Project assignment in TEK5360

By Furkan Kaya

Simulation of a PQED photodiode based on the principle of induced junction done in Silvaco

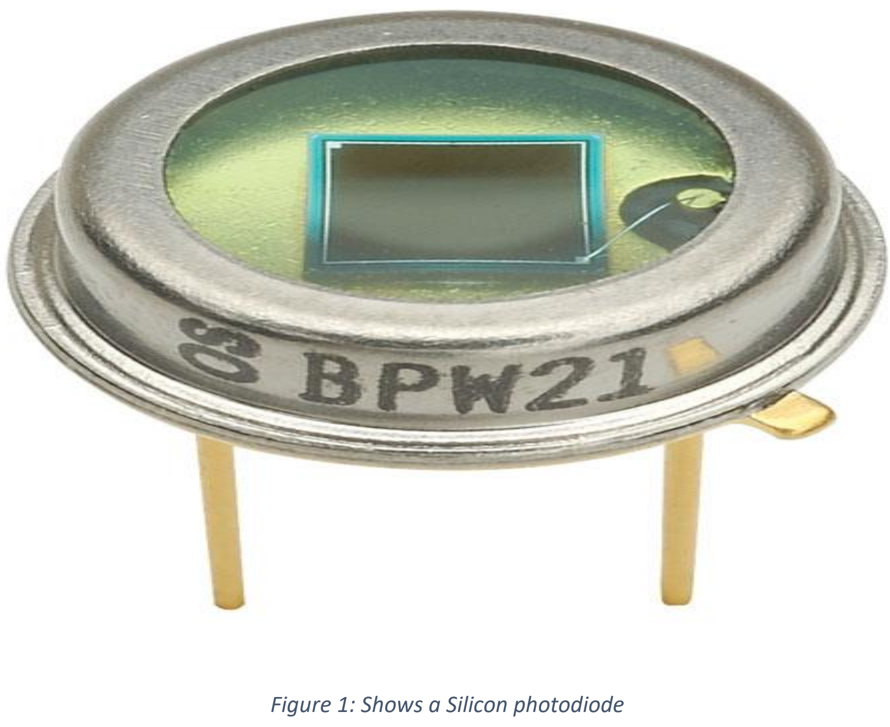


Figure 1: Shows a Silicon photodiode

Introduction and motivation:

The Predictable Quantum Efficient Detector, more known by its acronym PQED, is a photodetector based on the principle of the induced junction.[1] As part of a now aborted master's degree project I and several supervisors worked on measuring the performance of this rather new diode in both room temperature (298 K) as well as cryogenic temperature (77 K). Measurements done at Justervesenet (Norwegian Metrology Institute) showed little difference in performance for the two compared temperatures.

Intention of this project is to create a simulated detector that will be part of a larger component that will be used to evaluate the feasibility of a linear optical quantum computer based on parts like an interferometer, laser and of course the PQED detector. The PQED detector seems ideal for this task due to its low cost, little loss and adaptability to extreme temperatures.[1]

Background:

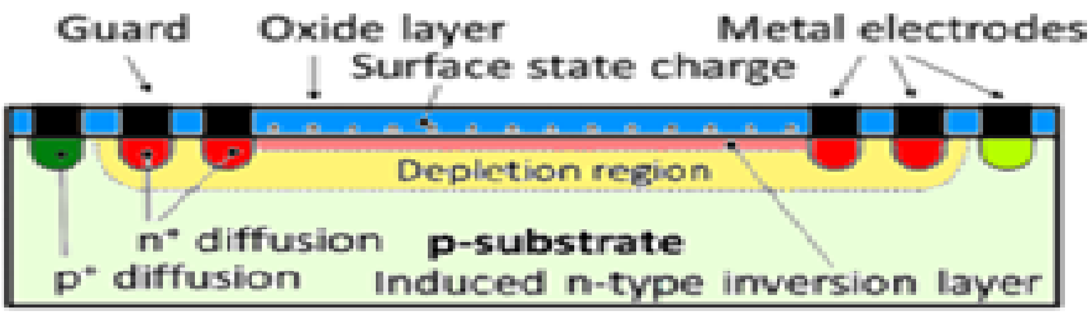


Figure 2: Schematic of a PQED-diode with the lightly doped p-type, n and p electrodes and the inversion layer

The PQED is different from other diodes in that it has an oxide layer on top of a p-type substrate that creates an inversion n-layer in the substrate. P-type part is lightly doped with a concentration of $2 * 10^{12} cm^{-3}$. From this a shallow pn-junction is formed. n^{+}-diffusion rings function as a contacting for the inversion layer, while a p^{+} serves as guarding and terminates the inversion layer.[2] As seen on figure 2 there are two n-layers. The function of the second one called "guard" is to increase the inversion layer slightly outside its "base".

Some simulation has been done on the diode by Chi Kwong Tang at Justervesenet. Results of this can be seen in figure 3. But a difference between this project and the one done at Justervesenet is that their simulation was done in Cogenda and this simulation is in Silvaco.

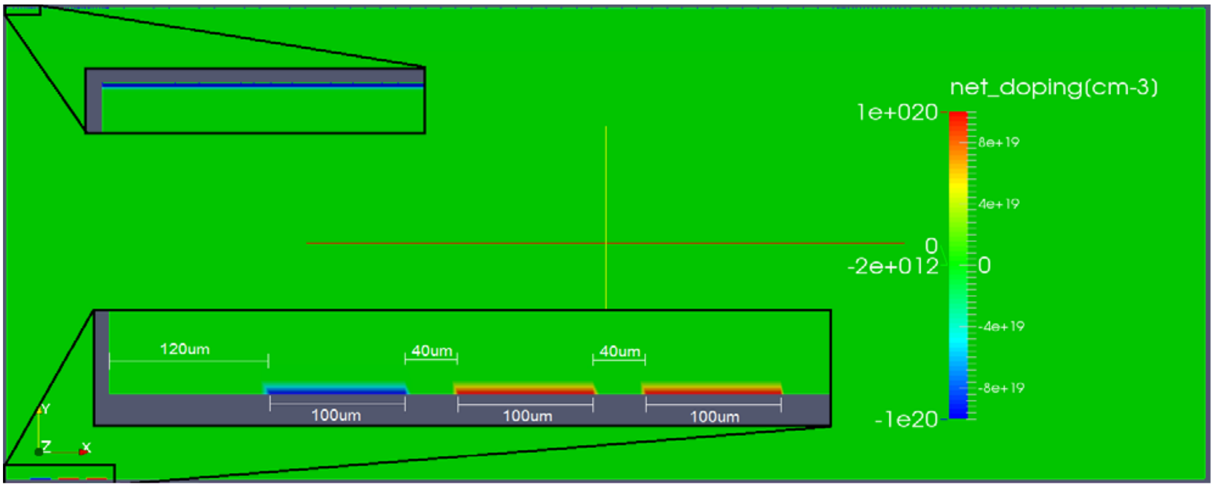


Figure 3: Simulation of PQED in Cogenda at the courtesy of Chi Kwong Tang

Description of deck-file:

In this part a very short description of the deck-file is done.[3] Initially, a mesh-file is created in Atlas (referencing to the Appendix for this). We use the R^2 space with x and y parameters. The interval of the x-parameter is [0,2100] μm. The spacing varies due to different need for resolution. Y-parameter interval is [0,15] μm. Spacing is much smaller here compared to the x-parameter.

