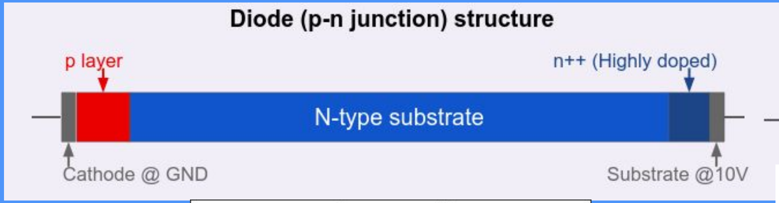
# TCAD Simulations of a Photoconductor

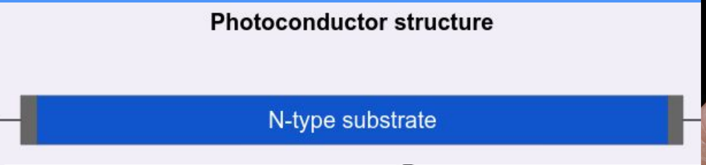
Kyle Loerker, Longwood High School
Gabriele Giacomini, Instrumentation Division, Brookhaven National Laboratory

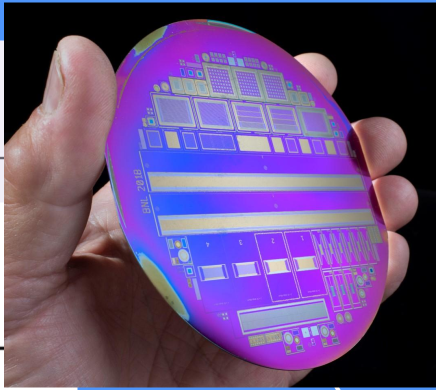
# Introduction

- Silicon sensors are cheap to manufacture, well understood, established technology, and have great capability to detect charged particles and photons in a wide energy range.
- Usually based on a diode, using a p-n junction.
    - A boron-doped layer (p-type) contacts a phosphorus-doped layer (n-type).
- **Can also be as simple as a silicon bar, a “photoconductor”.**
    - Acts as a resistor, and reacts to charged particles and photons
- We can use Technology Computer Aided Design to measure how this photoconductor performs compared to the diode.

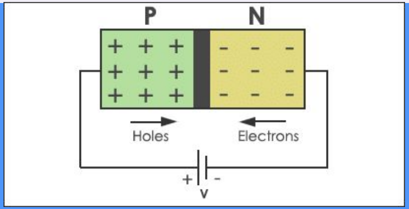
Silicon ingot



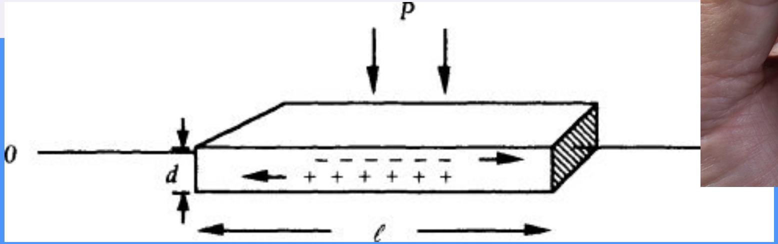



Silicon wafer as manufactured by BNL




Operation of a diode.




Operation of a photoconductor.

