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Switching behavior of nano scale light sources

Master Thesis

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Abstract

Nowadays IC components get smaller and smaller, but the die sizes increase. To be able to interconnect the large dies from one side to another and in-between IC's a new LED has been developed for on-chip optical communication.

In this work the switching behavior of a 5nm ultrathin silicon PIN LEDs has been investigated. To do so first simulations of regular PIN diodes have been performed. These have been extended to simulations of the 5nm ultrathin diodes in different geometries. The DC-simulations have been compared to existing measurements results. When both the simulation and the measurements matched, transient simulations have been run to take a look at the switching behavior and speed.

The simulation results show that there is a huge potential for the new 5nm ultrathin devices. Some premature measurements did unfortunately not show this potential yet because of oscillation occurring in the measurement setup, but might in the future confirm the simulations.

A setup for transient electrical measurements as well a for optical measurements has been proposed and can be of use in future research on the newly developed ultrathin PIN LEDs.

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1 Introduction

Nowadays Integrated Circuits get larger in die size and therefore the interconnect distances significantly increase. They increase so much that electrical interconnects start to cause problems such as power loss and interference between one and another. One way to solve these problems is by going from electrical interconnects to optical ones. For integrating these optical interconnects on-chip or from one chip to another; one needs a light source to transmit the data into an optical wave guide and a sensor to detect the send signal at the end of the waveguide.

A lot of research is going on at the moment on developing emitters and sensors for communications purposes on chip and from one to another. The University of Twente developed a Silicon-On-Insulator (SOI) PIN Light Emitting Diode (LED) which can be produced using standard a CMOS process [2]. Development of such a diode on SOI has not been done yet and is very useful since a considerable amount of the modern integrated circuits make use of the advantages that SOI offers. This realized LED emits a record in light emission power and gets in the same range as bulk silicon PIN LEDs, but its switching behavior has not yet been tested.

The ultimate goal of this master thesis is to determine the (maximum) switching speed of the LED. Since the device is very small the power output is very small for doing optical and even electrical measurements, even though the emitted electro luminescent power is a new record. This requires a proper investigation at how to measure the switching behavior.

This report shows a possible guideline to measure the switching speed with some initial results. The results are compared with extensive simulations done with Atlas (a device simulator [10]) and finally conclusions will be drawn based on the results.

1.1 The Assignment

The assignment description given by the Semiconductor Components chair can be found in Appendix 1. Shortly it consists out of the following parts:

- Switching behavior of nano scale light sources
- Literature survey
- Electrical or optical measurement
- Maximum switching speed
- Electrical measurements
- Possible optical measurements
- Data analysis

The main goal of the master thesis is to determine what determines the switching behavior in the newly developed SOI LEDs switch and which switching speed can be reached. This can then be of vital importance for further development of the LED. To find out in what way the LED switches, a literature survey is done on previous reports discussing the switching behavior of PIN LEDs. If comparable research has been done it can give an insight in how to determine the switching speed.

After the literature survey a decision should be made whether to measure the switching speed by optical measurement, by electrical measurements or both. Within the present time frame (6 months for the master thesis) a good decision was made to get some decent results at the end.

Initially, it is expected that electrical measurements will be easier and therefore the main focus will be on the electrical measurements when these measurements will give very good results. If time allows it a look at optical measurements can be briefly evaluated. To be able to tell whether or not the electrical measurements yield credible results data analysis is performed. The results of the electrical measurements will be compared to simulation predictions.

From the analysis of all the gathered data conclusions on the switching speed and switching behavior are drawn and recommendations for future research on the LEDs shall be given.

2 Basics

2.1 Theory

The SOI LED under test is a newly developed LED with outstanding performance compared to existing PIN LEDs. The LED has been developed at the MESA+ institute by Dr. Tu [2]. It is in principle a PIN SOI LED, but with some ultrathin regions to boost the optical power output. A cross section of the device is shown in Figure 1.

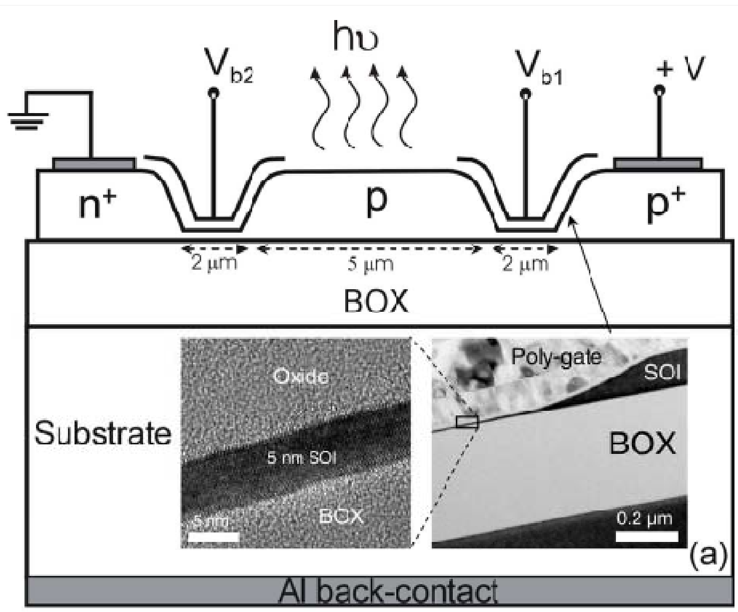


Figure 1 – Cross section of SOI LED under test

The SOI LED consists of a p-doped region on the right side, a lowly doped p-region in the middle and n-doped region on the left. Consequently, the device works in principle as a PIN Diode, but because of the ultrathin regions with two extra gates the efficiency of the LED has been increased by a factor two [2].

The LED can be switched on by applying a voltage on the anode of the device. Doing so, the device will inject holes from the p-doped region into the intrinsic region and electrons from the n-doped region. Inside the intrinsic region the charge carriers will recombine and a part of this recombination will generate light. The emitted light of the LED has a spectrum with a peak at about 1150nm. This means that the emitted light is Near InfraRed. From pictures made with an IR-camera from the device in on-state it shows that most light is emitted from the device transition regions where the thick silicon layer changes into the ultrathin layer. This can be ascribed to the fact that the ultrathin regions suffer from the band widening effect which occurs at these thicknesses. This will result in recombination in the intrinsic region because it takes less energy to recombine. This is important for optical measurements to take into consideration.

2.1.1 Thinning Effects

The ultrathin regions and applied biases on the gates on top of those regions affect the device behavior in 3 ways.

First of all the ultrathin regions make it harder for carriers to diffuse to the contacts since the space which they have to go through has drastically been decreased, which widens the bandgap in the ultrathin region and decreases the chance on recombination. Therefore the chance on recombination of these carriers inside the intrinsic region gets higher since they spend on average more time inside the intrinsic region. The simulated distribution of the radiative recombination rate across the device is shown in Figure 2 [2]. When the bandgap in the ultrathin regions increases, the recombination in these regions drastically decreases and results in more recombination in the intrinsic region.

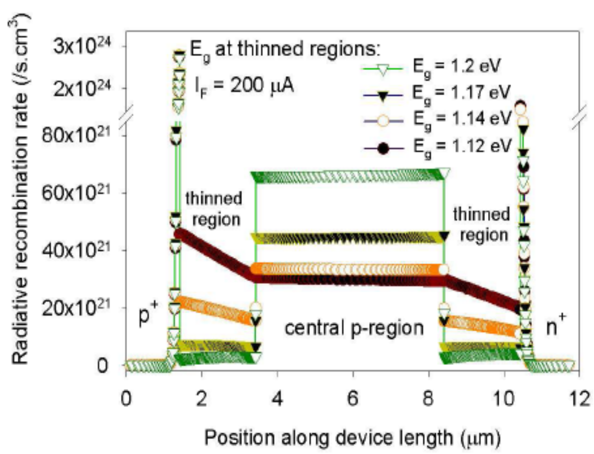


Figure 2 - Recombination rate distribution across the device [2]

Secondly the ultrathin regions reduce the contact recombination that normally occurs at the interface between the lowly doped middle "intrinsic" region and higher doped regions at the sides. Due to a smaller interface contact the carrier recombination has to take place inside the intrinsic region and therefore a part will contribute to the light emission.

The third mechanism for getting and keeping the carriers inside the intrinsic region is by applying a voltage on the gates adjacent to the ultrathin regions. By applying a negative voltage on the n-side gate and a positive voltage on the p-side gate the ultrathin regions will get an n-type and a p-type channel respectively. This attributes to a good transport of carriers from the p-region and n-region towards the intrinsic region. In the same time the negative voltage at the n-side is pushing away holes that want to recombine at that side and the positive voltage at the p-side does the same for electrons that want to recombine there. Since they will not be able to reach those sides they have to recombine inside the intrinsic region where they boost the light emission.

These three mechanisms together make the LED perform a lot better, which of the three is most important has to be investigated though. Dr. Tu reached significantly higher Electro Luminescent output power with ultra thin regions. A comparison between some different Si thicknesses of ultrathin regions can be found in Figure 3 [2].

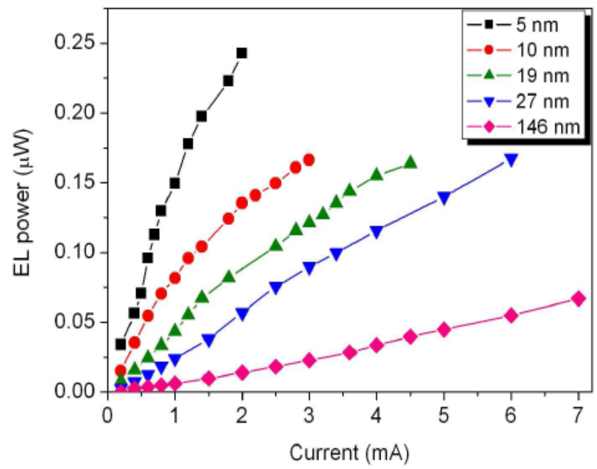


Figure 3 - Comparison of 5 devices with different ultrathin regions [2]

2.1.2 Switching Alternative

Besides switching by applying a voltage on the anode only a second option for switching the LED has been proposed. It operates by putting another gate on top of the (thick) intrinsic region and switches the light by putting a voltage on this gate. The effect is that when putting a positive voltage on the gate, electrons will be attracted to the top of the intrinsic region and holes will be pushed away so the two carriers will not have a chance to recombine. Therefore optically the device will be off. This method has a great disadvantage though, since continuously a current will keep flowing through the device it will not be power efficient which is not attractive.

At last there is an option of switching the device with the two gates that lay on top of the ultrathin regions. When instead of applying a bias to get a p-channel or an n-channel, the biases are switched, the channels in the ultrathin regions also change and therefore having a positive voltage on the anode should not result in a current since the gate creates a n-channel on that side and holes can not flow through.

2.1.3 Different Geometries

The new LED has been designed for several geometries; the intrinsic region as well as the ultrathin region has been varied in length. The ultrathin region also has variations in its thickness. Furthermore, all these different kind of LEDs are also made in different widths. LEDs with ultrathin regions have been designed for the following dimensions:

- Different intrinsic region lengths: 5µm, 10µm, 20µm, 30µ, 40µm, 50µm, 60µm
- Different widths: 20µm, 40µm, 60µm
- Different thinning region lengths: No thinning, 2µm, 5µm, 10µm, totally thinned
- Different thinning region thicknesses: 5nm, 10nm, 20nm, 30nm

Devices with an intrinsic region length of 5µm proved the largest current flow for the same applied cathode-anode bias (see 3.1.1). This is due to the fact that by increasing this length the series resistance also increases. More current (or low series resistance) yields more carriers to recombine in the intrinsic region and results in more light emission.

From previous research it has been concluded that the devices with 60µm width produce the most light, which is logical since the light production increases with larger widths, since there is more space for higher currents which increases the recombination. Furthermore from comparison it showed that devices with an ultrathin region yielded a higher light emitted output power compared to the one without these regions.

2.2 Expectations

Looking at the device structure some expectations on the switching speed can be given. The estimation of the switching speed depends on 2 parts: the on-switching of the LED and off-switching of the LED. Those two mechanisms are depending on different parameters and therefore will be dealt with separately.

2.2.1 On-Switching

On-switching of the LED is determined by the RC-delay that occurs when putting a voltage on the anode and leaving the cathode at ground level [3]. The capacitance of the device can be split into 2 parts, the gate capacitance from the bias gate and the depletion capacitance inside the intrinsic region. For this calculation a look has been taken at the smallest device with an intrinsic region of 5 x 60 x 0.15 μm^3. Bias voltages on the bias gates will not be taken into account. These conditions will give a worst case scenario, since applying the bias voltages will make the device faster.

The capacitance of the bias gate equals about 1pF. The depletion capacitance can be first order estimated at 7pF. Together with the bias gate capacitance this gives a total of 8pF capacitance which has to be charged when turning on the device [3].

The resistance of the device can be approximated at 1 kΩ. Together this gives a RC time of 8 ns which is pretty fast.

2.2.2 Off-Switching

When turning off the device a so called reverse recovery current occurs. During this reverse recovery, free carriers stored in the intrinsic region will recombine, but also start flowing towards the contacts which generates a current opposite to that in the on-state. The time it takes for all the free carriers to be gone is very important for the switching speed of the LED. When there is a reverse recovery current there are free carriers and therefore it is assumed that recombination occurs and the LED will still be able to emit light. In this work the device will be defined as electrically off when the reverse recovery current is reduced to 0A. That way it is sure that the LED is also optically off since no free carriers should exist anymore.

2.3 Simulations

Before measurements are done it is very important to have a reference on which the measurements can be compared with. Therefore device simulations were setup and run to get a realistic prediction of the measurements. The simulations were done in two steps.

First of all DC-simulations were done to compare with the measured data and to analyze the geometry dependency on the device performance.

Secondly, when the DC-simulations correspond (more or less) with the DC measurements, transient simulations were done to take a look at the switching behavior and speed of the devices. These simulations will give a first insight in the switching behavior and can be used as a reference for the measurements.

The simulations files are written in Deckbuild [9] and simulated in Atlas [10] from Silvaco. Deckbuild uses a so-called in-file for defining the simulation. In this in-file first the structure is defined and after that the simulation variables and output. Furthermore output-files are defined in which devices (structure .str-file) and simulations results (.log-files) are being stored. Depending on the place of the structure file it can contain detailed information on for example potentials, net doping concentrations, current density etc. throughout the whole device structure. This is very useful when one wants to find out what exactly happens at a certain time in the device. An example of an in-file can be found in Appendix 2.

In this part it will be shown what simulations exactly were done and what results are expected, to start with the DC-simulations and following after that the transient simulations.