Five regions are created. One oxide, one p-type main substrate and the rest are contacts. Two electrodes are put on and the doping has a p-type main substrate (as already explained), with three n^+ and p^+ diffusion regions to simulate the anode, guard and the stopping point of inversion layer.

For more on the actual deck-file a referral should be made to the Appendix A-section of this text. Some special thanks are sent to Dr. Halvard Haug for his help in eliminating all errors in the deck-file and providing with his expertise in creating the deck-file.

Results and discussion:

Several results were obtained in the simulation. The most important ones are evaluating how the structure is compared to figure 2, investigating whether it has diode-properties, the doping and if there is an inversion layer created.[4] Last aspect is particularly important for a PQED-diode based on induced junction. As the results are presented, a discussion-part will accompany it.

Figure 4 shows the structure of the diode obtained by the simulation in Silvaco.

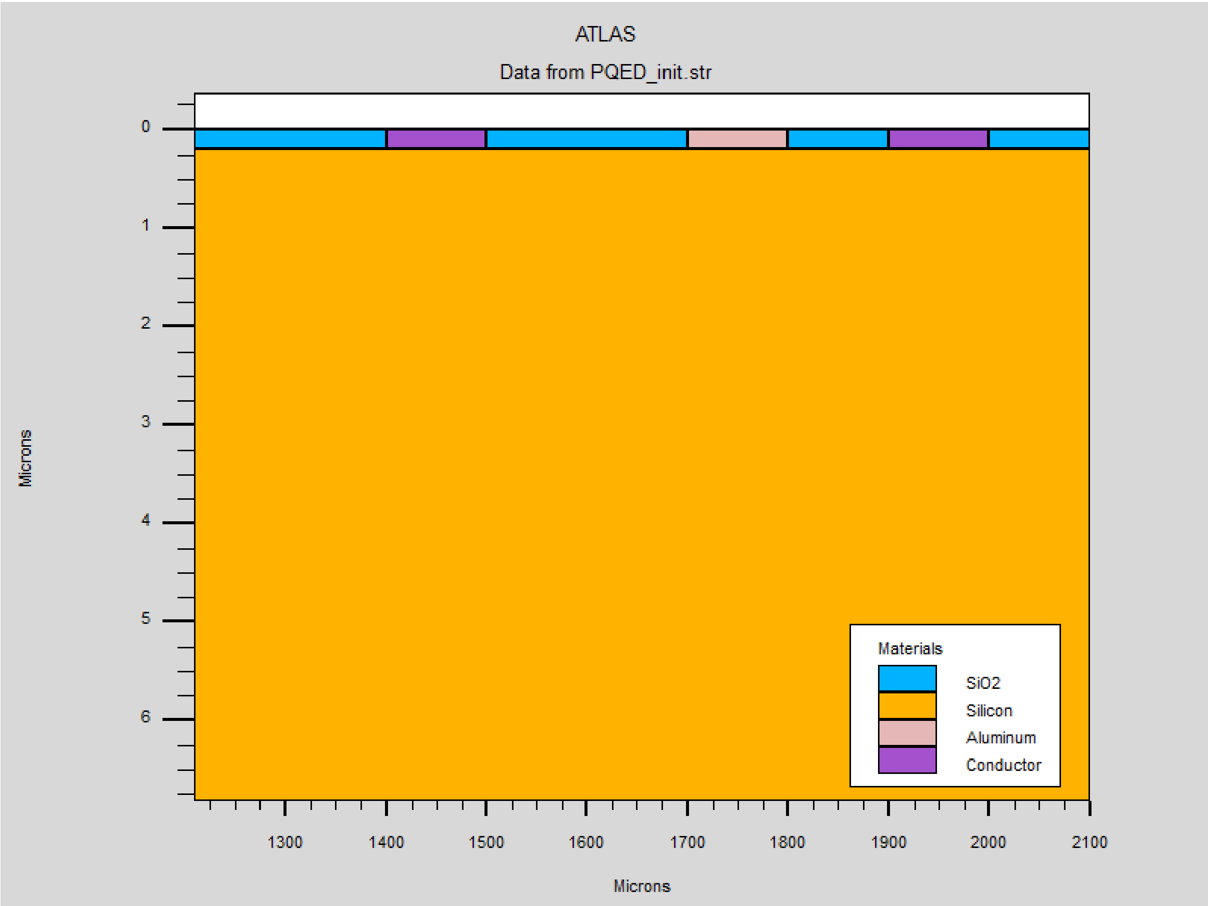


Figure 4: Schematic of the PQED diode structure

This structure is the basis for all the other results gained in this simulation. Compared to figure 2, the anode and cathode are placed on only one side. A setup like that was chosen because it would not have made much difference in properties to have an anode and cathode on the other side as well. A layer of SiO2 is "deposited" on top of the 2D-structure. Before any actual testing is done, the indication is that the structures in figure 2 and 4 are comparable to each other in shape and form.

