Photoconductor Research

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1 Calculating electrical current

We understand that intrinsic semiconductors do not conduct much electricity if any. Extrinsic semiconductors do conduct electricity, with their added amount of charge carriers. Given a uniform electric field and density, resistance can be represented by [wik, 2020a]:

$$R = \rho \frac{\ell}{A} \tag{1}$$

In our simulation of a thin slab of silicon, we may apply this equation as the density and doping of the material is uniform, and the electric field is constant, as seen in figure 1.

For a doped semiconductor, there are a couple of ways of determining the electrical resistivity ρ:

- Finding the resistivity of the doped material as a function of the amount of electrons and/or electron holes, with this equation [Zeghbroeck, 1996, 1997] [wik, 2020b]:

  $$\sigma = q(\mu_n n + \mu_p p) \tag{2}$$

  q is the charge, where $q = e = 1.60 \times 10^{-19}\,\mathrm{C}$. n is the number of electrons, and p is the number of electron holes. μ_n and μ_p are the mobilities of the electrons and holes, respectively. When there is a negligible amount of minority carriers, this equation can be simplified to $\sigma = q\mu_n n$ or $\sigma = q\mu_p p$. Finally, ρ is the reciprocol of electrical conductivity σ.

- Finding the resistivity at a single point, with the equation $\rho = \frac{E}{L}$. E is the magnitude of the electric field, and J is the magnitude of the current density, at this point. This is a more general equation, but it can be useful for us as E and J are constant throughout our chip.

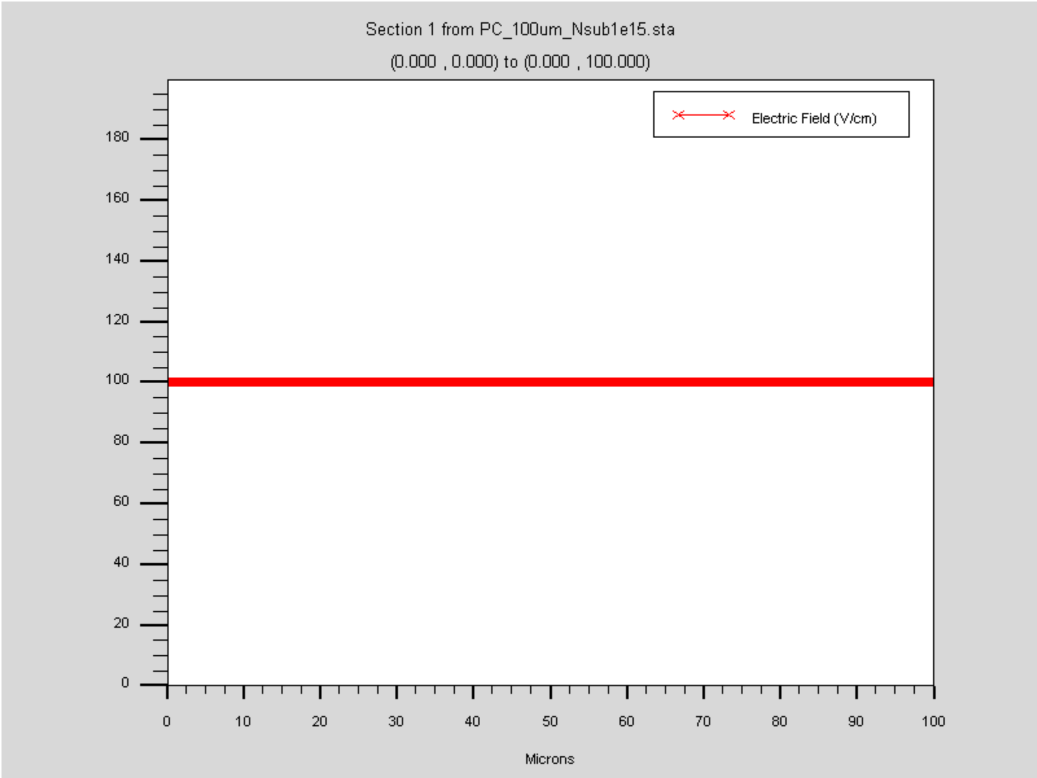

Figure 1: Graph of the magnitude of the electric field across the chip.

Unless specified otherwise, the following examples will assume the following:

- $N_d = 1 \times 10^{15}\,\mathrm{cm}^{-3}$.
- The substrate material is silicon, and the dopant material is phosphorus.
- The temperature is $300^{\circ}K$.

