-stage amplifier built with a p-FET differential pair as input devices.

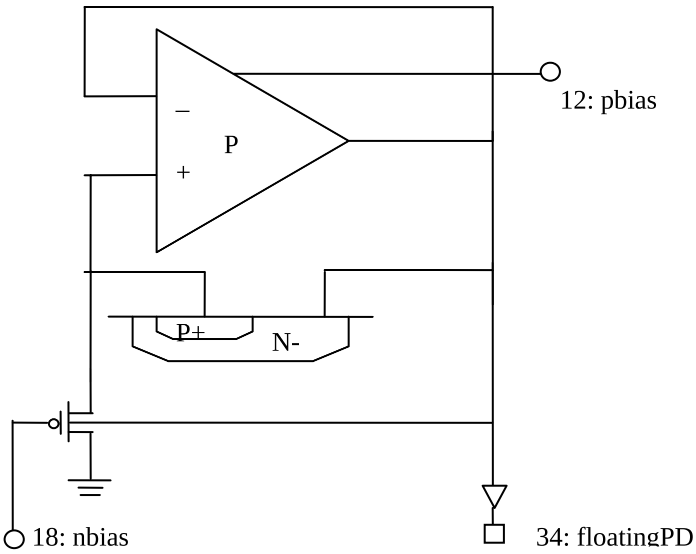


Figure 14 Schematic of 1 p-n Photodiode in the Feedback Loop of an Opamp

The negative feedback holds the inputs close to each other, i.e. at "Virtual Ground". The output follows the input as well due to the unity feedback. The photocurrent generated by light flows through the p-FET source follower to ground. Therefore, the output is determined by the bias condition and the characteristics of this p-FET device.

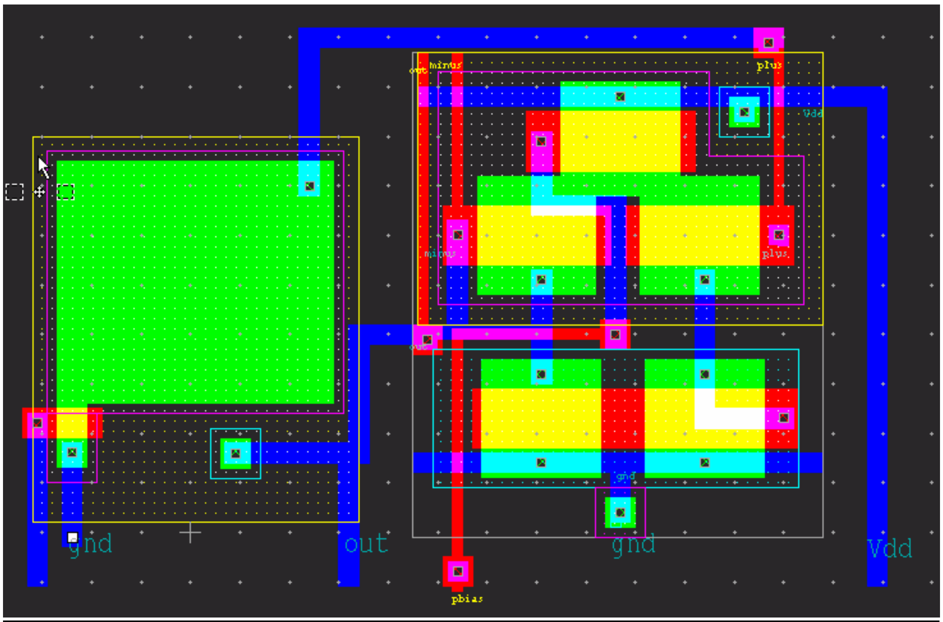


Figure 15 Layout of 1 p-n Photodiode in the Feedback Loop of an Opamp

Figure 15 shows the layout of this cell. The drawn size of the psd-nwell photodiode is 56um x 49um.

4.1 Responsivity Measurements

4.1.1 Setup

The gate of the p-FET transistor (*pin18: nbias*) is connected to a trianglular wave input alternating between 0V and 5V. The p-type OTA is biased (*pin12: pbias*) with a fix voltage of 4V. A green LED and a red LED are shinning on the die respectively. A filter strip with 4-decade densities is used to measure the response. The voltages at *pin34: floatingpd* are probed and measured by the oscilloscope, which represents the voltage at p+ diffusion, at n-well, at the source of p-FET source follower, and at the output of the OTA.

