CHARACTERISTICS OF A NOVEL X-RAY DETECTOR

FOR REAL-TIME RADIOGRAPHIC IMAGING.

I.Frumkin and A.Notea

Department of Quality Assurance and Reliability, Technion, Haifa 32000 Israel

A.Breskin, R.Cechik, L.Levinson and B.Weingarten

Department of Particle Physics, Weizmann Institute of Science, Rehovot 76100, Israel

V.Popov

El Mul Technologies Ltd, P.O.Box 2106 Rehovot 76120 Israel

ABSTRACT

New detectors for fast, real-time, high resolution X-ray imaging at high photon flux are described. A thin solid photoconverter is coupled to a multistage gaseous secondary electron multiplier operating at low pressure. The readout electronics connected to the wire electrodes of the chamber provides a two-dimensional localization of single registered photons. Prototype detectors were tested with CsI, Ag and Ta convertors in the photon energy range of 8-60 keV. Radiographic digital images are presented and compared to that of X-ray films. It is shown that compared to the film technique the secondary electron emission (SEE) detector provides radiographic images of an equivalent contrast at an order of magnitude lower exposure. This novel type of detectors is suited for static and dynamic in-line quality control at industrial production lines and for medical imaging.

Submitted to NDT&E International

INTRODUCTION

There has been a significant growth over the last decade in the scientific, medical and industrial application of real-time, high resolution digital X-ray radiographic techniques. Real-time X-ray imaging is very attractive as a non-contact and non-destructive method for in-line quality control of industrial products flow. In automatic inspection the system consists of an image forming front-end detector followed by an image-processing and image-analyzing subsystem that feeds into a decision-making back-end. The X-ray images should be generated within subsecond time intervals and require thus the registration of fluxes superior to 10^6 photons/cm²·s. Industrial products to be examined by radiographic methods vary considerably in dimensions and elemental composition. Hence, photons over a wide energy range, extending from several keV up to more than 1 MeV have to be detected.

Detectors applied now in digital radiography include films and phosphor plates, which are not suitable for real-time systems, scintillators and fluorescent screens, gaseous and solid-state detectors. The radiographic films have the advantages of a high spatial resolving power (down to 180 lp/mm [1]) and a high uniformity of response over the whole exposed area. The shortcomings are their relatively small dynamic range (less than 10^3) and the presence of an inherent "fog" level. Systems based on image storage phosphor plates [2] provide much higher dynamic range and a lower "fog" level compared to films. Fluorescent screens viewed by image intensifiers followed by a CCD camera or a solid state detector array have been employed successfully for the detection of intense X-ray beams [3]. They suffer mostly from a limited dynamic range, resulting from their operation in the integrating mode and from image distortions, due to a large number of opto-electronic conversions (5-6) in the system.

Large area gaseous wire chambers are used now in medicine and biology as accurate and efficient single photon counting devices [4]. Their application to X-ray imaging at energies ranging up to 40-60 keV provides a submillimeter spatial resolving power, high detection efficiency and a significant reduction of the required exposure time compared to films. However, most gaseous X-ray imaging detectors suffer from significant parallax errors in localization, due to different photon absorption depths in their sensitive volume. Rather complex solutions were proposed to solve this problem [5,6]. Relatively slow ion removal following an avalanche, limits the counting rate capability of traditional gaseous wire chambers. A drastic deterioration of their spatial

resolution at high photon energies results from the significant range of photo- and Compton electrons in the gas.

We present here an advanced gaseous detector technique capable of fast, parallax-free, accurate X-ray imaging at high radiation flux. It is based on coupling a thin solid photoconverter to a gaseous electron multiplier, sensing the low-energy secondary electrons emitted from the converter at the photon impact location. The converter material and thickness are chosen according to the photon energy. Besides high-Z metallic photoconvertors (Ag, Ta, Au etc.), different non-metallic materials like CsI can be successfully used, having a considerable yield of secondary electrons [7,8].