2.3.1 DC-Simulations

DC-simulations are necessary to see whether the simulations are in agreement with the measurements. Measurements have been done already before by Dr. Tu [2] and were taken as a reference, for a small number of devices additional measurements have been made to see whether same results can be obtained as the measurements that where done before. When the DC-simulations correspond with the measurements it shows that the simulations are good. A series of simulations are run, initially, straightforward simulations of regular PIN diodes without thinning. An example of these structures can be found below in Figure 4.

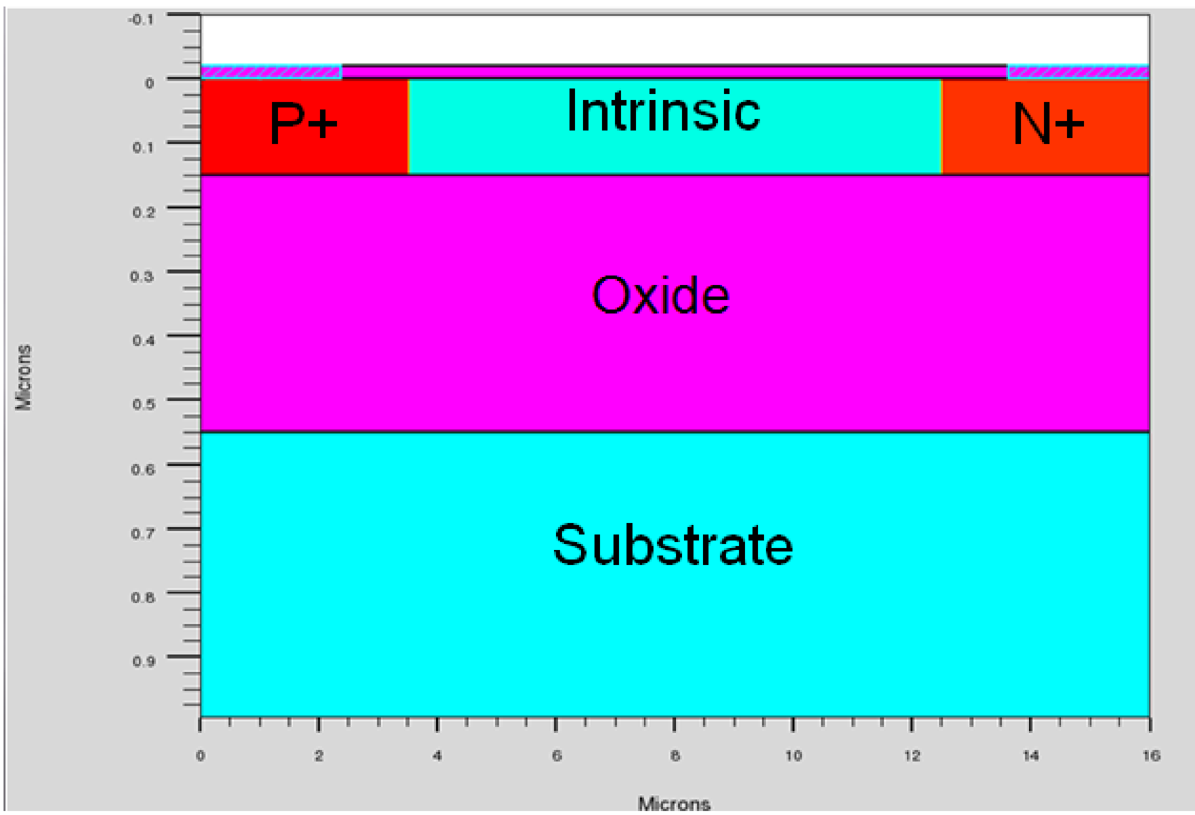


Figure 4 - Simulated Regular PIN diode structure example

This example is a regular PIN diode with an intrinsic region of 10µm, a doped P-Region on the left side and a doped N-region on the right. The DC-simulations are run as follows: The voltage on the anode is swept from -2V to 4V while the current trough the anode is being measured. The device has been simulated only in 2D so the values obtained from the simulator are per 1µm width and need to be multiplied by 60 to be comparable with the measured devices which are 60µm wide.

A limited number of regular PIN diodes have been processed and measured and therefore only the same sizes are being simulated. These sizes are the following: 5µm, 10µm, 20µm, 30µm, 40µm, 50µm, 60µm. For simulating the diodes the program in Appendix 2 has been written.

The in-file in Appendix 2 is globally built up as follows:

1. Loop declaration which sweeps the length of the PIN diode for each run
2. Mesh definition defining the number of calculation points
3. Structure definition
4. Doping definition
5. Contact creation
6. Simulation statements

Running the in-file on Atlas will output 7 log-files with information at all time steps. Per log-file information of 1 length of the intrinsic region is saved. When needed at any time an extra line in the in-file can output the state of the structure at a specific voltage at any time. This is convenient when unexpected behavior occurs at some place in the DC-sweep.

With all simulations different models have been used for simulating the devices. The models used are the following:

CVT	Lombardi mobility model, complete model including N, T, E// and E⊥
bgn.klassen	Bandgap narrowing model with Klaassen defaults
klaaug	The Klaassen Auger recombination model
klasrh	The Klaassen Shockley Read Hall recombination model
optr	Optical recombination model
conmob	Model for using concentration dependent mobilities
fldmob	Model for lateral electric field-dependent mobility

N = dopant concentration
T = lattice temperature
E// = parallel electric field
E⊥ = perpendicular electric field

With these models it is possible to get the best simulation results for SOI structures.

The methods used to solve the equations are Gummel, Block and Newton. The Gummel method is used to get a good initial guess after which the Block method takes over to solve the equations till convergence has been reached. The Block method is a combination of the decoupled Gummel method and the totally coupled Newton method. When the block method does not reach convergence, finally the Newton method will try to solve the equations. Using only the Newton method is also an option, but uses more time than the other two.

The 5nm ultrathin diodes have been made in a way just like the regular PIN diode. Just 2 thinned areas have been added. Furthermore the ultrathin layers in the structures have been defined as Poly-Silicon to be able to specify a different bandgap instead of the Silicon bandgap of 1.12eV. The value for the bandgap for the ultrathin regions comes from simulations done before [2]. An example of an ultrathin structure can be found in Figure 5. In this case it's an ultrathin PIN LED with a 5µm intrinsic region.

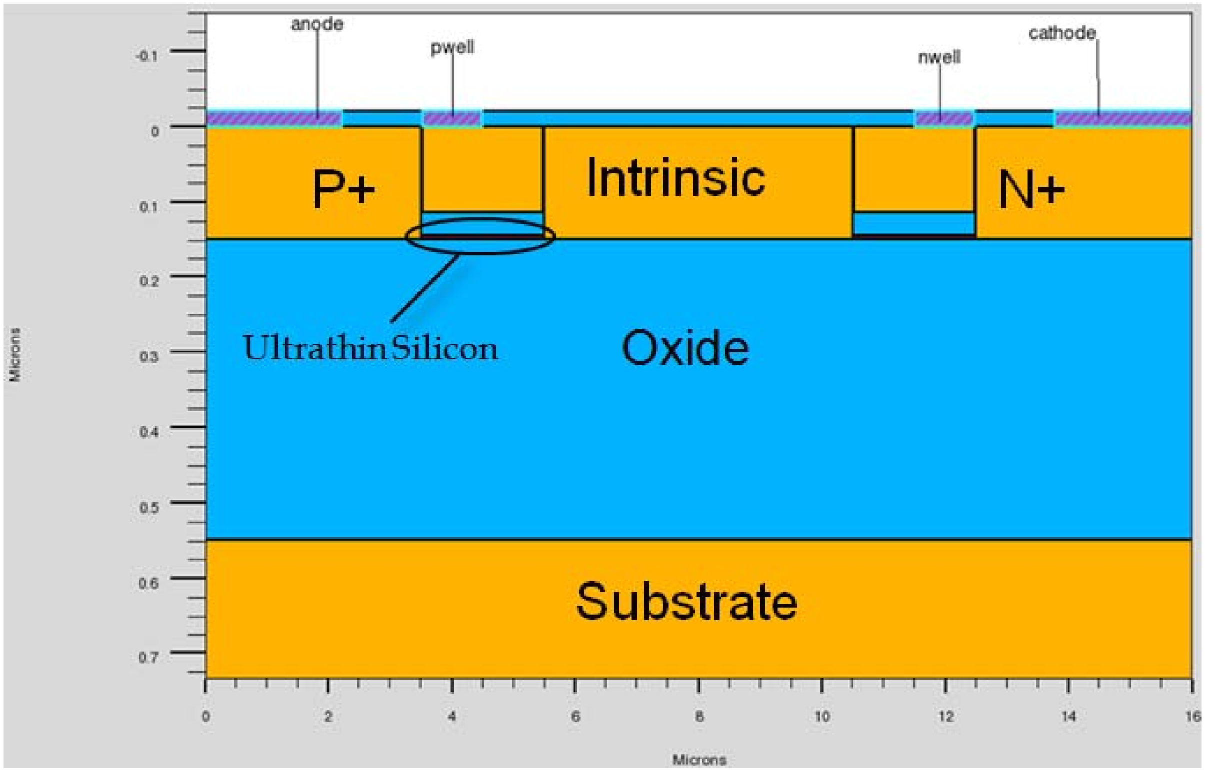


Figure 5 - Example structure of a 5nm thinned PIN LED

The way the in-file for the ultrathin diode is made up is identical to that of the regular pin. The used in-file can be found in Appendix 3.

2.3.2 Transient Simulations

Transient simulations are being run in the same way as the DC-simulations. The same in-file can be used, by just adding some extra sentences at the end of the file instead of the DC-simulations statements. The simulator will build up the structure just like in the DC-simulations but instead of sweeping the voltage on the anode the simulator makes voltage steps on the anode in time.

For transient simulations steps of 2V on the anode are used while the cathode is grounded. At 2V the LED should emit sufficient light.

In the in-file the following lines are added for transient simulations:

```
SOLVE l.wave=1.150 vanode=2.0 RAMPTIME=1e-11 TSTOP=10e-9 TSTEP=1e-12
SOLVE l.wave=1.150 vanode=0 RAMPTIME=1e-11 TSTOP=20e-9 TSTEP=1e-12
SOLVE l.wave=1.150 vanode=2.0 RAMPTIME=1e-11 TSTOP=30e-9 TSTEP=1e-12
```

Adding an extra L.WAVE parameter to the SOLVE statement puts out information about the Electro Luminescent power output of the device. That way it shows exactly when the LED emits light. It does not affect the simulation other than that it adds extra output information on electro luminescence. It can be used to define the switching speed of the LED. It has a small drawback though; the statement specifies a wavelength at which the EL power is being measured, so other wavelengths are kept out of scope. Since the spectrum of the LED has been measured already (see Figure 6) the specified wavelength will be at the peak at 1150nm [2].

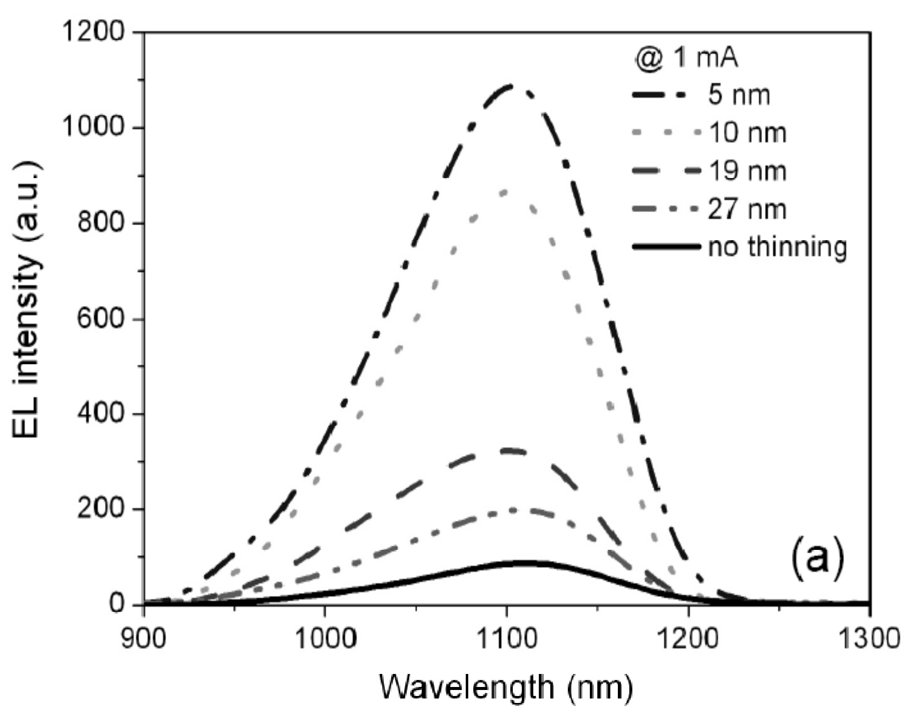


Figure 6 – Wavelength emission spectrum [2]

2.4 Measurements

The switching behavior and speed can be measured in several ways, for example by means of an optical measurement and by means of an electrical measurement. From a literature survey on these devices it appears that there has been very little research on measuring the switching behavior of PIN LEDs. Some simulation models [1] and analyses on PIN LED have been derived, but no device measurements have been found. This leaves all options open for measuring the switching behavior. The options of measuring, optical and electrical will be evaluated here, but before looking at these methods first an approximation of the values to be measured should be made.

2.4.1 Measurement conditions

The LED we will measure has a relatively high output power, but still the maximum Electro Luminescent (EL) power emission is very low. Measurements done in previous work of Dr. Tu [2] show a maximum EL power of about 0.25μW for the best device (5nm thick and 2μm long ultrathin regions, 5μm intrinsic region length and 60μm wide).

2.4.2 Optical measurement

The first option of measurement is an optical measurement of the light emitted by the LED. This can be done in several ways. The switching speed can be directly measured with an IR light sensor (for example a photodiode) by switching on and off the device and measure the current flowing through the light sensor. This is a straightforward method that does not need any lenses so that the total loss from the LED to the sensor can be kept small (approx. 10x). This seems the best way to say something about the switching speed in a quantitative way.

Another way of measuring the speed is by means of an IR-camera which already has been used to show where the LED emits light and how much power is emitted. This way of measurement has a couple of disadvantages: coupling the device to the camera introduces losses in the emitted power and the power emitted is already very low when switching speeds of about 1MHz have to be reached. Also IR-camera's consist of lots of pixels which have to be read out when a picture has been taken and therefore the speed of the camera is much too small. Measuring with a camera will work in the order of hertz's.

Photodiode

Since the chance on succeeding in an optical measurement was estimated at very small just a small investigation in this area has been done. From the literature survey no papers on optical measurements of PIN LEDs have been found and therefore a choice for a photodiode to measure with was wide open.

