Simple Monte Carlo Simulator

1. Introduction:

The Simple Monte Carlo simulator is a standalone executable written in C++ to allow for the Simple Monte Carlo modelling of Avalanche Photodiodes and Single Photon Avalanche photodiodes.

a) Current Materials available:

- Silicon (Si)
- Indium Gallium Phosphide (InGaP)
- Gallium Arsenide (GaAs)

b) Capable of simulating:

- Gain
- Excess Noise Factor
- Breakdown Probability
- Time to Breakdown
- Timing Jitter
- Drift Velocity
- Ionization Coefficients

2. Software Links:

GitHub Repository: TBD

Archived Copy vTBD: TBD

Software Metapaper: TBD

3. Modes:

There are three simulation modes in the software:

Mode	Capabilities
Diode Properties	• Gain • Excess Noise Factor • Breakdown Probability • Time to Breakdown • Timing Jitter
Drift Velocity	• Electron Drift Velocity • Hole Drift Velocity
Impact Ionization Coefficients	• Electron Coefficient • Hole Coefficient

4. Use of Diode Properties Mode:

a) Setup

Before launching the executable two text files need to be created:

1) *doping_profile.txt*, which contains the doping of the device to be simulated.

   The N-type region must be specified first. Doping concentrations to be specified in atoms/cm^3 and widths to be specified in µm. See example below for a P-I-N device with an N-type I region that's 0.13 µm.

   ```
   -3e18
   -2e16, 0.13
   3e18
   ```

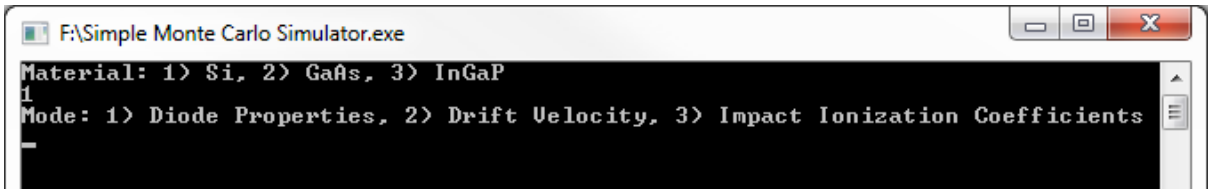
   The built in Poisson equation solver can work with an infinite number of layers, and it will always ignore the specified width of the 1st and last region specified.

2) *bias_input.txt*, which contains a list of applied biases to simulate. Only put 1 bias per line.

b) Running the Software

Launch the executable
Program will prompt for a material choice:

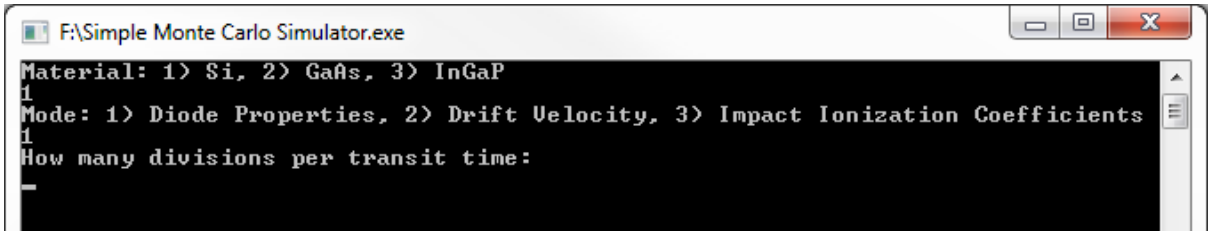
Program will then prompt for a mode choice. Enter 1 for Diode Properties.



Program will then prompt for a number of divisions per transit time. This decides size of the time bins. It is calculated as below

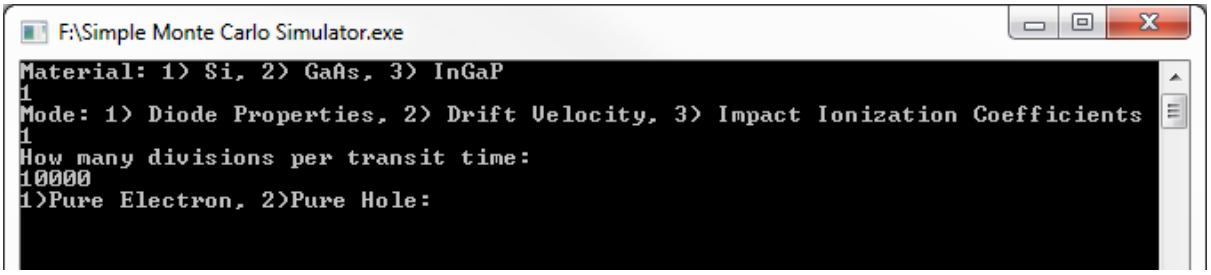
$$Bin\ Width = \frac{Time\ for\ electron\ at\ saturation\ velocity\ to\ cross\ depletion\ width}{Number\ of\ Divisions}$$

A typical value would be 10000.