4.1.2 Results

The following figure shows the response when there is light shinning on the diode as the gate voltage is drived by a triangular waveform. The source voltage or the output of the OTA follows the input triangular wave with an offset except for the clipping at the level around 4.2V. This is explained by the architecture of the OTA. With just a single-stage configuration (no current mirrors or any other dedicated output stage to enhance the dynamics), the output voltage has an upper limit of 4.2V due to the voltage drop across the p-type input pair and the current source.

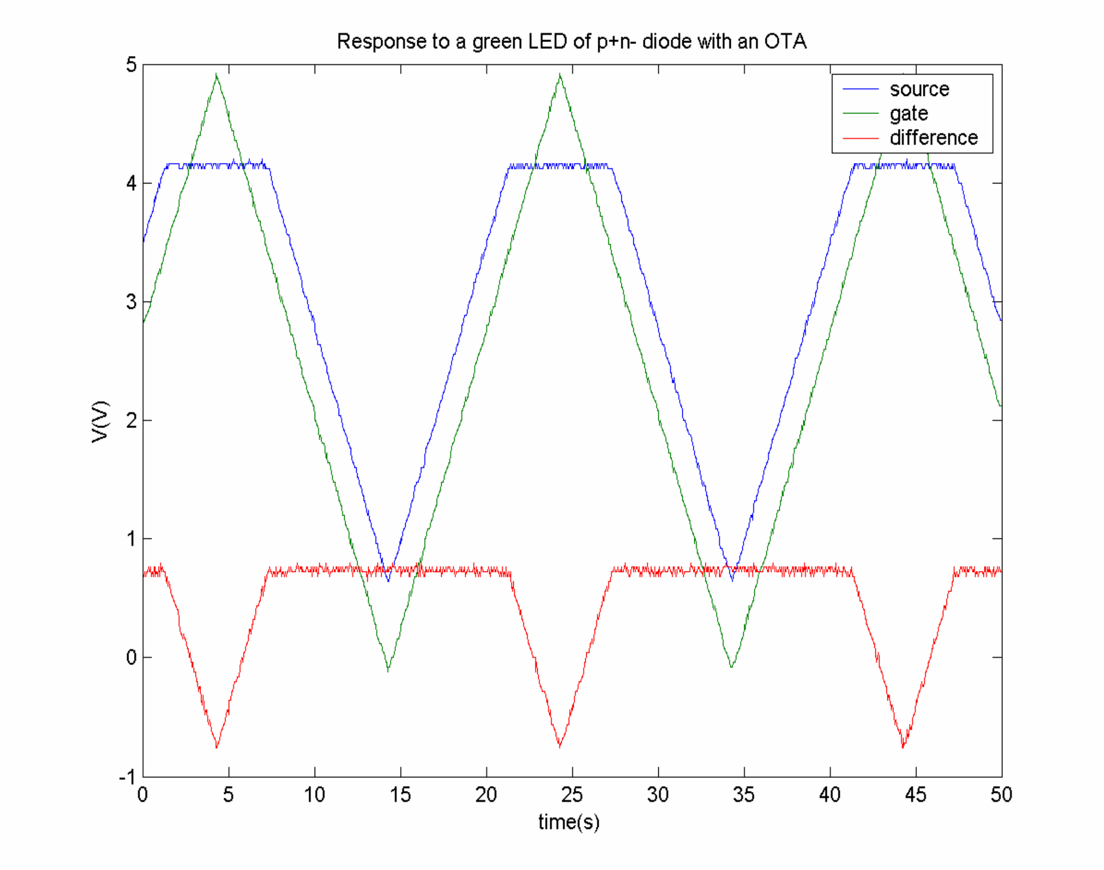


Figure 16 Response to a red LED of 1 p-n Diode in the Feedback Loop of an OTA

The offset is calculated and also shown in the same plot, which is at 0.71V. This offset is a value representing the responsivity to the optical power. Therefore, the offsets are recorded for different settings with the filters as shown in the following table.