A short search for a suitable photodiode for the first way of optical measurement mentioned before resulted in the following photodiode:

Figure 7 – Thorlabs FGA10 InGaAs photodiode [4]

This InGaAs photodiode [4] was selected because of its specifications which should be sufficient for detecting light coming from the LED. The photodiode has the following specifications:

Spectral range:	700-1800nm
Active Area:	0.79mm^2 (Ø1)
Diode package:	TO-5/PIN
Rise/fall time:	7ns @ 5V bias
Noise-equivalent power:	2.5x10^{-14} @ 900nm
Typical Dark Current:	25nA @ 5V bias
Junction Capacitance:	80pF @ 0V

The most important specifications are the spectral range and the rise/fall time together with the NEP. The NEP gives the sensitivity of the detector; it states in this case the minimum detectable power per square root bandwidth. Since for first measurements the switching speed will be low, the sensitivity should be high enough.

Looking at the responsitivity of the photodiode in Figure 8 the photodiode should deliver a current of about 0.2µA when the LED emits 0.25µW of EL power. Measuring over a 50Ω resistor should give a voltage of about 1µV which is a detectable value. Since the optical measurement is only meant as a quantitive way of looking at the switching speed, it is not really necessary to take a look at the exact values.

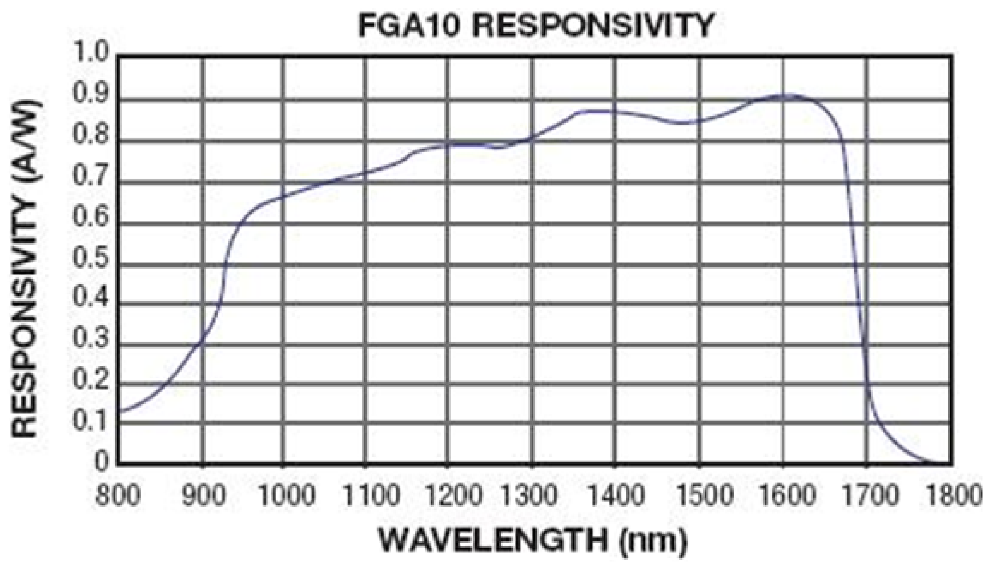


Figure 8 - Responsitivity of FGA10 photodiode

To start with a look at very low switching speed (1Hz till 10Hz) will give an insight in whether or not this optical measurement works. The 7ns rise/fall time is not needed and the photodiode should generate enough current to measure it without biasing. When this gives good results the switching speed can be increased and the diode can be biased to obtain the rise/fall time that might be needed.

2.4.3 Electrical measurement

Electrical measurements are done to get a good look at the switching behavior and to draw conclusions from this behavior. The main conclusion is the determination of the switching speed which can be derived from the electrical measurements. Since the current through the LEDs will be about 1mA and switching speeds up to preferably 1MHz want to be obtained it will still be hard to get good electrical results.

Various electrical measurements are relevant for this master thesis and will be discussed here, these are the following:

- DC-measurements
- Transient on-switching behavior measurement
- Transient off-switching behavior measurement
- Transient switching speed measurement

The DC-measurements are important to check whether the simulations are in agreement with the measurements. DC-measurements are relatively easy to do and can therefore be trusted as a good reference. The measurements have been done before by Dr. Tu. For this thesis some have been repeated to see if the same results can be obtained to verify the measurements done before.

Transient on-switching behavior measurements are measurements where the current is being measured while the anode of the LED is being stepped from 0V to a positive voltage. Zooming in on this point shows in what way the current reacts on this sudden change in voltage by which the operation of the LED during on-switching can be explained

Transient off-switching behavior measurements are just alike the on-switching measurements, but instead of putting a positive voltage on the anode it is switched from a positive voltage to 0V. This way the total time till the reverse recovery current reduces to 0A can be measured.

At last in an electrical transient measurement the switching speed can be determined by looking at the current value. When the current exceeds 1mA for a 5nm ultrathin LED it emits more than 0.15µw EL power and can be defined as being in an on-state.

2.5 Measurement Setup

Optical measurements have been tried briefly, but as expected coupling the light was very hard and therefore very little light reaches the photodiode; a short description of the setup will be shown here. Two kinds of electrical measurements have been done: DC measurements as well as Transient measurements. Both measurements need a different setup and will be treated apart from each other.

2.5.1 Optical Measurement Setup

For optical measurement the wafer with the different LED structures is placed on a Cascade Microtech low leakage manual probe station. The Anode is connected to an Agilent pulse generator supplying 2V to the Anode while the Cathode is being kept at ground level. By means of an optical probe the light is being caught and let to the photodiode through a fiber. The scope of a Keithley 4200 Characterization system [6] has been used to measure the current generated by the photodiode. The total setup is shown in Figure 9.

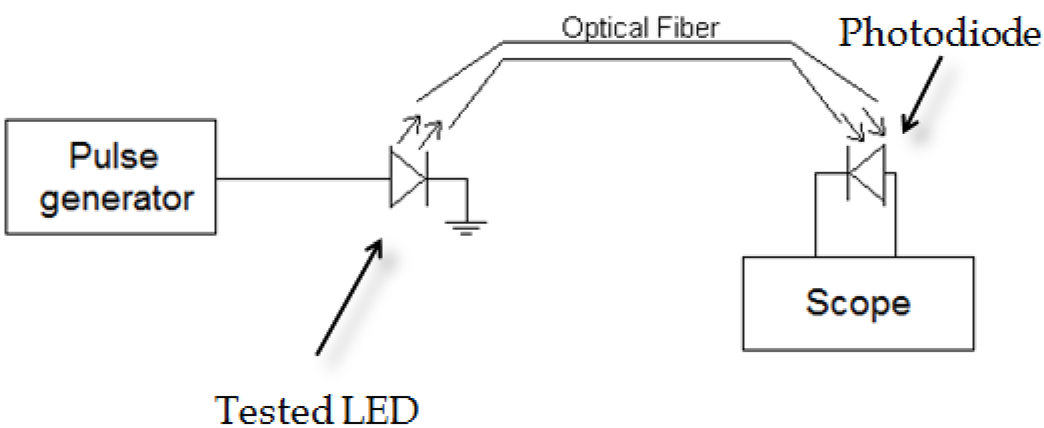


Figure 9 - Measurement setup for optical measurement

This setup has been built and tested but did not give any results. The connection between the fiber and the photodiode was far from optimal. Therefore it can be said for sure that not enough light has been caught by the photodiode and a measurement was impossible to do. For future research it would be beneficial to fix the photodiode together with the fiber onto a PCB.

2.5.2 Electrical DC-Measurement Setup

The DC-measurement setup is straightforward. The measurements are done on a Karl Suss PM8 low leakage manual probe station [5] in combination with a Keithley 4200 Characterization System. The program used on the Keithley is called KITE and via a simple graphical setup the DC-measurement is defined. A voltage sweep from -2V till 4V on the anode is used to be able to compare it to simulations and to previously done measurements by Dr. Tu. Since DC-measurements have been done before by Dr. Tu, only a couple of them are being repeated to see whether the same results can be obtained. If so there is no need for more DC-measurements and the old ones can be used as a reference. If the measurements do not agree with the old ones they have to be repeated for more devices.

To start with, measurements on regular PIN devices with different lengths are done. Devices with lengths of 5µm, 10µm, 20µm, 30µm, 40µm, 50µm and 60µm have been processed. Measuring one device from all seven different lengths should give a clear view whether or not the measurement results correspond with the measurements done before. If so the measurements done before can be used for comparison with the simulations later on.

An example of the device is given in Figure 10.

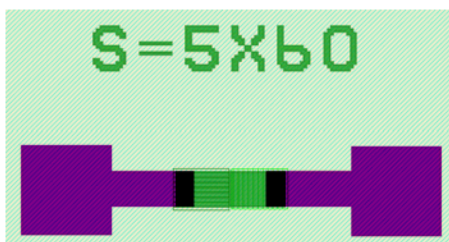


Figure 10 - Example Regular PIN diode of 5µm length and 60µm width

2.5.3 Electrical Transient Measurement Setup

For transient measurements the DC-measurement setup is extended with a Pulse Generator module [7] and a Scope module [8] to do pulsed DC-measurements. This setup has in principle been designed for pulsed DC-measurements of transistors but the test module has been adapted for measuring the on- and off switching behavior of the SOI LED. The connection block schematic of the device under test (DUT) can be found in Figure 11. In this setup the pulse generator is sending a pulse into a power divider which splits the power to the scope and further to a remote bias tee. The remote bias tee sends the pulse together with an optional bias voltage together to the Anode of the Device Under Test (DUT). The cathode of the device is being monitored by the scope and can also be biased. The cathode will be at ground level.

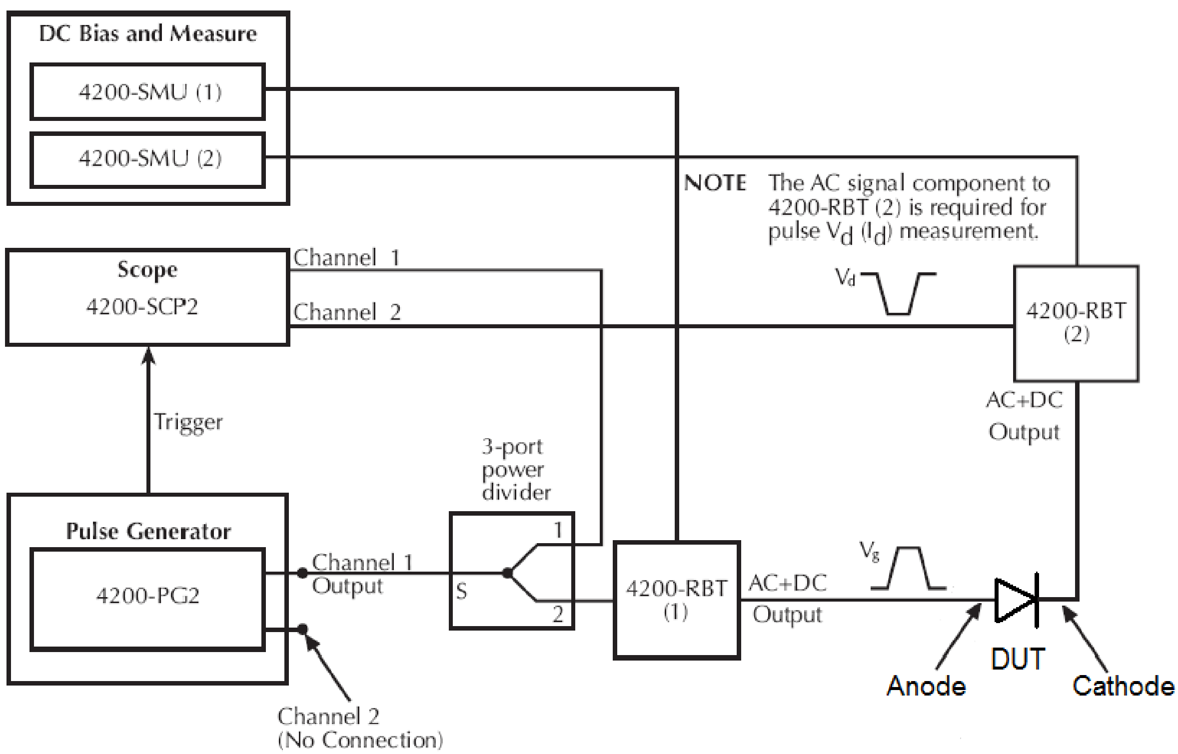


Figure 11 - Block schematic of transient measurement setup

The program used for pulsed DC-measurements is standard implemented in the KITE program and consists of various steps. To start with the scope card needs to be calibrated by disconnecting all connections and running a calibration program. During this calibration the temperature of the card is measured and stored. After the calibration of the scope card there is a second calibration for cable compensation. Very important in this case is the connection for the DUT. The following picture shows this connection for a transistor:

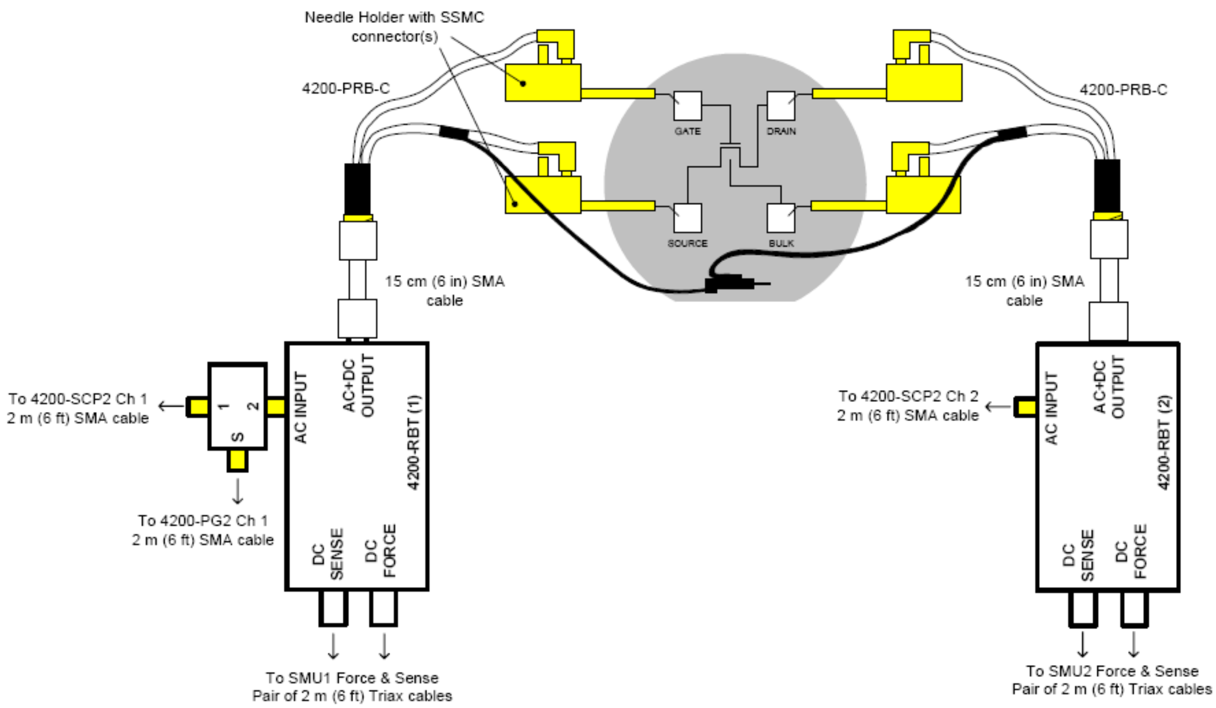


Figure 12 - Probe connection pulsed DC measurement

For measuring the PIN LED the setup in general is the same, but instead of connecting the top two probes to the gate and drain of a transistor they need to be connected to the anode and cathode respectively. The bottom 2 probes are grounded and not needed for a diode. The black grounding cable from the shields needs to be connected in all cases though. Without connecting them the calibration will fail. The substrate needs to be grounded.

