The Simulation Studies of PC-HPGe Detector

Zifeng Lv, Yulan Li, Jin Li, Qian Yue, Henry Wong, Yuanjing Li

Abstract–**Having the merits of low capacitance and low energy threshold, PC-HPGe (Point-Contact High Purity Germanium) detector has been proposed for the direct WIMP (Weakly Interacting Massive Particle) searches in CDEX (China Dark matter Experiment), which is located in CJPL (China Jing Ping underground Laboratory) with a rock overburden of about 2400 m. Intensive studies are underway to fully understand this detector's working principle and to fully explore its capability. By using Maxwell 3D, MaGe and Geant4, some basic characteristics of PC-HPGe were simulated and presented here.**

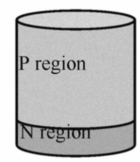
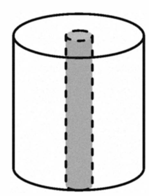
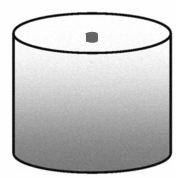
I. Introduction

DUE to the advantages of high detection efficiency, good energy resolution and especially low capacitance and low energy threshold[1], PC-HPGe detector is suitable for the direct detection of WIMP and has been proposed as the target and detector in CDEX[2][3][4]. This paper illustrates methods to simulate its basic characteristics, such as the capacitance, depletion process and voltage, electric field, drift process of carriers and induced current on electrodes. The simulation was carried out by using Ansoft Maxwell 3D, MaGe[5] and Geant4.

Ansoft Maxwell 3D is used for the simulation of electromagnetic field inside HPGe detector. MaGe (an open source software developed by Majarona and Gerda collaboration) is used for the simulation of drift trajectories of carriers (electrons and holes) and induced current on electrodes according to Shockley-Ramo theorem. Geant4 is used for the simulation of energy deposition and interaction points of particles in the HPGe detector. The version of MaGe software we have can only simulate coaxial HPGe detector, the authors developed an interface between Maxwell and MaGe and modified the code of MaGe to the simulation of PC-HPGe detector. Since Maxwell 3D calculates the electromagnetic field with adaptive finite element method, so if the boundary of HPGe detector in MaGe can be defined, the output signals of nearly all kinds of HPGe detectors can be simulated. Since there is no textbook formula for the calculation of PC-HPGe detector, in this paper, the simulations was first done on the planar and the coaxial detector. Then the results were compared with theoretical formula results to make sure the simulate methods are correct and effective. Then we move to the simulation study of PC-HPGe detector and to find the event discriminate methods to reduce the influence of background events to the detection of WIMP. The relative dielectric constant of germanium material of about 16 is used in Maxwell 3D.

The paper simulate three different kinds of HPGe detector, they are shown in Table I.

TABLE I. THERE DIFFERENT CONFIGURATIONS OF HPGE DETECTORS

#	Configuration	Description
A		▪ Planar; ▪ ϕ: 10 mm; ▪ P region: Thickness: 8 mm; Impurity density: 1.0×10^{10} /cm^3; ▪ N region: Thickness: 0.5 mm; Impurity density: 1.6×10^{11} /cm^3.
B		▪ P type coaxial; ▪ Impurity density: 1.0×10^{10} /cm^3; ▪ Inner radius: 5 mm; ▪ Outer radius: 35 mm; ▪ Height: 50 mm.
C		▪ P type PC-HPGe; ▪ Impurity density: $0.8\sim1.5\times10^{10}$/cm^3, linear distributed from the bottom to the top; ▪ Height: 50 mm; ▪ ϕ: 50 mm; ▪ Point-contact: Diameter: 1 mm; Depth: 1mm.

II. Electrostatic Simulation Study Based on Maxwell 3D

A. Electric field

To simulate the electric field in HPGe detector under depleted state, the space charge inside the detector must be set. There is negative charge distributed in P region while there is positive charge in N region. The charge density is equal to the impurity density.

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The electric field strength along the radial direction of detector B was simulated assuming that the voltage on the outer radius of detector B is 4000 V while 0V on the inner radius.

The simulation result and the calculated one from formula on reference literature 6[6] was shown in Fig.1. One can see that the simulation result matches the theoretical result closely. The conclusion is also valid for the detector A.

