A High-Performance Scintillator-Silicon-Well X-Rays Microdetector Based on DRIE Techniques

J. G. Rocha and J. H. Correia
University of Minho, Dept. Industrial Electronics
Campus de Azurem, 4800 Guimaraes, Portugal
e-mail: gerardo@dei.uminho.pt

***Summary**. This paper describes a X-rays detector based on an array of scintillator crystals, CsI:Tl, encapsulated in well-type silicon. The X-ray energy is first converted to visible light which is detected by a photodetector in the well bottom. DRIE techniques are used to achieve perfect vertical sidewalls* 515 μm *deep,* 100 μm *pixel square size and to maximize the fill factor. The inner walls of the well are electroplated with aluminum for improving the number of photons arriving in the detector and to reduce cross-talk between adjacent wells. Simulations and modeling show an improvement of approximately 26% in the detection efficiency using an aluminum layer* 5 μm *thick.*

Keywords: Scintillator, Digital Radiology, X-ray, DRIE, Micromachining

Introduction

The conventional X-ray imaging remains an analog technique while other medical imaging methods such as computed tomography, ultrasound and magnetic resonance imaging are digital. Digital radiography allows application of image processing techniques (e. g. detail improvement), application of sophisticated algorithms and real-time operation. Its requirements are sub-millimeter spatial resolution and good energy resolution. The application of X-ray imaging microdetectors in medical diagnostics is undeniably advantageous. Due to their compact size, wide dynamic range and digital data storage capacity, these imagers are very promising in the medical imaging technology when combined with readout microelectronics. A significant reduction of the dose of emitted radiation can also be achieved with these X-rays microdetectors[1].

X-rays detection methods

Incoming X-rays can be converted in an electrical signal by means of several methods. The three common methods are the intrinsic (using amorphous silicon), the photoconductor and the scintillator. Each method has its performance advantages and limitations on its use in practical X-ray imagers.

The intrinsic method

An array of photodiodes are done in the silicon substrate. Arriving X-rays are captured by the photodiodes where electron-hole pairs are produced. As a pair is produced for about each 5 eV of X-ray energy, the signals are high. Unfortunately, the X-rays absorption of silicon is very low. A standard silicon wafer (525 μm thick) only absorbs about 2.2% of 100 keV X-rays energy. A layer 16.2 mm thick absorbs 50% of the same radiation (Fig. 1), so in a practical application, each photodiode needs to be 20 mm thick or more.

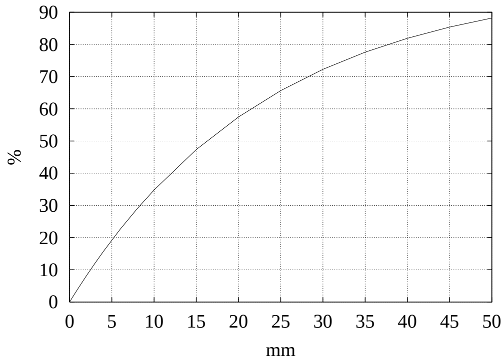

Fig. 1: Absorption rate of 100 keV X-rays by a silicon glass.

The photoconductor method

Photoconductive materials with higher absorption than silicon can be coated on an array of conductive charge collection plates each supplied with a storage capacitor. Currently, the best known commercial photoconductor, amorphous selenium, also has relatively low X-rays absorption and requires about 50 eV to produce an electron-hole pair. The main drawbacks are its high bias voltage which generates electrical insulation problems and its incompatibility with silicon technology.

Another promising photoconductor material for x-ray imaging is the lead iodide (PbI_2), a wide bandgap semiconductor ($E_g = 2.3\ eV$) It has a good X-rays absorption efficiency due to its high atomic number and good conversion efficiency[2]. The drawbacks are: as well as amorphous selenium it needs a bias voltage of several hundred volts and it is incompatible with silicon technology.

The scintillator method

A scintillator is a material that absorbs X-rays and converts its energy to visible light, which is easily detected by a photodiode. A good scintillator yields many visible light photons for each incoming X-ray. Usually consist of compounds of high-atomic number materials, which have high X-rays absorption. Once the interface with the readout electronics is optical, the problems with insulation or technology incompatibility are avoided.