3 Results

3.1 DC-Simulation results

As mentioned before the first step leading to good results for this thesis are DC-Simulations. A series of DC-simulations have been done and have been compared to DC-measurements done by Dr. Tu. In this chapter a summary of the most important simulations results will be given together with a short explanation of the data.

3.1.1 Regular PIN LED

First of all a regular PIN diode has been simulated to get to know the simulator and have a look at different intrinsic regions lengths. The devices are all 60µm wide and the doping concentration is as follows:

Region	Doping concentration
P-region	7e+18
Intrinsic region	1e+15
N-region	7e+18

These are the same concentrations as used in the processed devices so they can easily be compared.

The results of these DC simulations are as follows:

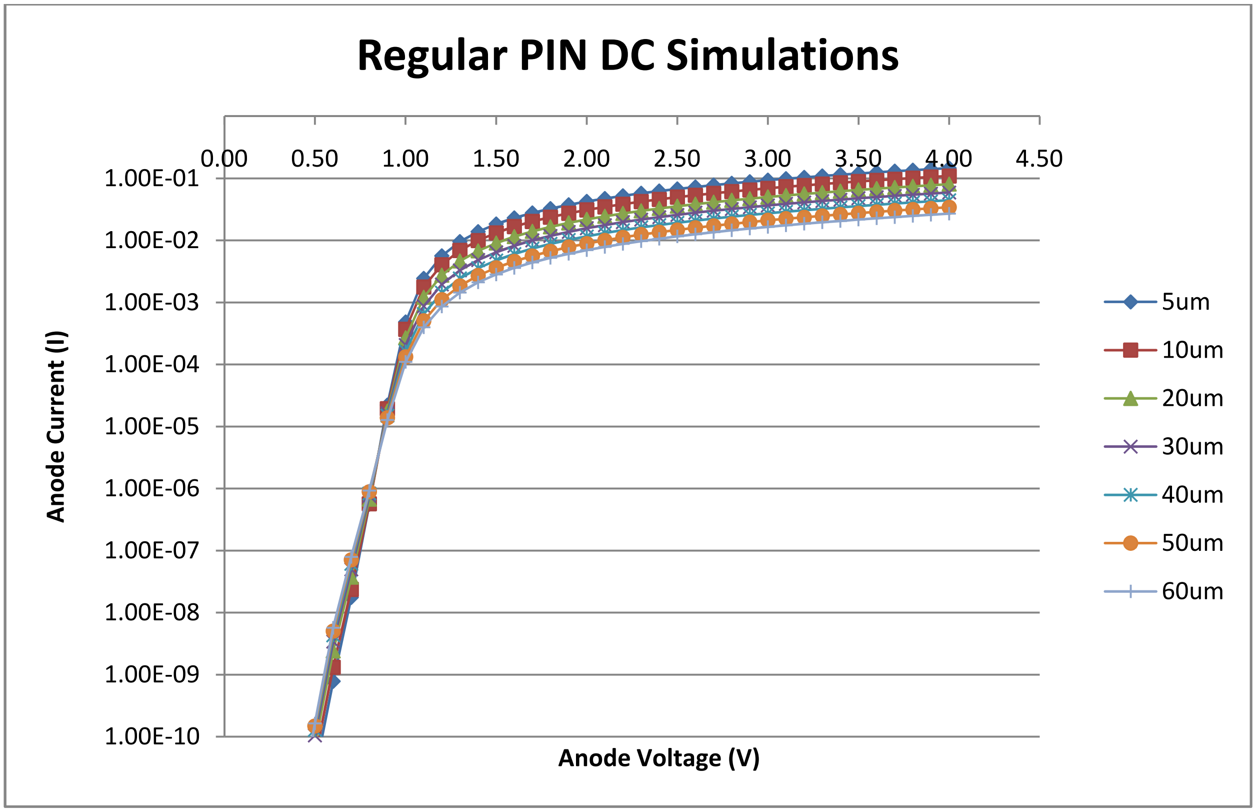


Figure 13 - Regular PIN DC Simulations, different intrinsic region lengths (Vsub = 0V)

These simulations show that a longer intrinsic area gives a higher series resistance this is logical since the intrinsic region is lowly doped and therefore does not conduct very well. At low injection the current is more or less the same, which is strange for a PIN diode. Calculation of the depletion layer thickness showed a thickness of 1.1µm, which explains this since the smallest device is already larger than that. Later on these simulation results will be compared to the measurements. The series resistance for the 5µm device has been calculated at approximately 18Ω and the series resistance of the 60µm device at 130Ω. They are different by a factor 12, just like the difference in length.

3.1.2 5nm Ultrathin LED with 0V Bias

The next simulations that have been run are those of the newly developed LEDs with 5nm thinning. Devices with this thickness show the best results (highest EL output) in the measurements and therefore the focus will be only on these devices. The device was first simulated at 0V bias. According the work of Dr. Tu the devices work better with a bias, but for comparison with the measurements it is better to have more structures. The DC simulation results from the 5nm ultrathin devices are shown in Figure 14.

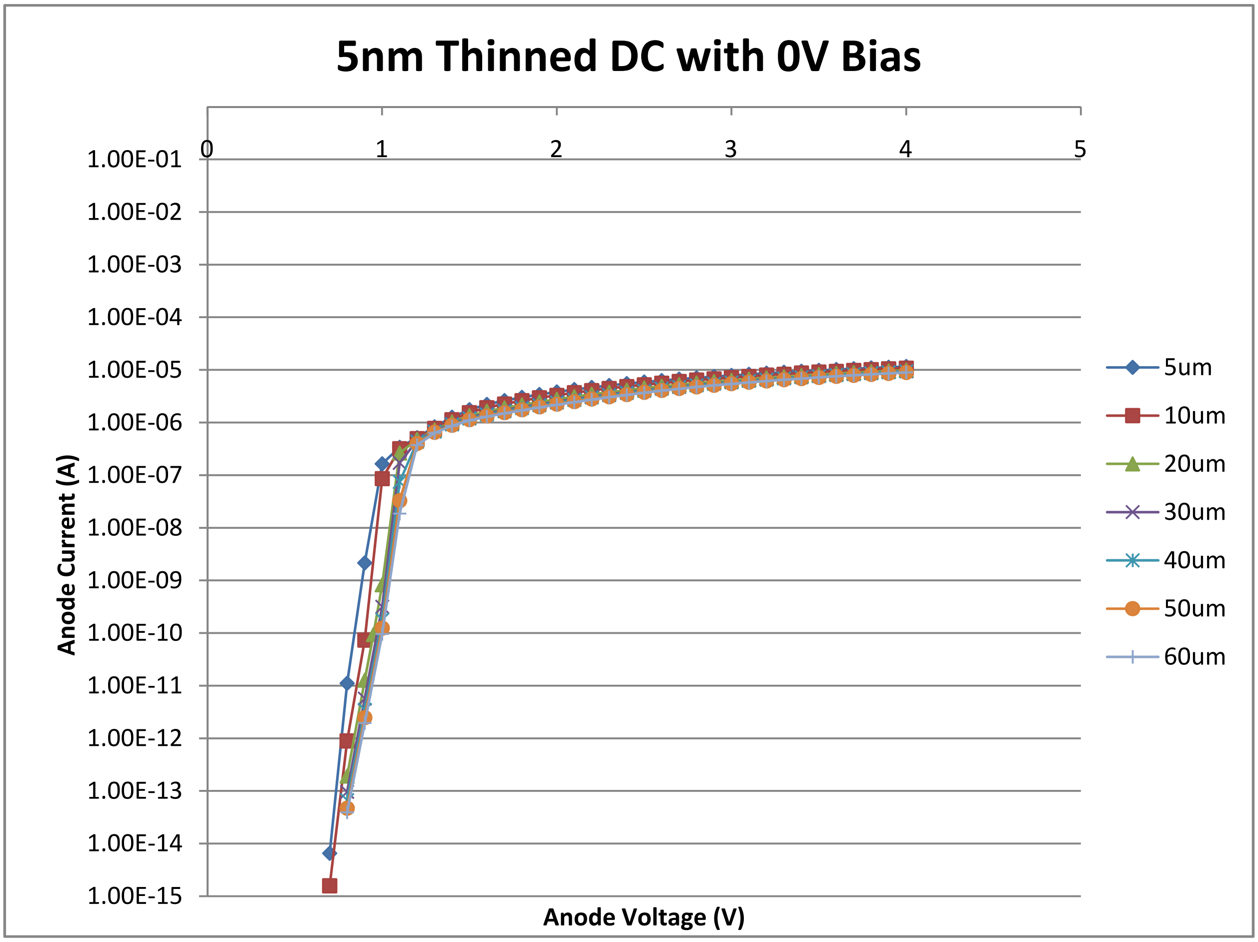


Figure 14 - 5nm ultrathin device with 0V bias on the gates and Vsub=0V

In the graph it can be seen that the length of the intrinsic region no longer determines the series resistance of the devices. Since they have two very thin regions the thin regions determine the series resistance and therefore the series resistance is the same for all different lengths. Since the series resistance is a lot higher (about a 5000x) the current through these devices is much smaller than the current flowing through the regular PIN diodes. The differences in current in the low injection region are strange and are subject for further research.

3.1.3 5nm Ultrathin LED with -1V and +1V Bias

The third series of simulations are also with 5nm ultrathin devices, but this time the gates are biased at -1V and +1V. This way the ultrathin regions have more free carriers to reduce the resistance in these areas. The result of these simulations is shown below in Figure 15.

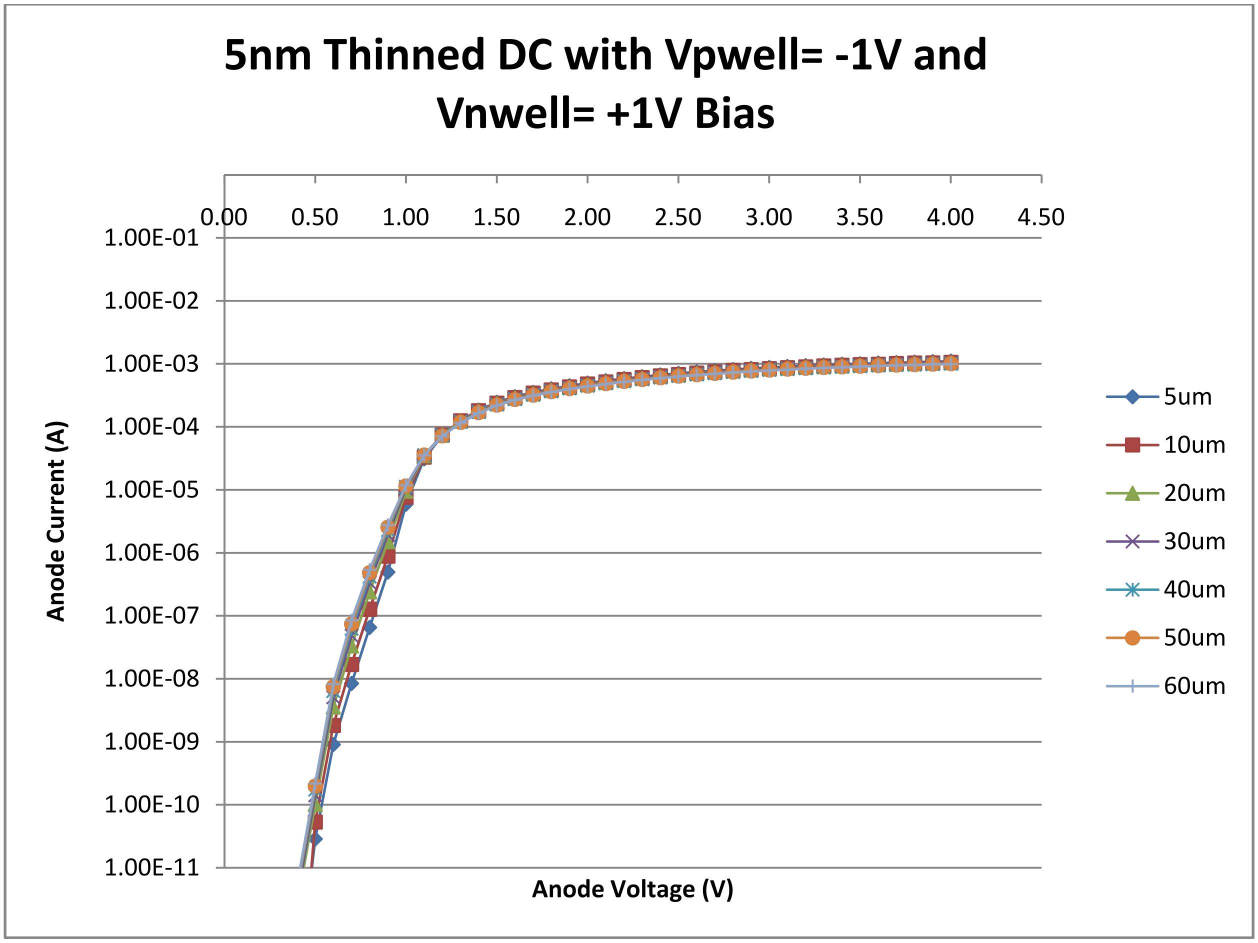


Figure 15 - 5nm ultrathin devices with -1V and +1V bias at the gates

Just like with the device with 0V bias the series resistance of all devices is the same. Even though the resistance has been decreased by a factor 100 the total series resistance is still a lot higher than a regular PIN diode without ultrathin region. Therefore the series resistance is still dominated by the thinned regions and is the same for all devices.

