Study on silicon drift detector efficiency using Monte–Carlo simulation and experimental methods

Siming Guo*, Jinjie Wu†, Jian Zhang†, Zihao Fan†, Weina Che†, Mengshi Li†, Dongjie Hou†, Ji Wang†
†National Institute of Metrology, Beijing, People’s Republic of China
*E-mail: gsm@nim.ac.cn

Abstract: The energy calibration and efficiency calibration of one silicon drift detector (SDD) are introduced here. The energy calibration is achieved using four radioactive sources, and the linear correlation coefficient is close to one. The efficiency curve of the SDD is obtained by Monte–Carlo simulations from 0.5 keV to 40 keV. Then, the efficiency of the SDD is calibrated using two radioactive sources. The results of experiments are compared with the calculated and the relative deviation are within 5.6%.

1 Introduction

Energy spectrum is the most direct and accurate description of X-ray radiation. [1] A complete X-ray continuum spectrum, which can reflect the X-ray tube voltage, half-value layer, the average energy, and Gy/Sv conversion coefficient. [2] Particle fluence is a way of describing the radiation field by recording the number of incident particles. When a particles reach a certain point in the radiation field, their energy is usually not monoenergetic, and the particle fluence has a spectral distribution of energy, which is called fluence spectrum. [3]

Silicon drift detector (SDD) is a kind of semiconductor detector commonly used in X-ray detection. [4] As of its counting rate, high energy resolution, and the ability to work at room temperature, it is widely used in energy dispersive X-ray fluorescence spectrometer (XRF) or energy dispersive spectrometer (EDS). The SDD used in this research project is a low-energy X-ray detector. The FWHM of the detector is <133 eV at 5.9 keV and the active detection area is 30 mm² chip collimated to 20 mm², the active Si thickness is 450 μm. The energy range of detection photons is (1–40) keV, and the crystals are protected by an 8-μm-thick beryllium window and stainless steel housing.

2 Energy calibration

When using SDD for X-ray measurement, the obtained data are the relationship between photon number and channel address, and cannot obtain the energy distribution intuitively. Usually, the detector can be calibrated using a radioactive source to obtain an intuitive photon energy distribution, which is spectrum. [5] In order to facilitate further research, we carried out the energy calibration of the detector.

There are few nuclides that can generate photons with energies below 20 keV. Four radioactive sources were selected in this study, which are 55Fe, 241Am, 57Co, and 88Y, respectively. The decay of 55Fe releases 5.9 keV of X-ray. When 241Am decays, α-ray is released. At the same time, a part of 59.5 keV γ-ray and (11.9–20.8) keV X-ray are released. When 57Co decays, it releases 6.4 and 7.1 keV of X-rays, releases 14.4 keV of γ-rays, and 88Y decays to produce 14.1 keV of X-rays. The energy spectra of several radioactive sources were measured using SDD, respectively. The energy spectra of 55Fe and 241Am are shown in Fig. 1.

The activity of 88Y is lowest in the four nuclides and can be used to verify the result of energy calibration. The 5.9 keV energy peak of 55Fe and the 13.9 keV energy peak of 241Am are obvious in the above figure. In addition, the 6.4 and 14.4 keV peak positions of 57Co are obvious, so the three sources of 55Fe, 241Am, and 57Co can be used for energy calibration. The relationship between the four energy points and the address of the three sources is shown in Fig. 2. The linear correlation coefficient is $R^2 = 1$, thus, the detector energy linearity is very good.

Where $y$ is energy of photon, its unit is keV, $x$ is the channel address. The calibration results were validated using the 14.1654 keV peak of 88Y, as shown in Fig. 3, which resulted in an energy of 14.1995 keV, the error is 0.2%.

3 Monte–Carlo simulation of the intrinsic efficiency

Efficiency calibration is the experimental work to determine the efficiency of a nuclear radiation detector in recording incident particles. A common method is direct calibration using a series of standard radioactive source with known rates of decay and branching. That can also be obtained by Monte–Carlo simulation...

---

*Fig. 1 Measured energy spectrum of 55Fe and 241Am

Fig. 2 Relationship between energy and channel
and then calibrate a few points with standard radioactive sources.

The Monte–Carlo codes MCNPX [7] and GEANT4 [8] are used to calculate the detector's efficiency. Both calculating software include reaction sections for neutron, photon, and electron transport. The detector model is necessary for Monte–Carlo simulations. The structure and size of the detector are very important in the model establishment. The parameters given by the manufacturer can be used as a reference. The most accurate and effective method is to perform fluoroscopic imaging of the detector. We performed X-ray radiographs of the detector to check the nominal dimensions specified by the manufacturer and the X-ray radiography [9]. The dimension and structure of the simulation model are shown in Fig. 4.

Fig. 5 shows the efficiency curve of the detector calculated by Monte–Carlo software. The response of the detector to the monoenergetic photons of 60 energy points is calculated from 0.1–40 keV. The intrinsic efficiency of the detector varied from 2 to 99.3% in the energy range. The results of some energy points of the simulation calculation are as follows: 99%@5.9 keV, 99%@6.5 keV, 87%@11.9 keV, 72%@14 keV, 51%@16.9 keV, 46%@17.8 keV. It can be seen that the detection efficiency of the detector is the highest at 5–10 keV, about 99%, the photon detection efficiency drops rapidly at energies >10 keV, and the detection efficiency at 40 keV is only about 5%. The reason is that crystal thickness is too small, high energy photons cannot be deposited energy within the crystal.

