Proceedings of the 5th WSEAS Int. Conf. on Signal Processing, Computational Geometry & Artificial Vision, Malta, September 15-17, 2005 (pp202-206)

Performance Analysis of p-i-n Radiation Detectors

MARIA RIZZI, MICHELE MAURANTONIO, BENIAMINO CASTAGNOLO

Dipartimento di Elettrotecnica ed Elettronica,
Politecnico di Bari
v. E. Orabona, 4 - 70125 Bari
ITALY

Abstract: In this paper the performances of radiation detectors based on GaAs and CdTe materials have been studied. The analysis is carried out adopting a 3D FEM model which takes into account the carrier trapping and generation phenomena by the Shockley Read Hall recombination theory.

The good accordance of the obtained values with the know experimental data confirms the general validity of the adopted model in simulating devices of any material and at any working temperature.

Key words: X-ray detector, GaAs, CdTe, p-i-n diode

1 Introduction

High sensitivity real time digital X-ray imaging with good spatial resolution is desired both for medical and industrial applications. Actually, high energy resolution is not the only parameter of interest in developing room temperature detector. Several other characteristics are also of great importance, including:

- high stability of detector characteristics for long periods of use;
- high values of analyzed peaks to background

Hybrid pixel detectors, in which sensor and electronic chip are separate entities, connected via bump bounding techniques, represent the state of the art for both particle detection and imaging applications.

Among the materials used to realize radiation detectors, semiconductors seem to be the best choice. While silicon is almost a perfect material for particle physics detectors, the need of high photon absorption efficiency in radiological applications requires the study and the use of semiconductor materials with high atomic charge, such as GaAs or CdTe [1], [2],[3], [4], [5], [6], [7], [8], [9]. Detectors realized adopting such materials are often affected by an incomplete collection of the photogenerated carriers which degrades the performance such as energy resolution, charge collection efficiency and photo peak efficiency. Possible causes of this signal reduction are material inhomogeneities, the presence of dead layers and the anomalous distribution of the electric field inside the detector [10].

To relate the semiconductor characteristics to the induced current signal, a 3D numerical model was conceived for detectors having different structures. Its validity has been proven in simulating several different GaAs detector structures (micro-strip or pixel), taking into account also the particle incidence angles [11], [12], [13].

In this paper, the studied model has used to compare GaAs and CdTe X-ray p-i-n detectors. Preliminary evaluations of performance of similar detectors have been previously reported and detailed experimental information and results can be found in the corresponding references [14]. The measured values are in accordance with the simulated results obtained using the three dimensional model and validated with a GaAs p-i-n junction.

Section 2 deals with semiconductor detection properties and the adopted detector configuration is described. In section 3 the principles of the model are summarized and the performances of p-i-n structures composed of different semiconductors and operating at different temperatures are studied. Moreover some conclusions are drawn out.

2 Semiconductor detection properties and detector architecture

The performance of detectors depend both on the adopted material for the fabrication of the single structure and the array architecture chosen.

Suppose that the radiation beam, composed of energetic particles (neutrons, electrons and α-particles) and photons (X-ray, γ-Ray and UV ray) interacts with a suitable material (detector), generating electrical charges (photoelectric effect). Applying an electric field to the detector, generated charges are converted into electric current, whose pulse amplitude depends on the collection time which is linked to the detector type, the mobility of the carriers and the electrodes position. The pulse number gives the number of particles or photons hitting the detector while the pulse amplitude measures the radiation energy.

Gases, cryogenic liquids and semiconductors are the most used materials to detect radiation. Due to the lower energy necessary to produce an electron-hole pair (3-6eV vs. 30eV necessary to free an electron in gas detectors), it is possible to produce a higher charge adopting semiconductor detectors with equal energy amount. Moreover, materials with high atomic mass, have high X-ray sensitivity. In fact, the probability of interaction between an X-ray beam and a material having atomic number Z is proportional to Z^n ($4<n<5$) [15].

For these reasons, semiconductors are the best choice for a digital detector, because of the high efficiency, the high spatial and energetic resolution expected.