3.2 DC-Measurement Results

3.2.1 DC Measurement Regular PIN diode

Initially the results of the DC measurement are compared to those done earlier on by Dr. Tu as mentioned before. Only a couple of devices have been simulated and the result is in the next graph:

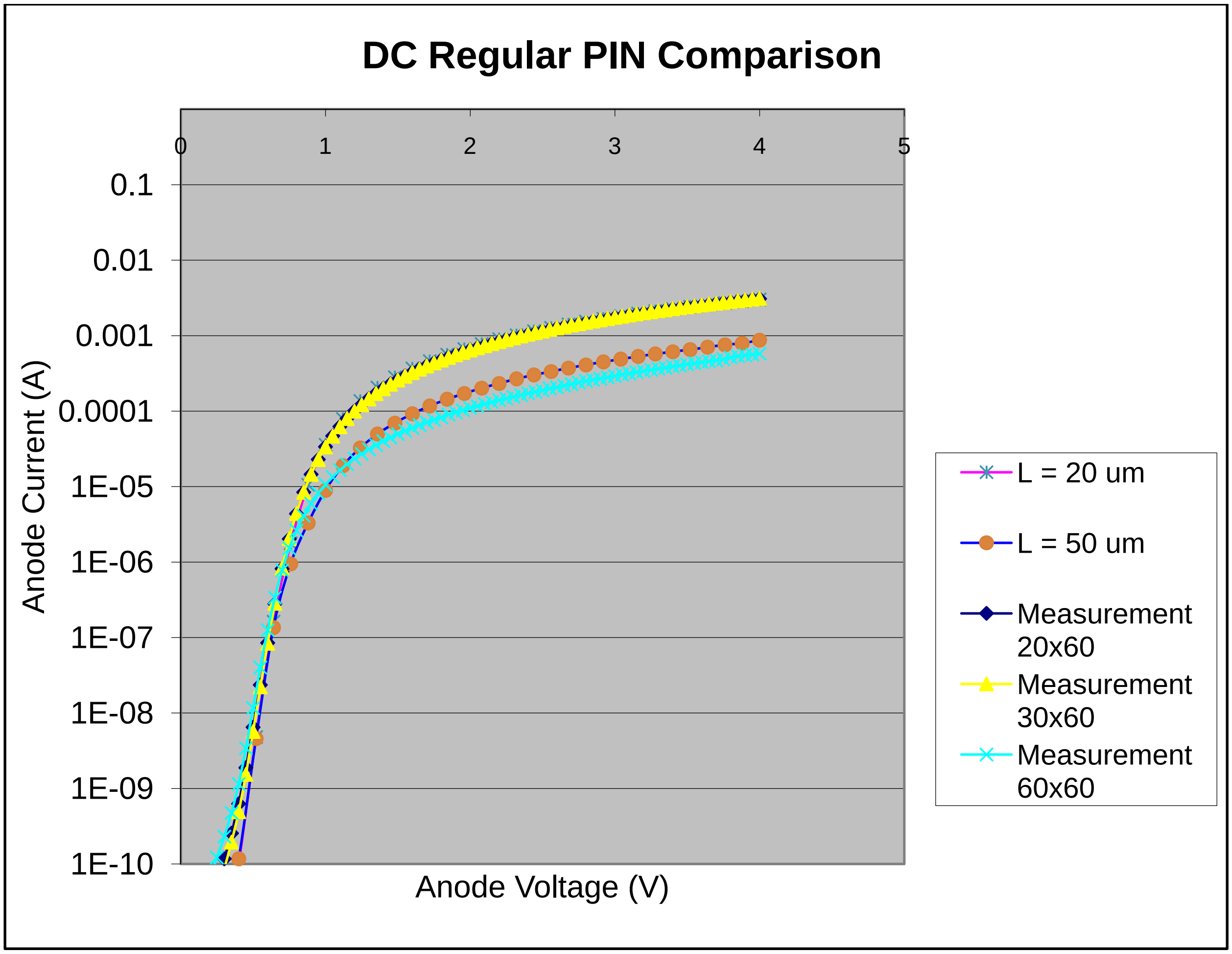


Figure 16 - DC measurements comparison; Vsub=0V

The L=20µm and L=50µm plots are measured by Dr. Tu and the others were measured for this work. All devices were 60µm wide. The measurement of the 20x60 and 30x60 devices seem to be equal. A brief view on the layout showed that the 20µm device was abusively designed and processed as a 30µm device. Since it was assumed that there were measurements for all devices done before, only 3 measurements had been redone. It showed that not all devices had been measured by Dr. Tu and therefore the 60x60 device cannot be compared directly, but looking at the 50µm device it seems that the measurements are in agreement. The 30µm device matches exactly, so the measurements by Dr. Tu can be used for the rest of this work.

3.2.2 DC Measurement Ultrathin SOI LED

The following results are from Dr.Tu. [2] and show the measured DC characteristics of a 5nm ultrathin SOI LED at 1V bias at the gates. These measurement results are from 5nm ultrathin devices with 5 different lengths of the intrinsic region. Not all 7 lengths have been measured since 2 of the devices didn't survive the measurements.

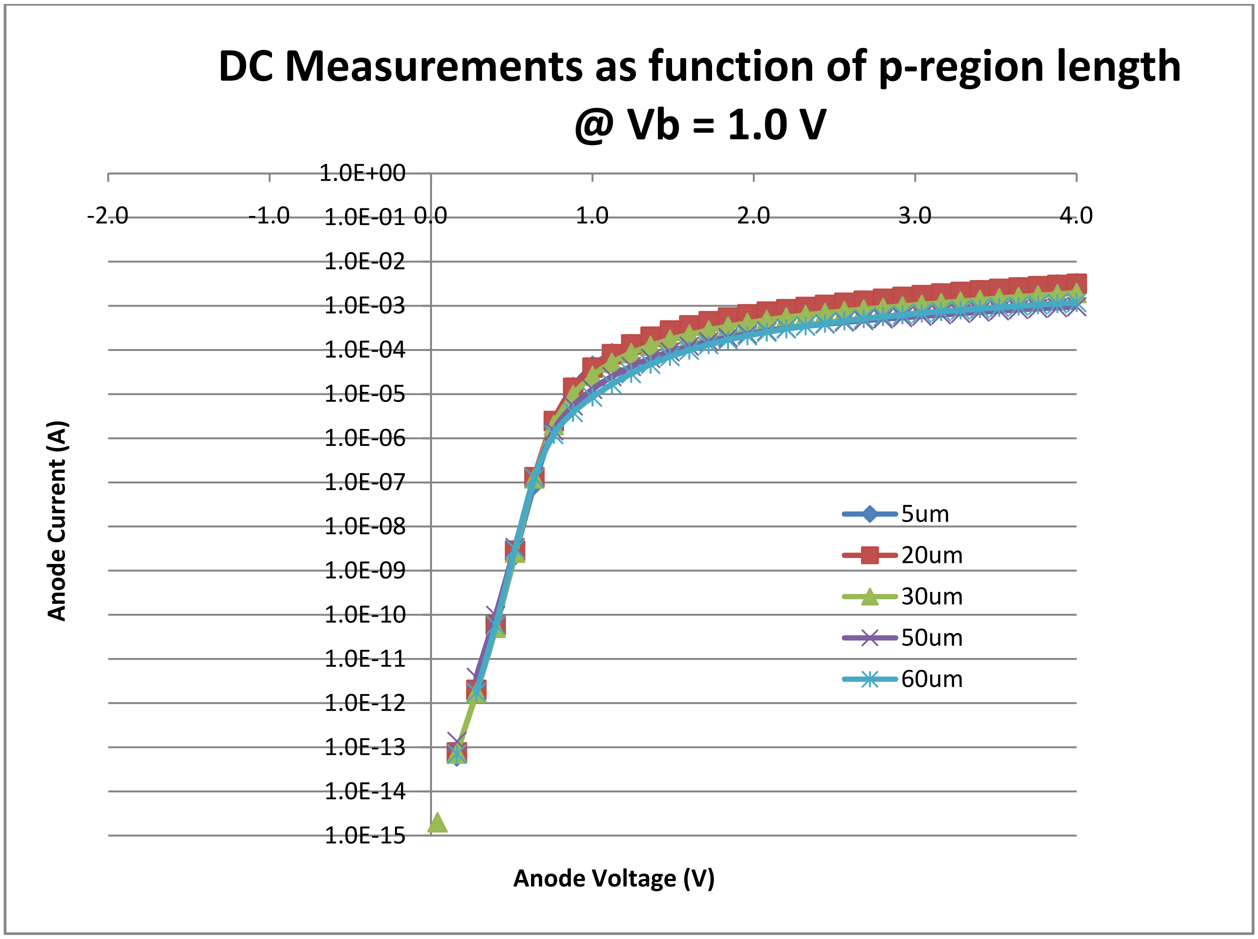


Figure 17 - DC Measurement results 5nm ultrathin device; Vnwell=+1V, Vpwell=-1V, Vsub=0V

As can be seen in Figure 17 all 5 devices don't have the same series resistance. They are not quite alike as in the simulation, which can be ascribed to variation in doping profiles of the different devices. Also the processing of the thinned region might influence the resistance. When making 5nm ultrathin regions, a small difference in thickness can already affect the series resistance and having some deviation during processing such ultrathin devices is very likely.

3.3 DC-Measurement and DC-simulations of 5nm ultrathin devices comparison

Looking at the DC simulations and DC measurements of the 5nm ultrathin devices with a 1V bias at the gates, it seems that they are pretty much alike. To get a good comparison they have been put together per length in 1 graph. All devices are biased as follows: Vpwell=-1V, Vnwell=+1V, Vsub=0V. The width of all devices is 60 µm. The results can be found in the following graphs:

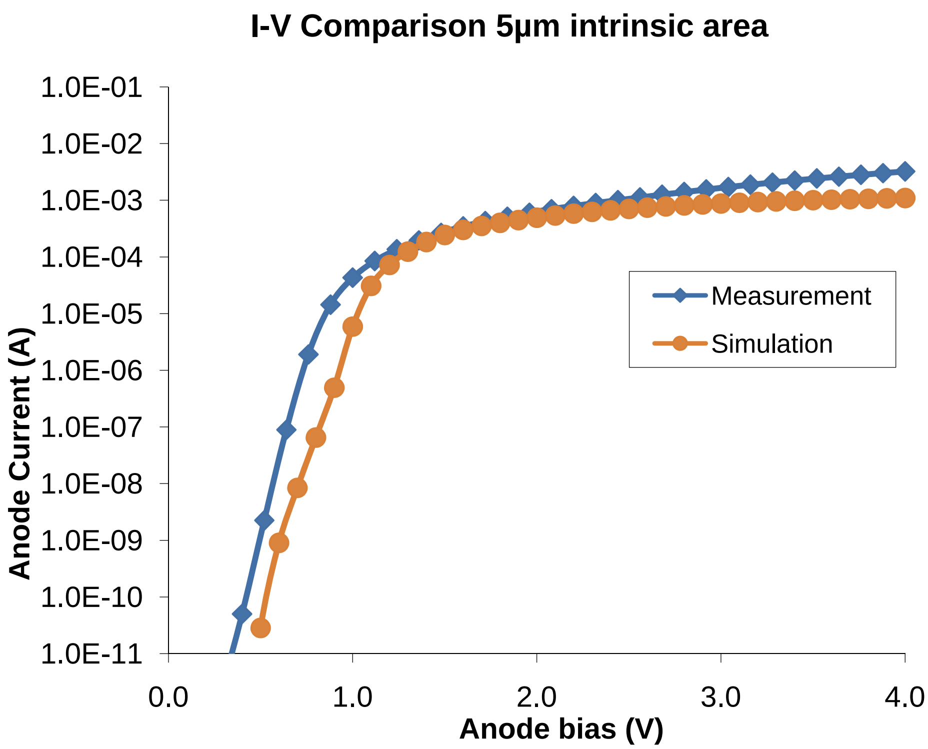
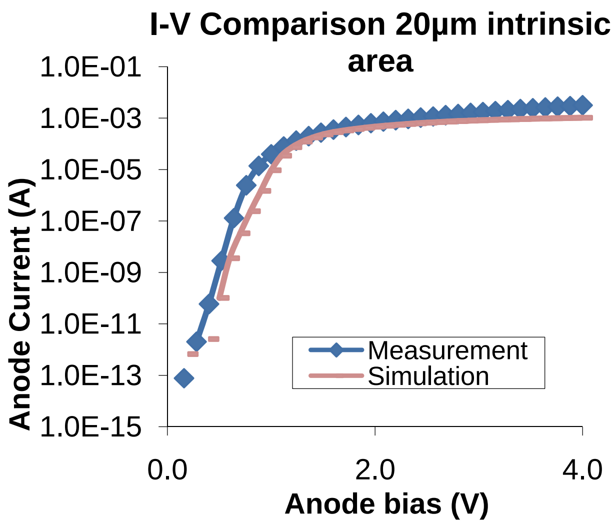


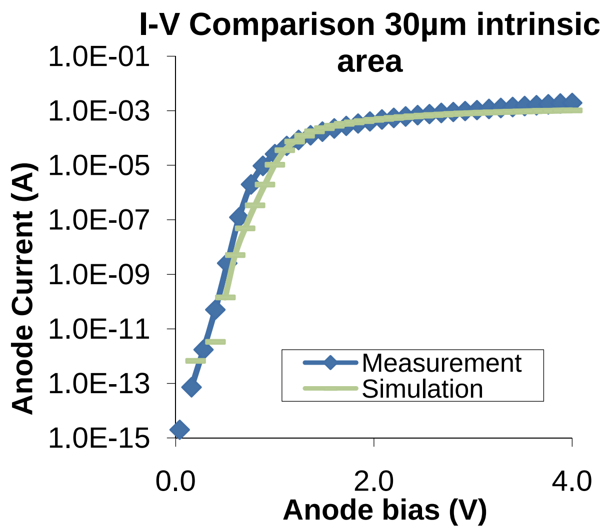
Figure 18 - DC Comparison of 5nm ultrathin device with 5µm intrinsic area length

The first one is the device with an intrinsic region of 5µm long. The graphs are almost the same, although the series resistance of the measured device is a little lower. This will need to be investigated further. The difference in the low injection region between measurement and simulation might be ascribed to the fact that in the thinned regions a bandgap of 1.3eV has been used in the simulations, this might be too high. Measuring the real bandgap in the devices and using that value in the simulations might show a better comparison.