4 Measurements with radioactive sources

The intrinsic efficiency is a function of X-ray energy and which can be expressed by the equation [10],

\[
e_i = T(E) \cdot A(E) \cdot (1 - P_{esc}(E)),
\]

where \(e_i(E)\) is the intrinsic energy, \(E\) is the photon's energy, \(T(E)\) is the transmittance of be window, \(A(E)\) is the photon absorption in sensitive areas, \(P_{esc}(E)\) is the probability of generating K fluorescence escape. Where \(T(E)\) and \(A(E)\) are expressed as follows,

\[
T(E) = \exp(-\sum_{\text{layers}} \mu_l \cdot d_l),
\]

\[
A(E) = 1 - \exp(-\tau_{Si} \cdot d_{Si}),
\]

where \(\mu_l\) is the attenuation coefficient in material layer \(l\) for X-rays with energy \(E\), \(d_l\) is the material thickness, \(\tau_{Si}\) is the Si's photoelectric absorption coefficient and \(d_{Si}\) is the Si's thickness. Mass attenuation coefficients can be inquired in database or calculated by computer program. [11]

The relevant data of the sources used in the experiments are shown in Table 1. The comparison of the MC simulated spectrum and the measured spectrum of the \(^{241}\text{Am}\) and \(^{55}\text{Fe}\) are shown in Fig. 6. For better visualisation, the calculated spectra have been shifted to the right a little.

Using the results of experimental tests to verify that the positive results of the simulation results are a reliable method [15].
The experimental results at these energy points are: 96.0%@5.9 keV, 96.5%@6.5 keV, 90%@11.9 keV, 69%@14 keV, 50%@16.9 keV, 44%@17.8 keV. The comparison of the simulation and experiment are shown in Fig. 7. The relative deviation between experimental and simulated efficiencies are within 5.6% in most cases. Due to the influence of air in the experiment, most of the experimental values are lower than the theoretical simulation values.

5 Conclusion

The energy calibration curve and detection efficiency curve are obtained in this work. The studies have shown that the Monte-Carlo simulation results are in good agreement with the results of the radioactive source calibration, indicating that the results of the computational model are reliable. The SDD is suitable for low energy X-ray detection, especially soft X-ray below 10 keV.

6 Acknowledgments

This work was supported by National Key R&D Plan of China under Grant No. 2017YFF0205102, Research Fund for the Research on key technology of high injection rate synchronous radiation X-ray measurement.

7 References

[1] Malinowski, K., Chernyshova, M., Czarski, T., et al.: ‘Simulation of energy spectrum of GEM detector from an X-ray quantum’, J. Instrum., 2018, 13, (1), pp. C01018–C01018
[2] Li, H.B., Jia, M.Y., Wu, R., et al.: ‘Calculation of spectrum to dose conversion function of portable HPGe γ spectrometer’, Medizintechnik/nuclear Electron. Detect. Technol., 2013, 33, (6), pp. 699–704
[3] Cerofolini, G.F., Bertoni, S., Meda, L., et al.: ‘The fluence spectrum allowing the formation of a connected buried layer in silicon by oxygen implantation’, Semicond. Sci. Technol., 1996, 11, (3), p. 398
[4] Lechner, P., Eckbauer, S., Hartmann, R., et al.: ‘Silicon drift detectors for high resolution room temperature X-ray spectroscopy’, Nucl. Instrum. Methods Phys. Res., 1996, 377, (2–3), pp. 346–351
[5] Gualdi, V., Tain, J.I., Agrament, J., et al.: ‘Calibration of a DSSSD detector with radioactive sources’. American Institute of Physics, La Rábida, Spain, 2013, pp. 173–174
[6] Peyres, V., García-Toroño, E.: ‘Efficiency calibration of an extended-range Ge detector by a detailed monte carlo simulation’, Nucl. Instrum. Methods Phys. Res., 2007, 580, (1), pp. 296–298
[7] Hendricks, J.S.: ‘MCNPX version 2.5.c’, Availability, 2003
[8] Asai, M.: ‘Geant4-A simulation toolkit’, Nucl. Instrum. Methods Phys. Res., 2007, 506, (3), pp. 250–303
[9] Maleka, P.P., Mauučec, M.: ‘Monte carlo uncertainty analysis of germanium detector response to γ γ mathContainer loading mathjax -rays with energies below 1 MeV’, Nucl. Instrum. Methods Phys. Res., 2005, 538, (1–3), pp. 631–639
[10] Hansen, J.S., Mcgeorge, J.C., Nix, D., et al.: ‘Accurate efficiency calibration and properties of semiconductor detectors for low-energy photons’, Nucl. Instrum. Methods, 1973, 106, (2), pp. 365–379
[11] Nowotny, R.: ‘MC4: photon attenuation data on PC version 1.0.1 of August 1998 – summary’, 1998
[12] Bé, M.M., Chisté, V., Dulieu, C.: ‘Detailed calculation of K- and L-auger electron emission intensities following radioactive disintegration’, Appl. Radiat. Isot. Incl. Data Instrum. Methods for Use Agric. Ind. Med., 2006, 64, (10–11), p. 1435
[13] Lépy, M.C., Plagnard, J., Ferreux, L.: ‘Measurement of (241)Am L X-ray emission probabilities’, Appl. Radiat. Isot. Incl. Data Instrum. Methods for Use Agric. Ind. Med., 2008, 66, (6–7), p. 715
[14] Chechey, V.P., Kuzmenko, N.K.: ‘Updated evaluations of the 233Th and 241Am decay characteristics [J]’, Applied Radiation and Isotopes, 2010, 68, (7–8), pp. 1578–1582
[15] Lépy, M.C., Pearce, A., Sima, O.: ‘Uncertainties in gamma-ray spectrometry’, Metrologia, 2015, 52, (3), pp. S123–S145

Fig. 7 Experimental and simulated intrinsic efficiencies of the detector

This is an open access article published by the IET under the Creative Commons Attribution License