# Creation of silicon structures

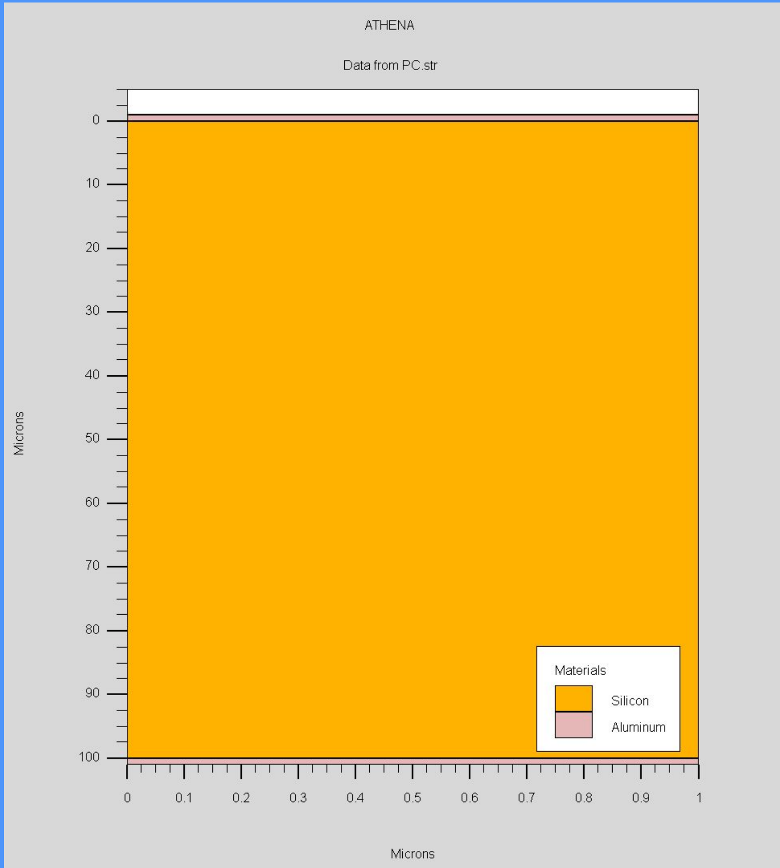
- We used Silvaco's *Athena* simulator to create the geometry of the silicon chips.
- We used the Deckbuild program to interface with Athena, which uses its own programming language.
    - Keywords prepended with $ are variables that we input values for.

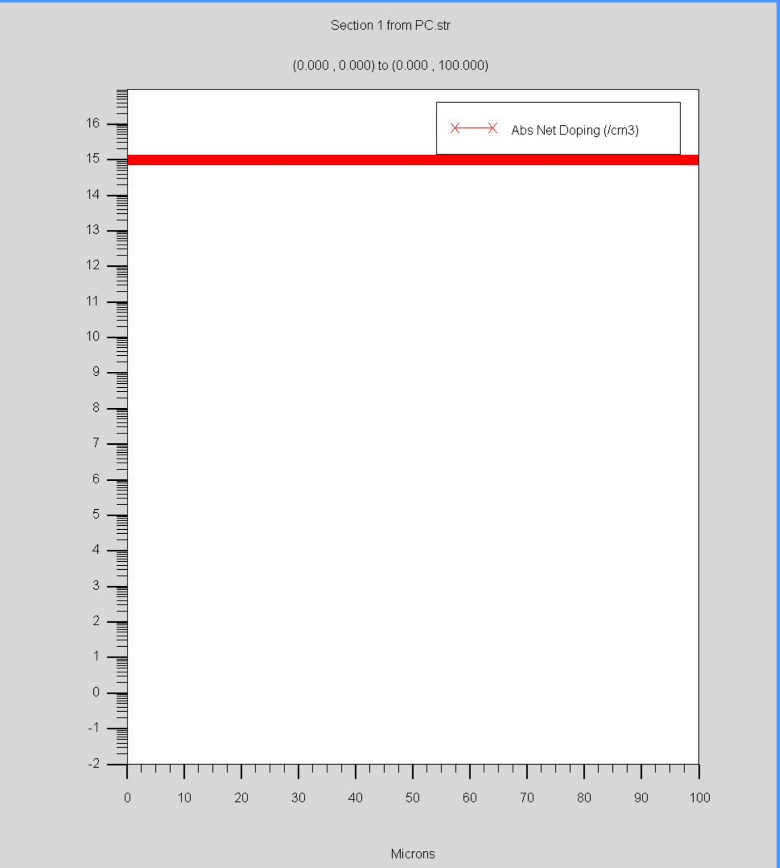
```
# Define the initial rectangular grid.
 line x loc=0 spac=0.5
 line x loc=1 spac=0.5
 line y loc=0 spac=0.1
 line y loc=$si_len spac=0.1
 # Define the initial substrate from the
rectangular grid, using Silicon.
 init silicon c.$dopant_bulk_m=$dopant_c \
                  orientation=100 two.d
 if cond = ($device_t = Diode)
   # Add Boron doping to the edge in the case
of Diode.
   implant boron dose=1.0e15 energy=10 \
              tilt=0 rotation=0 amorph
 if.end
```

```
# Deposit a layer of aluminum at the top.
deposit aluminum thick= $al_len division= 5
# Deposit a layer of aluminum at the bottom.
structure flip.y
if cond = ($device_t = Diode)
   # Dope the silicon with phosphorus in the
case of Diode.
   implant phosphor dose= 1.0e15 energy=10 \
                 tilt= 0 rotation= 0 amorph
if.end
deposit aluminum thick= $al_len division= 5
structure flip.y
```