1.1 Using a calculator

This online calculator can be used to determine what the resistivity of a given doped semiconductor will be, taking dopant concentration N_d as an input. According to this calculator, $\rho = 4.584\Omega cm$.

1.2 Using a graph

Similarly to the last method, one can also use a graph of N_d vs. ρ to determine resistivity, such as that of this Quora answer. According to this group, $\rho \approx 5\Omega cm$.

1.3 Calculating from E-field and current density

Using Silvaco TCAD, it can be found that $E = 100.\frac{V}{cm}$ and $J = 21.9\frac{A}{cm^2}$ (see figure 2), which can be used to find the resistivity:

$$\rho = \frac{E}{L} = \frac{100.\frac{V}{cm}}{21.9\frac{A}{cm^2}} = 4.564\Omega cm \tag{3}$$

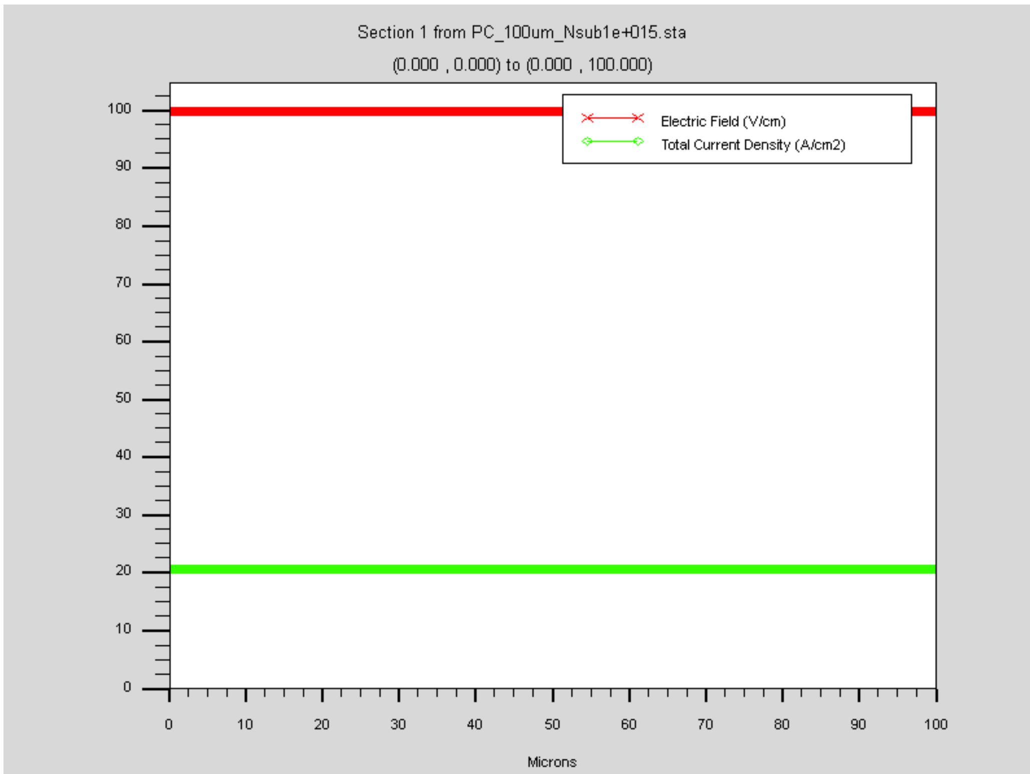

Figure 2: Magnitude of the electric field and current density across the chip.

1.4 Calculating from doping concentration

μ_n is tricky to determine by hand, as it is related to the drift velocity [wik, 2020c]. I have used the calculator from before to determine that $\mu_n = 1324\frac{cm^2}{Vs}$. The calculator takes electron and hole lifetimes as a parameter, which we can extract from the `material` parameter of the deck:

```
material region=1 taun0=1e-7 taup0=1e-7
```

These parameters do not seem to affect the mobilities anyways, though. The concentration of electrons can be found using TCAD (see figure 3), $n = 1 \times 10^{15}\,\mathrm{cm}^{-3}$ (equivalent to our doping concentration). These can be used to find the resistivity:

$$\rho = \frac{1}{q\mu_n n} = \frac{1}{(1.60 \times 10^{-19}\,\mathrm{C})(1324\frac{cm^2}{Vs})(1 \times 10^{15}\,\mathrm{cm}^{-3})} = 4.54\Omega m \tag{4}$$

