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:

- Avalanche Gain/ Multiplication Factor
- Excess Noise Factor
- Avalanche Current versus time
- Breakdown Probability
- Time to Breakdown
- Drift Velocity
- Ionization Coefficients

2. Software Links:

GitHub Repository: https://github.com/jdpetticrew/Simple-Monte-Carlo-Simulator

Archived Copy v1.0.0: https://doi.org/10.15131/shef.data.5683939

Software Metapaper: TBD

3. Modes:

There are three simulation modes in the software:

Mode	Capabilities
Diode Properties	• Avalanche Gain/Multiplication Factor • Excess Noise Factor • Avalanche Current versus time • Breakdown Probability • Time to Breakdown
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 profile of the device to be simulated.

   The P-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 0.13 µm N-type I region.

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

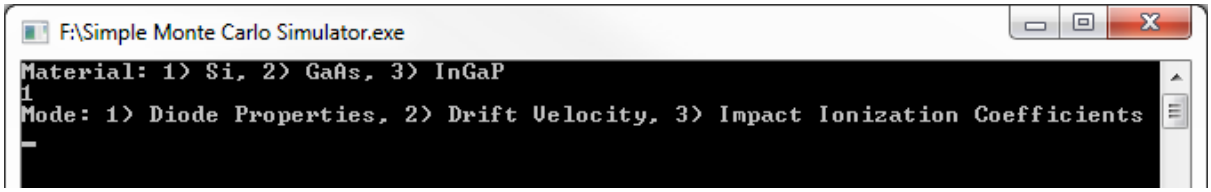
   The built-in Poisson equation solver can work with an arbitrary number of layers, and it will always ignore the specified widths of the first and last regions if entered.

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

b) Running the Software

Launch the executable
Program will prompt for a material choice:

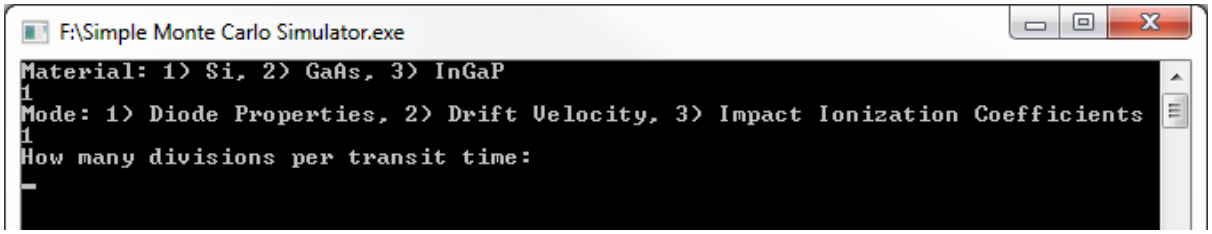
Program will then prompt for a mode choice. Enter 1 for Diode Properties.



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

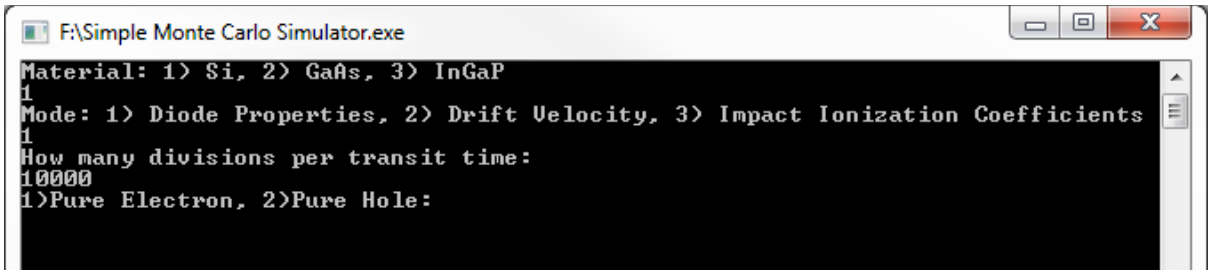
$$Bin\ Width = \frac{Time\ for\ electron\ at\ saturation\ velocity\ to\ cross\ depletion\ width}{Number\ of\ Divisions}$$

A typical value would be 10000.