System Design

In medical imaging diagnosis, the X-rays are produced with voltages from 25 kV to 120 kV approximately. This produces an intensity peak ranging from 10 keV to 100 keV. The intrinsic method, using amorphous silicon, as it was seen, is not a practical approach. Therefore, in this project, a X-rays stimulable layer (scintillator crystal) is used to convert X-rays in visible light. The intensity of light is then converted to an electric signal by means of an array of photodiodes. The simplest method consists on the use of a phosphor scintillator above an array of photodiodes as is shown in Fig. 2.

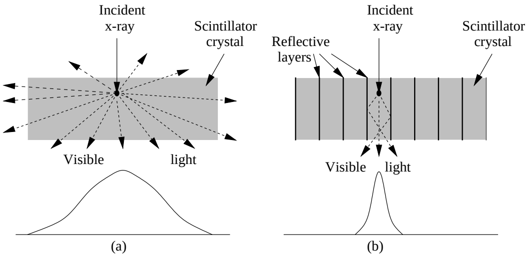

Fig. 2: Effect of reflective layer on the spatial resolution.

The blur diameter on image is comparable to the scintillator thickness, i. e. the thicker the scintillator (desirable to increase the quantum absorption efficiency) the more blurry the image will be. In Fig. 2 (b) is shown another approach with structured columnar scintillators, which alleviates the blurring, increasing the spatial resolution. Moreover, introducing a reflective layer above the scintillator (in the X-rays path) confines the light inside of the well increasing the efficiency. Thus, the device consists in many micromachined silicon wells (Fig. 3 and Fig. 4).

The walls of the wells are coated by an aluminum layer which is deposited by means of selective electroplating. Aluminum has a better performance than other metals (e.g., silver, gold) due to its low density and consequently low X-rays absorption. Moreover, aluminum is a silicon-compatible material. The scintillator is deposited below the aluminum layer. The X-rays penetrates the silicon and aluminum walls and hit the scintillator which produces visible light (wavelength near to 560 nm for CsI:Tl). Electroplated-inner-well walls allow multiple reflections and guides almost all produced light to the photodiodes.

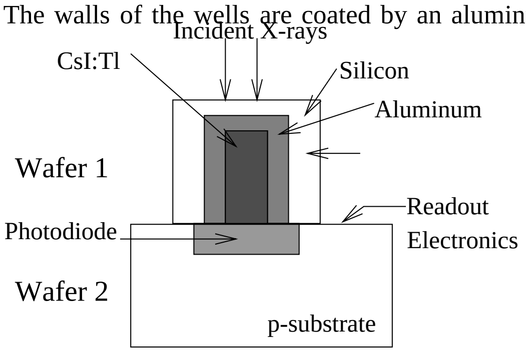

Fig. 3: Photodiode aligned with the scintillator (side view).

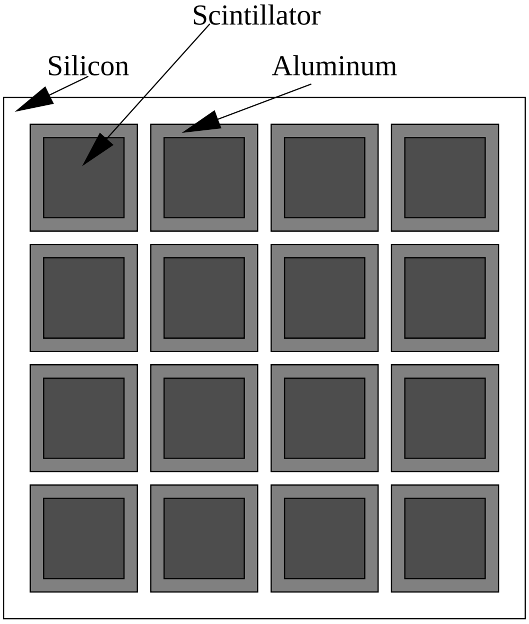

Fig. 4: Array of filled silicon wells (bottom view of wafer 1).