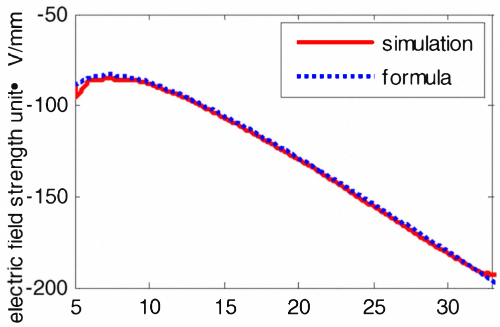

Fig. 1. Simulation result of electric field strength of detector B

Then the electric field in detector C with 3000 V on outer radius and 0 V on center hole was simulated. The voltage distribution and electric field line is shown in Fig.2.

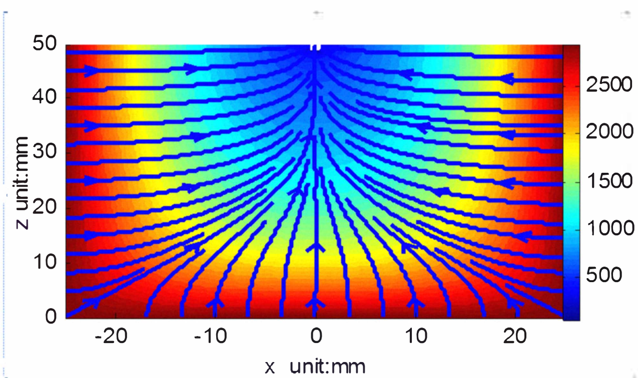

Fig. 2. Electric field distribution inside detector C

B. *Weighting field*

The weighting field distribution is used for calculating the induced charge (or current) on the specific electrode when carriers are drifting in the detector [7]. It is simulated by setting the voltage on the interested electrode to 1 and the other electrodes to 0 without regard to the space charge.

The simulation results for the center point electrode of detector C is shown in Fig.3. It is the distribution of log(V) in the detector; here V is the voltage value. According to the Shockley-Ramo theorem, only when carriers drifting near the center point electrode region will make significant contribution to the total induced charge.

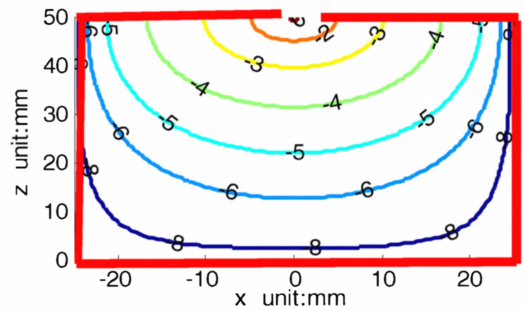

Fig. 3. Weighting field of center point of detector C

C. *Capacitance*

Some assumptions were made to simulate the capacitance of HPGe detector under depleted state:

- Relative dielectric constant of detector material does not change with electric field.
- The space charge distribution will keep the same while there is a small voltage change on the electrodes.

With these assumptions, the capacitance of the detector is the same as the capacitor with the same shape, material and electrode arrangement without the space charge distribution caused by depletion. The formulas to calculate the capacitance of detector A and detector B can be found in reference literature 6[6]. So if Maxwell can calculate capacitance of detector A and detector B, it can also calculate the capacitance of PC-HPGe detector. The result is shown in table II. Table III further shows that the capacitance of a PC-HPGe is mainly determined by the contact size.

TABLE II. CAPACITANCE OF DETECTORS

Detector	Theoretical value/pF	Simulation/pF
A	1.31	1.30
B	22.86	22.91
C		0.72

TABLE III. CAPACITANCE OF PC-HPGE DETECTORS

Crystal Size/mm	Point Contact Size/mm	Capacitance/pF
ϕ=50, H=50	ϕ=1, depth=1	0.73
	ϕ=2, depth=1	1.11
	ϕ=4, depth=1	1.84
	ϕ=4, depth=2	2.31
ϕ=40, H=40	ϕ=2, depth=1	1.11
	ϕ=4, depth=2	2.37

Conclusion can be made that the simulation result agrees with the theoretical value. As for the detector C, the capacitance is only about 1 pF, so the electronics noise of PC-HPGe detector caused by capacitance will be decreased due to the application of point contact electrode technology.

D. *The depleted voltage*

The voltage under which the detector is just fully depleted can be simulated with the following method according to the certainty and uniqueness principles of static electric field:

- Set the voltage on electrode which should be under lower voltage to zero at first;
- Then set the space charge distribution in detector as that the detector is under the depleted state;
- Simulate the electric field by Maxwell 3D;
- Get the voltage on another electrode. This voltage is exactly the fully depleted voltage.