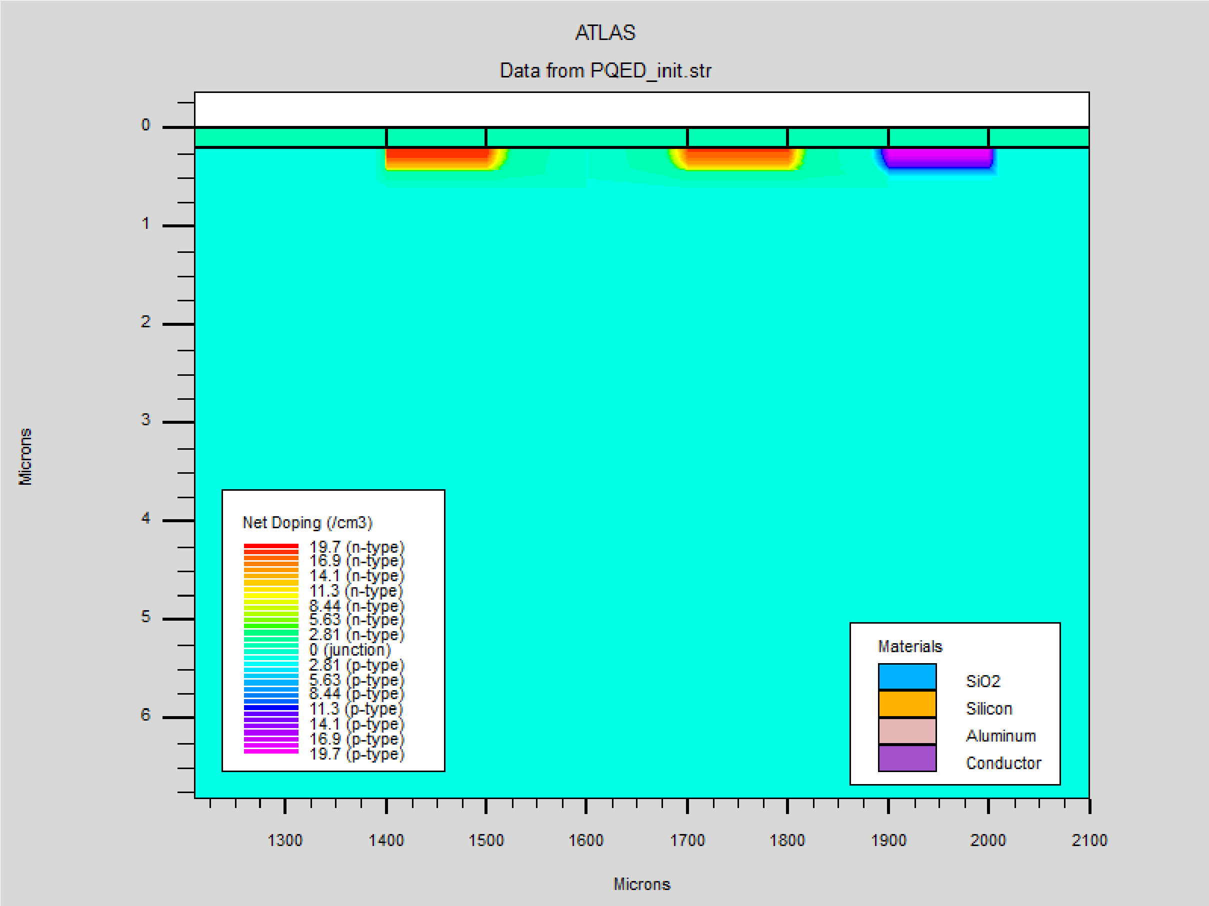


Figure 5: Shows the net doping of the entire PQED diode

On figure 5 the net doping is shown. In the oxide layer and electrodes, no doping is seen. As expected, based on the deck-file. The Silicon substrate is lightly p-type doped, while the regions under anode and "guard" is heavily n-type doped. The cathode is likewise heavily p-type doped. Schematic over net doping on figure 5 is, in this text, used as a possible confirmation of the coding done in the deck-file. It clearly shows that the doping of the different regions has gone according to the initial plan for the PQED diode.

Inversion layer is an important parameter used to judge the functionality of the PQED diode. The entire intention with the diode was to create an inversion layer with an interface charge in the oxide layer. In figure 6, a schematic of the entire structure is included.

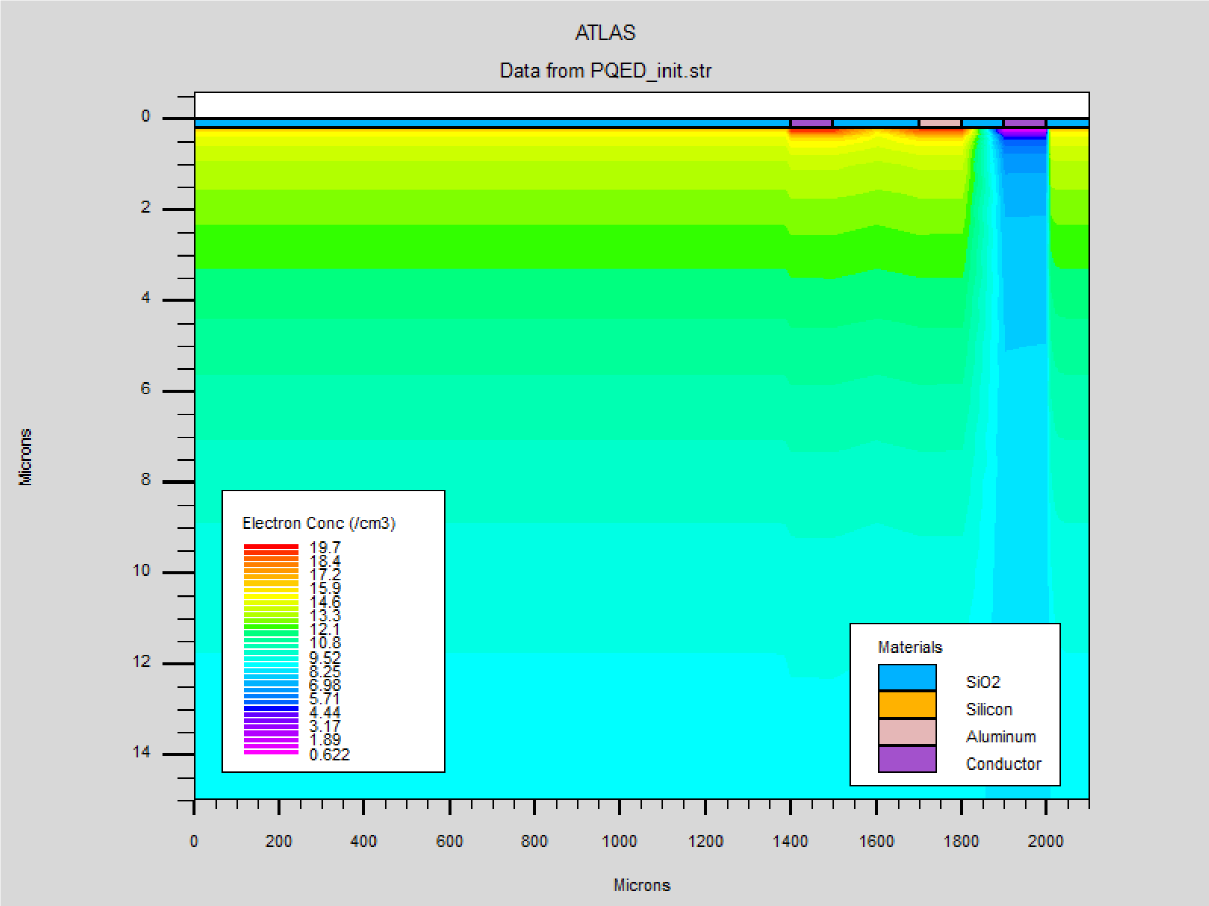


Figure 6: Shows the electron concentration throughout the PQED diode. An inversion layer can be clearly seen beneath the oxide layer

Before further discussion, it should be mentioned that a figure with closer zoom in around the anode and cathode can be found in Appendix B. The figure was omitted from this section due to space constraints.

From figure 6, we see that there is a very high electron concentration under the anode region. Just beneath the oxide layer, the concentration is also high. Though not as high as under the anode. This could be remedied by increasing the interface charge. Although the electron concentration is satisfying as it is. The schematic of the entire structure shows that the further down we go on the structure, the lower the electron concentration becomes. A clear indication of the existence of a proper inversion layer.