LED	Filter Settings				
	X 1	X 10	X 100	X 1000	X 10000
Green	0.710V	0.629V	0.560V	0.524V	0.520V
Red	0.666V	0.591V	0.521V	0.516V	0.517V

Figure 17 shows that the voltage again responds linearly to the each decade of optical power decrease, until the dark signal starts to dominate the total output.

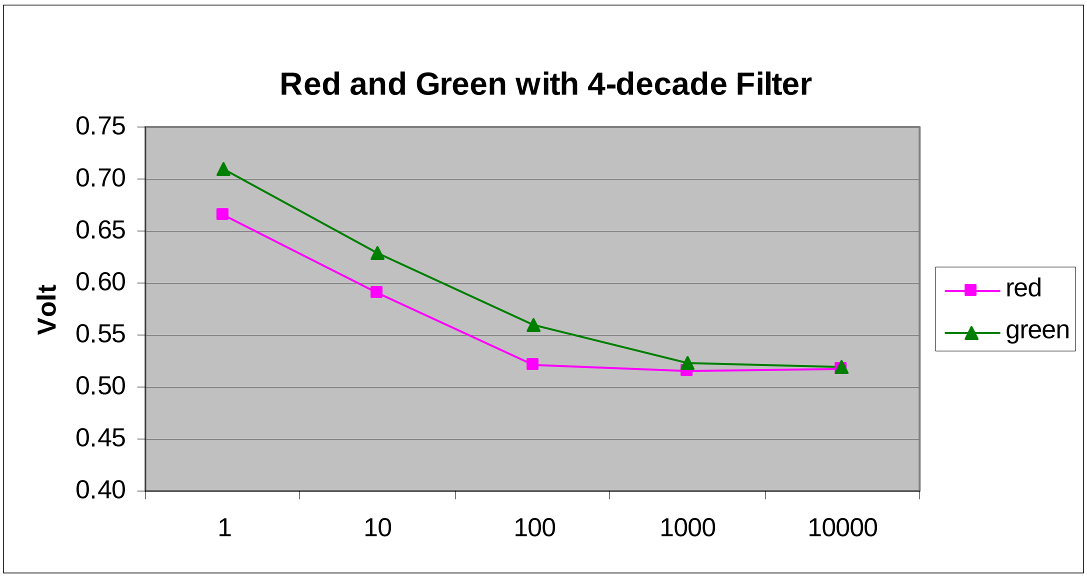


Figure 17 Response of 1 p-n Diode to Red and Green LEDs with 4-decade Filtering

4.2 Spectral Response Measurements

4.2.1 Setup

The gate of the p-FET transistor (*pin18: nbias*) is connected to a fixed voltage of 1V. The p-type OTA is biased (*pin12: pbias*) at 4V. A series of colors are displayed on the LCD screen in front of the die with a dark cloth shielding the stray light. The voltages at *pin34: floatingpd* are probed and recorded by the oscilloscope, which represents the voltage at p+ diffusion, at n-well, at the source of p-FET source follower, and at the output of the OTA.

4.2.2 Results

The diode voltages are shown on the first column from left of the following table. The offsets are then calculated and the relative responsivities are shown on the other column.

Figure 18 shows the relative responsivity in the spectral domain.