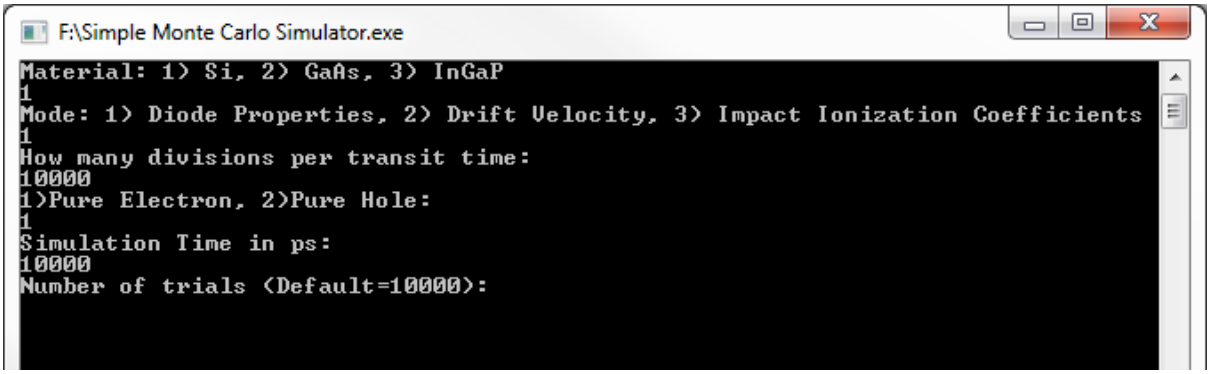


Next the Program will prompt for the injection condition:

Number	Condition	Description
1	Pure Electron	Injects a Single electron at the P-Region edge.
2	Pure Hole	Injects a Single hole at the N-Region edge.

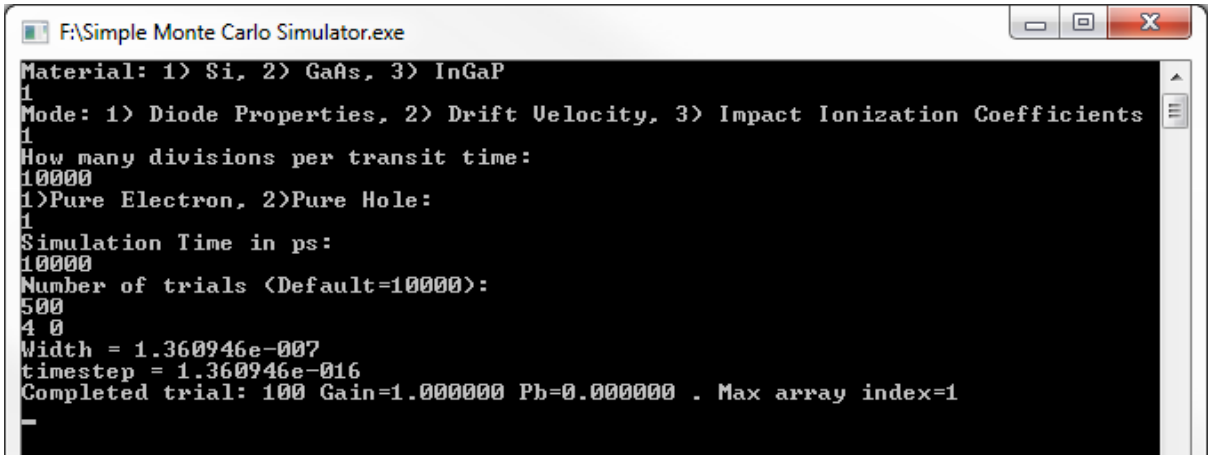


The program will prompt for a simulation time. This is the maximum time from injection of carriers that it will simulate the device for encase not all the carriers have left the device. Typically we specify 1000 ps for this.



Finally the program will ask for a number of trials per voltage. A Table of typical values is provided below.

