Joint Institute for Nuclear Research

Report of Summer Student Program

Simulation of a signal formation in a hybrid semiconductor pixel detector

Participant:

Annie Meneses González
Faculty of Nuclear Science and Technology
Higher Institute of Technologies and Applied Sciences, Cuba

Supervisor:

Alexey Zhemchugov
Dzhelepov Laboratory of Nuclear Problems
Joint Institute for Nuclear Research, Dubna, Russia

Dubna, 2015

Contents

1. Description to the project

I was participant of 2015 Summer Student Program in the Joint Institute for Nuclear Research (JINR) in Dubna for twelve weeks. During the practice I visited the reactor building and the following laboratories:

- ✓ Dzhelepov Laboratory of Nuclear Problems-DLNP(where I worked),
- ✓ Veksler and Baldin Laboratory of High Energy Physics,
- ✓ Frank Laboratory of Neutron Physics-FLNP,
- ✓ Flerov Laboratory of Nuclear Reactions-FLNR.

The purpose of my work was determine the induce charge in hybrid semiconductor pixel detector using mathematical simulation.

In recent years hybrid pixel semiconductor detectors have been finding more use in various fields of science where high spatial resolution and low noise are required from radiation detectors. In high-energy physics such detectors are used for registering particle tracks, in geology - for X-ray radiography in studies of the internal structure of different samples,in biology and medicine – for computer tomography. In most of these hybrid semiconductor detectors sensing elements are made of silicon (Si, Z=14), which has both undeniable advantages and considerable disadvantages in comparison with other semiconductors. In particular, Si has a very low efficiency of detection of photons with energies greater than 20 keV and insufficient resistance to radiation. So, heavier alternatives to silicon such as gallium arsenide (GaAs, Z=31, 33) and cadmium telluride (CdTe, Z=48, 52) have increasingly being used as sensor material for hybrid pixel detectors.

The JINR Laboratory of Nuclear Problems together with the Tomsk State University, Medipix collaboration [1], Czech Technical University (Prague) and the research center DESY (Hamburg), is working on developing and testing hybrid pixel detectors based on the Timepix readout chip [2] with sensor matrix of chromium-doped gallium arsenide(GaAs:Cr) [3].

2.Charge collection

The common principle of an extensive range of radiation detection techniques can be described as the following: *the incident radiation generates free charges q in the active volume and these in their movement induces a charge Q on the electrode reading, which is amplified each and formed into an output signal*.

The output signal of a charge sensing device can be predicted if the induced charge Q reading on the electrode it can be calculated as a function of the instantaneous position of the charge q moving within the device. To this must calculate the instantaneous electric field E when the charge q is moving at each point of its path, and then calculate the induced charge Q integrating the normal component of E on the surface S of electrode:

$$Q = \oint_S \epsilon E * dS, \tag{2.1}$$

where $\epsilon$the dielectric constant of the medium.

This calculation process is very tedious because of the large number of possible electrical fields, which correspond to different locations q along its path. Shockley [4] and Bouquet [5] separately found a method to calculate the charge induced on any electrode vacuum tube. This is known as Shockley –Ramo theorem [6] and can be applied not only to vacuum tubes but also a stationary cargo spaces.

Shockley –Ramo theorem states that the charge Q and the current i snapshots induced in an electrode by the motion of a point charge q are given by relations:

$$Q = -q\varphi_0(x), \tag{2.2}$$

$$i = qvE_0(x), \tag{2.3}$$

where v is the instantaneous speed of the charge q, while φ_0 and E_0 are the potential and the electric field at positions x determined under the following boundary conditions : the selected electrode has a potential of 1 V, all other electrodes have potential zero and all the trapped charges are neglected.