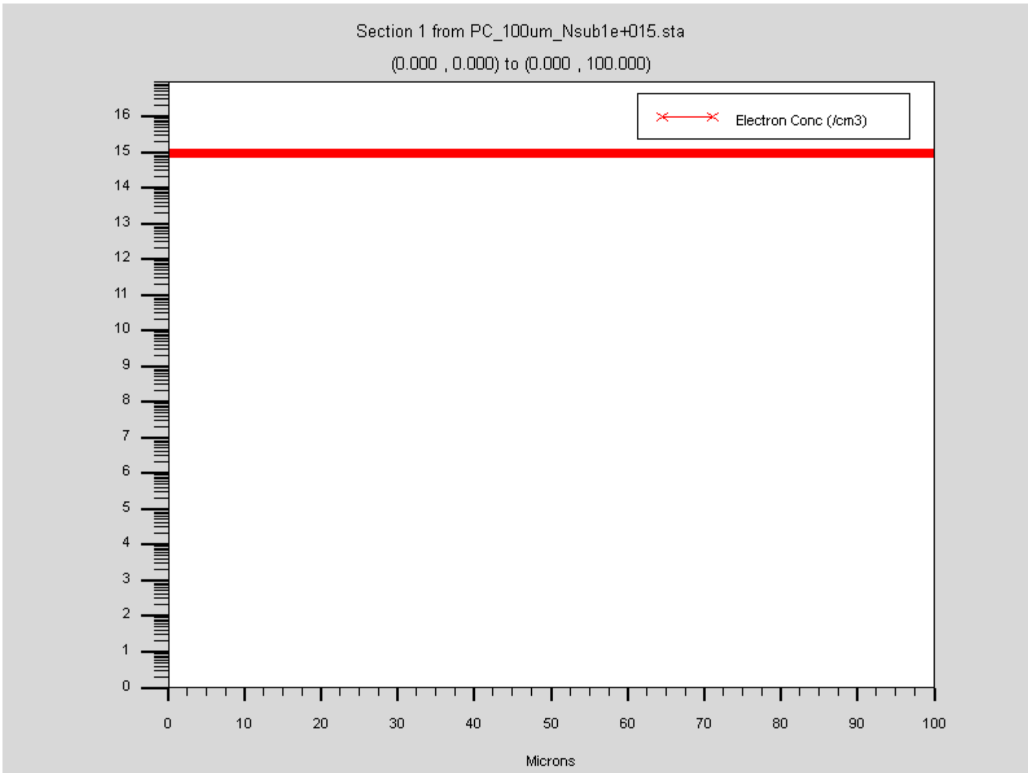

Figure 3: Electron concentration across the chip.

2 Effect of dopant concentration and voltage on current

Electrical current varies with the dopant type, dopant concentration, and voltage applied. The data from these experiments is available here. Figure 4 shows the relationship between dopant concentration, and current. This graph includes the simulated current from the TCAD log files, and the current calculated using equations (2) and (1), where $I = \frac{V}{R}$. As N_d increases, current I increases. For phosphorus, the simulated currents are lower, but for boron, the simulated currents are higher, when compared to their calculated counterparts.

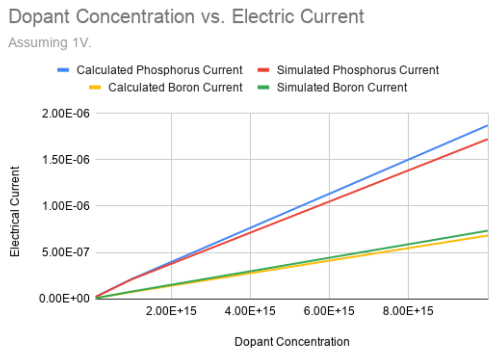

Figure 4: Electron concentration vs. dopant concentration for phosphorus and boron.

Figure 5 shows the relationship between voltage, and current. As expected, larger voltages yield larger currents; it is worth noting that the deficit was much larger with phosphorus than with boron.