Formulas to calculate depleted voltage of detector A and detector B can be found in reference literature 6[6]. The comparison of simulation result and theoretical value is shown in table IV. The simulation results agree with theoretical value very well; and the fully depleted voltage of detector C is 2.2 kV.

TABLE IV. DEPLETED VOLTAGE OF DETECTORS

Detector	Theoretical value/V	Simulation/V
A	384	375
B	3115	3027
C		2200

III. SIMULATION OF CHARGE COLLECTION AND SIGNAL INDUCTION BASE ON MAGE FOR PC-HPGE DETECTOR C

The procedure of the signal simulation is:

- Simulate the electric field and weighting field of detector C using Maxwell 3D;
- Simulate the interact points and energy deposition of inject particles using Geant4
- Import output data of previous steps to MaGe and set the related parameters. Run the simulation and record induced current on the electrodes.
- Convolve induced current with response function of following readout electronics to get the finally output signal of detector system.

Here only some results of part of the procedure are illustrated.

A. *Drift tracks of carriers*

Assume that there are several energy deposition points along Z=-20 mm and X=20 mm in detector C; then the carriers released by energy deposition will drift along the electric filed. The simulation result is shown in Fig. 4.

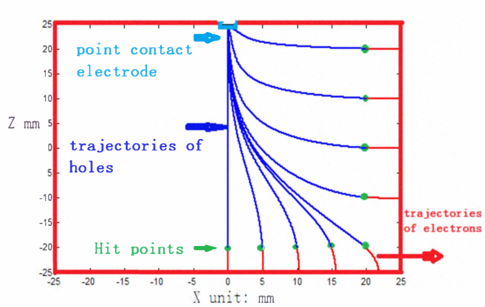

Fig. 4. Drift track of carriers in detector C

Form the result conclusion can be drawn that the drift tracks of carriers agree with related physical sense. For example the moving direction and drift tracks of electrons and holes are in accordance with the electric field of detector C shown in Fig. 3.

B. *Induced current*

Having weighting field of specific electrode and drift tracks of carriers, the induced current on this specific electrode can be calculated according to Shockley-Ramo theorem.

The induced charge waveforms of energy deposition points along X=20 mm in Fig.4 is shown in Fig.5. The beginning time of rising edges of waveforms of different drift tracks varies from 200 ns to 800 ns. This is very important for the discrimination of single- and multi-site events.

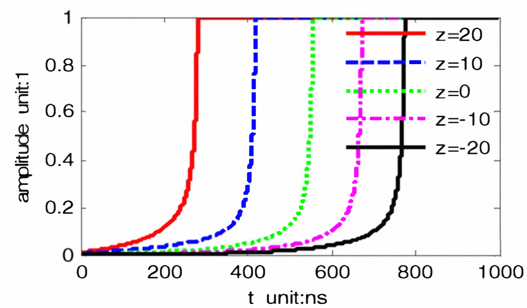

Fig. 5. Induced charge (not current) waveform

C. *Charge collection time*

Assuming that carriers are collected thoroughly when the amplitude of charge waveform in Fig.5 reaches 1. Then we can get the distribution of collection time of carriers in the detector. The result is shown in Fig.6

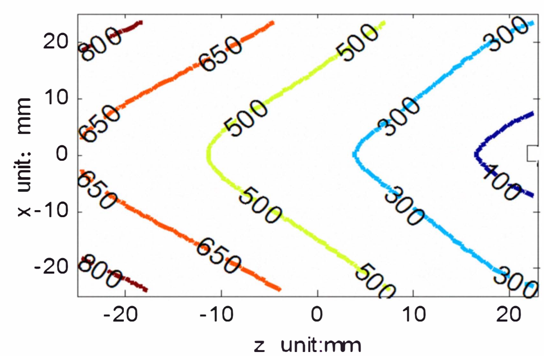

Fig. 6. Collection time distribution of carriers

Numeral on the contour line is the value of collection time. So the 1D location of interact point of particles in the detector may be found by taking advantage of this distribution.

D. *Multi-site event and signal- site event*

The definition of multi-site event (MSE) is that the incident particle has more than one energy deposition points in the detector and those points can be distinguished by following electronics. While the single-site event (SSE) is the event that the incident particle only has a single energy deposition point in detector or has several energy deposition points in detector but they cannot be distinguished. They will be treated as a single energy deposition point.