GaAs and CdTe high resistivity, due to their high energy band-gap, reduces leakage currents [16] and their high atomic number improves the photoelectric interaction.

These features, together with the high electron mobility, allow a decrease in the exposure time of the radiographed object, which determines a reduction in the radiation amount, very important in some applications, for example, in medical field.

As far as the architecture is concerned, the need for an intrinsic, direct relation between the detector array and the radiographic image makes the pixel-matrix arrangement the best choice [17]. In this structure, each pixel is interfaced to a front-end electronic chain. Hence there are as many channels as the pixel number.

3 Adopted model and performance evaluation

To link the semiconductor characteristics to the induced current signal, a 3D-numerical model for detectors having different structures has been conceived [11], [12], [13]. The model adopts the finite element analysis (FEM) and it is implemented in Matlab R14 environment. A variable step mesh has been created to solve the discrete Laplace equation by using an iterative method.

The model evaluates the current signal induced by the motion of the single photo generated carrier by the Ramo’s theorem [17], [18].

When a carrier pair is generated in a given position, the charge induced on the collecting electrode is calculated taking into account the contribution of both electrons and holes.

If trapping occurs, an incomplete charge collection is observed. The Shockley Read Hall (SRH) recombination theory is considered as base model for the carrier trapping and generation phenomena. The carrier trapping is described by means of two characteristic times: the mean trapping time of electrons and that of holes. Trapping of a carrier occurs when its trapping time is shorter than the transit time. Also the detrapping mechanism is taken into account in this model [19], [20], [21], [22], [23].

In this model the efficiency is substituted by the determination, point by point, of the net charge due to the carriers trapping and re-emission actions.

By iterating the mathematical process for every generation point, the evaluation of the overall collected charge is made possible summing all the contributions from all the generation points.

To test the validity of the model to study radiation detectors independently from the semiconductor composing the devices, two different implementations of p-i-n junction have been analyzed: GaAs and CdTe structure. The study is carried out considering junctions having equal dimensions. The analyzed model simulates p-i-n structures made with undoped thick epitaxial layers (about 2µm), an intrinsic region supposed grown on an n+ substrate which is the n+ side of the diode, a p+ layer to reduce the dark current and improve the energy resolution and two ohmic contacts on the front and back surface of devices. The detectors simulated in this paper have a residual doping concentration of 10^{14}cm^{-3} corresponding to a depleted zone (W) 0.88µm thick at 1.8V bias. The detectors have been modelled with a three-dimensional geometry (fig.1), 3µm thick and 10µm width and length.

Each p-i-n junction is surrounded by a guard-ring with the aim to obtain a better performance in terms of charge collection. The guard-ring is 1µm wide and the distance between the guard-ring and the pixel is 1µm. The presence of guard-ring makes the electric field uniform and electrons move along fairly straight lines, orthogonal to the contacts. The model simulates the behaviour of a ^{241}Am source which irradiates 60KeV X-ray photons, impinging on the back side ohmic contact.

In the simulation of the induced signal, donor/acceptor traps have been considered. The spatial distribution of the electric field is obtained with the following set of parameters: electrode distance equal to 3µm, bias voltage equal to 1.8V and a single couple of electron/hole generation, 1.5µm from the back side ohmic contact.