Scintillator

A large number of materials have been found to emit light, when ionizing radiation is incident upon the material. The most widely employed scintillators include inorganic based liquids and plastics. The inorganic tend to have the best light output and linearity, but are known to be slow in their response times, whereas organic scintillators are faster but yield less light. At present the industry routinely produces about two dozen types of inorganic crystalline scintillators. A great many inorganic compounds are considered as good scintillation candidates, being characterized at the moment more than four hundred[3]. Thin layers of most inorganic scintillators effectively absorb gamma quanta in the energy region 1 to 100 keV. The main requirement of scintillators for these energies is a high light output. Table 1 presents a group of scintillators with the highest light outputs at room temperature.[4]. Very high scintillation efficiency $\eta = 0.25$ has been found for $\mathrm{CaI_2}$ and $\mathrm{CaI_2}$:Eu crystals[5]. The application of scintillators based on $\mathrm{CaI_2}$ is far from being wide because they are highly hygroscopic and easily cleaveable.

Table 1: Light yield by some scintillator crystals at room temperature.

Crystal	L_y (ph/MeV)	λ (nm)
NaI:Tl	38000	303
CsI:Tl	59000	560
CsI:Na	39000	420
Lu_2SiO_5:Ce	30000	420
Y_2SiO_5:Ce	45000	420
$Y_3Al_5O_1$2:Ce	19700	390
ZnS:Ag	49000	450
CaI_2	86000	410

The most used scintillators are CsI:Tl and NaI:Tl because of their high light yield and reasonably fast decay time and most importantly because of the low costs to grow these materials. CsI has quite a high X-rays absorption coefficient and is less susceptible to thermal and mechanical shock than Sodium Iodide (NaI). CsI:Tl also is somewhat malleable, which permits shaping to a certain extent without fracture. One of the most important characteristics of cesium iodide is that it emits visible light at about 560 nm when doped with 0.02 to 0.03% of thallium ions. This is just the peak of the spectral sensitivity of amorphous silicon. The combination of CsI:Tl and amorphous silicon has one of the highest quantum efficiencies of all used materials. As a drawback, being significantly less hygroscopic than NaI:Tl, CsI:Tl is a good water absorber and must be protected against humidity.

Fabrication process

The wells on the silicon are very deep (about 515 μm) to be done with conventional etching techniques or Reactive Ion Etching (RIE). So, the best solution is to use Deep Reactive Ion Etching (DRIE).

The walls of the wells are vertical, which makes the aluminum vapor deposition difficult. The solution is the use of selective electroplating.

The scintillator is deposited in the wells by evaporation techniques.

The photodiodes are integrated with the readout electronics, in another silicon wafer using a CMOS standard process.

Simulation results

Fig. 5 shows the incident X-rays rate that go through the silicon and aluminum walls, as a function of the radiation energy and the thickness of the aluminum layer. As it can be seen on the graphic, for wall thickness of about 15 μm (10 μm of silicon and 5 μm of aluminum), 89% of 10 keV incident radiation goes through the wall.

Fig. 6 shows the rate of X-rays which is absorbed by each scintillator crystal, regarding the effect of the top walls. It can be seen on the same figure that for the 40 keV X-rays, about 99% of them are absorbed by a 510 μm scintillator.

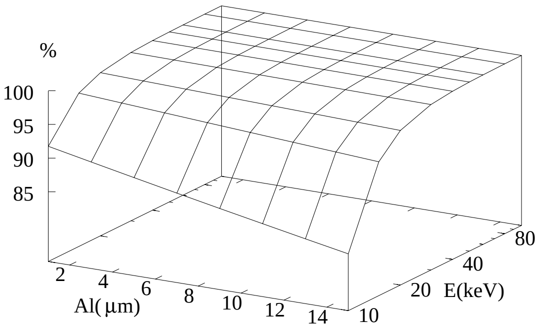

Fig. 5: Behavior of a film composed by 10 μm of silicon and 1 μm to 15 μm aluminum.

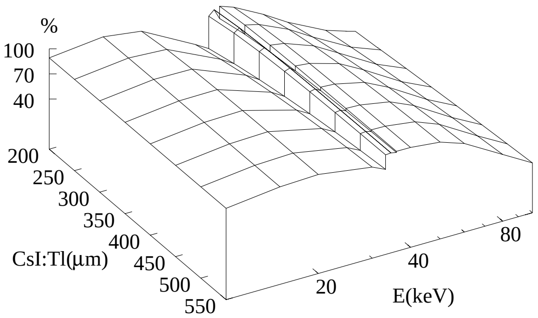

Fig. 6: Energy rate absorbed by the scintillator as a function of its thickness and X-ray energy.

