Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Sensors and Actuators A 115 (2004) 215–220
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Comparison between bulk micromachined and CMOS X-ray detectors

J.G. Rocha [a,*], C.G.J. Schabmueller [b], N.F. Ramos [a], S. Lanceros-Mendez [c], M.V. Moreira [c], A.G.R. Evans [b], R.F. Wolffenbuttel [d], J.H. Correia [a]

[a] *Department of Industrial Electronics, University of Minho, Campus de Azurem, 4800-058 Guimaraes, Portugal*
[b] *Department of Electronics and Computer Science, Microelectronics Centre, University of Southampton, Southampton SO17 1BJ, UK*
[c] *Department of Physics, University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal*
[d] *Laboratory for Electronic Instrumentation, Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands*

Received 22 September 2003; received in revised form 28 January 2004; accepted 4 February 2004
Available online 26 April 2004

Abstract

This paper compares two X-ray detectors fabricated using two different technologies: one is based on a bulk micromachined silicon photodetector and the other is based on a standard CMOS photodetector. The working principle of the two detectors is similar: a scintillating layer of CsI:Tl is placed above the photodetector, so the X-rays are first converted into visible light (560 nm) which is then converted into an electrical signal by the photodetector. The different aspects of the fabrication and the experimental results of both X-ray detectors are presented and discussed.
© 2004 Elsevier B.V. All rights reserved.

Keywords: X-rays; Scintillator; Micromachining

1. 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].

Two detectors for digital X-ray imaging are reported and compared in this article. Both are based on the same working principle: a scintillator material is placed above a photodetector. When the X-ray photons reach the scintillator, they are absorbed and converted into visible light. This visible light is then converted into an electrical signal by the photodetector (Fig. 1). In order the visible light to achieve the photodetector and avoid cross-talk between adjacent pixels, it is necessary to have a good reflective material between them. Some approaches have been attempted by using silicon to this purpose [2,3]. The problem of these approaches is that CsI has a low refractive index (≈1.8) at 560 nm when compared with silicon (≈4). Only the light produced by the scintillator that reaches the silicon wall at low angles is reflected. The remainder light is absorbed by the silicon walls or transmitted to the adjacent pixels [4].

The first X-ray detector described in this article is based on a n^+/p-epilayer junction placed inside a bulk micromachined cavity [5]. The cavity is then filled with a scintillating material.

The second X-ray detector is based on a CMOS standard n^+/p-epilayer junction. The scintillating material is placed inside cavities opened in an aluminum film, which is then placed above the photodetectors [6].

2. Bulk micromachined X-ray detector

Figs. 2 and 3 show the schematic cross section, the top view and the dimensions of the device. A cavity with 2 mm × 2 mm square size and 400 μm depth is fabricated in a p-type

* Corresponding author. Tel.: +351-253-510190;
fax: +351-253-510189.
E-mail address: gerardo@dei.uminho.pt (J.G. Rocha).

0924-4247/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2004.02.035

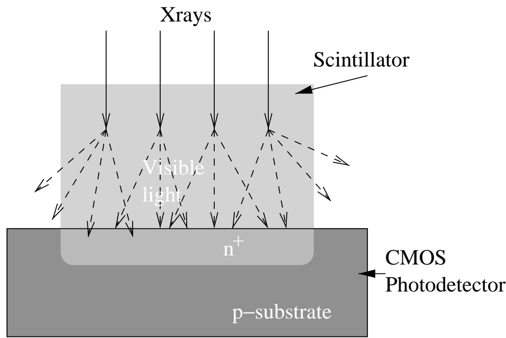

Fig. 1. Schematic design for a digital X-ray sensor: scintillator placed above a photodetector.

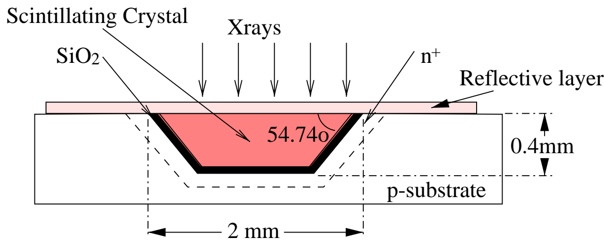

Fig. 2. Cross-section of the BMM X-ray detector.

silicon substrate using KOH etching. Inside the cavity, arsenic is implanted in order to form the n^+/p-epilayer junction of the photodiode.