Detectors combining metallic photoconvertors with traditional multiwire proportional chambers were applied to industrial radiography, with high energy X-rays and gamma-rays [9]. They suffer from counting rate limitations, and their localization accuracy, of the order of several mm, is affected by the primary electron range in the gas. The combination of thin solid photoconvertors with *multistep* gaseous electron multipliers working at *low pressure*, proposed by Breskin et al [10], allows for a significant improvement in photon localization and timing properties. The principle of the novel two-stage detector is shown in Fig.1. A thin photoconverter is followed by a preamplification gap, across which a strong electric field provides immediate multiplication of secondary electrons at their emission point. The low gas pressure and the exponential nature of the electron avalanche growth in the first amplification element make the detector sensitive mostly to ionization electrons generated close to the photoconverter surface, preserving thus the information about the impact point even at an inclined photon incidence. Multistep gaseous chambers working at low gas pressure (a few tens of Torr) provide gas amplification factors superior to 10⁷, allowing for high detection efficiency of electrons escaping the photoconverter [11]. Their high counting rate capability is derived from the fast ion removal in this operation mode [12]. We proposed the application of this novel fast X-ray imaging technique to photon localization at high intensity synchrotron radiation sources [13]. We also believe it to be a highly promising technique for the ultrafast radiographic imaging of static and dynamic objects and processes. The results of a systematic study of a CsI-based secondary electron emission (SEE) X-ray imaging detector were recently published [14].

We demonstrate here the imaging properties of SEE detectors obtained in the photon energy range of 8-60 keV with different converter materials. The detector performance was studied at the Detector Physics Laboratory at the Weizmann

Institute of Science with a Cu-target 30 kV X-ray tube and with a ^{241}Am source (59.5 keV).

THE DETECTOR SYSTEM

Two SEE detector prototypes of a similar configuration, shown in Fig.1, were built: a circular detector, of 50 cm² sensitive area and about 40 mm thick, and a larger area rectangular detector, of 20x20 cm². They consist of a stack of electrodes, each mounted on a G-10 epoxy resin frame. An entrance window made of Kapton is followed by a thin photoconverter. The study was performed with CsI and Ag photoconvertors, 200-2000 nm thick, vacuum deposited on an aluminized Mylar foil, and with a Ta photoconverter, 25 μm thick, produced from a commercially available foil. The detectors were operated with 20 Torr of isobutane in a flow mode.

X-ray induced secondary electrons emitted from the photoconverter surface are immediately multiplied in a preamplification gap, and the resulting electron avalanche is transferred through a mesh to a multiwire element (second step) for the final amplification and localization. The multiwire element has an anode and two cathode wire grids connected to the readout electronics. The wires of the two cathode planes are orientated in an orthogonal way to allow for an X-Y readout of the avalanche centroid, according to the distribution of signals induced by the avalanche process on adjacent wires. The imaging properties of the prototype detectors were studied with a PC-interfaced 2D-readout electronics based on delay-line position sensing [15]. Dedicated software provided a real-time monitoring of the process of data accumulation on the PC-computer display. Radiographic images contained 512x512 pixels and were displayed with a color coded intensity scale. Unidimensional quantitative intensity distributions, at chosen cross-sections of the images, are also available.

2D X-RAY RADIOGRAPHIC IMAGING

The 2D X-ray imaging properties of the SEE detectors were studied with various convertor materials. **Cesium iodide** was found to be the most efficient soft X-ray photoconverter [14]. It provided an intrinsic spatial accuracy of 200 - 300 μm (FWHM) recorded at respective photon energies of 8 - 20 keV, and about 500 μm (FWHM) with 60 keV photons. Fig.2 presents the radiographic image of a thin-wall

plastic tube, containing a thin metal wire, recorded with a CsI convertor and 8 keV photons. The measured intensity distribution along a vertical cross-section reflects well the cylindrical tube shape and detects the inner wire.

A silver photoconvertor was used for radiographic imaging over a broad range of the X-ray tube voltages. Figure 3a presents the digital image of an electric plug performed at 25 kV. It clearly shows all metallic parts embedded within the plastic body, including a sectioned wire in the central lead (indicated by an arrow).