# Generated structure:

# Cutline across structure:



# Simulating semiconductor physics

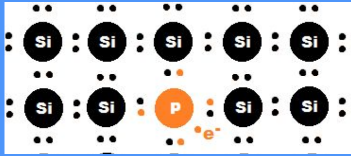
- We used Silvaco's *Atlas* program to simulate the physics of our chip:
  - An external voltage is applied across the bar.
  - A single-event upset is created, generating electron/hole pairs which move through the bar.

```
# Configure the electron and hole lifetime parameters.
material region=1 taun0=$lifetime taup0=$lifetime
# Use Newton's method for solving, specifying the maximum time-step.
method newton carriers=2 trap itlimit=20 \
              maxtraps=10 dt.max=0.02e-9
# Introduce a single-event upset, with a given number of electron-hole pairs.
singleeventupset entrypoint="0,50"                    \
  exitpoint="1,50" pcunits b.density=$ehp_density \
  radialgauss radius=1 t0=$time_event_start tc=0
# Solve with initial parameters.
solve initial
# Include the net charge in the output.
output charge
```

```
# Solve with an increasingly high voltage applied to the substrate electrode.
solve vsubstrate=0 vstep=1 vfinal=$voltage name=substrate
# Simulate the pedestal of the current, with large time-steps.
method newton carriers=2 trap itlimit=20 maxtraps=10 \
        dt.max=100e-9 solve tfinal=$time_event_start \
                                              tstep=1e-9
# Simulate the development of the pulse, with smaller time-steps.
method newton carriers=2 trap itlimit=20 maxtraps=10 \
                              dt.max=$pulse_width/50
# Simulate the rest of the pedestal.
method newton carriers=2 trap itlimit=20 maxtraps=10 \
                                         dt.max=100e-9
solve tfinal=2*$time_pulse_end tstep=1e-9
```

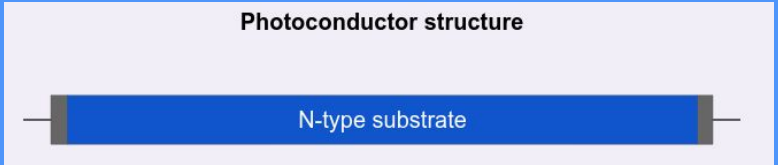
# Simulation parameters

- There are 3 important variables that we modified for different simulations:
  - **Lifetime** ($\tau$). When the charged particles are generated within the silicon bar, there are excess holes (particles representing a lack of negative charge) which will eventually recombine with electrons. The lifetime parameter controls the amount of time it takes until this recombination occurs.

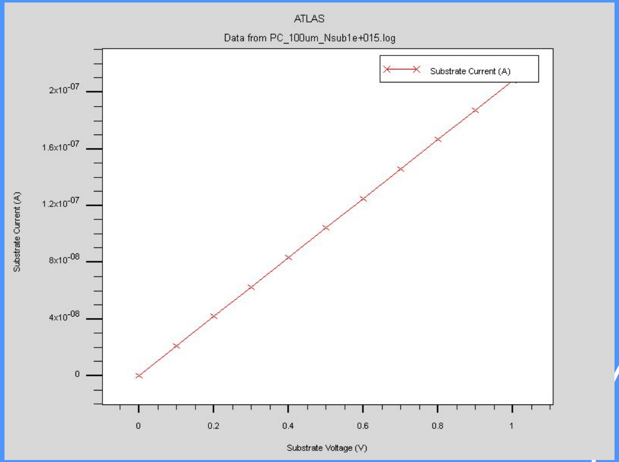



An atomic view of the n-type semiconductor doped with phosphorus. The phosphorus atoms introduce free electrons which the generated holes will combine with.

  - The **density** of the generated electron/hole pairs.
  - The **voltage** applied to the semiconductor.