Measured Source Voltage	Normalized Response
1.526E+00	4.194E-01
1.532E+00	5.161E-01
1.533E+00	5.323E-01
1.534E+00	5.484E-01
1.534E+00	5.484E-01
1.533E+00	5.323E-01
1.545E+00	7.258E-01
1.551E+00	8.226E-01
1.548E+00	7.742E-01
1.552E+00	8.387E-01
1.558E+00	9.355E-01
1.560E+00	9.677E-01
1.561E+00	9.839E-01
1.560E+00	9.677E-01
1.560E+00	9.677E-01
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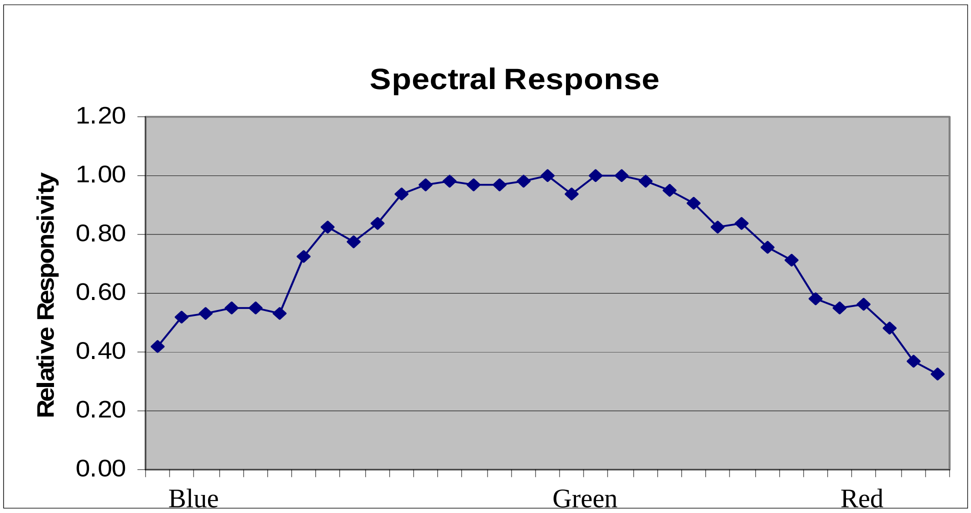

Figure 18 Relative Spectral Response of 1 p-n Diode in the Feedback Loop of an OTA

5 Adaptive Photoreceptor with LMC Circuit

The adaptive photoreceptor circuit described by Delbrueck [1] is used in this block. The photodiode acts like a current source with an n-FET source follower on top. A negative feedback loop is added to clamp the photodiode voltage so that the small photocurrent does not have to charge or discharge the big photodiode capacitance. The capacitor divider in the feedback loop amplifies the transient output voltage to have a higher small-signal gain. The resistive element implemented by a p-FET (Tobi's element [1]) is responsible for the adaptive behavior of the photoreceptor circuit. This adaptation allows the receptor to accommodate a large change in the background illumination i.e. a large dynamics.