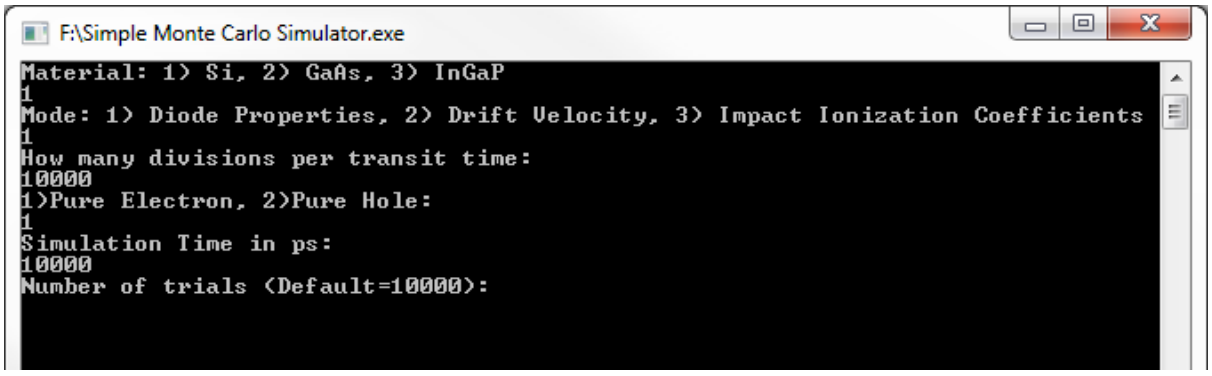


Next the Program will prompt for the injection condition:

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.

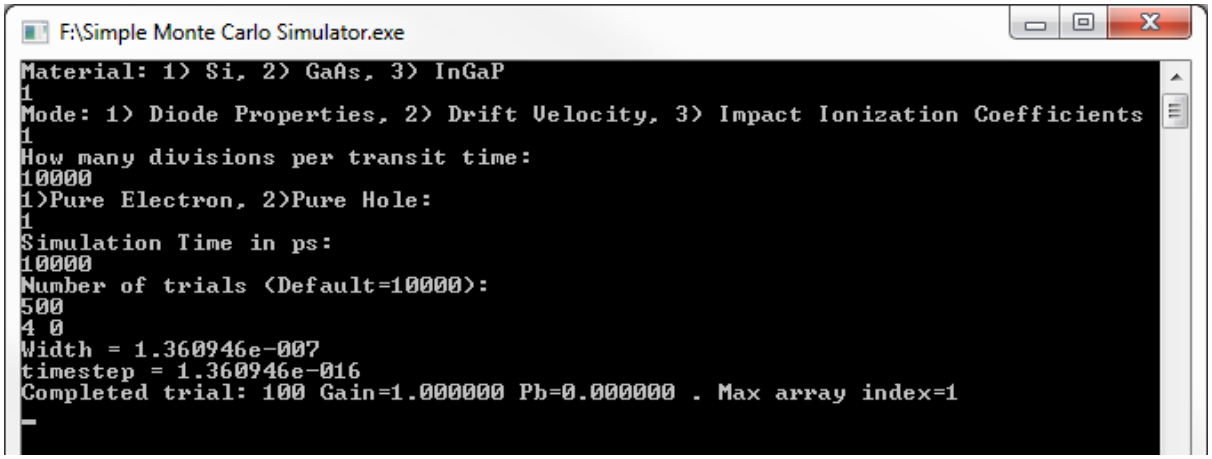


The program will prompt for a simulation time (in ps). This is the maximum time from injection of carriers that it will simulate the device for in case not all the carriers have left the device. Typically we specify 1000 ps for this.



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

Purpose	Typical Number of Trials
Gain and excess noise simulation	10000
Approximate breakdown probability	1000
Accurate breakdown probability simulation	10000-20000
Avalanche breakdown 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 mean avalanche gain (from the mean number of impact ionization events per trial), the breakdown probability and the Max array index (the peak 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, three columns. Column 1 is the trial number, column 2 is the gain from simulated avalanche current, column 3 is the gain from counting impact ionization events.
Vtime_to_breakdown.txt	V=simulated voltage, two columns. Column 1 has the trial number, column 2 is time (in ps) the trial took to reach a current threshold of 0.1 mA
Veventcounter.txt	Ignore this file
Result_1.txt	Contains Gain (M) and excess noise factor (F) calculated from the number of impact ionization events. It also contains the breakdown probability (Pb) for each voltage.
Result_2.txt	Contains Gain (M), excess noise factor (F) and Mean time to breakdown (ps) calculated from avalanche current for each voltage.
VHist.txt	V=simulated voltage, two columns. Column 1 is the central value for the histogram bin (in ps), column 2 contains the number of breakdown events detected in that bin.
Vcurrent.txt	V=simulated voltage, two columns. Column 1 has the time (in s) and column 2 has the current (in A) of the mean avalanche current. This file is only generated if breakdown probability is zero.
User_inputs.txt	Contains a record of the user input variables.

d) Post Processing

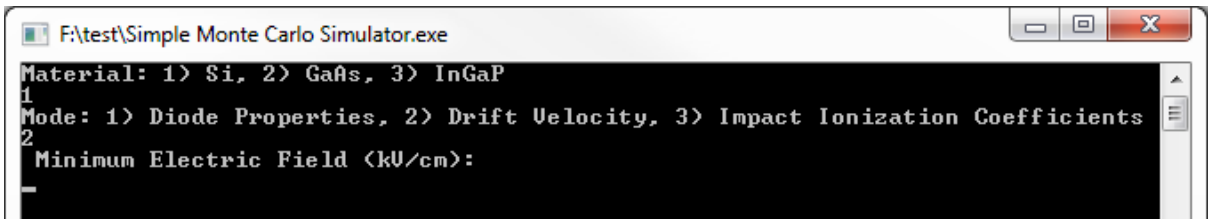
Using a script it is possible to extract the timing jitter value from either the *Hist.txt* files or from the raw time to breakdown data in the ***time_to_breakdown.txt*** files.