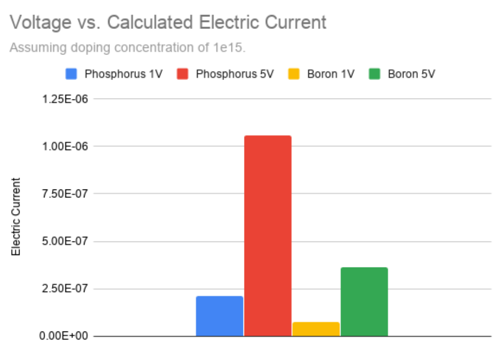

Figure 5: Dopant concentration for phosphorus and boron at different voltages.

3 Change in current over time (Baseline 1)

To study the change in current flowing through the chip, the single-event upset was modified from it's original behavior of moving from $(50, 10)$ to $(60, 10)$, to moving from $(0, 50)$ to $(1, 50)$. Additionally, the density was changed from $1.14 \times 10^{-4}\,\frac{\text{pC}}{\mu\text{m}}$ to $1.0 \times 10^{-4}\,\frac{\text{pC}}{\mu\text{m}}$.

We have already logged the current flowing through the chip for different applied voltages. As can be seen in figure 6, V and I are proportional, which makes sense as the two electrodes are configured to be ohmic. Now, we will study the current flowing through the chip for different times after the single-event upset.

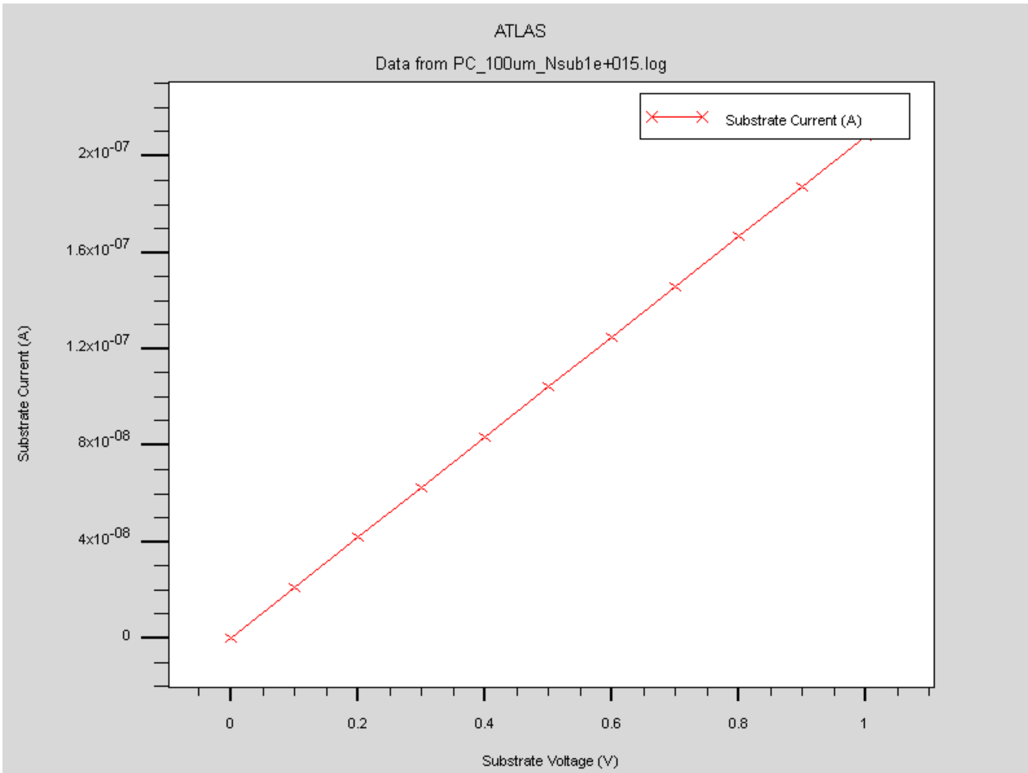

Figure 6: Substrate voltage vs substrate current.

In order to study this change, three variables were modified:

- `dt.max`, the maximum time-step for the transient simulation to run to. Transient simulations allow one to study the changed caused by an event like a sudden charged particle, and how the electronics react. This is opposed to studying electronics in their stable condition, without these upsets [Deshpande].
- `dt`/`tstep`, the time-step to start at.

- `tfinal`, the time-step to end at.

All three of these variables were increased by an order of magnitude each time.

The current gradually decreases over time. It decreases linearly at first, before the rate starts to lessen at about 1×10^{-7} s.