Fig. 7 shows the number of photons that reach the photodiode, for a scintillator thickness of 510 μm and walls with 10 μm of silicon. Each pixel is 100 μm square size. The X-ray source is powered with 20 kV to 120 kV, 500 mA and the exposure time is about 10 ms. The maximum efficiency is reached near 60 keV with this setup. The quantum efficiency at photon energies below 60 keV can be increased lowering the thickness of the top-wall well (e.g., reducing the silicon or aluminum layers). The quantum efficiency increases with the scintillator thickness at energies above 60 keV. Fig. 7 shows that an aluminum layer 5 μm thick allows an improvement of approximately 26% in the detection efficiency because this layer avoids light-losses and cross-talk between adjacent wells.

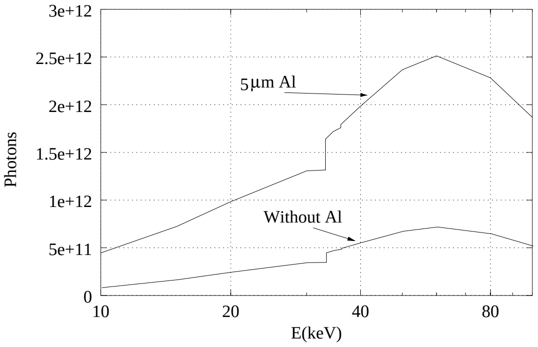

Fig. 7: Number of photons that reach the photodiode.

ISBN 87-89935-50-0

The light intensity produced by the scintillator (CsI:Tl) that reaches the photodiode as a function of temperature can be found in Fig. 8. As can be seen, the maximum efficiency yield is achieved at room temperature.

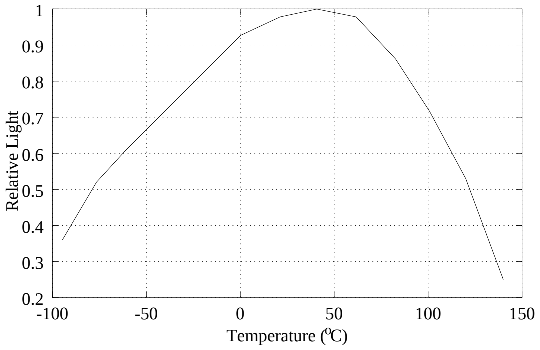

Fig. 8: Relative light output of CsI:Tl as a function of temperature.

Conclusions

This approach with structured columnar scintillator and high-reflective inner walls has better performance than the classical method (only one powder phosphor screen [6]). Moreover, the electroplating of the well walls with a high-reflective layer avoids cross-section problems and decrease losses. Hexagonal-well shape is being studied in order to increase detection efficiency and the fill factor.

Acknowledgments

The authors wish to acknowledge the cooperation of Professor R. F. Wolffenbuttel's group from the Laboratory for Electronic Instrumentation, TUDelft, The Netherlands.

References

[1] Heyne, J. P., Merbold, H., Sehner, J. Newmann, R., Freesmeyer, M. G., Mentzel, L. J. and Kaiser, W. A., "Reduction of radiation dose by using digital luminescence radiography compared to conventional screen film system with grid cassete," proceedings of ECR-99, March 1999.

[2] K. S. Shah, P. Bennett, L. Cirignano, Y. Dmitriyev, M. Klugerman, K. Mandal, L. P. Moy, "X-ray imaging with semiconductor films," SPIE Conference, San Diego, California,pp.102-113, July 1998.

[3] Derenzo, S. E., Moses, W. W., Cohoom, J. L., DeVolt, T. A. and Boatner, L., "X-ray fluorescence measurement of 412 inorganic compounds," IEEE Nucl. Sci. Symp. Conf. Rec., 143, 1992.

[4] Derenzo, S. E. and Moses, W. W., "Experimental efforts and results in finding new heavy scintillators," Heavy Scintillators for Scientific and industrial Applications, proc. of the "Crystal 2000" int. Workshop, France, 1993.

[5] Hofstadter, R., "CaI_2 and CaI_2:Eu scintillation crystals," rev. Sci. Instrum., 35, 1964.

[6] J. A. Rowlands, "Current Advances and Future Trends in X-ray Digital Detectors," IEEE Instrumentation & Measurement Magazine, pp. 26-28, December 1998.

[7] S. M. Seltzer, "Calculation of Photon Mass Energy-transfer and Mass Energy-Absorption Coefficients," Rad. Res. 136, pp. 147-170, 1993.