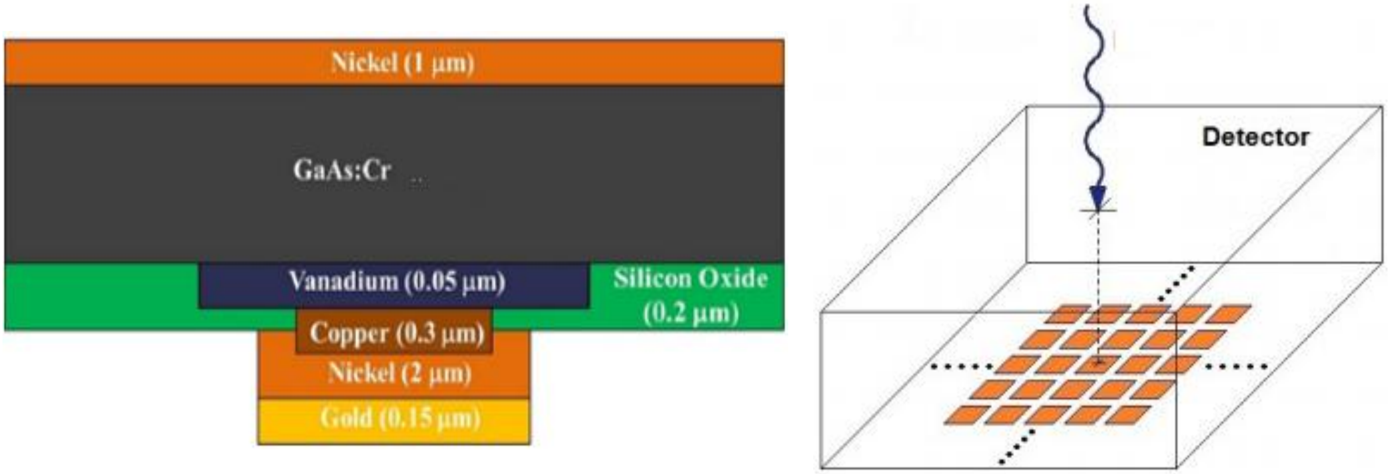
φ_0 and E_0 are known as the weighting (or weighted) potential and the field respectively. While the path of the charge q is determined by the actual electric field polarization induced charge Q can be easily calculated using the potential weighted.

The spatial distribution of weighted potential and its electric field can be calculate analytically for some simple cases, but for complex geometries this is only possible with the use of numerical techniques implemented as systems of codes [7].

Optimized programs to solve the Poisson and the Laplace equation, starting points for all calculations to electric potential [8], for highly complex geometries and diverse configurations of the electrodes. The result is a numerical solution to the electric potential at any point within the detector volume.

3.Characteristics of the source-detector system in studio

The study detector is formed by a GaAs crystal compensated with Cr. Glass thickness is 300 microns. The cathode is constituted by a nickel layer 1 micron thick, while the anodes are comprised of an array 256 x 256 pixels, each of 45 x $45\mu \; m^2$ and a separation between them of 10 μm^2. Each pixel has a layered structure type Au / Ni / Cu / V / GaAs which gives rise to a Schottky barrier [9] type. The regions between the pixels are wrappers by a layer of silicon oxide acts as insulation and protective.



(a) Basicschemeofthe internalstructure of thedetector [10].

(b) General configuration of the geometry used in the detector.

Figure 3.1:Simulated detector.

As source was used a proton beam of 150 MeV, impacting perpendicularly in the center of the detector, as shown in Figure 3.1 (b).

4.Mathematical simulation

To apply the Shockley –Ramo theorem, charge generated in the detector and the weighted potential is needed.

To determine the charge generated in the detector was used the 3D system of codes MCNPX, which consists of a group of subroutines for sequential simulation by the Monte Carlo method of probabilistic individual events that make up transport processes of 34 different types of particles and photons in a given three-dimensional geometry and a variety of materials.

In this simulation output *F8 was used to determine the energy deposited by the radiation in the detector, by which the charge created is calculated by dividing it by the necessary energy for the formation of a pair electron positron (4.184 eV in our study material).

For determining the weighted potential the software ARCHIMIDES was used. This is a simulator of semiconductor devices and can be used to model the design and operation of devices as small as the nanometer scale, quickly and reliably. The following figure shows its distribution in a 2D plane (Figure 4.1).