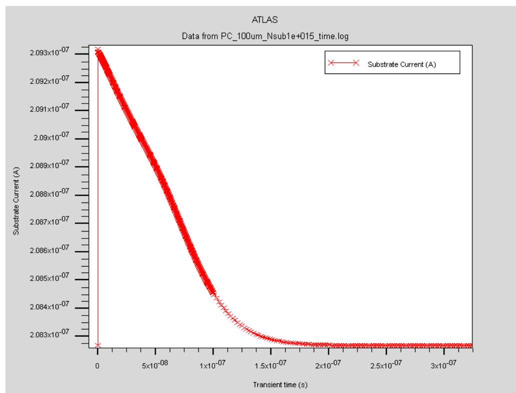

Figure 7: Time vs substrate current.

In the initial simulations of specific time-stamps depicted in figure 8, it can be seen that a change in the electric field is propagated. By 1×10^{-6} s, the electric field seems to become constant once more.

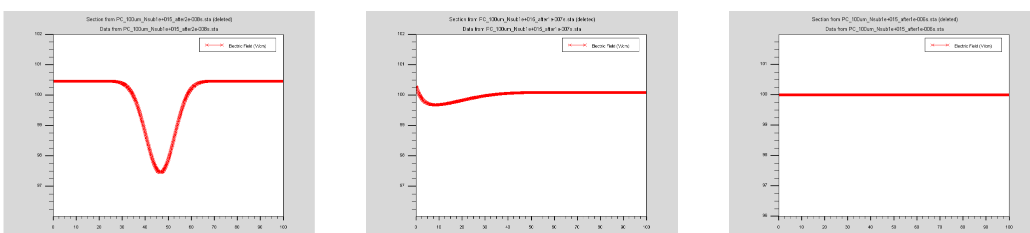

Figure 8: Distance vs substrate current after 20 ns, 1×10^{-7} s, and 1×10^{-6} s.

3.1 Modifying electron-hole pair density

To further study this, the density of electron-hole pairs present in the single-event upset was changed from it's default of $1.0 \times 10^{-4} \frac{\text{pC}}{\mu\text{m}}$, from

$1.0 \times 10^{-2}\,\frac{\mathrm{pC}}{\mu\mathrm{m}}$ to $1.0 \times 10^{-5}\,\frac{\mathrm{pC}}{\mu\mathrm{m}}$. According to figure 9, greater densities yield greater electron and hole concentrations. Fluctuations in electron holes are greater than that of electrons. This data seems to confirm that the event is finished at 1×10^{-6} s.

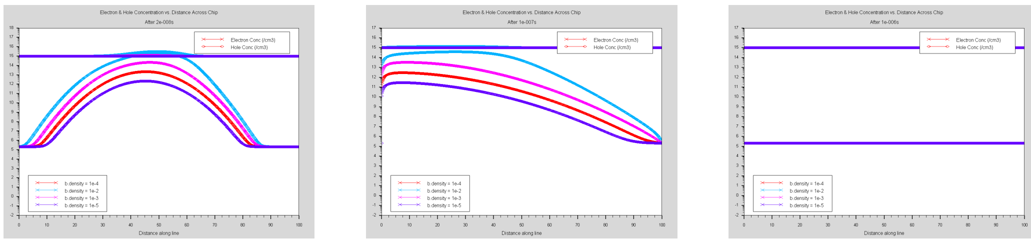

Figure 9: Distance vs e^-/h^+ concentraion after 20 ns, 1×10^{-7} s, and 1×10^{-6} s.

3.2 Modifying electron-hole pair lifetimes

The parameters for the lifetimes for the electrons and holes were changed from 1×10^{-7} s, from 1×10^{-6} s to 1×10^{-8} s. According to figure 10, greater lifetimes yield greater concentrations. The difference made from going from 1×10^{-7} s to 1×10^{-8} s looks to be greater than to 1×10^{-6} s.

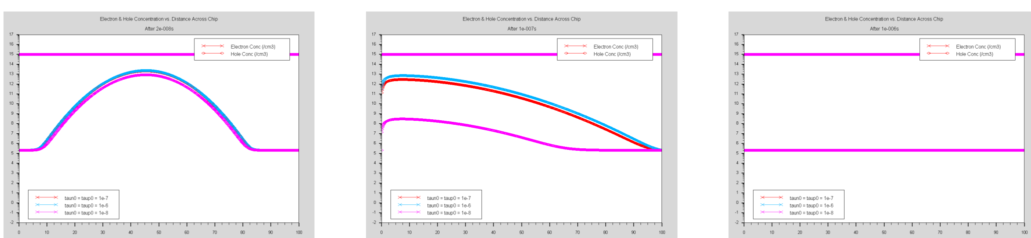

Figure 10: Distance vs e^-/h^+ concentraion after 20 ns, 1×10^{-7} s, and 1×10^{-6} s.