Usage	Value
Gain and Excess Noise simulation	10000
Quickly working out breakdown probability	1000
Accurate breakdown probability simulation	10000-20000
Timing Characteristics	20000+



The program will now output the width (µm) and the time step size (ps). It will also update the output every 100 trials with the Gain, calculated by counting impact ionization events, the breakdown probability and the Max array index. The max array index is the maximum number of electron hole pairs that have been created at this voltage.

c) Output files

File Name	Description
scattering_rates.txt	Calculated scattering rates for the material
scattering_pb.txt	Calculated scattering probabilities for the material
Vgain_out.txt	V=simulated voltage, two columns. Column 1 has the trial number, column 2 is the simulated current from Ramos theorem.
Vtime_to_breakdown.txt	V=simulated voltage, two columns. Column 1 has the trial number, column 2 is time (ps) the trial took reach a current threshold of 0.1 m
Veventcounter.txt	Ignore this file
Multiplication.txt	Contains Gain (M), excess noise factor (F) from counting impact ionization events, breakdown probability (Pb) per voltage.

d) Post Processing

Several Matlab scripts, tested using R2015a, are available for post processing these are:

- *SMCAnalysis_v2.m*
- *GainAnalysis.m*
- *TimeAnalysis.m*

Calling SMCAnalysis_v2() in the same folder the Main Simple Monte Carlo was run in will read the files produced by the simulator and using GainAnalysis.m and TimeAnalysis.m will produce a text file, result.txt.

GainAnalysis uses the Ramo theorem current values to calculate gain and excess noise factor.

TimeAnalysis uses the time to breakdown data to calculate mean time to breakdown and timing jitter.

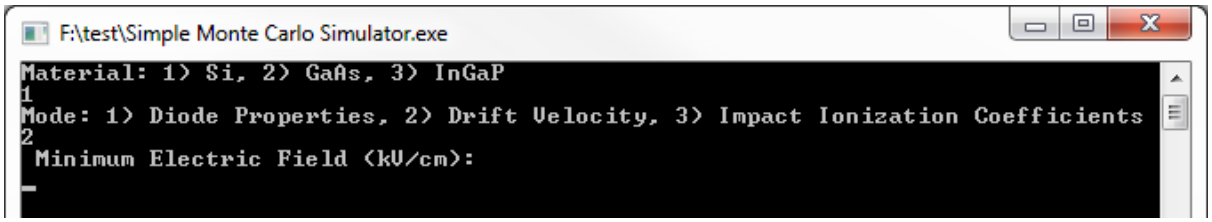
Result.txt has 5 columns, Applied bias (V), Gain, Excess noise factor (F), Mean time to breakdown (ps), Jitter (ps).

5. Use of Drift Velocity Mode:

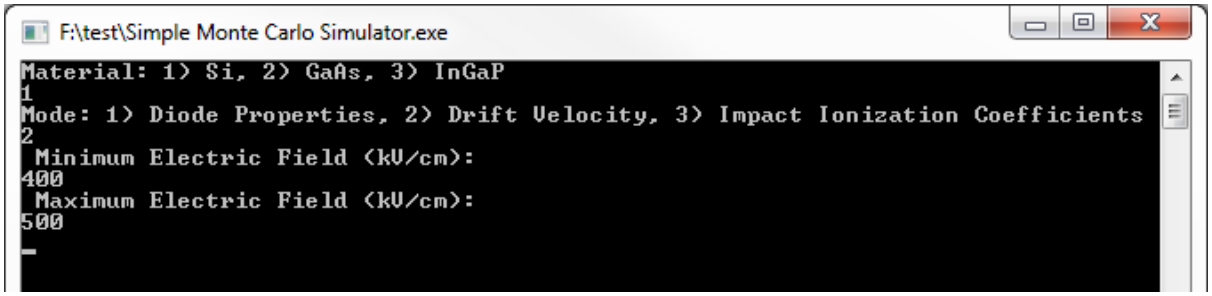
a) Running the Software

Launch executable
Program will prompt for a material choice.

Program will then prompt for a mode choice. Enter 2 for Drift Velocity.