The photoconductor structure from earlier. Between the two strips of aluminum on the sides, the cathode is grounded, and the substrate has voltage applied to it.




Substrate current vs. substrate voltage, for the photoconductor. The electrodes have been configured to be ohmic, as the photoconductor is a resistor. As a result, these are proportional.

# Workflow

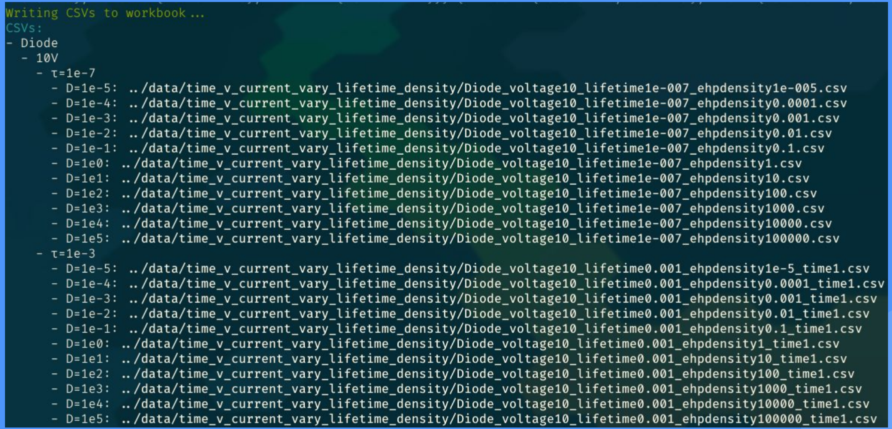
- Atlas produces `.log` files which can be:
  - Viewed and overlayed in Tonyplot.
  - Exported as comma separated values, and analyzed in a spreadsheet program.
    - The latter part of this process was automated using Python.
- We used the following workflow:

Athena creates a structure file (`.str`).

Atlas simulates using the structure file, creating solutions (`.sta`) and logs (`.log`).

Tonyplot exports the log as comma separated values (`.csv`)

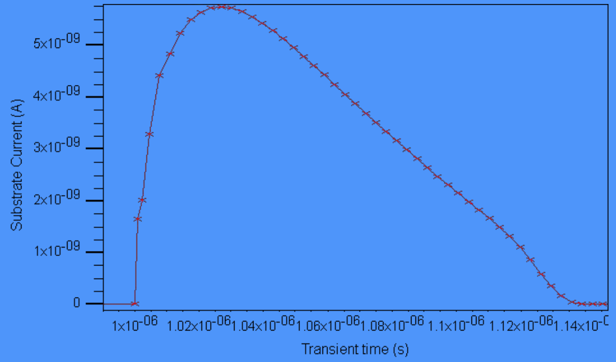
`exportcsv.py` organizes the CSV files, and produces an Excel spreadsheet.




`exportcsv.py` deducting experiment parameters from filenames.

# Results on diode

- Our simulations output the current of the device as a function of transient time.
- We can calculate the charge by taking the integrals of the current pulses:

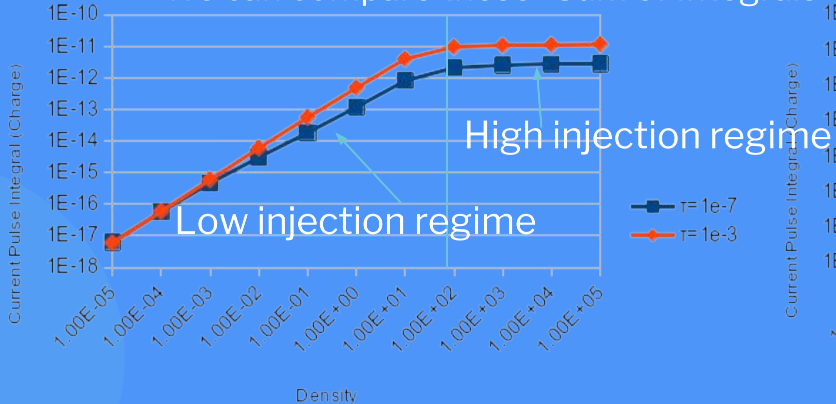


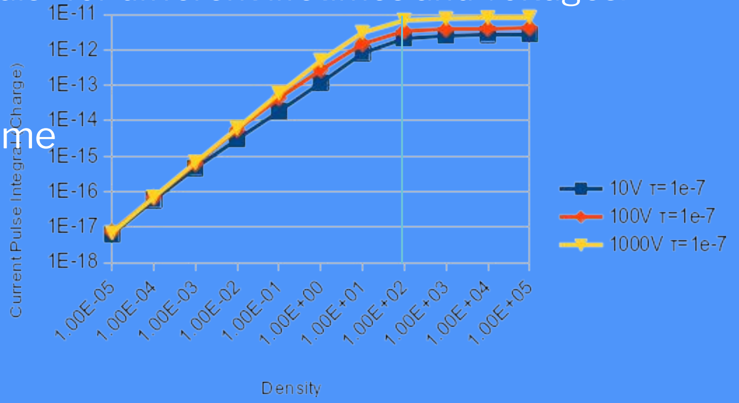

Current vs. transient time for the Diode, in Tonyplot.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Transient time | Substrate Current | Difference from Start | Integral | Sum of Integrals |
| 2 | 1.0000000000e-09 | 1.0433371420e-12 | 0 | | 4.63252E-16 |
| 3 | 3.0000000000e-09 | 1.0433357510e-12 | -1.391E-18 | -2.782E-27 | |
| 4 | 7.0000000000e-09 | 1.0433356460e-12 | -1.496E-18 | -5.984E-27 | |
| 5 | 1.5000000000e-08 | 1.0433364360e-12 | -7.06E-19 | -5.648E-27 | |
| 6 | 3.1000000000e-08 | 1.0433358750e-12 | -1.267E-18 | -2.0272E-26 | |
| 7 | 6.3000000000e-08 | 1.0433358290e-12 | -1.313E-18 | -4.2016E-26 | |
| 8 | 1.2700000000e-07 | 1.0433360700e-12 | -1.072E-18 | -6.8608E-26 | |
| 9 | 2.2700000000e-07 | 1.0433365340e-12 | -6.08E-19 | -6.08E-26 | |
| 10 | 3.2700000000e-07 | 1.0433353330e-12 | -1.809E-18 | -1.809E-25 | |
| 11 | 4.2700000000e-07 | 1.0433350320e-12 | -2.11E-18 | -2.11E-25 | |

Integrals of current pulses for the same Diode, in Microsoft Excel.

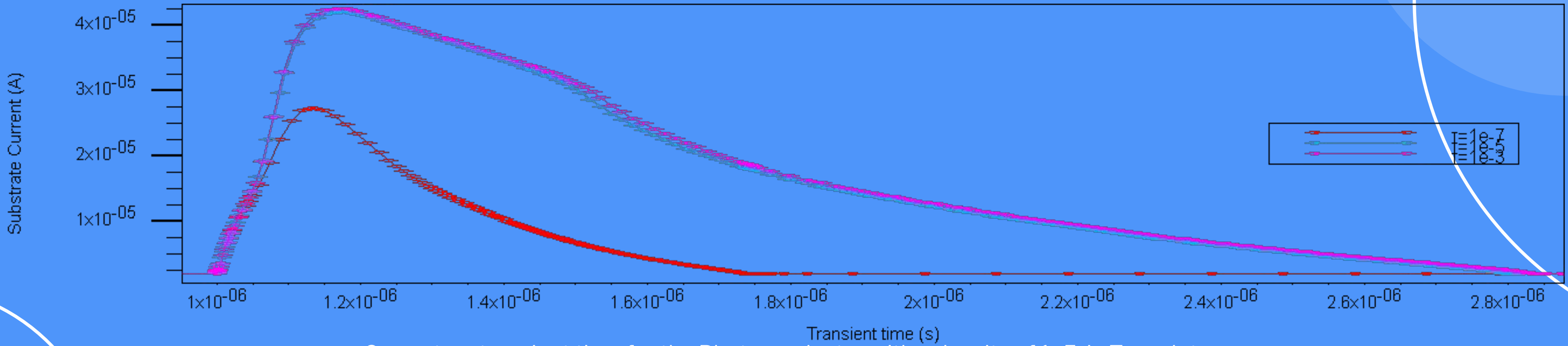
- We can compare these “Sum of Integrals” for different lifetimes and voltages:



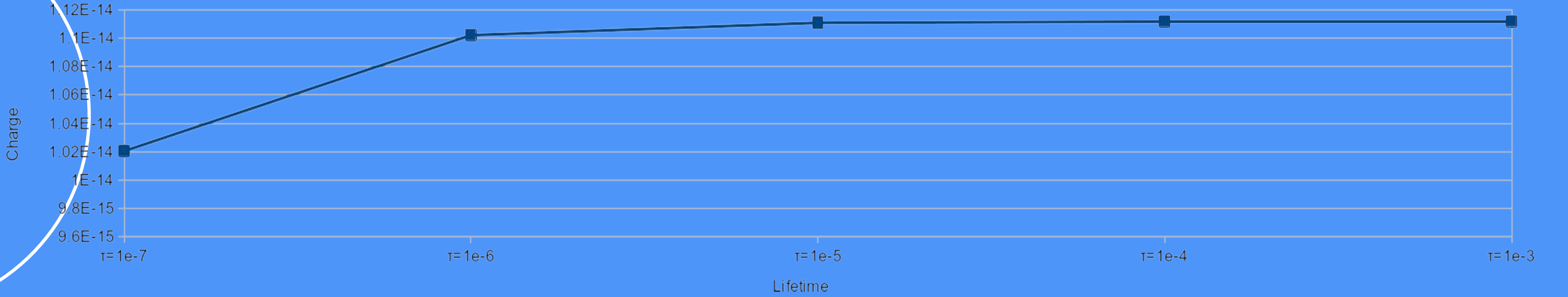



# Results on photoconductor

- As with the diode, we calculated the charge of the photoconductor with different lifetimes.



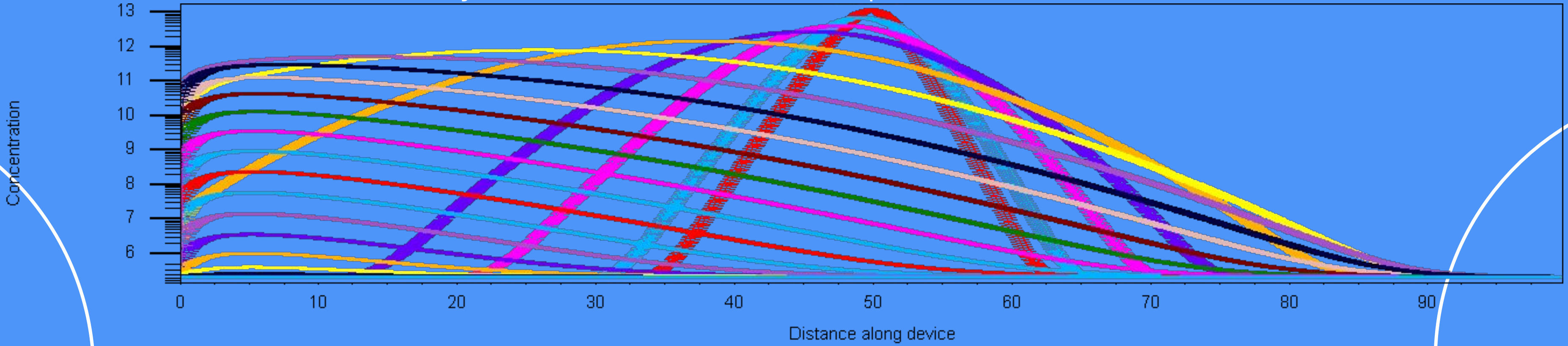

Current vs. transient time for the Photoconductor with a density of 1e5, in Tonyplot.




Charge vs. lifetime, in Excel. The charge plateaus at a lifetime of 1e-6s.