3.3 Modifying applied voltage

The applied voltage was changed from $1V$ to $2V$, $5V$, and $10V$. At first, this has the effect of translating the graphs. As time goes on, though, the higher voltages seem to taper out sooner.

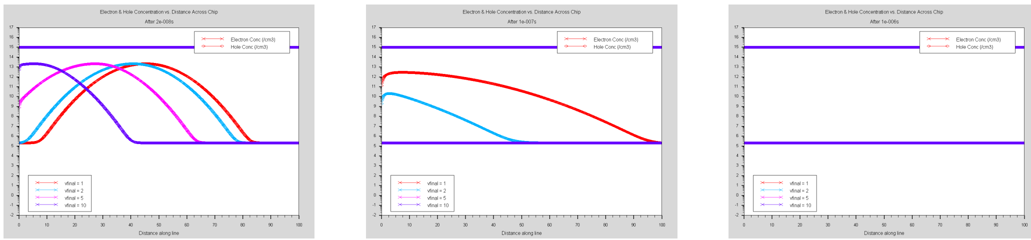

Figure 11: Distance vs e^-/h^+ concentraion after 20 ns, 1×10^{-7} s, and 1×10^{-6} s.

4 Change in current over time (Baseline 2)

A new baseline was created, where `b.density = 1e-015` rather than `b.density = 1e-015`, and `radius = 1` rather than `radius = 5`. Additionally, the time intervals at which data is collected was tuned. Given a lifetime of 1×10^{-7} s, the electron hole concentration is flattened out completely by 500ns. Figure 12 shows how there is an electron hole cloud that starts out thin, before widening out. Data for this figure was collected at 1 ns, 2 ns, 5 ns, 10 ns, and then at 50 ns intervals.

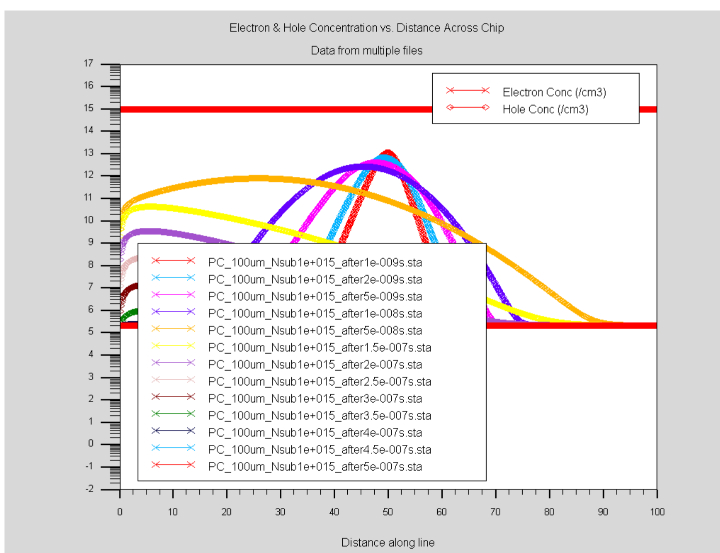

Figure 12: Distance vs e^-/h^+ concentraion with 14 samples.

This plot does a pretty good job at conveying the transformation that the electron hole cloud undergoes, but there are a couple of considerations to have, moving forward.

- In fact, the hole concentration flattens out as early as 450 ns. For this electron lifetime, we could remove any results after that. However, as we vary the lifetime values, it's possible we may see activity in time intervals beyond this, so it would be wise to keep up to at least 500 ns in the baseline.
- After the initial <50 ns solutions, the plot loses a lot of detail. updates should be made more frequent.