A so-called complementary property to the electron concentration is the hole concentration.

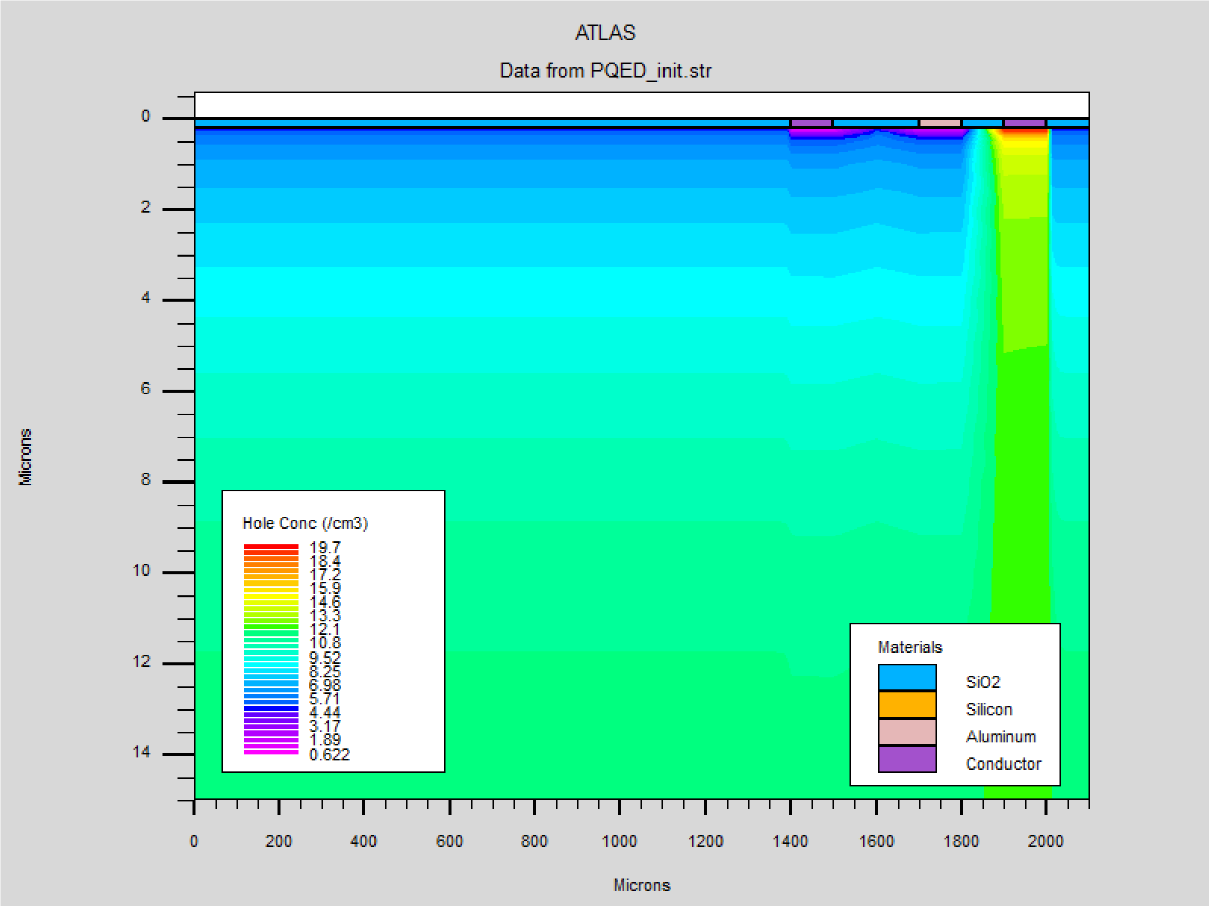


Figure 7: Schematic of the hole concentration throughout the structure

The hole concentration decreases the closer one gets to the oxide layer. This shows the complementary function of the holes to the electrons and is another confirmation of the inversion layer.

To achieve the diode-classification, the diode equation must be fulfilled. Best way to investigate this is by comparing the plot with an ideal diode-plot. For the ideal diode-plot literature like Jenny Nelsons: “Physics of Solar Cells” should be read. Figure 8 might be difficult to comprehend. But it shows the that the diode-equation is fulfilled.