Assume there are a single-site event and a multi-site event. For the single-site event, there is an energy deposition point [unit : mm] at (X，Y，Z)=(20，0，0) ; For the multi-site event, there are two energy deposition points at (X, Y, Z) = (20, 0, 20) and (X, Y, Z) = (20, 0, -20), value of energy deposition of these two points is the same. The normalized induced charge waveform and induced current waveform are simulated and shown in Fig.7. From the figure, significant difference between signal of single-site event and signal of multi-site event can be found.

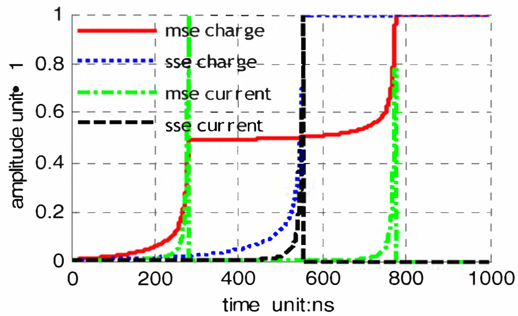

Fig. 7. Induced signal of multi-site event and single-site event

So PC-HPGe detectors can be used for distinguishing single-site events from multi-site events. As we know, gamma particles and neutrons may product multi-site events in detector in a great probability. But the WIMPs probably produce only single-site event in detector according to related literatures.

IV. ENERGY SPECTRUM SIMULATION OF A PC-HPGE DETECTOR

Including all the factors that affect the energy spectrum of a PC-HPGe detector, such as the fluctuation of generation of carriers, lifetime of carriers and electronics noise, a ^{133}Ba gamma spectrum is simulated and compared with the measurement result, shown in Fig.8. It can be seen that they matched fairly well. The parameters of the studied detector are as following:

- Diameter: 60 mm;
- Height: 60 mm;
- Impurity density: 1.0~1.5×1010 /cm3, linear distributed from the bottom to the top;
- The point contact:
  - Diameter: 5 mm;
  - Depth of the hole: 5 mm.

V. CONCLUSION AND DISCUSSION

Three simulation packages (Maxwell 3D, MaGe and Geant4) were successfully adopted to study PC-HPGe detector. Preliminary simulated results match the calculated or measured ones very well. The advantages of Point-contact were confirmed in details. This paved the way for further studies.

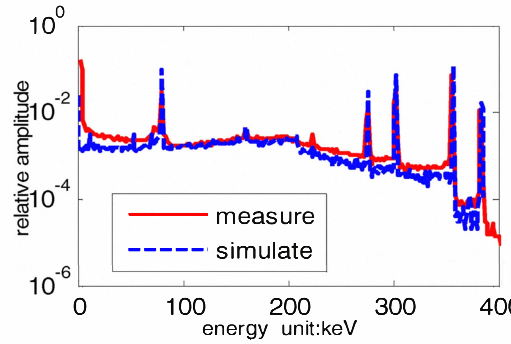

Fig. 8. Simulation and measurement results of γ spectrum

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REFERENCES

[1] C. E. Aalseth, Results from a Search for Light-Mass Dark Matter with a p-Type Point Contact Germanium Detector, Physical Review Letters, 2011, vol 106, p 131301-1-131301-4

[2] K.J. Kang, Status and Prospects of a Deep Underground Laboratory in China, Journal of Physics: Conference Series 203 (2010) 012028

[3] QianYue, China JinPing underground Laboratory (CJPL) and China Darkmatter Experiment (CDEX) Symposium on Future Applications of Germanium Detectors in Fundamental Research, Beijing, March, 2010, http://wwwgerda.mppmu.mpg.de/

[4] Henry T. Wong, Dark Matter Searches with Germanium Detectors with sub-keV Sensitivities, 35th International Conference of High Energy Physics, Paris, France, July 22-28, 2010

[5] Boswell, M, MaGe-a Geant4-Based Monte Carlo Application Framework for Low-Background Germanium Experiments, IEEE Transactions on Nuclear Science, June 2011, Volume: 58 Issue:3, p1212 - 1220

[6] Glenn F.Knoll, Radiation Detection and Measurement 3rd ed. John Wiley&Sons, Inc. New York, 1999, pp. 353-457

[7] Zhong He, 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