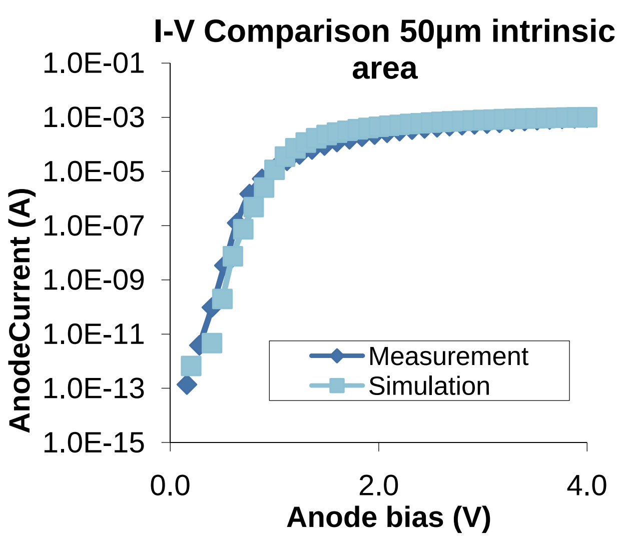
In the other 4 compared devices the same effect can be seen as is shown in Figure 19.



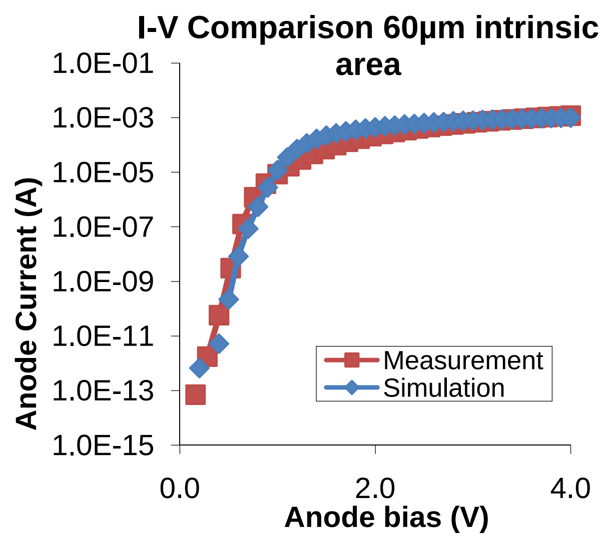
(a)



(b)



(c)



(d)

Figure 19 - 4 different 5nm ultrathin devices DC comparison with intrinsic region lengths of 20µm (a), 30µm (b), 50µm (c) and 60µm (d)

From these results it can be concluded that the simulated structure corresponds with the real structure. Therefore the device can be simulated in a transient simulation which should correspond with measurements and conclusion can be drawn from that.

3.4 Transient simulation results

The transient simulations have been done for a 5µm regular PIN diode and for 5nm ultrathin diodes. Both will be showed here.

3.4.1 Regular PIN diode

The fastest Regular PIN diode is the one with a 5µm long intrinsic region. This device shows the following response on a pulse of 2V.

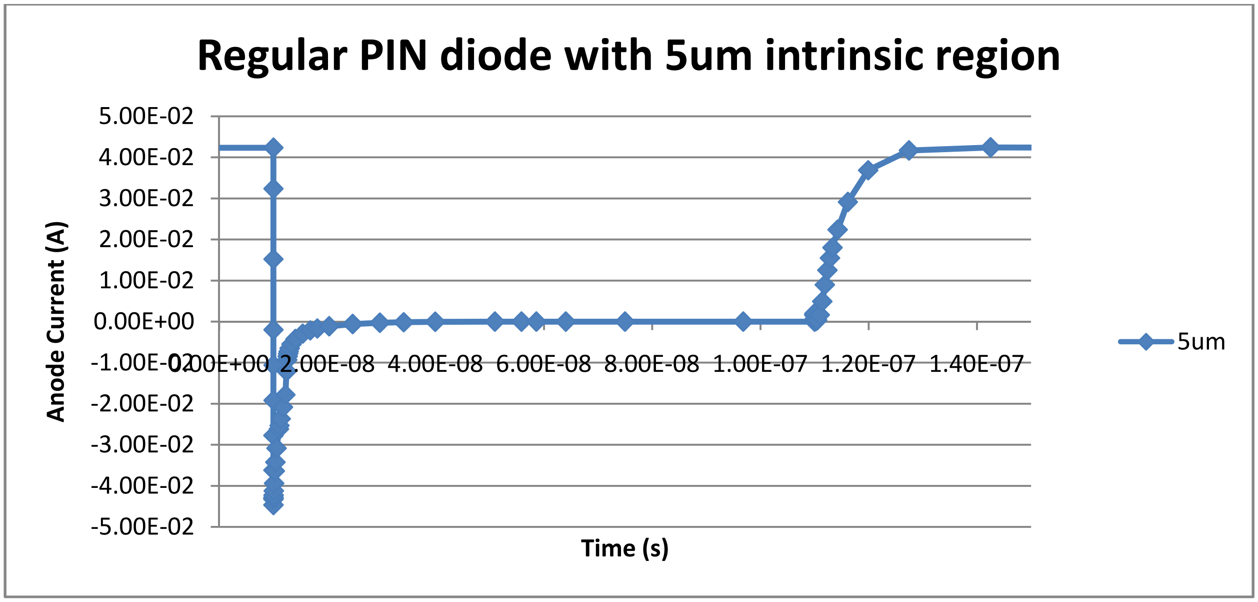


Figure 20 - Transient simulation of regular PIN LED; Vsub=0V

From this the on-switching time can be determined as 20ns and the off-switching time as approximately 15ns. The off-switching switching generates a reverse recovery current as high as the current in the on-state. The on-switching is just loading up the intrinsic area and is slower than the off-switching. Together this device should already be able to switch at about 20MHz.

3.4.2 5nm ultrathin LED

Simulating the 5nm ultrathin diode with a step of 2V on the anode and thereby measuring the anode current resulted in the following graph:

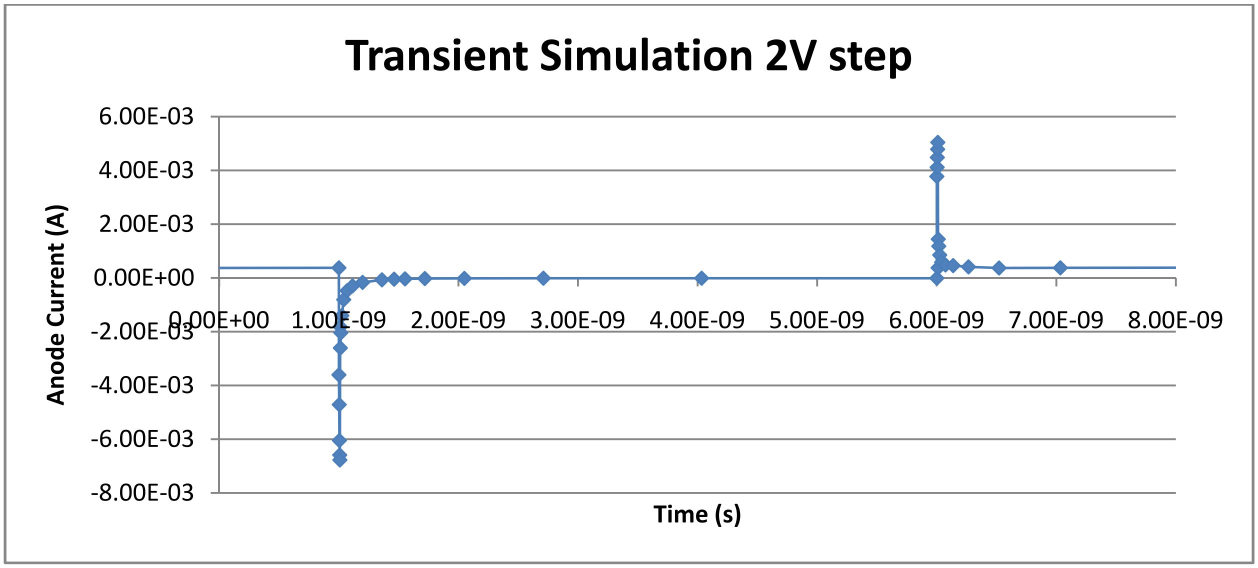


Figure 21 - Transient simulation of 5nm ultrathin LED; Vpwell=-1V, Vnwell=+1V, Vsub=0V

The off-switching speed has been determined at 0.5ns and the on-switching takes place instantly and gets to its stable value after 0.2ns. These are very high switching speeds compared to the hundreds of nano seconds of a regular PIN diode. Noticeable here is the peak when the device is turned on. Where a regular PIN diode charges itself slowly the ultrathin LED peaks right away and then gets to a stable state. This might be explained by a displacement current in the device, but is still subject for research. It cannot be concluded that the device is optically on during the peak, it might as well be a very high charging peak and during that time band to band recombination doesn't have to take place.

A few tries have been made to take a look inside the device at the on and off-switching peak. Since in Deckbuild a simple statement puts out all the data inside the device at a certain point it seemed pretty straightforward, it wasn't that easy though. The transient simulation was made by 3 statements namely:

```
SOLVE l.wave=1.150 vanode=2.0 RAMPTIME=1e-11 TSTOP=1e-9 TSTEP=1e-12
SOLVE l.wave=1.150 vanode=0 RAMPTIME=1e-11 TSTOP=2e-9 TSTEP=1e-12
SOLVE l.wave=1.150 vanode=2.0 RAMPTIME=1e-11 TSTOP=3e-9 TSTEP=1e-12
```

Since a look at the structure wanted to be taken during one of these statements, one statement had to be split up like for example:

```
SOLVE l.wave=1.150 vanode=1.8 RAMPTIME=9e-12 TSTOP=1e-9 TSTEP=1e-12
save  outfile=IntermediateStructure.str
SOLVE l.wave=1.150 vanode=2.0 RAMPTIME=1e-12 TSTOP=1e-9 TSTEP=1e-12
```

When simulating this it did not give the same result as taking 1 step. Therefore taking a look inside the structure at a certain point during the step did not succeed.

3.5 Transient measurements results and transient simulation comparison

The last results are from measurements done with the setup described in 2.5.3. First of all transient measurements of regular PIN diodes have been made to check if the setup works, since these don't need any biasing they are easier to measure.

3.5.1 Regular PIN Diode Transient Measurement

The first results are of a PIN diode with an intrinsic region length of 5µm. For this measurement a step of 2V has been put on the anode with a pulse length of 300ns. The voltage in the off-state is 0V.

The transient behavior is shown in Figure 22.

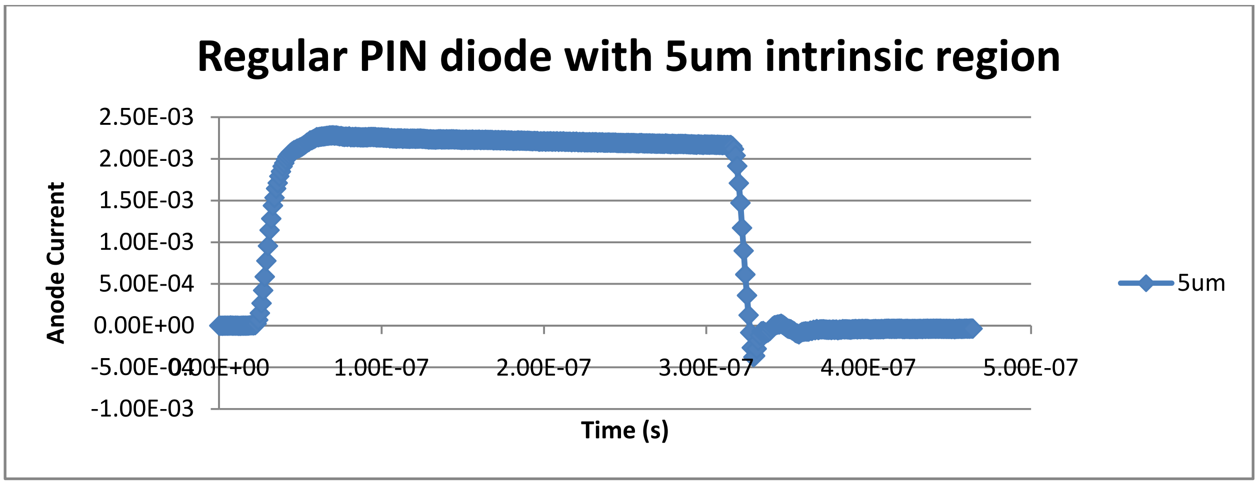


Figure 22 - Transient measurement of regular PIN diode with 5µm intrinsic region length

This seems a very reasonable result for a regular PIN diode. The shape is alike that of the simulation and no strange effects occur. Just a very little bit of oscillation might be seen during the off-switching.

The on-switching time is about 25ns as can be seen in Figure 23.

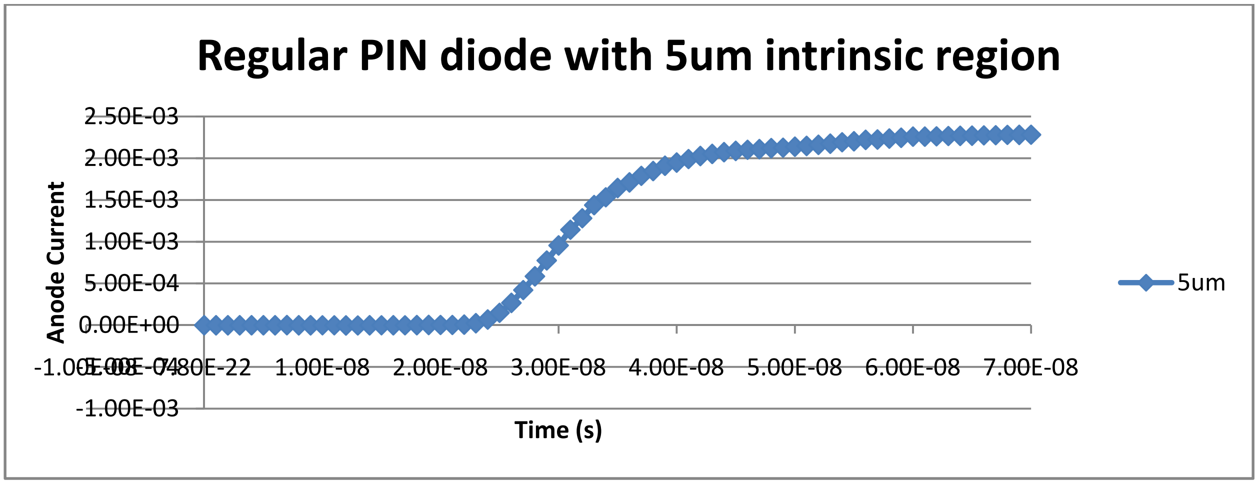


Figure 23 - Regular PIN diode on-switching time

The off-switching time can be determined in the following picture from where it can be concluded that the diode switches off in about 20ns.