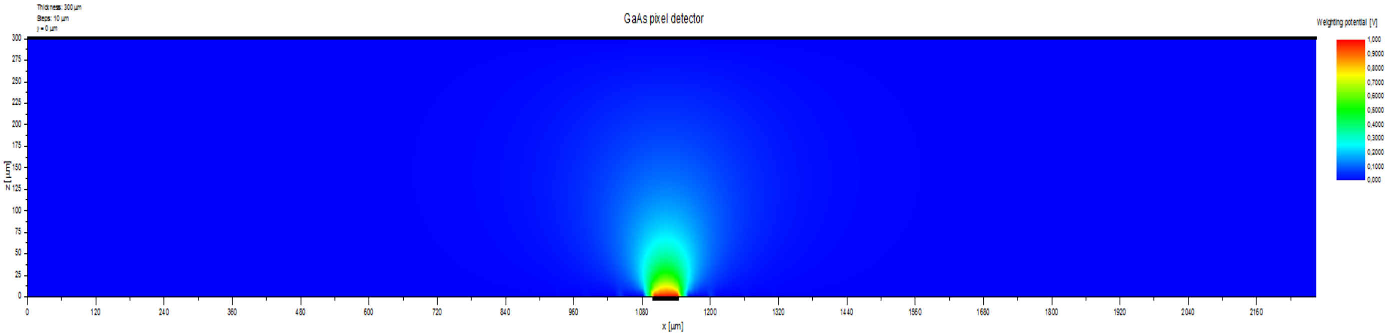


Figure 4.1: Distribution of weighted potential in a GaAs pixel detector 300 µm thick.

Then for the determination of the charge induced in the matrix of 256 *x* 256 pixels a program was created in ANSI C ++ language which takes the results of the two previous simulations and combines them into the equation of Shockley - Ramo.

5.Discussion of induced charge results

After having obtained the charge induced at different points in time, we can calculate the total charge induced integrating the same along the entire path. Figure5.1 shown the behavior in time of the charge induced on a random pixel. A qualitative analysis shows that it is in correspondence with the behavior of the signal obtained in semiconductor detectors.

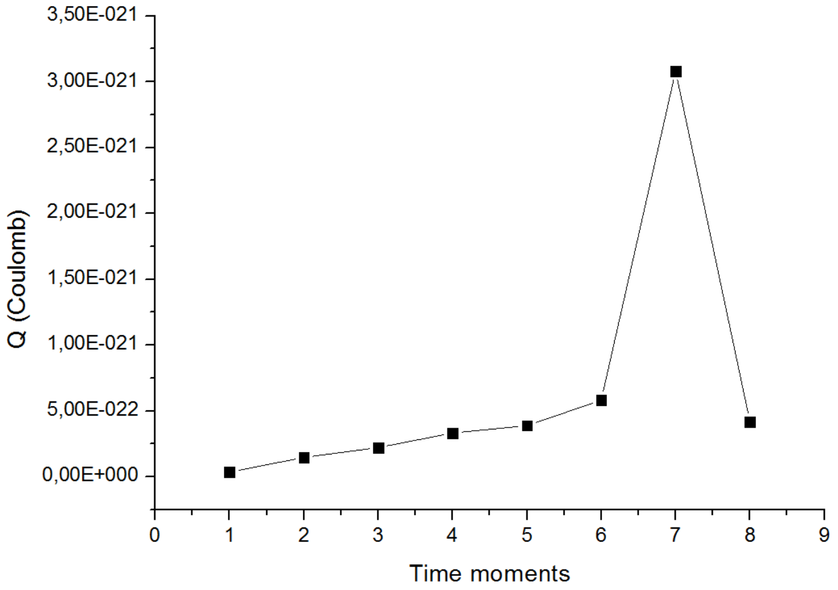


Figure 5.1: Time behavior *of the charge induced on a random pixel [pxlx, pxly][150, 73].*

Making an analysis of the cluster of pixels from the simulated and obtained experimentally data, along the *X* axis, we can observe that both follow the same behavior (see Figure 5.2). The observed numerical differences are due to work with different scales: Time-over-Threshold (TOT) scale for the experimental data obtained from the readout chip output [11] (Figure 5.3), while the simulation results are in units of charge.