Thus, we need to modify the deck to satisfy the conditions of going to 500 ns, at a suitable frequency. After tuning the parameters, I arrived at this plot:

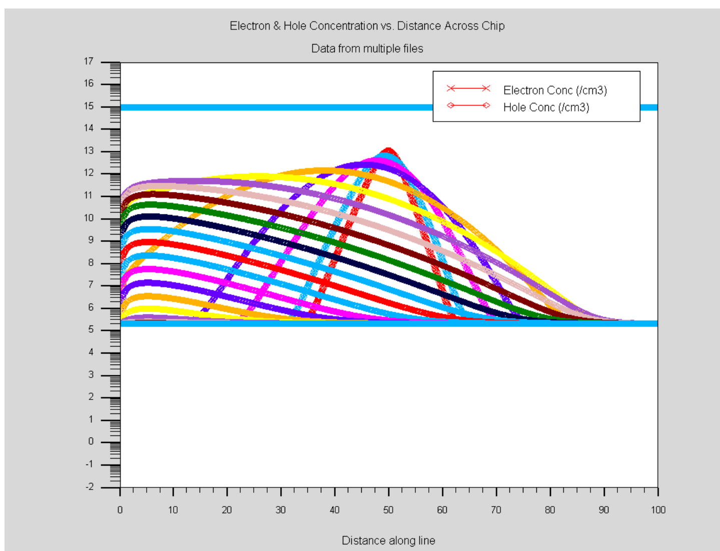

Figure 13: Distance vs e^-/h^+ concentraion with 24 samples.

4.1 Modifying electron-hole pair lifetimes (Baseline 2)

The electron/hole lifetimes were modified once more, now with the new baseline. As can be seen in figure 14, most changes are subtle, except for that of the transition to 1×10^{-8} s.

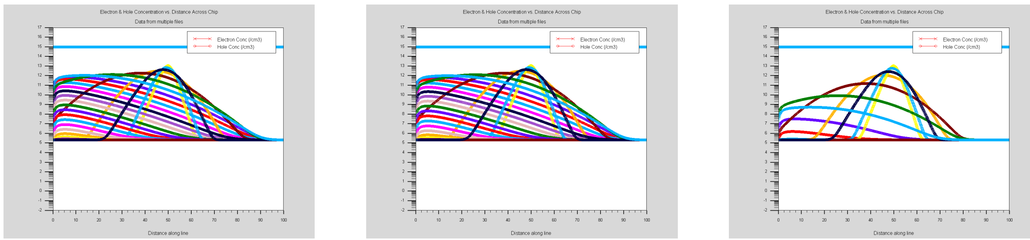

Figure 14: Distance vs e^-/h^+ concentraion with electron/hole lifetimes of $1 \times 10^{-5}\,\mathrm{s}$, $1 \times 10^{-6}\,\mathrm{s}$, and $1 \times 10^{-8}\,\mathrm{s}$.

4.2 Measuring transient time

The transient time t of the single-event upset depends on the length l it travels, and the drift velocity u with which it travels - in fact, this is essentially a rearranged form of $u = \frac{d}{t}$:

$$t = \frac{l}{u} \tag{5}$$

Since the single-event upset moves across the whole chip, $l = 100\mu m$. u can be calculated from electron mobility μ_n/μ_p, and electric field E [wik, 2020d]:

$$u = \mu E \tag{6}$$

Finally, the electric field E can be calculated from the voltage applied V, and the distance across which it is applied d:

$$E = \frac{V}{l} \tag{7}$$

With TCAD, it can be found that $\mu_n = 1299.89745 \frac{cm^2}{Vs}$, $\mu_p = 488.780635 \frac{cm^2}{Vs}$, and $E = 100 \frac{V}{cm}$. Therefore:

$$\begin{aligned} u_n &= \mu_n E = (1299.89745 \frac{cm^2}{Vs})(100 \frac{V}{cm}) = 129989.745 \frac{cm}{s} \\ t_n &= \frac{l}{u_n} = \frac{0.01cm}{129989.745 \frac{cm}{s}} = 7.69 \times 10^{-8}\,\mathrm{s} \\ u_p &= \mu_n E = (488.780635 \frac{cm^2}{Vs})(100 \frac{V}{cm}) = 48878.0635 \frac{cm}{s} \\ t_p &= \frac{l}{u_p} = \frac{0.01cm}{48878.0635 \frac{cm}{s}} = 2.05 \times 10^{-7}\,\mathrm{s} \end{aligned} \tag{8}$$

4.3 Modifying electron-hole pair lifetimes and density

Now, both the densities, and the electron-hole pair lifetimes were modified. The results of this can be found in the Current Data Excel file, generated by the `exporcsv.py` script.

References

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