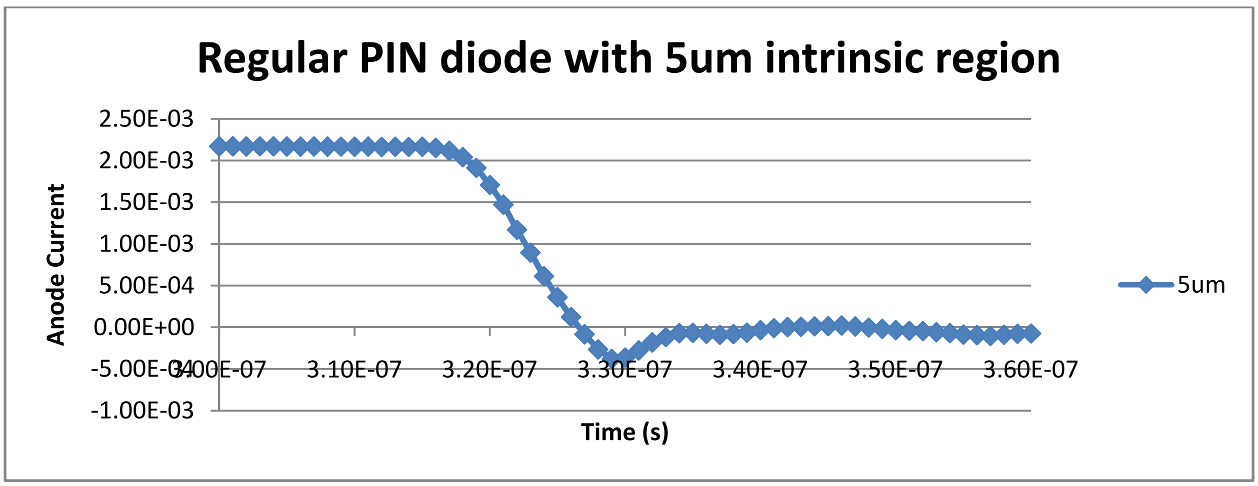


Figure 24 - Regular PIN diode off-switching time

Compared to the simulated on-switching time of 20ns and off-switching time of 15ns these values are very reasonable results.

After measuring the diode with an intrinsic region length of 5µm also devices with 10µm, 20µm, 30µm, 40µm, 50µm and 60µm have been measured. Here the same 2V step with a 300ns pulse length has been applied; the results are put together in the following graph:

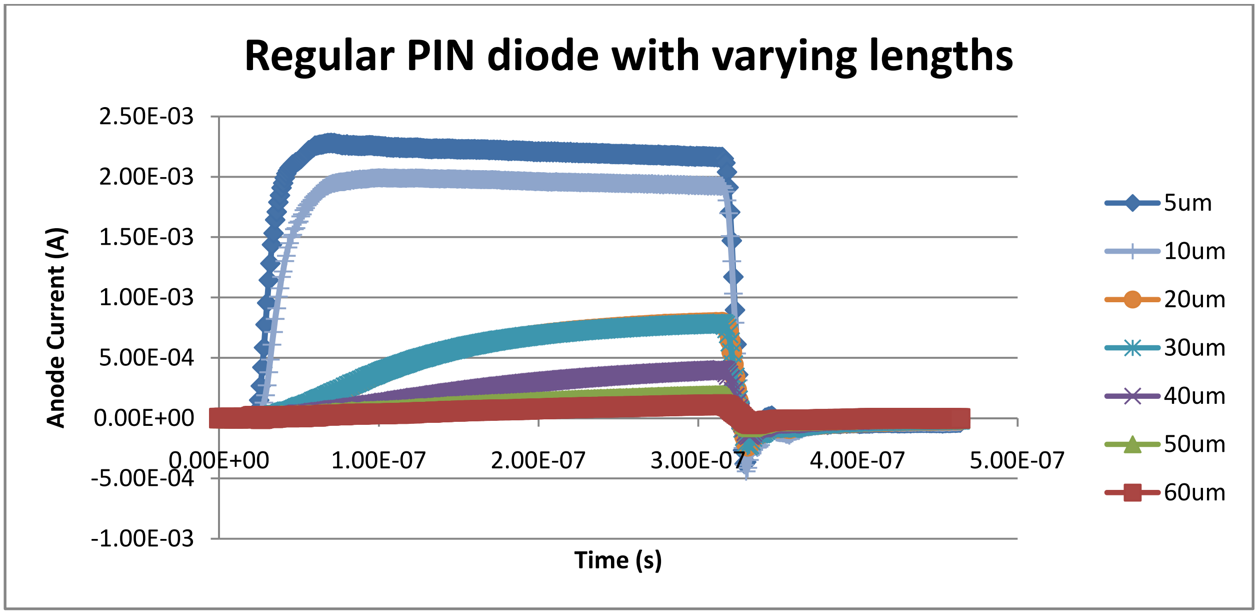


Figure 25 - Comparison of different intrinsic region lengths for regular PIN diode

From the graph it shows once more that the 5µm devices have a lower resistance than the larger devices. This is in agreement with the conclusions drawn from the DC measurements. Also the 20µm and 30µm devices are the same, since as mentioned before the layout of the 20µm device was wrong.

The 30µm and bigger devices does probably not turn on to its maximum value, but the Keithley 4200 does not support larger pulse lengths than 300ns in pulsed DC-mode.

3.5.2 Ultrathin LEDs Transient Measurement

After measuring the regular PIN diodes the ultrathin LEDS were next. Just like with the regular PIN diodes a pulse of 2V was put on the Anode with a pulse length of 300ns. The gates of the device were biased at +1V (nwell gate) and -1V (pwell gate). Unfortunately the result is not what was wished for. The device started to oscillate, but still some behavior can be seen in de measurement of the 5nm ultrathin device with 5µm intrinsic region. The result can be seen in Figure 26 below.

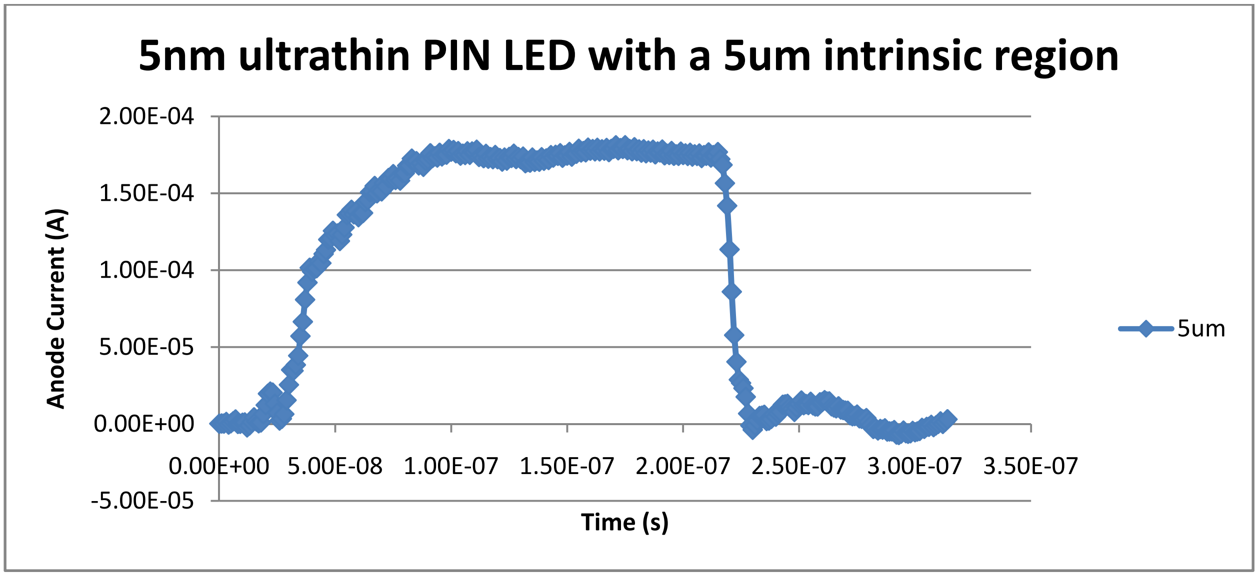


Figure 26 - 5nm thinned PIN LED with 5µm intrinsic region

From this measurement it can be concluded that the on-switching time is about 100ns, which is pretty long. The off-switching speed is about 10ns which is a lot better. The thinned devices should be a lot faster though than regular PIN diodes. Most likely reason for this slow on-switching is probably the measurement setup. Since the device starts to oscillate it is for sure not an optimal measurement. Also questions about the supplied biases have risen since changing them did not affect the measurements. This indicates that some way the biases were not supplied to the gates. When that is the case the switching speed drastically decreases.

Comparing this measurement with the simulation done in 3.4.2 also shows huge differences. The applied biases could very well explain the difference. When a bias is being applied to the gates they can really easily transport the carriers towards the intrinsic region. Since the thinned region on the anode side has a p-channel and needs to transport holes towards the intrinsic region and on the cathode side it is the other way around.

The devices with intrinsic region lengths of 10µm and higher showed even a lot worse results. An example of the 10µm intrinsic region length device is given in Figure 27.

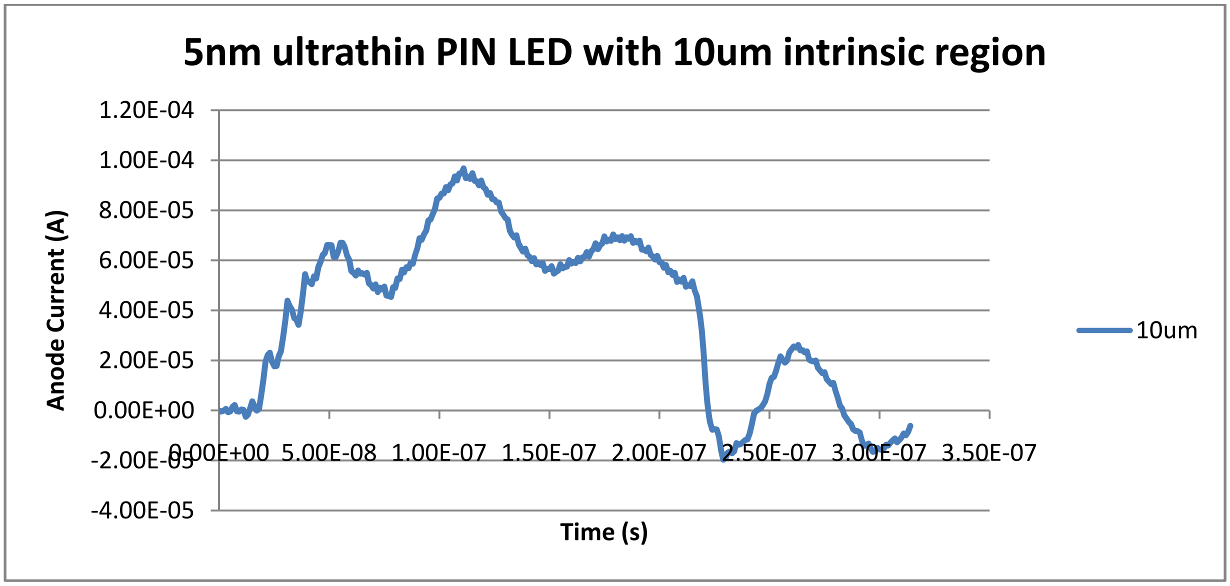


Figure 27 - 5nm ultrathin PIN LED with 10µm intrinsic region length

Looking at these results something went really wrong during the measurements. A cause might be the length of the cables used or interference of some kind on the measurement setup. Anyway for this work the measurements for the ultrathin devices cannot be used.

4 Conclusions and Recommendations

This chapter contains the conclusion that can be drawn from the simulations and measurements done, furthermore recommendations will be given for future research on the subject.

4.1 Conclusions

Simulations have been performed during this master thesis. These simulations are in agreement with the measurements. The transient simulations of the regular PIN diode show the same results as the measurements. Looking at the DC-simulations of the 5nm ultrathin device with different intrinsic region lengths it is striking how close the simulations match with the measurements. Therefore the simulations can be used to have a look at the transient behavior of the device, since the structure during both simulations stays the same. Only the simulation parameters change from a DC-sweep to a transient input.

Looking at the expected values of on-switching time mentioned in 2.2.1 of 8 ns the simulations show even much higher switching speeds. An on-switching time of 0.2ns and an off-switching time of 0.5ns will together result in a switching frequency of about 1GHz. This looks very promising, but when measurements haven't been made yet, it cannot be confirmed.

When the measurements of the regular PIN diodes are being analyzed it shows that the fastest device with a 5µm intrinsic region should already reach switching speeds up to 20MHz. Assuming that the ultrathin LEDs switch a lot faster than regular PIN diodes, the switching speed of the LEDs can be assumed at least 20MHz.

4.2 Recommendation

Future research on the ultrathin LEDs should focus on a couple of things. First of all a closer look should be taken inside the LED when it switches on or off. In this work during the simulation it has been tried, but there was no success.

Secondly transient electrical measurements should be made on the ultrathin devices. The use of different probes or maybe a totally different measurement approach could help. Writing a new program for the Keithley 4200 which makes use of the pulse generator and the scope only should be possible, but takes some effort.

The last recommendation would be making a good optical measurement setup. The photodiode that was used in this work should be sufficient to do optical measurements. Placing it on a PCB together with a good fiber connector and a fixed small distance between both should do the trick. Even better would be removing the case of the photodiode and placing the optical fiber directly on top of it. Biasing the photodiode with 5V at the cathode makes it more precise and could therefore increase the sensitivity during a measurement. An example of such a bias circuit can be found in Figure 28. Placing all this on a PCB so it will be fixated would be beneficial for a good measurement.