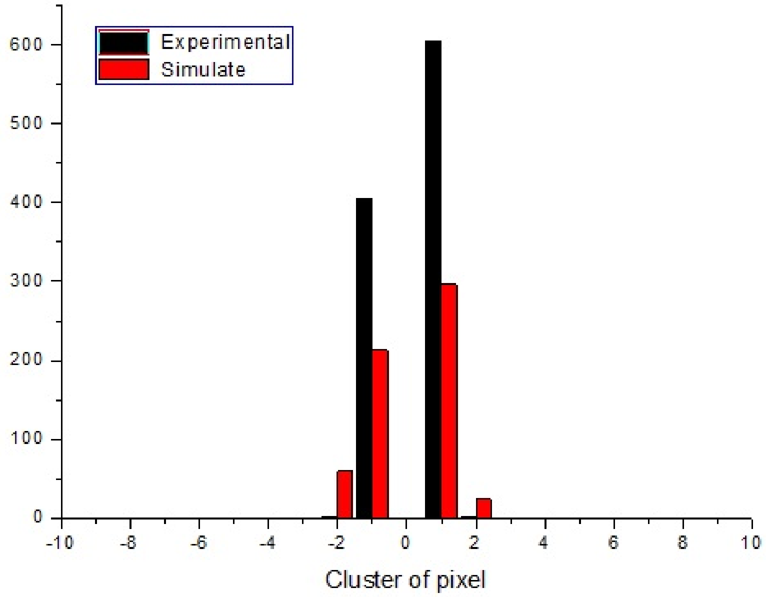


Figure 5.2: Comparison between proton cluster in GaAs for experimental and simulate results.

Note that the total charge induced in the pixels was found as the integral charge in time shown in Figure 5.1.

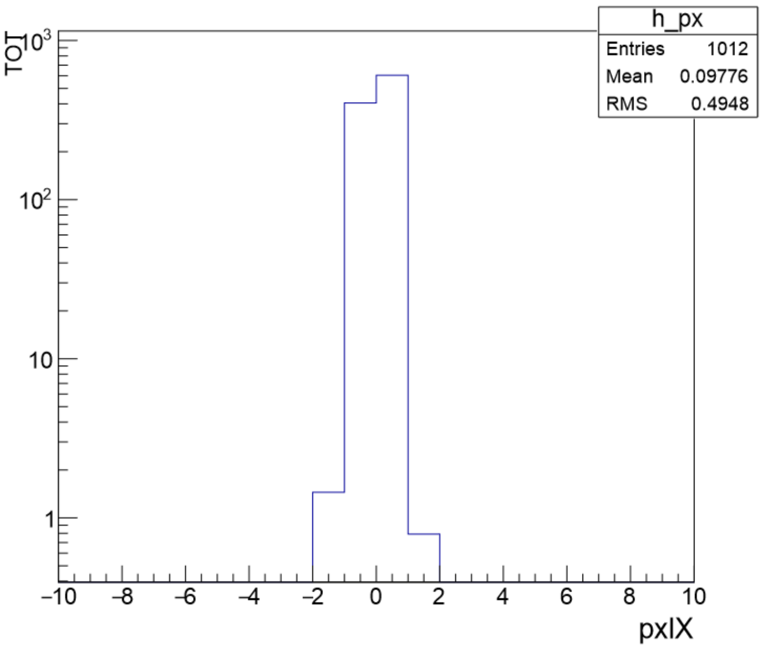
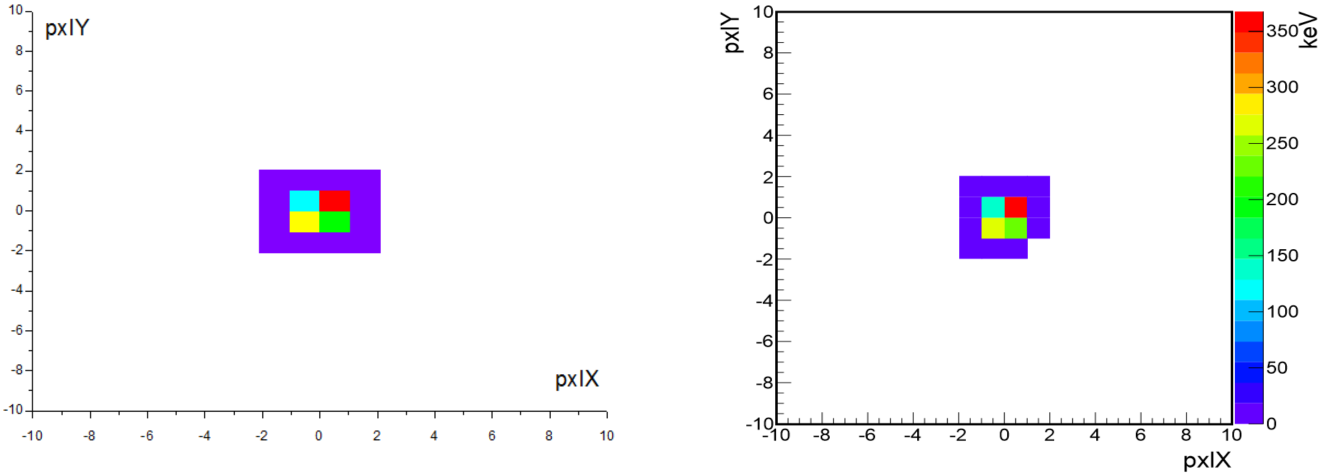


Figure 5.3: Proton cluster in GaAs for experimental results in scale ToT.