Then it will prompt for a minimum electric field, followed by a maximum electric field. Unless the hard coded value has been changed the program will calculate the drift velocity incrementing the electric field between user specified min and max in 1 kV/cm steps.



b) Output files

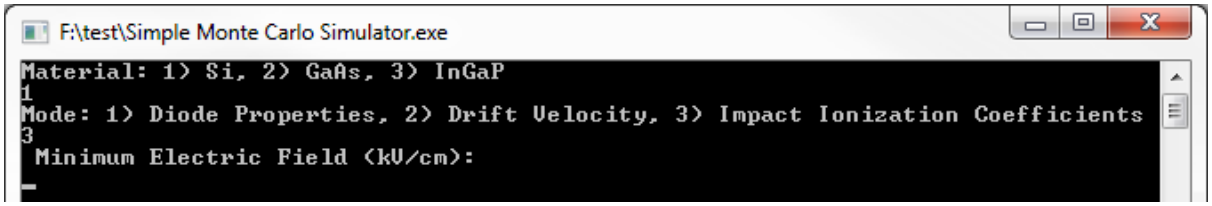
File Name	Description
scattering_rates.txt	Calculated scattering rates for the material
scattering_pb.txt	Calculated scattering probabilities for the material
evelocity.txt	Two Columns. Column 1 is the electric field (kV/cm), column 2 is the drift velocity (m/s).
hvelocity.txt	Two Columns. Column 1 is the electric field (kV/cm), column 2 is the drift velocity (m/s).

6. Use of Impact Ionization Coefficient Mode:

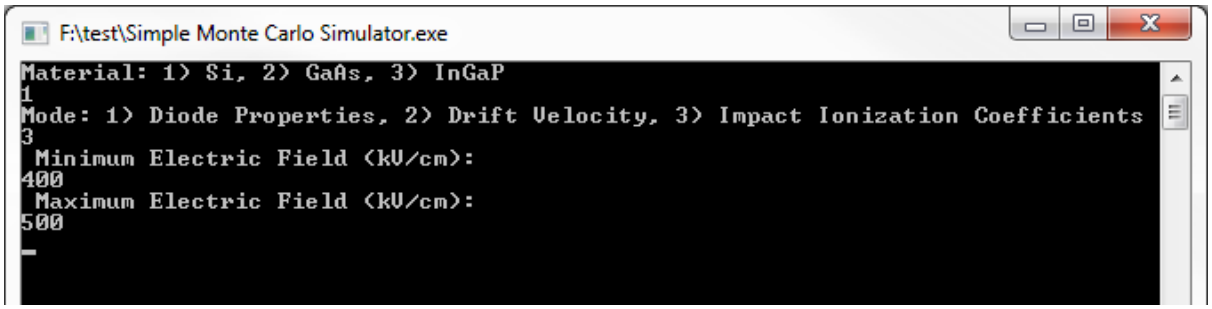
a) Running the Software

Launch executable
Program will prompt for a material choice.

Program will then prompt for a mode choice. Enter 3 for Impact Ionization Coefficient Mode.



Program will prompt for electric field values then will simulate electric fields in 20kV/cm steps between the minimum and maximum specified value. The simulation will calculate the distance travelled between 20000 consecutive impact ionization events for both electrons and holes.



b) Output Files

File Name	Description
Fepdf.txt	Contains the electron data, where F is the electric field strength in kV/cm. Contains 2 columns. Column 1 is the impact ionization event number, column 2 is the distance travelled, in meters, since either injection or the previous impact ionization event.
Fhpdf.txt	Contains the hole data, where F is the electric field strength in kV/cm. Contains 2 columns. Column 1 is the impact ionization event number, column 2 is the distance travelled, in meters, since either injection or the previous impact ionization event.
Alpha_beta.txt	Contains three columns. Column 1 Electric Field (kV/cm). Column 2 and 3 are alpha and beta respectively (1/m). Alpha and beta have been calculated as the inverse of the mean distance between consecutive impact ionization events.

7. Citations

Please use the following citations for the material parameter sets:

Silicon

X. Zhou, J. S. Ng, and C. H. Tan, 'A simple Monte Carlo model for prediction of avalanche multiplication process in Silicon', J. Inst., vol. 7, no. 08, p. P08006, 2012. DOI: https://doi.org/10.1088/1748-0221/7/08/P08006

Indium Gallium Phosphide

C. H. Tan, R. Ghin, J. P. R. David, G. J. Rees, and M. Hopkinson, 'The effect of dead space on gain and excess noise in In0. 48Ga0. 52P p+ in+ diodes', Semiconductor science and technology, vol. 18, no. 8, p. 803, 2003. DOI: https://doi.org/10.1088/0268-1242/18/8/314

Gallium Arsenide

S. A. Plimmer, J. P. R. David, D. S. Ong, and K. F. Li, "A simple model for avalanche multiplication including deadspace effects", IEEE Trans. Electron Devices, vol. 46, no. 4, pp. 769–775, 1999. DOI: https://doi.org/10.1109/16.753712