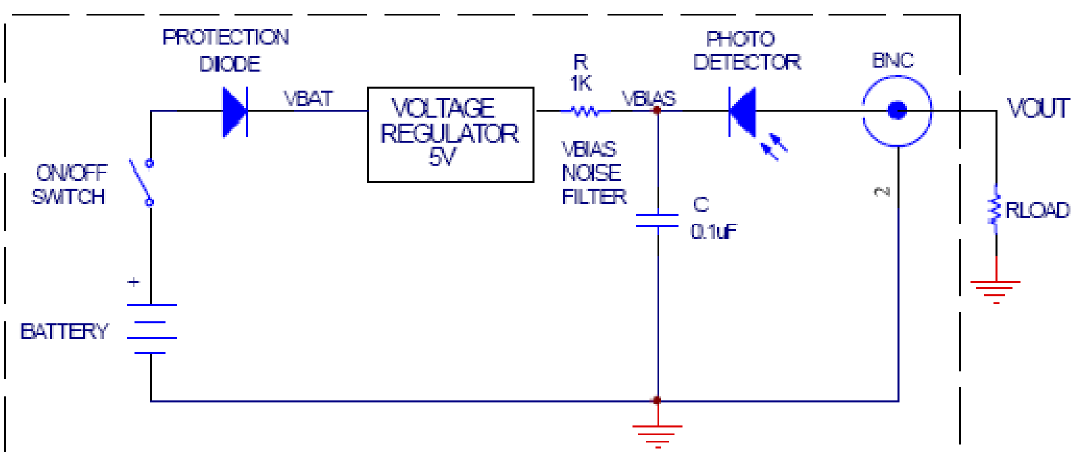


Figure 28 - Biasing circuit for the FGA10 photodiode

5 References

[1] A Simple Diode Model with Reverse Recovery - *Peter O. Lauritzen;* IEEE Transactions on Power Electronics; Volume 6, Issue 2; page 188-191

[2] High Efficient Infrared-Light Emission from Silicon LEDs – *Hoang Tu*; ISBN: 978-90-365-2557-2

[3] On the switching speed of SOI LED's - *Jurriaan Schmitz et al*

[4] http://www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=285&visNavID=646

[5] http://www.suss.com/products/test_systems/manual_systems/pm8

[6] http://www.keithley.com/products/currentvoltage/multichannelivtest?mn=4200-SCS

[7] http://www.keithley.com/products/currentvoltage/multichannelivtest/?mn=4205-PG2

[8] http://www.keithley.com/products/currentvoltage/multichannelivtest/?mn=4200-SCP2HR

[9] http://www.silvaco.com/products/interactive_tools/deckbuild/deckbuild_br.html

[10]http://www.silvaco.com/products/device_simulation/atlas.html

[11] http://www.keithley.com/data?asset=50633

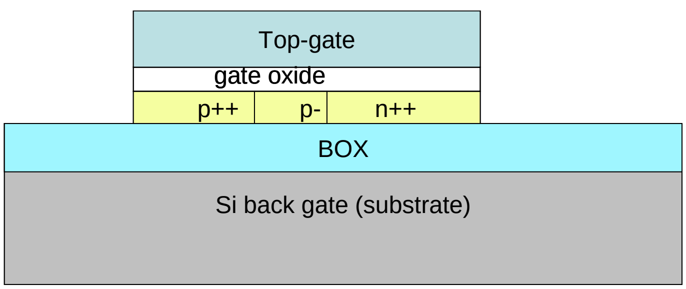
6 Appendices

6.1 Appendix 1 – Original Assignment

Switching behavior of nano scale light sources

Background:

In the semiconductor components (SC) group we have fabricated nano scale light sources in thin silicon (Si) films using standard IC processing steps. A schematic drawing of the used structures is given in figure 1. By injecting holes from the p++ area and electrons from the n++ area a sea of charge carriers can be created in the intrinsic or lowly doped Si film in between called the active area. Upon recombining (infrared) light is emitted. So far we have studied the light emission using spectra techniques that integrate the light over a long time.



Schematic of an advanced gated nanoscale PIN diode

Research Question

For the use in integrated optical applications the lightsource needs to be switched on and off. When turning off the voltage (reversing the polarity of the pin-diode from forward to reverse) the charge carriers present in the intrinsic area will not disappear instantaneously but there will be some time before all the carriers have reached the contacts, in which time there is still the possibility of recombination and light emission.

The SC group want to know how fast we can switch our light off. We want to find ways to do electrical measurements to find the ammount of charge (current) or optical measurements to directly observe the decay in light intensity. "We can use the top and bottom gate electrode to separate the carriers that will stop the light emission which can be measured with optical techniques."

The assignment consists of :

- Literature study to find possible ways to measure the transient behavior
- Rough estimate of the amount of carriers to see which of the devices are suitable (due to detection limit of the measurement setup)
- Electrical measurements
- If feasable build and use optical set up
- Data analysis

Supervisors

Ray Hueting, Cora Salm (+ Hoang Tu+ Jurriaan Schmitz)

6.2 Appendix 2 – Infile for Regular PIN diode simulation

```
loop steps=7

assign name=L n.value = (5, 10, 20, 30, 40, 50, 60)

go atlas
TITLE SOI device simulation
#
# 0.15um of silicon on 0.4um BOX-oxide on Si-substrate
#
mesh   space.mult=1.0
#
x.mesh loc=0.00         spac=2.0
x.mesh loc=3            spac=0.5
x.mesh loc=4.8          spac=0.01
x.mesh loc=5            spac=0.001
x.mesh loc=5.2          spac=0.01
x.mesh loc=7            spac=0.5
x.mesh loc=$L/2         spac=2
x.mesh loc=$L+3         spac=0.5
x.mesh loc=$L+4.8       spac=0.01
x.mesh loc=$L+5         spac=0.001
x.mesh loc=$L+5.2       spac=0.01
x.mesh loc=$L+7         spac=0.5
x.mesh loc=$L+10        spac=2.0
#
y.mesh loc=-0.02  spac=0.01
y.mesh loc=0.00   spac=0.01
y.mesh loc=0.15   spac=0.02
y.mesh loc=0.55   spac=0.1
y.mesh loc=3.0    spac=0.2
y.mesh loc=6.0    spac=1.0

#

region      num=1       y.max=0                             oxide
region      num=2       y.min=0         y.max=0.15          silicon     LED
region      num=3       y.min=0.15      y.max=0.55          oxide
region      num=4       y.min=0.55                          silicon     LED
#
#*********** define the electrodes ************
# #1-GATE #2-ANODE #3-CATHODE #4-SUBSTRATE(below oxide)
#
#electrode  name=gate   x.min=5     x.max=11    y.min=-0.02 y.max=-0.02
electrode   name=anode  x.max=2.5   y.min=-0.04 y.max=0
electrode   name=cathode            x.min=$L+7.5      y.min=-0.04 y.max=0
electrode   substrate
#
#*********** define the doping concentrations *****
#
doping      uniform     p.type      conc=1e15                           reg=2
doping      uniform     p.type      conc=7e18   x.right=5   direction=x reg=2
doping      uniform     n.type      conc=7e18   x.left=$L+5 direction=x reg=2
doping      uniform     p.type      conc=1e15                           reg=4
```

```
material    copt=3.2e-14
material    material=poly     EG300=1.3   affinity=4.17     NC300=2.9e19
      NV300=1.04e19
material    material=silicon  EG300=1.12  affinity=4.17     NC300=2.9e19
      NV300=1.04e19
material    material=oxide    NC300=2.9e19      NV300=1.04e19

# set interface charge separately on front and back oxide interfaces
interface   y.max=0.1   s.n=6.0     s.p=6.0     qf=5e10
interface   y.min=0.1   s.n=2.0     s.p=2.0     qf=2e10

models      cvt bgn.klassen klaaug klasrh optr conmob fldmob print

# set workfunction of gate
contact     name=gate         n.poly
#
contact     name=anode  neutral
contact     name=cathode      neutral
contact     name=substrate    neutral

# do IDVG characteristic

method      gummel block newton autonr trap maxtrap=10 carriers=2

output      e.field  j.electron  j.hole  j.conduc  j.total  ex.field  ey.field
flowlines \
            e.mobility h.mobility e.temp h.temp val.band con.band qfn qfp \
            j.disp photogen impact band.param u.aug u.srh u.rad
#
solve       init
save        outfile=RegularPINLED.str

probe       name="Recombination"    recombination     integrate       left=0.0
right=16.0 top=0.0 bottom=0.15
probe       name="Radiative         radiative   integrate  left=0.0  right=16.0
top=0.0 bottom=0.15

solve vsubstrate=0.00001
solve vsubstrate=0.0
#solve vgate=0.00001
#solve vgate=0.0        outf=temp1

log   outfile=RegularPINLED"$L"um.log

solve vanode=-2 vstep=0.1 name=anode vfinal=4

tonyplot

measure     u.total
measure     u.radiative

l.end

quit
```

6.3 Appendix 3 – In-file for ultrathin SOI LED simulation

```
loop steps=7

   assign name=L3 n.value = (5, 10, 20, 30, 40, 50, 60)

go atlas

TITLE SOI device simulation
#
# 0.15um of silicon on 0.4um BOX-oxide on Si-substrate
#
mesh   space.mult=1
# Set Variables         L1: Edge till thinned region  L2: Thinned region
length      L3:Intrinsic region length
SET L1=3.5
SET L2=2
#SET L3=5

#

x.mesh loc=0.00               spac=1
x.mesh loc=$L1                spac=0.01
x.mesh loc=$L1+($L2)/2        spac=0.05
x.mesh loc=$L1+$L2            spac=0.01
x.mesh loc=$L1+$L2+($L3)/2    spac=0.2*$L3
x.mesh loc=$L1+$L2+$L3        spac=0.01
x.mesh loc=$L1+$L2*1.5+$L3    spac=0.05
x.mesh loc=$L1+$L2*2+$L3      spac=0.01
x.mesh loc=$L1*2+$L2*2+$L3    spac=1



#
y.mesh loc=-0.02  spac=0.01
y.mesh loc=0.00   spac=0.01
y.mesh loc=0.02   spac=0.005
y.mesh loc=0.09   spac=0.01
y.mesh loc=0.13   spac=0.001
y.mesh loc=0.15   spac=0.001
y.mesh loc=0.55   spac=0.2
y.mesh loc=3.0    spac=0.5
y.mesh loc=6.0    spac=1.0

#

region      num=1  y.max=0
                  oxide
region      num=2  y.min=0                      y.max=0.15
                  silicon LED
region      num=3  x.min=$L1                    y.min=0.145
      x.max=$L1+$L2                 y.max=0.15  poly LED
region      num=4  x.min=$L1+$L2+$L3            y.min=0.145
      x.max=$L1+$L2*2+$L3           y.max=0.15  poly LED
```

```
region      num=5  x.min=$L1                   y.min=0
      x.max=$L1+$L2                y.max=0.145       oxide
region      num=6  x.min=$L1+$L2+$L3           y.min=0
      x.max=$L1+$L2*2+$L3          y.max=0.145       oxide
region      num=7  x.min=$L1+0.03              y.min=0.0
      x.max=$L1+$L2-0.03           y.max=0.115       silicon LED
region      num=8  x.min=$L1+$L2+$L3+0.03      y.min=0.0
      x.max=$L1+$L2*2+$L3-0.03     y.max=0.115       silicon LED
region      num=9  y.min=0.15                  y.max=0.55
                  oxide
region      num=10 y.min=0.55
                  silicon
#
#*********** define the electrodes ************
# #1-GATE #2-ANODE #3-CATHODE #4-SUBSTRATE(below oxide)
#
electrode   name=pwell    x.min=$L1+0.03  x.max=$L1+1             y.min=-0.04
      y.max=0.0
electrode   name=nwell    x.min=$L1+$L2+$L3+1   x.max=$L1+$L2*2+$L3-0.03
      y.min=-0.04 y.max=0.0
#electrode   name=gate     x.min=5             x.max=11
      y.min=-0.02 y.max=-0.02
electrode   name=anode    x.max=2.5
      y.min=-0.04       y.max=0
electrode   name=cathode  x.min=($L1+$L2)*2+$L3-2.5
      y.min=-0.04       y.max=0
electrode   substrate
#
#*********** define the doping concentrations *****
#
doping       uniform conc=8e15 p.type  reg=2
doping       uniform conc=5e20  p.type x.right=$L1 direction=x reg=2
doping       uniform conc=5e20  n.type x.left=$L1+2*$L2+$L3 direction=x reg=2
doping       uniform conc=1e16 p.type  reg=3
doping       gauss p.type conc=1e16 char=0.2 direction=x reg=3 peak=$L1+$L2
doping       uniform conc=1e16 p.type  reg=4
doping       gauss p.type conc=1e16 char=0.2 direction=x reg=4
peak=$L1+$L2+$L3
doping       uniform n.type conc=5e20 reg=7
doping       uniform n.type conc=5e20 reg=8
doping       uniform p.type conc=5e15 reg=10

material copt=3.2e-14
material material=poly        EG300=1.3   affinity=4.17 NC300=2.9e19
NV300=1.04e19
material material=silicon     EG300=1.12  affinity=4.17 NC300=2.9e19
NV300=1.04e19 taun=1.3e-6 taup=1.3e-6
material material=oxide       NC300=2.9e19      NV300=1.04e19

# set interface charge separately on front and back oxide interfaces
interf       qf=3e10 y.max=0.1
interf       qf=1e11 y.min=0.1
interface    y.max=0.1 s.n=6.0 s.p=6.0 qf=5e10
interface    y.min=0.1 s.n=2.0 s.p=2.0 qf=2e10

models srh auger cvt bgn.klassen klaaug klasrh optr conmob fldmob print
```

```
models material=silicon OPTR
models material=poly OPTR

#models arora auger klaaug klasrh optr conmob print lat.temp

# set workfunction of gate
#contact      name=gate n.poly
#
contact name=pwell n.poly
contact name=nwell n.poly
contact name=anode  neutral
contact name=cathode neutral
contact name=substrate neutral


#impact selb

# do IDVG characteristic
#
#method   block newton trap maxtrap=10
method gummel block newton autonr trap maxtrap=10 carriers=2

output e.field j.electron j.hole j.conduc j.total ex.field ey.field flowlines
\
        e.mobility h.mobility e.temp h.temp val.band con.band qfn qfp \
        j.disp photogen impact band.param u.aug u.srh u.rad
#
solve       init
save  outfile=5nm2uwLEDDC"$L2"umnoBias.str


probe name="Recombination" recombination integrate left=0.0 right=16.0
top=0.0 bottom=0.15
probe name="Radiative" radiative integrate left=0.0 right=16.0 top=0.0
bottom=0.15

solve vsubstrate=0.00001
solve vsubstrate=0.0

solve vpwell=0.00001
solve vpwell=-1
solve vnwell=0.00001
solve vnwell=1


# DC SIMULATIONS

#log outfile=5nm2uwLEDDC"$L3"umNOBias.log


#solve vanode=-2 vstep=0.1 name=anode vfinal=4

#save outfile=5nm2uwLEDDC"$L3"umwBias.str

#tonyplot 5nm2uwLEDDC"$L3"umwBias.log
```

```
# TRANSIENT SIMULATIONS

log   outfile=5nmThinnedPINLED"$L3"umBiasTrans2VStepTEST.log


SOLVE l.wave=1.150 vanode=4.0 RAMPTIME=1e-11 TSTOP=1e-9 TSTEP=1e-12
SOLVE l.wave=1.150 vanode=0 RAMPTIME=1e-11 TSTOP=2e-9 TSTEP=1e-12
SOLVE l.wave=1.150 vanode=4.0 RAMPTIME=1e-11 TSTOP=3e-9 TSTEP=1e-12

tonyplot 5nmThinnedPINLED"$L3"umBiasTrans2VStepTEST.log

measure u.total
measure u.radiative

l.end

quit
```