PSIMOD - A generalised system model for investigating the performance of hybrid pixel detectors

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Abstract. Recent advances in hybrid pixel detectors (HPD), motivated by the stringent demands of high-energy-physics experiments, have made a new type of spectroscopically-enabled photon-counting detector feasible. These developments could lead to improved imaging in medical and tomographic applications where detector noise currently imposes limitations. PSIMOD is a generalised system model based on a combination of GEANT4, the TCAD semiconductor simulation package and the SPICE analogue circuit simulation program. It has been developed to reproduce the response of the analogue front end of a pixilated single photon counting detector. With this suite of correlated simulations, it is possible to quickly characterise different system configurations for various detectors.

1. Background
The motivation for implementing modelling techniques lies in the ability to optimize detector development with respect to time and prototypization expenditure. It has been demonstrated that, while the empirical approach is expensive and time consuming, numerical device simulation expedites the design cycle [1]. Adapting the PILATUS [2] hybrid pixel detector system for detection of high-energy photons associated with medical imaging will require replacing the Silicon sensor with a semiconductor material of higher atomic number, such as Cadmium Telluride (CdTe). The ability to model proposed modifications will improve system understanding and expedite the design cycle.

2. Model Configuration
PSIMOD is constructed from three separate simulation packages; GEANT4, TCAD and NGSpice combined with customised glue code. Each program has been designed to accurately simulate a step from probe particle creation to a measured count within the detector, with the information flow from particle to analogue response shown in Figure 1.

Each stage of the simulation chain is modular – programs which provide the same service can be exchanged (GEANT4 can be swapped for G4Beamline [3] for example).
2.1. GEANT4
GEANT4 [4] is a set of simulation libraries which calculates the motion of a particle through a physical system, taking into account physical processes such as scattering, absorption and particle creation. An example GEANT4 model is shown in Figure 2a.

For PSIMOD, GEANT4 is used to simulate an experimental setup and create an output file describing where incident photons interact with the HPD sensitive area. The HPD active area is described in the GEANT4 simulation as a plane, where each particle impinging on the surface is removed from the simulation immediately after its position (X,Y,Z), energy and particle type is recorded. Currently all recorded particles which are not photons are discarded; an investigation into electrons interacting with the silicon surface is currently being undertaken to extend the model.

2.2. TCAD / DESSIS
Once charge is liberated within the silicon, the approximation of non-interacting particles is no longer appropriate and a different simulation technique is required. Using an FEM (Finite-Element Method) algorithm, DESSIS solves Poisson’s equation on a given set of spatial nodes. Transient solutions can be obtained by allowing the charge elements to evolve a given time-step and solving in an iterative fashion.

A photon interaction in one pixel can result in the splitting of charge into neighbouring pixels. This charge sharing will result in a position dependance on the resultant signal for each pixel, so multiple incident locations on the semiconductor material must be simulated. If it is assumed that the charge is only spread to neighbouring pixels, with symmetry considerations the system reduces to a four pixel system, where the incident charge is deposited in one quadrant of the “center” pixel. The TCAD model for this system is shown in Figure 3. A full simulation using DESSIS is prohibitively slow for every photon interaction to be simulated so a position / energy lookup table is generated prior to running the simulation.

Using a simulation package such as TCAD allows for the calculation of a variety of factors unique to the semiconductor material such as charge sharing, transit time and pulse shapes.
Streamtraces which show the trajectory of liberated charge.

(b) Detected current from an incident photon.

Figure 3: TCAD/DESSIS Simulation results of a 10 keV photon incident on a PILATUS sensor.

also gives the opportunity to change semiconductor material parameters relatively easily while keeping the rest of the simulation chain intact.

2.3. NGSpice
NGSpice [5] is an open-source implementation of the venerable SPICE simulation package - a powerful tool for analysis of electronic circuits [6]. The description of a circuit is read using the internal NGSpice parser and the system is solved using a set of non-linear differential equations.

Once the induced charge versus time is retrieved from DESSIS, it is included within a circuit as a time varying current source. Transferral of the data from DESSIS to NGSpice is achieved using custom python library construct specifically for PSIMOD which converts the data into a format readable by the NGSpice PWL (Piece-Wise Linear) format. A transient analysis of the system is performed for a predetermined time slice and the output voltage as a function of time of the circuit is written to a binary file.

Figure 2b shows an example analogue front end setup which is implemented in PSIMOD; in this case the current is passed through an amplification stage followed by pulse shaping.

2.4. Python
Although each of the previous simulation packages are powerful tools in their own right, some of the available power is limited by the ability to export data between the programs. It is possible to integrate some of the tool within each other, for example a GEANT4 simulation could in theory be constructed which links to the NGSpice libraries as the source code for both of these packages are freely available. For PSIMOD however each stage was designed as a module which could be swapped or altered easily. This allows an expert in one simulation package to propagate changes through the chain without necessarily being proficient with all the intermediate programs.

A set of Python libraries is used to read in simulation configuration options, run simulations and propagate data from one stage to another. Each stage has a defined input and output datafile format as well as specific simulation options. The Python code also implements much of the digital side of the HPD system, enforcing descriminator levels, re-arm timing and constructing output images.
3. Preliminary Results

Preliminary results of the PSIMOD simulation chain are promising. Initial characterisation of a single-event detector system typically involve discriminator threshold scans in order to calculate the levels required to effectively suppress double counting, fluorescence within the system. Figure 4a shows an example of a threshold scan for 16 keV incident photons at a flux of $1 \times 10^5$ photons per second per pixel. Deviation from the ideal due to the photon pile-up can be seen, with higher gains showing more susceptibility to paralysis than lower gains. Another important characteristic of a discriminating detector is the dead-time of the system which has recently been studied in depth for the PILATUS detector [7]. Figure 4b shows a simulated flux scan versus data measured for the PILATUS HPD system. The PSIMOD Simulation matches the measured drop-off in detector response, though this simulation utilised an analytic form of the analytic front-end and has yet to be repeated with the NGSpice module implemented.

4. Conclusions

PSIMOD has been used to study the effects of proposed modifications on the PILATUS hybrid pixel detector. Using it, the associated dependencies of the various physical processes involved in each stage of data acquisition have been explored. Validation with prototype Silicon sensors provides confidence in the model to now take on the formidable challenges associated with CdTe. Further advances in the simulation package are being investigated, including the introduction of non-ideal components to the analogue circuit simulation and a complete particle interaction model with electrons and heavy-ion charge depositions.

References

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