The shape of the cluster on the plane of pixels is shown in Figure 5.4 (a) and like in Figure 5.2 this follows a similar pattern to the experimental results (Figure 5.4 (b)).



(a) Simulate results

(b) Experimental results

Figure 5.4: Proton cluster shape in GaAs

6.Conclusions

The obtained in this study results show that the simulations using the Archimedes MCNPX and software, as well as subroutines in C++ specially developed for this work, have similar behaviors that obtained in the physical experiments. This also indicates that all the considerations made for the simulations are effective and are consistent with the physical reality of the experiment.

To increase the degree of reliability of the developed software to study the detector behavior interacting with other particles as heavy ions and neutrons should be made other simulations and comparisons.

During the Summer Student Program at Joint Institute for Nuclear Research, introductory lectures and excursions were held. I got familiar with the GaAs semiconductor detector, its characteristics and properties. I learned about simulation in GEANT4 and ROOT.

7.Acknowledgements

I want to thank my supervisor Prof. Alexey Zhemchugov for the opportunity to work in his group and for all the things that I learned from him, and also all the colleagues for their help.

8.References

[1] Medipix home page. http://medipix.web.cern.ch/MEDIPIX/

[2] *Llopart X. Ballabriga R., Campbell M., Tlustos L., Wong W.*Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements // Nucl. Inst. and Meth. A. 2007. V.581. P.485-494.

[3] *Ayzenahtat G.I., Budnitsky D.L., Koretakaya O.B., Novikov V.A., Okaevich L.S., Potapov A.I., Tolbanov O.P., Tyazhev A.V., Vorobiev A.P*. GaAs resistor structures for X-ray imaging detectors // Nucl. Inst. and meth. A. 2007 V.487. P96-101.

[4]*Shockley W*. Currents to conductors induced by a moving point charge // J. Appl. Phys., (9):635. 1938 DOI: 10.1063/1.1710367.

[5]*Ramo S*. Currents induced by electron motion // Proceedings of the IRE, (27):584–585. 1939 DOI: 10.1109/JRPROC.1939.228757.

[6]*H, Z.* Review of the Shockley-Ramo theorem and its application in semiconductor gamma-ray detectors // Nuclear Instruments and Methods in Physics Research A. 2001 (463):250–267. DOI: S 0168-9002(01)00223-6.

[7] *Knoll G. F*. Radiation detection and measurement // John Wiley and Sons, 4 edition. 2010 ISBN: 978-0-470-13148-0.

[8]*Owens A*. Compound semiconductor radiation detectors // Taylor and Francis Group, Boca Raton. 2012 ISBN: 13:978-1-4398-7313-7.2012.

[9]*Sharma B. L.* Metal-semiconductor Schottky barrier junctions and their applications // Plenum Press, New York. 2013 ISBN: 978-1-4684-4657-9.

[10] *Veale M. C., Bell, S. J., and Duarte, D. D.* Chromium compensated gallium arsenide detectors for X-ray and gamma-ray spectroscopic imaging // Nuclear Instruments and Methods in Physics Research A, (752):6–14. 2014 DOI:10.1016/j.nima.2014.03.033.

[11*] Butler A.P., Butler P.H., Bell S.T., Chelkov G.A., Dedovich D.V., Demichev M.A., Elkin V.G., Gostkin M.I., Kotov S.A., Kozhevnikov D.A., KruchonakU.G.d, NozdrinA.A.d, PorokhovoyS.Yu., Potrap I.N., Smolyanskiy P.I., Zakhvatkin M.M., Zhemchugov A.S.*Measurement of the energy resolution and calibration ofhybrid pixel detectors with GaAs:Cr sensor andTimepix readout chip //Educational-research-innovation center “Semiconductor sensors”, Tomsk, RussiaJanuary 15, 2015.