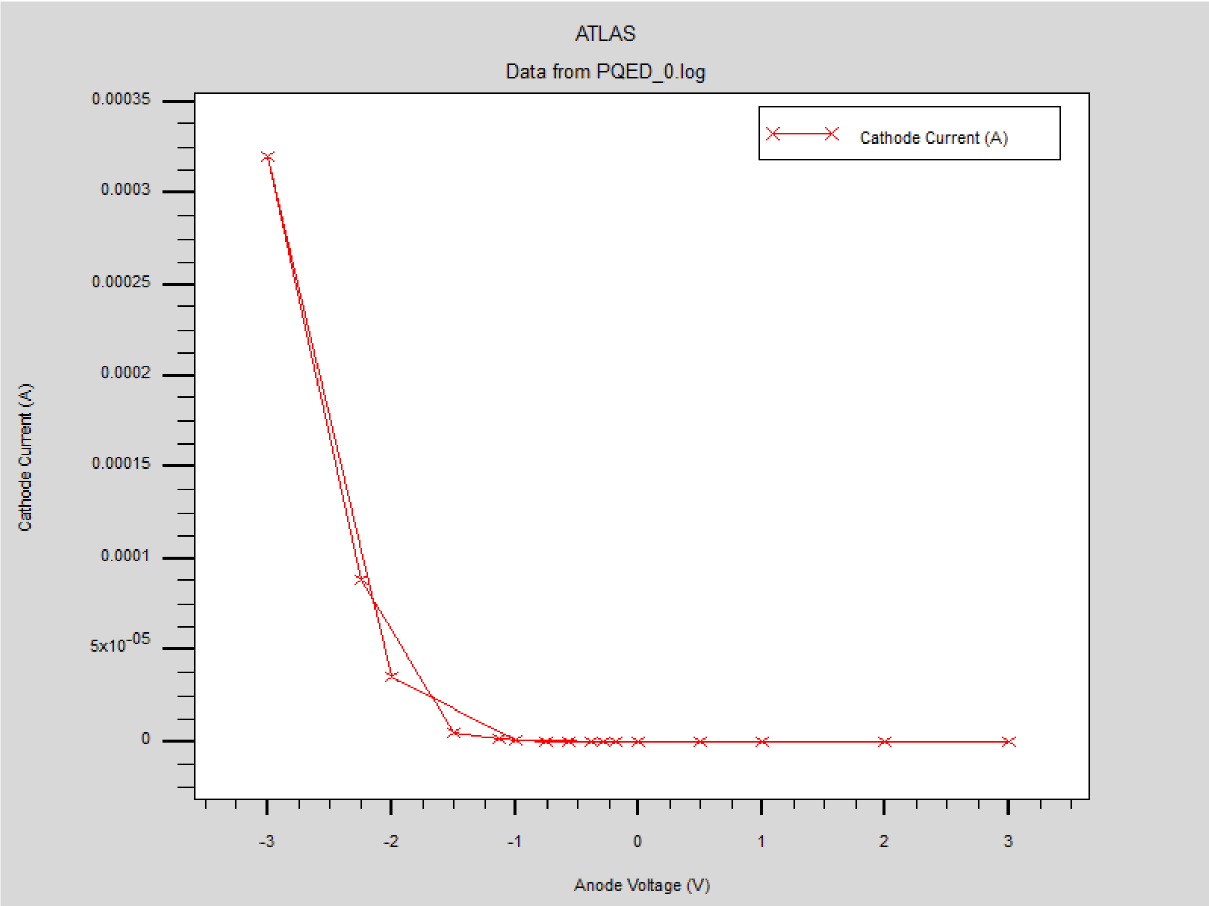
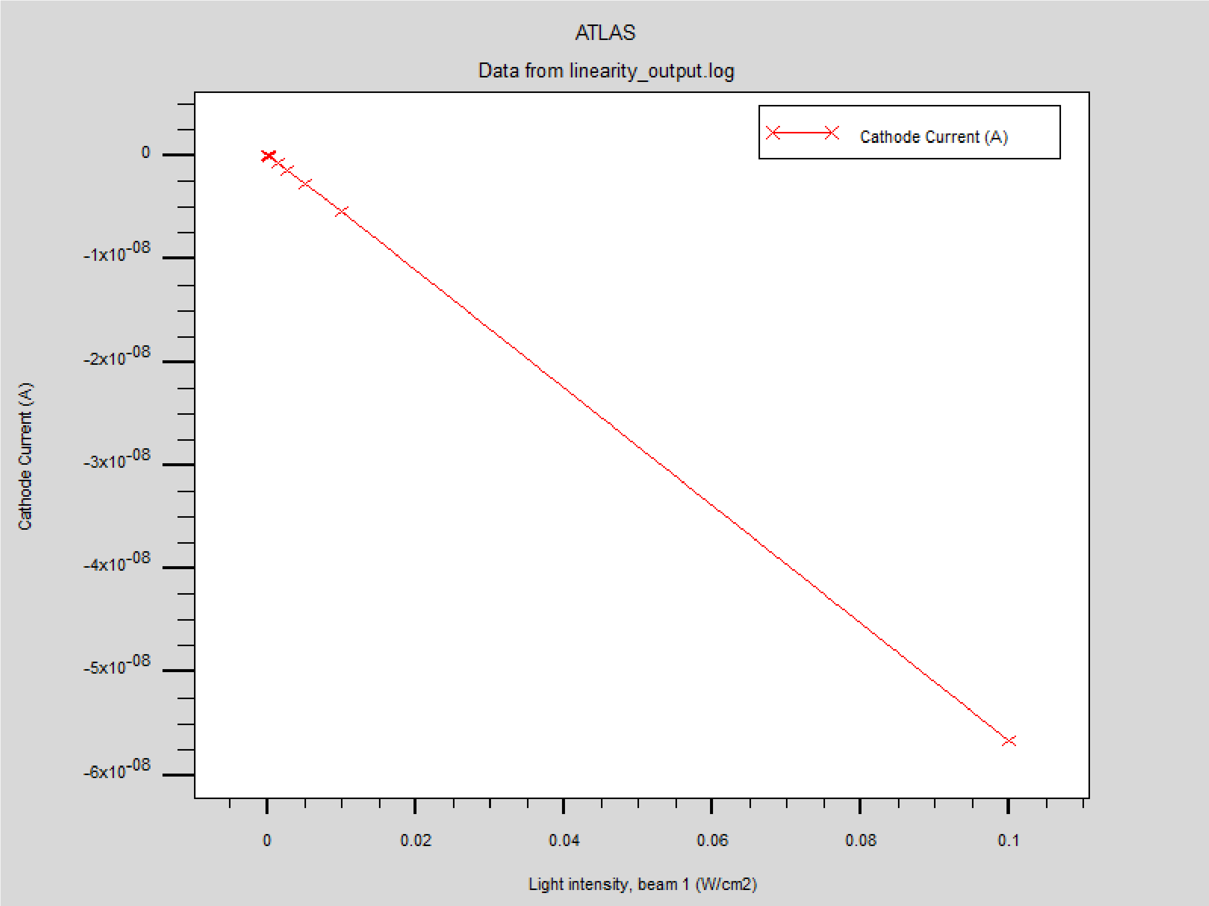


Figure 8: IV-curve of the PQED diode simulation

Linearity of photosensitivity with light intensity is an important parameter.[5] In real-life experiments this aspect could be rather difficult to measure. However, in a simulation it is rather straightforward. In this regard, the most important thing is to evaluate whether the linearity is accomplished.

Figure 9 clearly shows that the linear relationship between light intensity (from 0 to the suns $0.1\,\frac{W}{cm^2}$ in radiation) and current. This is as expected since each incident photon has a certain fixed probability of being absorbed and turned into photocurrent.



Figur 9: Schematic of the light intensity vs current. The expected linearity is seen

For the next two results, an illumination source was created. The first result is a photogeneration of the entire structure and the second shows the IQE vs current. In the research at Justervesenet IQE was considered to be a very important parameter since they intended to use the PQED as a possible primary standard (basically using the PQED to calibrate other instruments).[1] Inferred from that is the importance of the IQE vs current result.

Photogeneration is a form of carrier generation dependent on external photons. Basically, the absorption of a photon by the material generates an electron-hole pair. The actual absorption rate depends on if a direct or indirect (like Silicon) bandgap semiconductor is used. From theory we have that the carriers generated in the depletion region will be transported to the bulk of the material.