A comparative study of the radiographic quality at various exposures was done with the SEE detector and with a STRUCTURIX D4 (Agfa-Gevaert) X-ray film. The inspected object was a disposable plastic syringe. The syringe plunger has a rubber tip and a plastic body in a form of two orthogonal ribs, about 1 mm thick. The needle has a 0.7 mm diameter. Imaging was performed at 15 kV. Film images were digitized with a CCD camera (JAI, Denmark). Fig.4 shows 2D digital images recorded with the SEE detector and with the film technique, at relative exposures indicated in the images. One can see that the radiographic image from the SEE detector (Fig.4a) is equally informative compared to the film image shown in Fig.4c, though obtained at an order of magnitude lower exposure. Besides, the image presented in Fig.4c is of a low contrast and not in the "linear range" since the optical density of the film has hardly reached the value of 0.3. Film imaging of the syringe started demonstrating its good spatial resolving power only after an additional 4 fold increase of the radiation dose (Fig.4d).

The resolving power of these two radiographic methods was quantitatively compared by the analysis of the image density profile along a line vertical to the syringe symmetric axis (see arrow in Fig.4a). Density profiles are presented in Fig.5a,5b, respectively. Initial data obtained with the SEE detector were subject to logarithmization and background subtraction procedures, in order to allow for a direct comparison with the film data. The profiles show a central peak corresponding to the projection of the longitudinal syringe rib, orientated perpendicular to the detector surface. Figure 5c presents the amplitude of this peak reduced to the r.m.s. of the noise provided by these two techniques, as a function of the relative exposure. The noise in case of the SEE detector image is due mostly to statistical fluctuations in the number of counts, while for the film it is related to a non-linearity of its characteristic curve. Indeed, at the lower graph shown in Fig.5b, obtained at an exposure corresponding to a part of that curve with a very small gradient (close to the "fog"

level), all variations of the film density fluctuate within several digitization levels, which makes them unresolvable. Fig.5c shows that the film-based technique reaches the SEE detector resolving power only at exposures higher by about an order of magnitude. At the dose sufficient for a satisfactory SEE detector image, the rib projection on the film is completely undetectable.

A 25 μm thick **tantalum** photoconverter was used for the imaging with 60 keV photons (^{241}Am source) to simulate future detector operation with industrial X-ray machines. The radiographic image of the previously described electric plug is presented in Fig.3b. A comparison of the images taken at the two energies clearly indicates a noticeably higher contrast at 60 keV. This can be explained by a screening of low-energy scattered and fluorescent radiation from the object with the rather thick Ta photoconverter. Both, the soft X-rays and most of the liberated primary electrons are absorbed in the solid. This demonstrates that a proper choice of the photoconverter material and thickness in the SEE detector can provide an efficient suppression of scattered background, analogous to that of the lead screens applied in film radiography for hard X-rays imaging.

The relative resolving power of the SEE detector and the X-ray film at 60 keV, as a function of exposure, was carried out in a similar way as described above. We prepared a reference object of brass, the profile and the dimensions of which are shown in Fig.6a. Image density profiles of two rectangular steps, 1.5 mm apart, obtained with our technique and with STRUCTURIX D4 films at different exposures are shown in Fig.6b,6c, respectively. The ratio of the central peak amplitude reduced to the r.m.s. of the noise is presented in Fig.7, as a function of the relative X-ray exposure. This figure clearly indicates that the peak amplitude registered with our technique reaches the detection threshold (at 95% confidence level (C.L.)) at exposures lower by an order of magnitude as compared to that of the X-ray film. At higher exposures the film image quality improves significantly as the gradient of the film response drastically increases, while for the SEE detector it approximately follows the statistical law.

It should be noted that SEE detector radiographs shown above were obtained without any image processing procedure except for some corrections in the readout electronics differential non-linearity, and obviously the intrinsic spatial resolution of the film is by far better. Besides, each pixel of the 2D image was at present as large as $200 \times 200 \mu\text{m}^2$, thus limiting the spatial resolution of the instrument. Next detector

prototypes will have a much smaller gap between the photoconverter plane and the entrance window. Note that the present 40 mm distance between the object and the converter resulted in our case in a geometrical unsharpness of about 0.3-0.5 mm. Despite all these factors the SEE detector has demonstrated a submillimeter localization accuracy in the photon energy range under study.