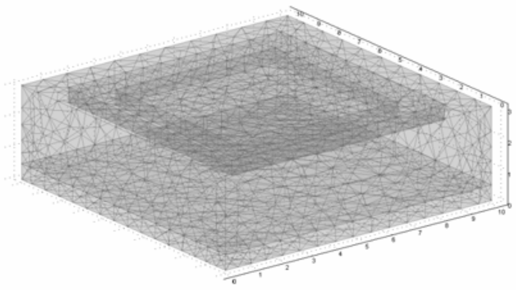


Fig.1 The adopted mesh structure to simulate each p-i-n pixel

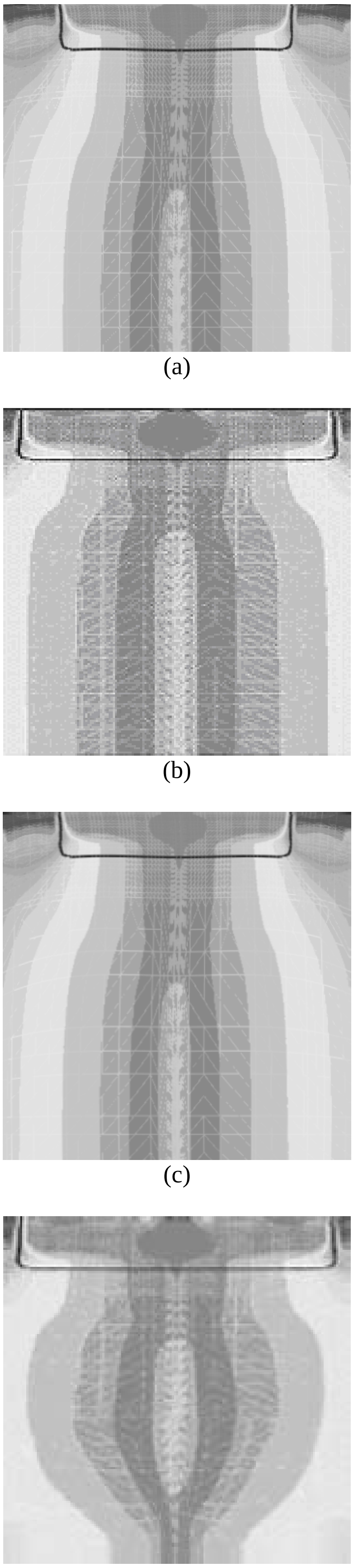
In fig.2, the shape of the J flux distribution lines is indicated for GaAs and CdTe pixels, considering a Single Event Upset (SEU) normal to the pixel surface. The analysis is carried out both at room temperature and at 243°K.

The CCE parameter is determined for the two different pixels adopting the 3D model and is compared with the values obtained sperimentally. Indicating by H_0 the channel number corresponding to the maximum count number, the CCE is determined using the following expression:

$$CCE[\%] = \frac{H_0(s)}{H_0(Si)} \frac{\varepsilon(s)}{\varepsilon(Si)} 100$$

where H_0 (s) and ε(s) represent the channel number and the average electron-hole generation energy of the substrate composing the pixel.

For the GaAs detector, a CCE value of about 90 - 95% is obtained at room temperature, for an electron/hole generation point 0.9 - 1µm from the back side ohmic contact (fig.3a). An equal value is obtained at 243°K (fig.3b). For the CdTe detector a CCE value of about 95% is obtained at 243°K. At room temperature a nearly zero CCE value is obtained in good accordance with the expected experimental values [14].



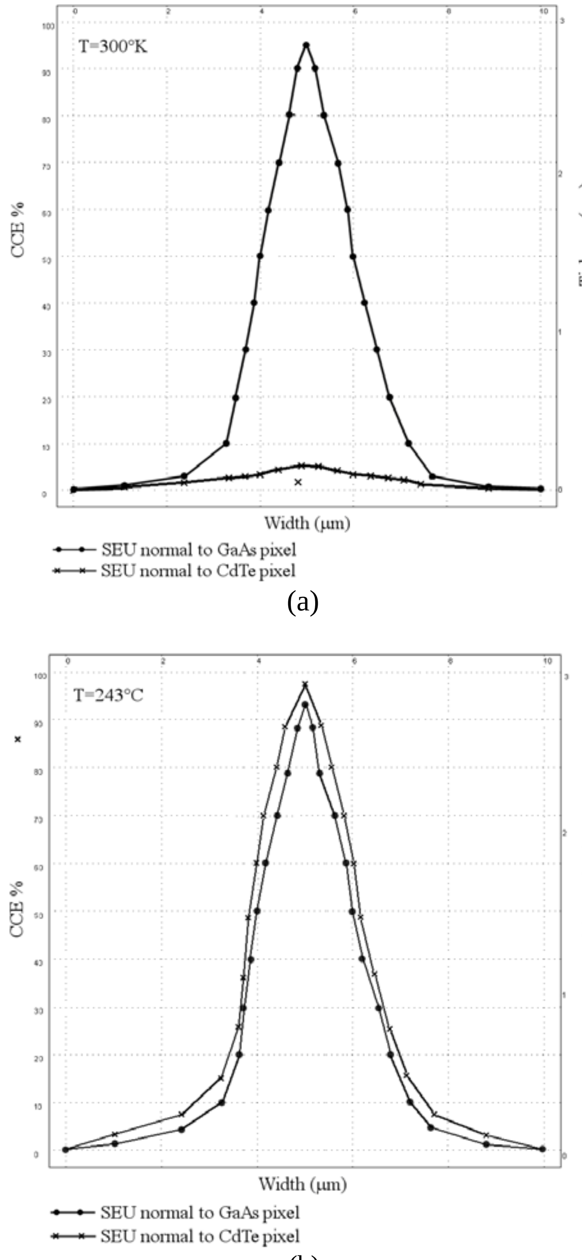
(a)