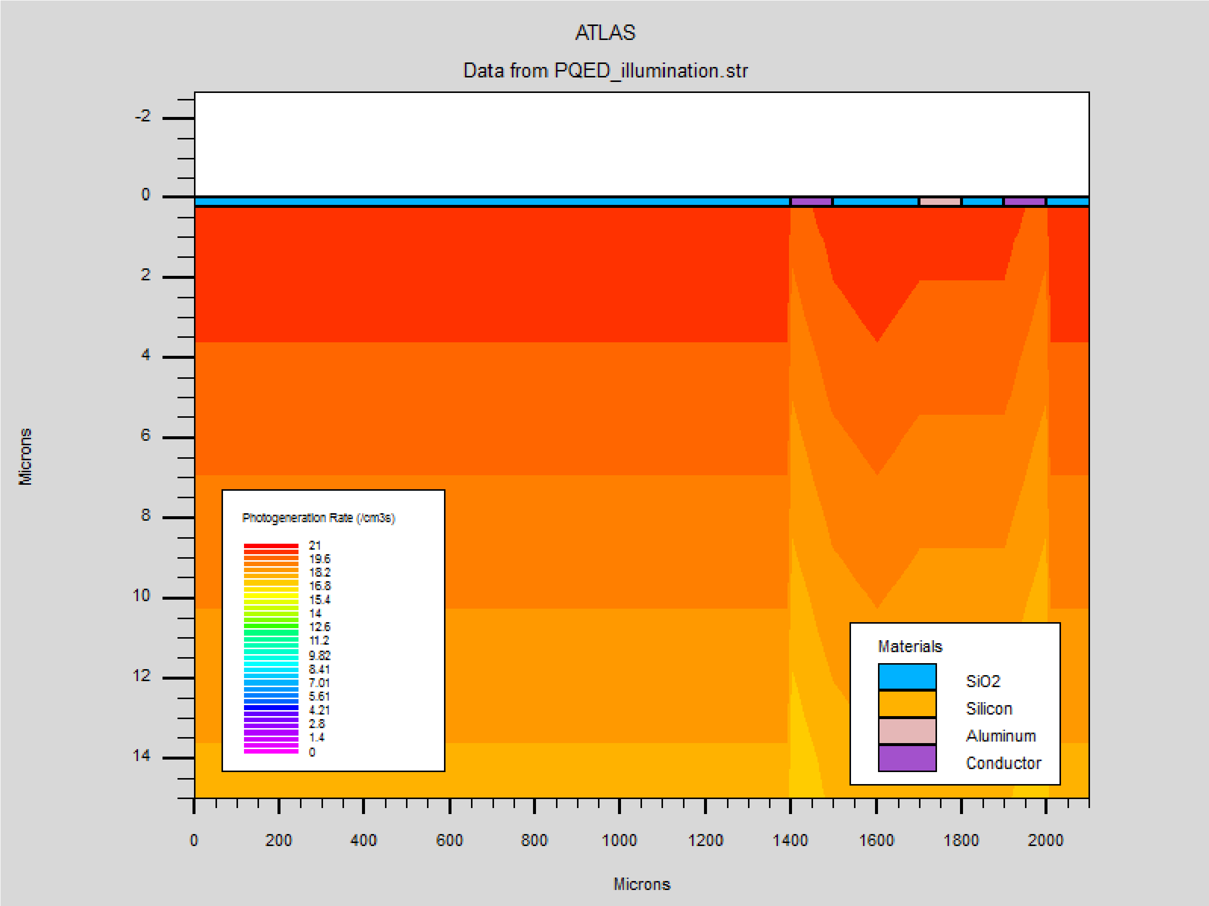


Figure 10: Schematic of the photogeneration rate of the PQED

Figure 10 shows that there is a lot more generation of photoelectrons in the inversion layer compared to the bulk material. This is understandable. One interesting aspect though is the fewer photoelectrons generated under the anode. We remember that there were more electrons in the layer under the anode compared to the inversion layer under the oxide. More research is needed before a conclusion is reached in this case.

Internal Quantum Efficiency (IQE) is the relative amount of photons that produce charge carriers collected by an external measurement circuit.[1] The actual schematic is of the current vs optical wavelength with an interval between 300 nm to 1200 nm. In this brief discussion the focus will be on if the plot in figure 11 is comparable to literature standard plots. Appendix B contains a certain figure 13 which shows a standard literature plot of IQE for Silicon. As can be seen, the simulation provides adequate IQE vs current values.

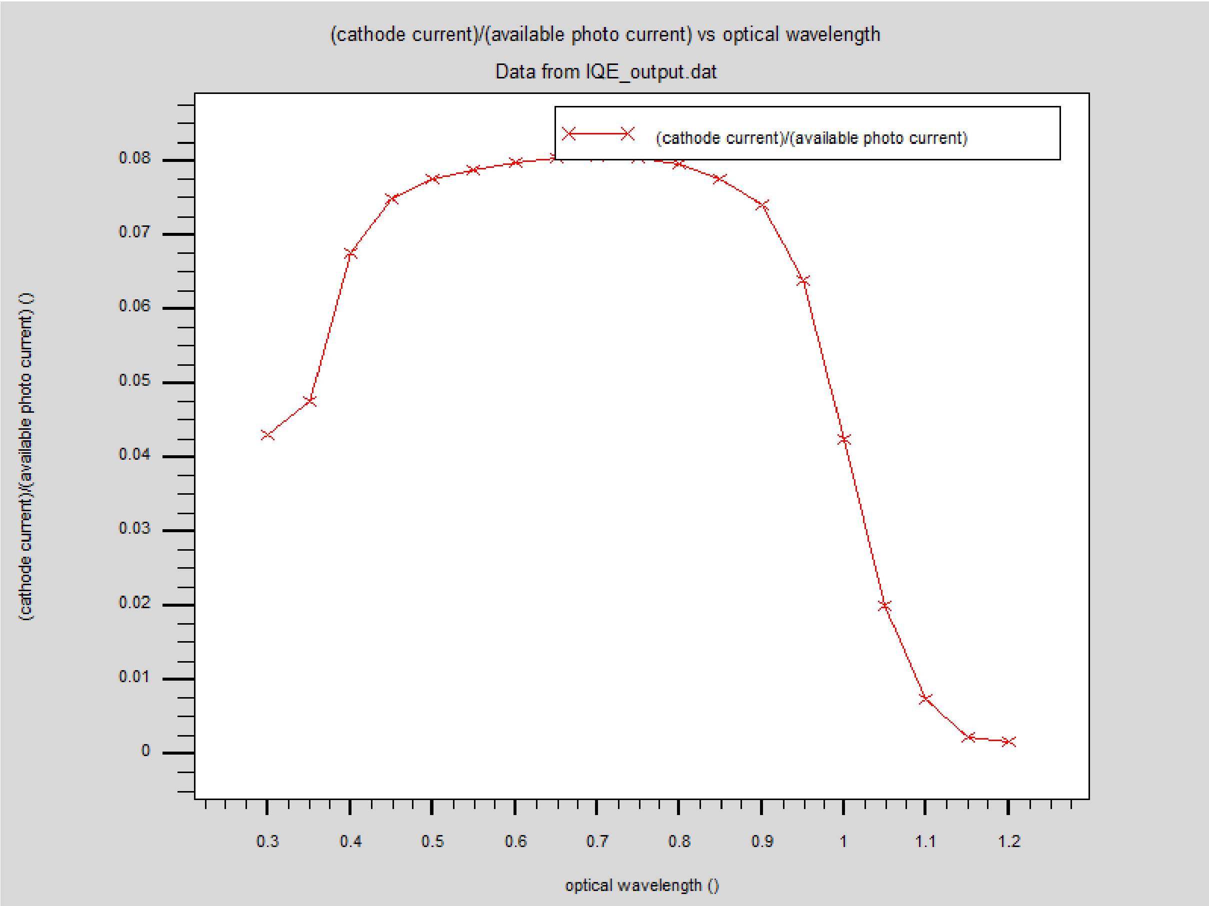


Figure 11:Schematic of the current vs optical wavelength. Shows the simulated IQE for the PQED

For a final analysis several factors must be summarized.