Radiographic images shown above contain several million registered photons over the whole area. It was found out that the detector preserved its performance at photon counting rates exceeding 5×10^5 photons/s $\cdot$ mm². The principal limitations in data taking (about 1 kHz) are due to the rather slow CAMAC-PC based presently used readout system. A novel readout system has been designed by us and is presently under advanced stages of construction and testing [16]. It contains very fast time-to-digital converters (TDC) [17] and a RISC processor, providing a rapid calculation of the X-ray photon coordinates. Image generation takes place in a histogramming memory, while a PC computer acquires the data by frames. The expected counting rate of 1 MHz per readout module will permit the formation of the images shown above within a few seconds. A further improvement of the detector speed can be achieved by a division of the detector area into modular parts and their parallel readout, or by using a highly integrated pixel readout electronics.

SUMMARY

We have presented the imaging properties of a novel secondary electron emission (SEE) X-ray detector combining a solid photoconverter with a low-pressure multistep gaseous electron multiplier. The multiplication of secondary electrons at their emission location provides high accuracy, parallax free, fast photon detection, suitable for real-time imaging at high radiation flux.

The detectors were tested in the photon energy range of 8-60 keV, and the generated radiographic images are sufficiently detailed for many applications. The image generation required about an order of magnitude smaller exposures, compared to industrial film radiography, for an equal contrast. The film speed can be improved significantly by combining them with fluorescent screens, but at the expense of a much lower resolution (screen-film combinations are traditionally applied in medical imaging where the dose reduction is of prime importance). A systematic study of SEE detector characteristics in comparison with direct-exposed films and screen-film systems (lead, fluorescent) is in progress [18].

Fast readout electronics providing image registration at photon counting rates reaching 10^6 counts/s is presently under advanced stages of design and tests. This technique is presently under study to expand the operating range of the detector to higher energy X-rays and gamma-rays, by using proper photoconvertor materials and geometries.

The SEE detector has a lower spatial resolution as compared to industrial X-ray films. However, this is largely compensated by its ability to provide a fast, accurate, dynamic information required for an on-line decision-making, and by the smaller radiation doses necessary for an equal radiographic quality. Applications to industrial in-line quality control and medical radiography are foreseen.

ACKNOWLEDGEMENTS

We would like to thank Mr. L.Sapir for his assistance in preparation of the photoconvertors, and the members of the electronics laboratory at the Physics Department of the Weizmann Institute of Science for their collaboration.

This research work was supported by the Foundation Mordoh Mijan de Salonique and the Israel Ministry of Science and Technology. I.F. was supported by the Fund for the Promotion of Research at the Technion and by the EEC under contract no. CII*-CT91-0927. B.W., a visiting engineer, was partially supported by the French Government.

REFERENCES

1. E.E.Babylas "Advantages of the image processing systems in industrial real-time radiography" Proceedings of the symposium "X-ray real-time radiography and image processing" Newbury,England 1988 ed. R.Halmshaw. pp.31-52
2. M.Sonada, M.Takano, J.Miyahara and H.Kato "Computed radiography utilizing scanning laser stimulate luminiscence" Radiology 148 (1983) pp.833-838
3. R.A.Robb "Three dimensional biomedical imaging " CRC Press, Boca Raton, Florida 1985 Chapter 2
4. F.Sauli "Applications of gaseous detectors in astrophysics, medicine and biology" Nucl.Instrum.Methods A323 (1993) pp.1-11 and references therein