5. Use of Drift Velocity Mode:

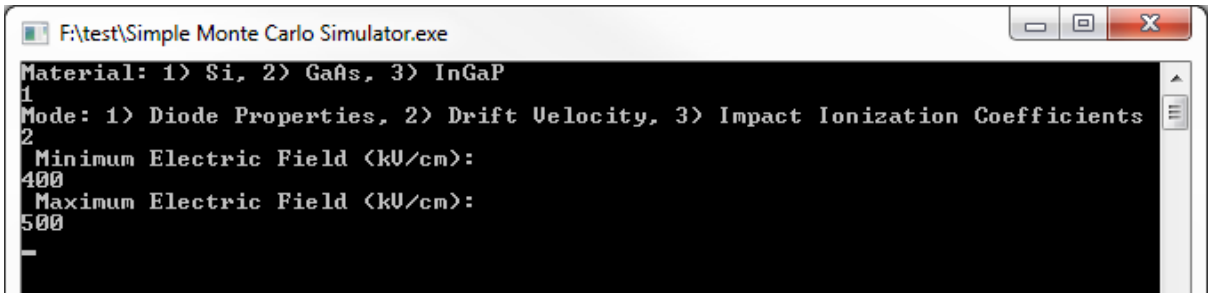
a) Running the Software

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 (in kV/cm), column 2 is the drift velocity (in m/s).

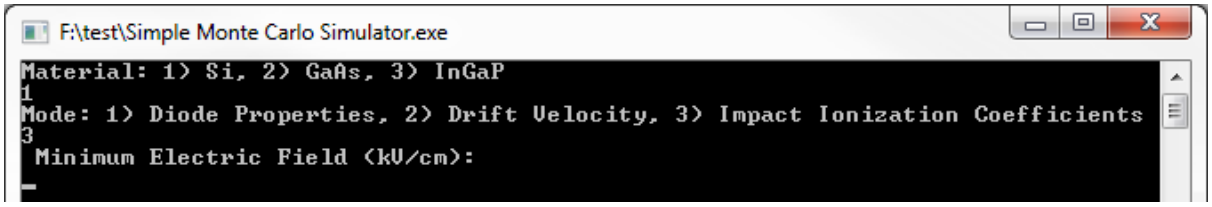
hvelocity.txt	Two Columns. Column 1 is the electric field (in kV/cm), column 2 is the drift velocity (in m/s).

6. Use of Impact Ionization Coefficient Mode:

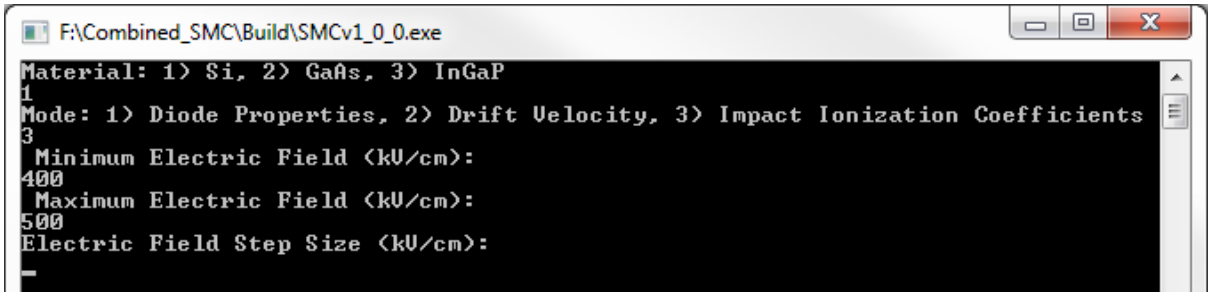
a) Running the Software

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 minimum and maximum electric field values. It will increase the electric field using the user-specified step size (from the minimum to the maximum values). The simulation will record the distances between 20000 consecutive impact ionization events for both electrons and holes in order to derive the mean distance between ionization events.



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, from either the carrier 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, from either the carrier injection or the previous impact ionization event.
Alpha_beta.txt	Contains three columns. Column 1 is Electric Field (in kV/cm). Column 2 and 3 are alpha and beta respectively (in 1/m). Alpha and beta are 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 $In_{0.48}Ga_{0.52}P$ 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