- Net doping and structure file shows that the correct structure and doping was obtained
- The expected inversion layer was found.
- IV-curve shows that the structure is a diode
- The relationship between current and light intensity was linear
- Both photogeneration and IQE plots proved the existence of an inversion layer and the correct level of photon to photocurrent ratio

These factors show that the structure and the simulation of it went as it should. With the structure now created, more research could be done on the PQED diode in Silvaco. The simulation results are obviously valid. Mesh and regions with different doping were inputs that gave the correct structure. IV-curve was found by a basic coding but creating a radiation on the diode was more difficult. After several attempts (and crucial supervision) a correct deck-file was made.

Conclusion:

Due to this being the first attempt (both for the author and the diode in general) on creating a PQED structure in Silvaco some initial baby steps with trials and errors were necessary. Despite that, the end result is satisfying and could be used as a foundation stone for more research on this particular type of diode.

With regards to the actual simulation the result was as expected. The diode structure was obtained and adding voltage and illumination further confirmed this. Furthermore, by evaluating the electron- and hole concentration an inversion layer was found. As already explained, creating an inversion layer in a low-doped p-type Silicon semiconductor by an oxide layer was the primary working principle of the PQED. This was again further confirmed by simulating the photogeneration by judging the amount of generation over the entire structure.

References:

[1] Furkan Kaya, *Surface Passivation at Cryogenic Temperatures*, 2017

[2] T. Hansen, *Physica Scripta*, 1978

[3] Silvaco, https://www.silvaco.com/examples/tcad/index.html, Retrieved 30.05.2018

[4] Conversations with Chi Kwong Tang

[5] Ilja Gouschcha, Bernd Tabbert and Alexander O. Goushcha, *Linearity of the Photocurrent Response with Light Intensity for Silicon PIN Photodiode Array*

Appendix A: The deck-file used

In this appendix part, the deckfile used in this assignment is added. A special thank you to Halvard Haug for supervising the work.

```
go atlas
#
#Title Simulation of a PQED diode in Silvaco
#
mesh auto
x.m l=0.0 spac=50

x.m l=1300 spac=10
x.m l=2100 spac=10
#
y.m l=0.0 spac=0.02
y.m l=0.2 spac=0.01
y.m l=0.5 spac=0.1
y.m l=1 spac=1
y.m l=15.0 spac=1
#
#
region num=1 material=oxide y.max=0.2
region num=2 material=silicon y.min=0.2 y.max=15.0
region num=3 material=aluminum x.min=1400 x.max=1500 y.min=0 y.max=0.2
region num=4 material=aluminum x.min=1700 x.max=1800 y.min=0 y.max=0.2
region num=5 material=aluminum x.min=1900 x.max=2000 y.min=0 y.max=0.2
```

```
electrode num=1 name=anode x.min=1400 x.max=1500 y.min=0.0 y.max=0.2

electrode num=2 name=cathode x.min=1900 x.max=2000 y.min=0.0 y.max=0.2


doping region=2 uniform p.type conc=2e12

doping region=2 gauss n.type conc=5e19 peak=0.2 junct=0.5 x.left=1400 x.right=1500

doping region=2 gauss n.type conc=2e19 peak=0.2 junct=0.5 x.left=1700 x.right=1800

doping region=2 gauss p.type conc=5e19 peak=0.2 junct=0.5 x.left=1900 x.right=2000

#

#

INTERFACE QF=1e12


material region=3 imag.index=1000

material region=4 imag.index=1000

material region=5 imag.index=1000


material region= 2 taun0=1e-6 taup0=1e-6


models srh


solve init


save outfile=PQED_init.str

tonyplot PQED_init.str
```

```
#-set PQED_1.set

#I-V curve
#The code used for the I-V curve was added to the main code from appendix A.

#models bipolar print

#Qimpact selb

output e.field

method newton trap maxtraps=10
#solve init

log outf=PQED_0.log
solve vanode=-3 vstep=1 vfinal=3 name=anode
log off

tonyplot PQED_0.log

save outfile=PQED_3V.str
tonyplot PQED_3V.str
#-set PQED_0.set
```

#creating optical light source

#This appendix concerns creating an optical light source. This source was used to evaluate the photogeneration rate, photoabsorption rate and #recombination rate. The log.part is ignored in the results-section.

```
# set monochromatic light beam for spectral analysis

beam num=1 x.origin=10.0 y.origin=-2.0 angle=90.0


# saves optical intensity to solution files

output opt.int


#models conmob fldmob consrh print


# spectral response

#solve init

#solve previous

#solve previous b1=0

#log outf=PQED.log

#solve b1=1 beam=1 lambda=0.3 wstep=0.025 wfinal=1.0


#tonyplot PQED.log

#-set PQED.set
```

```
# Set to reverse bias for illumination

solve vanode=1



# Ramp up light intensity;


# Log curent vs intensity for linearity check:

log outfile="linearity_output.log"

solve b1=1e-24

solve b1=1e-22

solve b1=1e-20

solve b1=1e-18

solve b1=1e-16

solve b1=1e-14

solve b1=1e-12

solve b1=1e-10

solve b1=1e-8

solve b1=1e-6

solve b1=1e-4

solve b1=1e-2

solve b1=0.1

log off


save outfile=PQED_illumination.str

tonyplot PQED_illumination.str
```

```
tonyplot linearity_output.log



# Solve for range of wavelengths and save to log file

log outfile="EQE_output.log"

solve b1=0.5 beam=1 lambda=0.3 wstep=0.05 wfinal=1.2

log off



# Export EQE data

extract init infile="EQE_output.log"

# extracting IQE
extract name="IQE" curve(elect."optical wavelength",abs(i."cathode")/(elect."available photo current")) outfile="IQE_output.dat"

# extracting EQE
extract name="EQE" curve(elect."optical wavelength",abs(i."cathode")/(elect."source photo current")) outfile="EQE_output.dat"

#tonyplot EQE_output.dat
```

#

tonyplot IQE_output.dat

Appendix B: Extra figures

The first figure is a zoom in of the region beneath the anode and cathode. This is done to show the electron concentration at that particular area.