(b)

(c)

(d)

Fig.2 J flux distribution for a collision normal to the centre of the pixel surface at 243°K (a-GaAs, b-CdTe) and at room temperature (c-GaAs, d-CdTe)



(a)

(b)

Fig.3 CCE values for an X-ray collision in the center of the pixel area at 300°K (a) and 243°K (b)

4 Conclusions

The analysis shows the model validity independently from the adopted material and the operating temperature. The simulated values are in good accordance with the experimental data and with the results described in literature. Drawing further conclusions, it is confirmed that GaAs, having comparatively low cost for the production of large area thick epitaxial layers, because of the availability of standard processing technologies and the possibility to work well at room temperature, is still a better candidate for imaging with respect to the CdTe.

References

[1] G.C. Sun, H. Samic, J.C. Bourgoin, D. Chambellan, O. Gal, P. Pillot, “A comparison between GaAs and CdTe for X-ray imaging”, *IEEE Trans. On Nuclear Science*, vol.51, No.5, pp.2400-2404, 2004

[2] O. Limousin, “New trends in CdTe and CdZnTe detectors for X-and- gamma-ray applications”, *Nuclear Instruments & Methods in Physics Research*, vol.A 504, pp.24-37, 2003

[3] W. Bencivelli, E. Bertolucci, U. Bottigli, A. Cola, M.E: Fantacci, P. Rizzo, V. Rosso, A. Stefanini, “Electrical Characterization and Detector Performances of a LPE GaAs Detector for X-Ray Digital Radiography”, *Nuclear Instuments and Methods in Physics Research*, vol. A-346, pp. 372-378, 1994

[4] E. Vittone, C,. Manfredotti, F. Fizzotti, K, Mirri, E. Gargioni, P. Polesello, A. Lo Giudice, S. Galassini, F. Nava, P. Vanni, P. Rossi, ”IBIC analysis of gallium arsenide Schottky diodes”, *Nuclear Instuments and Methods in Physics Research*, vol. B-158, pp. 470-475, 1999

[5] D. R. Dance, “The Physics of Medical Imaging” pp. 27, *S. Webb editor*, 1990

[6] E. Bertolucci, “Digital Medical Imaging with GaAs Detectors”, *Proceedings of 3rd International Workshop on Gallium Arsenide and Related Components*, pp. 211-216, 1996

[7] P. Randaccio “Evaluation of Elemental and Compound Semiconductor for X-Ray Digital Radiography”, *Nuclear Instuments and Methods in Physics Research*, vol. A-310, pp. 210-214, 1991

[8] D.S. McGregor, G.F. Knoll, “Bulk GaAs Room Temperature Radiation Detectors” *Nuclear Instuments and Methods in Physics Research*, vol. A-322, pp. 487-492, 1996