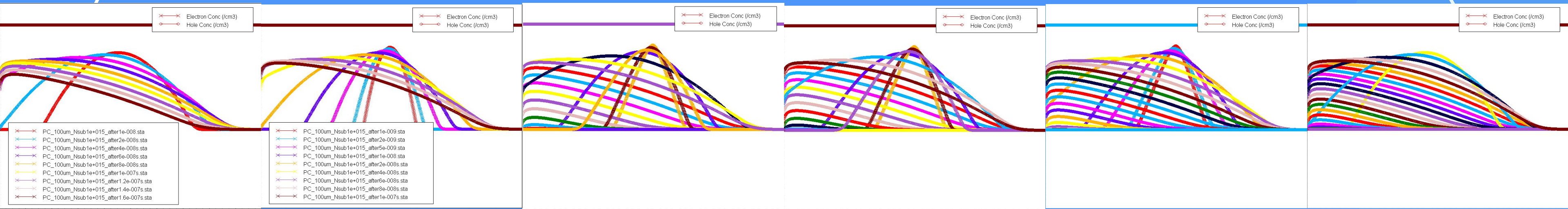
# Movement of holes

- We can have Atlas save the solution of the photoconductor at repeating time intervals, and then overlay the solutions via Tonyplot.
- We can use this to study how the holes move within the photoconductor over time.




Each line here represents a different time, over 200ns intervals.

- This graph illustrates how the single-event upset starts as a dense hole cloud, before flattening out.
- This hole buildup causes electrons to be injected to compensate for the hole charge, to keep charge neutrality.

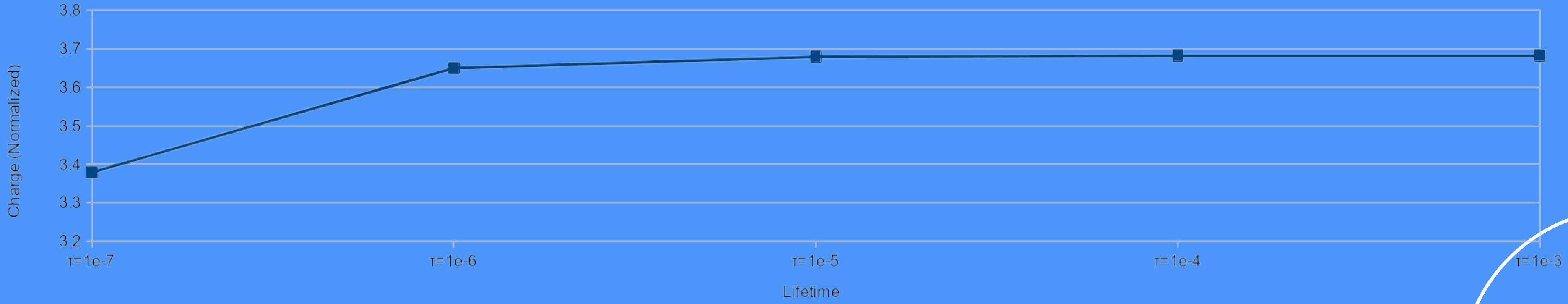


# Comparing normalized results

- We can normalize the charge values of the photoconductors by dividing by the charge value of the diode at lifetime τ=1e-7.

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Diode: | | | | | | | | | | | | |
| 2 | Voltage | Lifetime | 1.00E-05 | 1.00E-04 | 1.00E-03 | 1.00E-02 | 1.00E-01 | 1.00E+00 | 1.00E+01 | 1.00E+02 | 1.00E+03 | 1.00E+04 | 1.00E+05 |
| 3 | 10V | τ=1e-7 | 6.23369E-18 | 5.72789E-17 | 4.63252E-16 | 3.01978E-15 | 1.83279E-14 | 1.17481E-13 | 8.04993E-13 | 2.07745E-12 | 2.47445E-12 | 2.69088E-12 | 2.7509E-12 |

For photoconductors with density 1e-2pC/um, this value is used for normalization.




Normalized charge vs. lifetime for the photoconductor, with with density 1e-2pC/um.

- Theoretically, charge should be proportional to lifetime. More work will be needed to understand this.

# Resources

- The source code for the scripts and Deckbuild code used to create this project are available at **https://gitlab.com/CodingKoopa/photoconductors**.
- Images used:
  - https://www.svmi.com/silicon-wafer-manufacturing-semiconductor-process/
  - "Real Detectors: Vacuum Photodiodes and Photomultipliers, Photoconductors, Junction Photodiodes, and Avalanche Photodiodes" (Robert H. Kingston)
  - https://www.researchgate.net/figure/PN-Junction-Diode-Forward-Biased_fig2_325768332
  - https://energyeducation.ca/encyclopedia/Dopant
- Presentation template: https://slidesgo.com/.