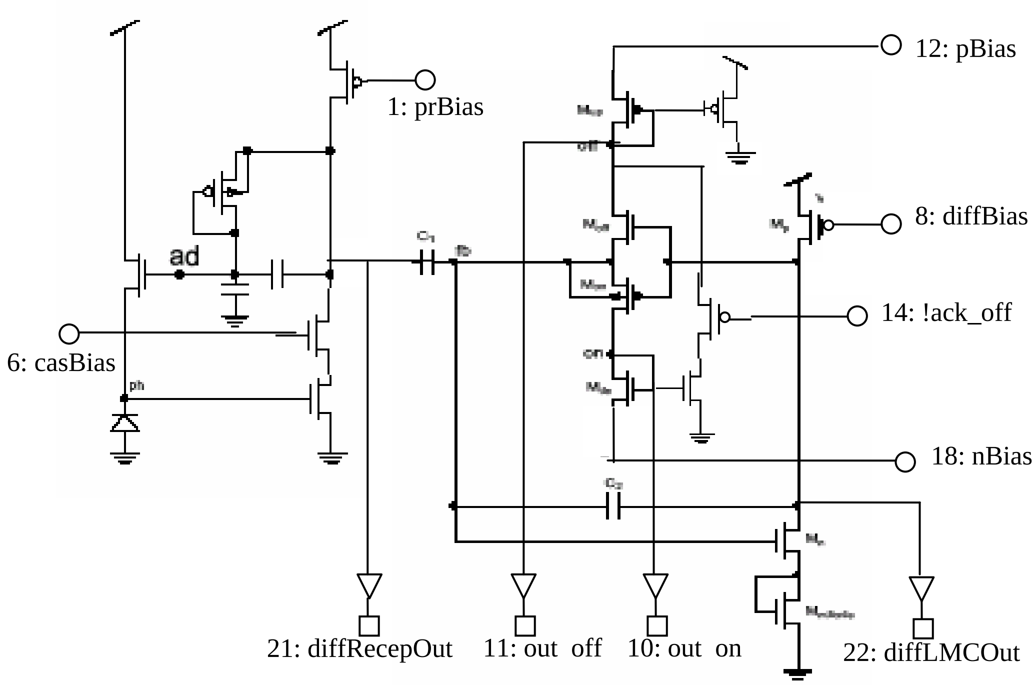

Figure 19 Schematic of Adaptive Photoreceptor and LMC Circuit

The output of the photoreceptor is then AC coupled to the LMC circuitry [2]. It works as a temporal differentiator with on/off circuitry built by a n-FET and a p-FET in common-source configuration. When diffRecepOut increases, fb node rises up and hence diffLMCOut decreases. This truned on the p-FET in on/off circuitry, and it discharges the fb node until it settles. When the diffRecepOut is decreasing, diffLMCOut increases. N-FET is turned on and it charges up the fb node until it settles.

5.1 Functionality Test

5.1.1 Setup

The die is illuminated by a pulsed LED at 20Hz 400mVpp. The bias condition of the circuit is as follows: *pin1: prBias*= 4.0V, *pin6: casBias*=1.14V, *pin8: diffBias*=4.0V, *pin12: pBias*=5V, *pin18: nBias*=0V, *pin14: !ack_off*=0V.

The outputs of both the photoreceptor and the LMC circuit are probed by oscilloscope. The on/off outputs are also recorded.

5.1.2 Results

The LED is pulsed by two types of function: square wave and triangular wave. Figure 20 shows the outputs of photoreceptor and LMC circuitry, and Figure 21 shows the on/off signals.