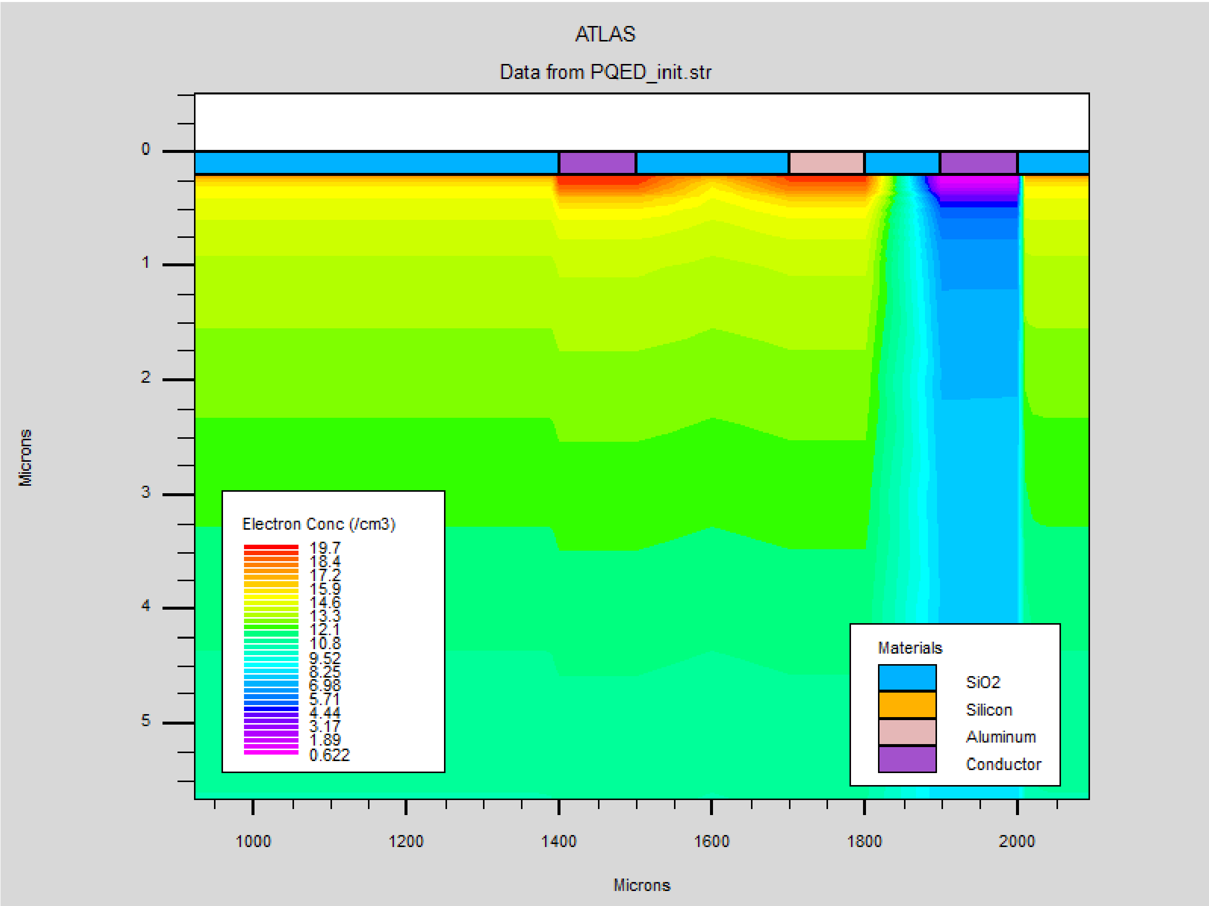


Figure 12: Shows the electron concentration under the anode and cathode area

Next figure is a standard plot of IQE found in solar cell literature:

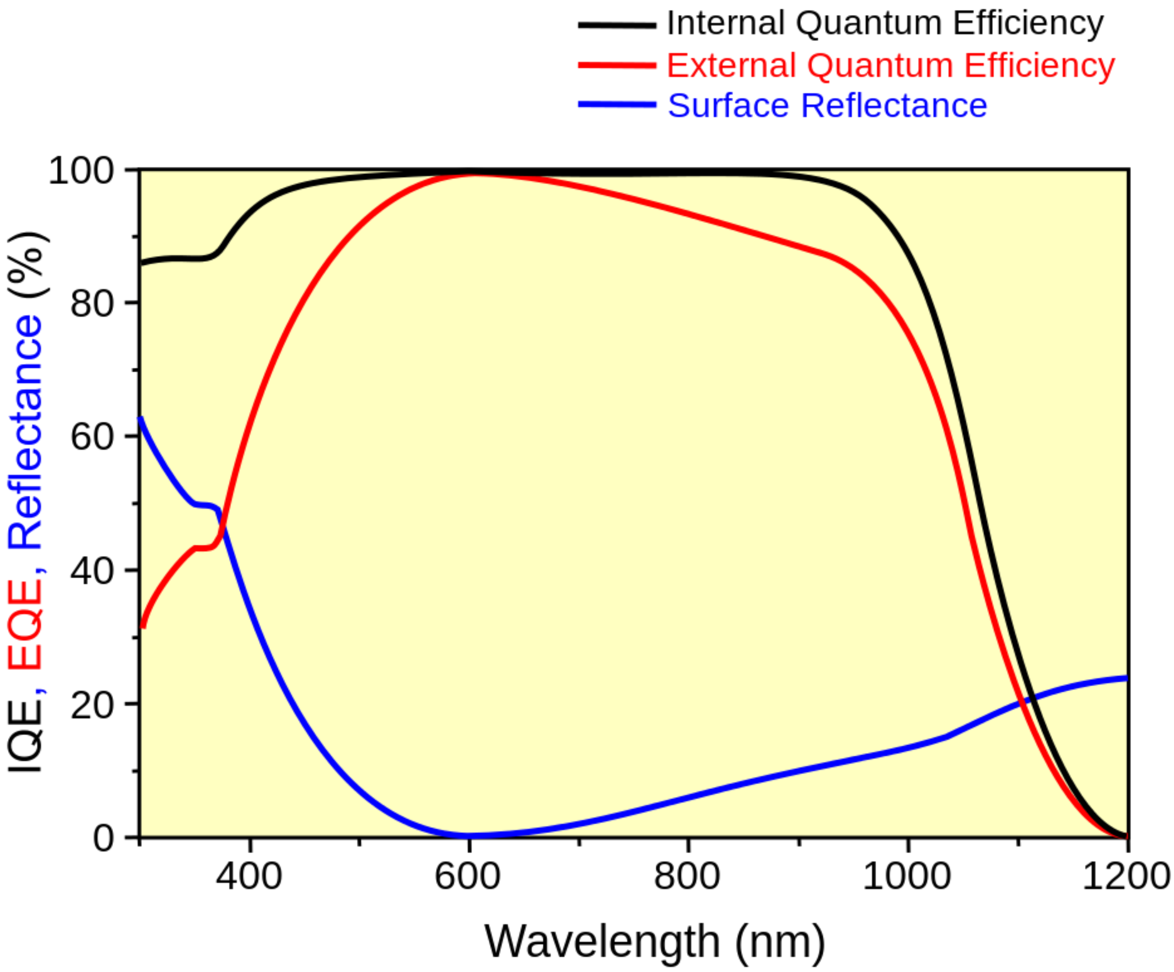


Figure 13: Shows the IQE, EQE and surface reflectance for Silicon