5. S.E.Baru, A.G.Kharabakhpashev and L.I.Shekhtman "Medical proportional chamber for a digital radiographic installation" Nucl.Instrum.Methods A283 (1989) pp.431-435
6. G.Charpak "Applications of proportional chambers to some problems in medicine and biology" Nucl.Instrum.Methods 156 (1978) pp.1-18
7. S.A.Schwarz "Application of a semi-empirical sputtering model to secondary electron emission" J.Appl.Phys. 68 (1990) pp.2382-2391
8. A.Gibrekhterman, A.Akkerman, A.Breskin, R.Chechik "Characteristics of secondary electron emission from CsI induced by X-rays with energies up to 100 keV" J.Appl.Phys. 74 (1993) p.7506
9. I.Dorion, U.Ruscav and A.P.Pilot " A novel unidimensional position sensitive multiwire detector" IEEE Trans.Nucl.Sci. NS-34 (1987) pp.442-447
10. A.Breskin, R.Chechik, V.Dangendorf, S.Majewski, G.Malamud, A.Pansky and D.Vartsky "New approaches to spectroscopy and imaging of ultrasoft-to-hard X-rays" Nucl.Instrum.Methods A310(1991) pp.57-69
11. A.Breskin and R.Chechik "Detection of single electrons and low ionization radiation with low pressure multistep chambers" IEEE Trans Nucl.Sci. NS-32 (1985) pp.504-509
12. A.Breskin "Progress in low-pressure gaseous detectors" Nucl. Instrum. Methods 196 (1982) pp.11-21
13. A.Akkerman,A.Breskin,R.Chechik,V.Elkind, I.Frumkin and A.Gibrekhterman "Ultrafast secondary emission 2D X-ray imaging detectors" Proceedings of the European Workshop on X-ray Detectors for Synchrotron Radiation Sources. Aussois, France September 1991, ed. A.Walenta pp.118-121
14. I.Frumkin, A.Breskin, R.Chechik,V.Elkind and A.Notea "Properties of CsI-based gaseous secondary emission X-ray imaging detectors" Nucl.Instrum. Methods A329 (1993) pp.337-347
15. see for example R.A.Boie, J.Fischer, Y.Inagaki, F.C.Merritt, V.Radeka, L.C.Rogers and D.M.Xi "High resolution X-ray gas proportional detectors with delay line position sensing for high counting rates" Nucl.Instrum. Methods 201 (1982) pp.93-115
16. A.Breskin, R.Chechik, Y.Gal, L.J.Levinson, M.Sidi, B.Weingarten and I.Frumkin "Imbedded RISC Data Acquisition at 1 MHz for the delay line readout of a gas imaging X-ray detector" Presented at the IEEE Symp.on Data Acq.Systems, Vancouver,Canada,June 1993

17. TDC 2001, Time-to-Digital Converter, MSC-Vertriebes GmbH, Description of operation.
18. I.Frumkin, A.Breskin, R.Chechik and A.Notea " A comparative study of the radiographic characteristics of a secondary emission gaseous X-ray detector, direct-exposed X-ray films and film-screen systems" (in preparation).

Figure Captions

- Fig.1 The structure of the secondary emission (SEE) X-ray imaging detector.
- Fig.2 A radiographic image of a thin (0.2 mm) plastic tube, 6 mm in diameter, containing a 0.4 mm in diameter metal wire (a) and a projected intensity distribution across the tube at a location marked by an arrow (b). 8 keV photons, 200 nm CsI-photoconverter.
- Fig.3 A radiographic image of an electric plug obtained with the SEE detector, generated by a) 25 kV X-rays, using a 200 nm thick Ag photoconverter, and b) 60 keV X-rays, with a 25 μ m thick Ta photoconverter. An arrow indicates a sectioned wire.
- Fig.4 Radiographic images of a plastic syringe, generated by 15 kV X-rays with: (a) the SEE detector (Ag-photoconverter, 200 nm thick), (b-d) STRUCTURIX D4 film. The relative radiation exposures are shown in each image.
- Fig.5. The image density profile at the vertical cross-section of the syringe shown in Fig.4a), obtained with (a) the SEE detector, and (b) with an X-ray film. The relative exposures are indicated in the figures. The amplitude of the central peak (the syringe central rib projection) reduced to the r.m.s. of the noise is shown in (c), as a function of the relative X-ray exposure.
- Fig.6 The profile of a brass-made reference object (a) and density distributions obtained with the SEE detector (Ta-photoconverter, 25 μ m thick) (b) and a STRUCTURIX D4 X-ray film (c) at different X-ray exposures, with 60 keV photons.
- Fig.7 The amplitude of the central peak corresponding to the 1.5 mm gap between the steps of the object shown in Fig.7a, reduced to the r.m.s. of the noise, as a function of the radiation exposure with 60 keV photons. The detection threshold level at 95% confidence level is also shown in the figure.

Figure 1

a

b

Figure 2

a

b

Figure 3

Figure 4

a

b

c

Figure 5

a

b

c

Figure 6

Figure 7