[9] G.C. Sun, M. Lenoir, E. Bréelle, H. Samic, J.C. Bourgoin, H. El-Abbassi, P.J. Sellin, J.P. Montagne, “X-ray detector with thick epitaxial GaAs grown by chemical reaction”, *IEEE Transactions on Nuclear Science*, vol. 50 ,No 4 , pp. 1036 – 1038, 2003

[10] A. Burger, K. Chattopadhyay, H. Chen, X. Ma, J.O. Ndap, M. Schierber, T.E. Schlesinger, H.W. Yao, J. Erickson, R.B. James, “ Defects in CZT crystals and their relationship to gamma-ray detector performance”, *Nuclear Instruments & Methods in Physics Research*, vol.A 448, pp.586-590, 2000.

[11] M. Rizzi, M. Maurantonio, B. Castagnolo “3D-Finite Element Model for GaAs α-

particles pixel detector" *WSEAS Transactions on Electronics*, vol. I, N° 4, pp 595-600, 2004

[12] M. Rizzi, M. Maurantonio, B. Castagnolo "Novel Microstrip System Detectors for Medical Applications", *WSEAS Transactions on Biology and Biomedicine*, vol. 2, N° 2, pp 220-227, 2005

[13] M. Rizzi, V. Antonicelli, B. Castagnolo, "New model for a GaAs X-ray pixel detector", *IEE Proceedings of Circuits, Devices and Systems*, vol. 150 ,No. 3, pp.210 – 216, 2003

[14] F. Nava, G. Bertuccio, P. Vanni, M. E. Fantacci, C. Canali, A. Cavallini, Peroni "Improved performance of GaAs radiation detectors with low ohmic contacts ", *IEEE Trans. On Nuclear Science*, vol.44, pp.943-949, 1997

[15] T. E. Schlesinger, R. B. James "Semiconductor for room temperature nuclear detector applications, *Semiconductors And Semimetals*, *Accademy Press Inc.*, vol.43, pp 3-7, 1995

[16] G. F. Knoll, "Radiation Detection and Measurement" pp. 473-477, *J. Wiley & Sons*, 1989

[17] P. De Visschere "The validity of Ramo's Theorem", *Solid State Electronics*, vol.4, pp.455-459, 1990

[18] H. Kim, H.S. MIN, W. Tang, Y.J. Park "An extended proof of the Ramo-Shockley theorem", *Solid State Electronics*, vol.34, pp.1251-1253, 1991

[19] D. S. McGregor, D. A. Rojeski, "Evidence for field enhanced electron capture by EL2 centers in semi-insulating GaAs and the effect on GaAs radiation detectors", Journal of Applied Physics, Vol. 75 N. 12, p. 7910, 1994

[20] A.Cola, F.Quaranta, L.Vasanelli, C.Canali, A.Cavallini, F.Nava, and M.E.Fantacci, "A Study of the Trap Influence on the Performances of Semi-Insulating GaAs Pixel Detectors" *Nuclear Instruments and Methods in Physics Research*, pp. 395 349, 1997

[21] A. Cola, F. Quaranta, M. A. Ciocci, M. E. Fantacci, "A Study of the Electrical and Charge Collection Properties of Semi-Insulating GaAs Detectors", *Nuclear Instruments and Methods*, Vol. A380, pp. 66-69, 1996

[22] S. P. Beaumont, F. Foster, G. Hughes, B. K. Jones, J. Santana I. J. Saunders, T. Sloan, "GaAs solid state detectors for particle physics", *Nuclear Instruments and Methods in Physics Research*, A322, pp. 472-482, 1992

[23] J.S. Laird, T. Hirao, S. Onoda, H. Mori, H. Itoh " Temperature dependence of heavy ion induced current transients in Si epilayer devices", *6th European Conference on Radiation and Its Effects on Components and Systems*, pp.125 - 131, 10-14 Sept. 2001

Acknowledgement

The work is carried out under the financial support of the Ministero dell'Istruzione, dell'Università e della Ricerca Scientifica, in the frame of Cluster C26: "*Modellazione, sperimentazione e diagnostica di strutture in materiali innovativi*".