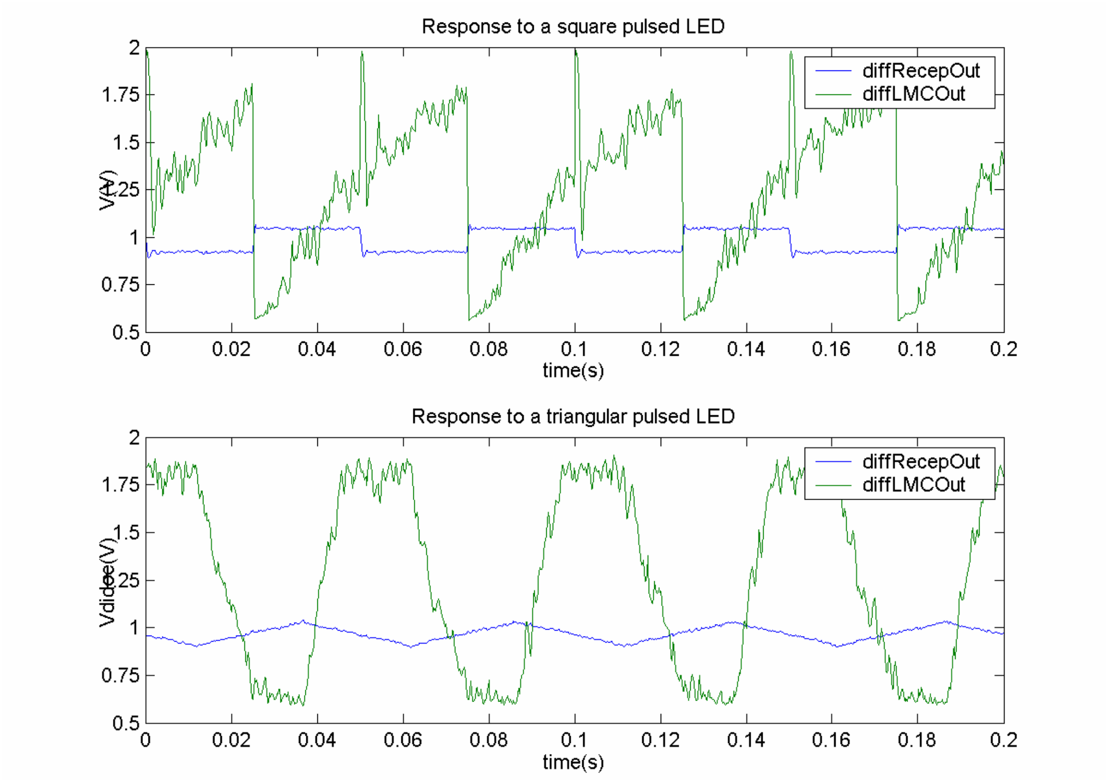

Figure 20 Response to Square and Triangular Wave Inputs of Photoreceptor and LMC

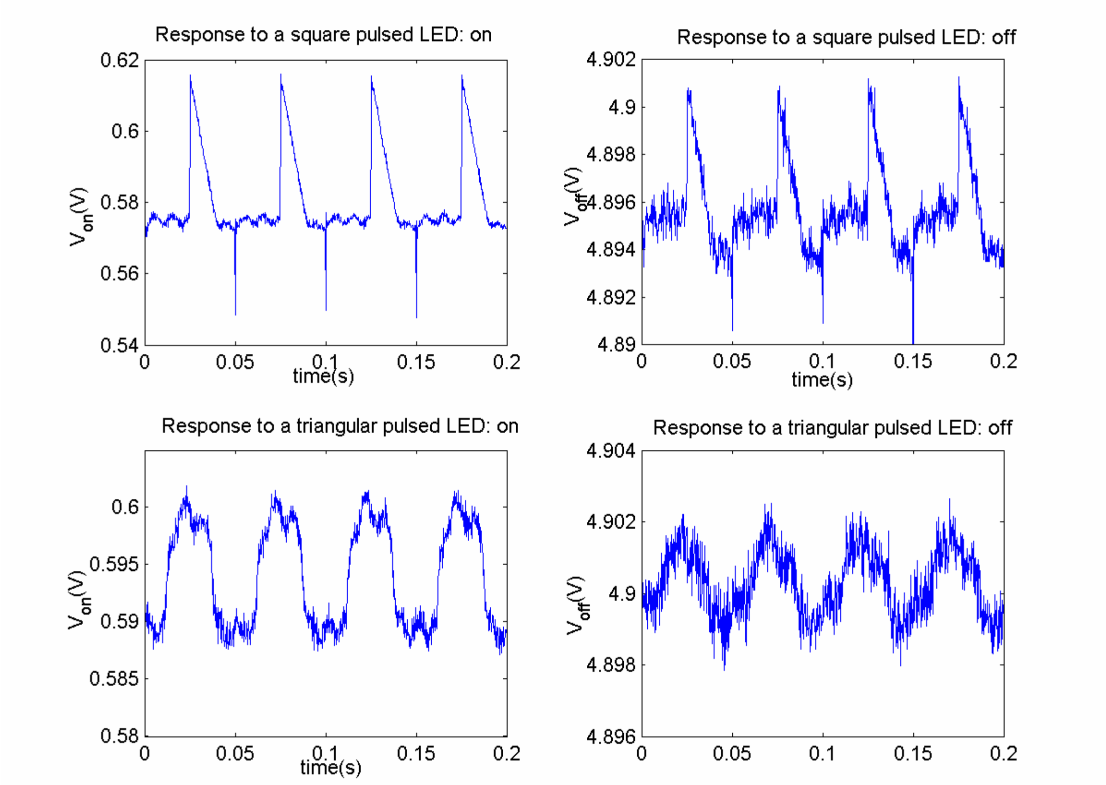

Figure 21 On/Off Signals in Response to Square and Triangular Wave Inputs

The output of photoreceptor well resembles the input waveform, and the output of LMC circuit represents the differentiation of the input signals as expected. For the square wave input, the LMC output has spikes in the opposite direction whenever the inputs toggles; for the triangular wave input, the LMC output changes states when the input wave toggles from rising to falling. The on/off signals also show the similar waveforms. The asymmetry is due to the difference between n-FET and p-FET.

References

[1]. T. Delbrueck and C.A. Mead; Analog VLSI adaptive logarithmic wide dynamic-range photoreceptor; In Proceedings of the International Circuits and Systems Meeting, London, May 1994.

[2]. S.-C. Liu, A neuromorphic aVLSI model of global motion processing in the fly , IEEE Transactions on Circuits and Systems II, Analog and Digital Signal Processing, 47:(12) 1458–1467, Dec, 2000

APPENDIX: Chip Layout