The scintillating crystal (CsI:Tl) was produced by Molecular Technology GmbH, Berlin, Germany. The main parameters of this single crystal are presented in Tables 1 and 2. It was placed inside the cavity using a clamping pressure. When cut into thin sheets, cesium iodide may be bent into various shapes without fracturing, and it is reasonably soft and malleable [7]. Due to its elastic properties, a clamping pressure of 10 MPa is enough for transferring and fixing the crystal into the cavity without breaking [5]. Nevertheless this process induces some residual stresses within the material that reduces the optical transmissivity of the scintillator. So, after this step, it is necessary to anneal the scintillator in order to improve its optical transmissivity. The

Table 1
Physical properties of CsI [10–12]

Crystal class and space group	Cubic *Pm*3*m* (221)
Unit cell lattice parameters (Å)	4.566
Formulas per unit cell (*Z*)	1
Molecular weight (amu)	259.81
Density (g/cm^3)	4.53
Melting point (K)	898
Cold water solubility (g/100 g)	44.0
Elastic moduli (GPa)	18
Shear moduli (GPa)	7.3
Bulk moduli (GPa)	12.6
Poisson's ratio	0.26
Flexure strength (MPa)	5.6

Table 2
Scintillation properties of CsI:Tl [13,5]

Density (g/cm^3)	4.51
Effective atomic number	54
Light yield (photons/MeV)	65900
Emission wavelength (nm)	560
Decay time (ns)	10^3

scintillating crystal must be a good absorber of X-ray photons, but it is also desirable that the produced visible light reaches easily the surface of the photodiode. The placement of the scintillating crystal inside the cavity, by means of a clamping pressure, does not degradate the X-ray absorption, but its transmissivity for visible light is reduced. Due to this factor, the annealing process becomes necessary. The annealing is made at 340 °C during 2 h at normal atmospheric pressure [8,5]. Experimental results show that this annealing increases 12.9% the scintillator transmissivity [9].

When the X-rays reach the scintillator, the visible light is emitted randomly in all directions. In order to avoid losses of light, a reflective film above the scintillating material becomes necessary. So, as a final step, a film of reflective ink was deposited above the scintillating crystal. This film was deposited using a pressurized spray through a deposition mask.

Fig. 4 shows a picture of the device before the placement of the scintillating material and the reflective layer.

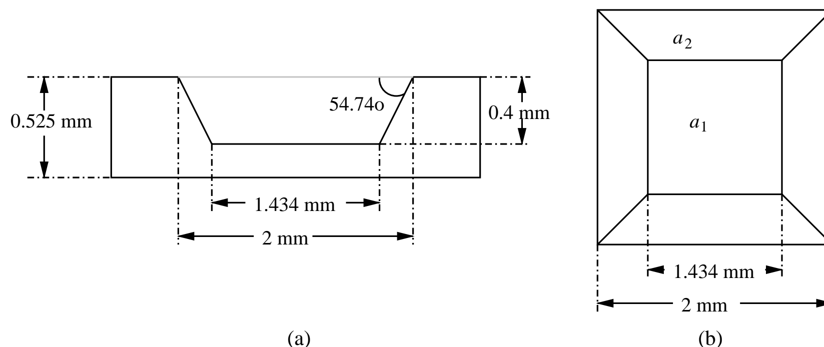

Fig. 3. Dimentions of the cavity: (a) cross-section; (b) top view. a_1 is the area of the bottom of the cavity and a_2 is the area of the lateral wall.

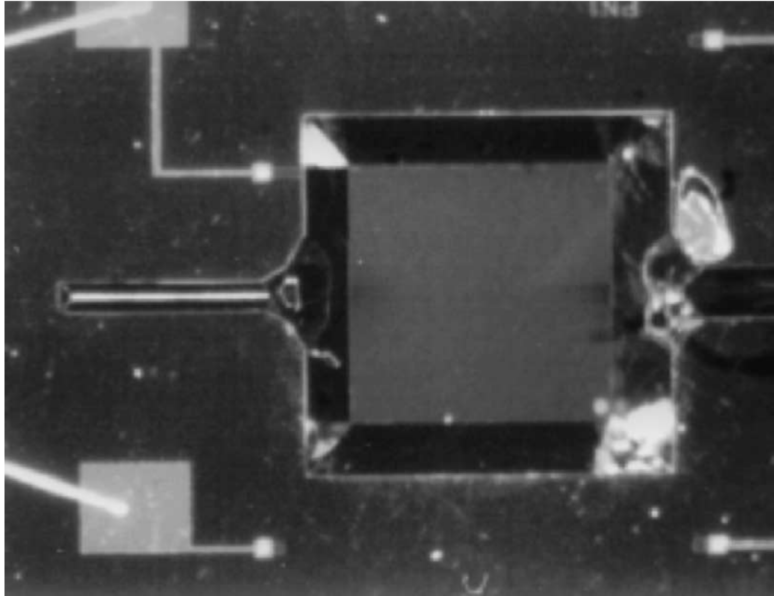

Fig. 4. Picture of the BMM X-ray detector before the placement of the CsI:Tl. The external side of the square is 2 mm.

3. CMOS X-ray detector

The second device that is described here consists in four 400 μm × 400 μm photodiodes fabricated in a standard CMOS process. The photodiode structure chosen for this work was the n^+/p-epilayer junction due to its highest quantum efficiency and to its spectral response in the green region of the spectrum. As it was seen in Table 2, the light yield by the scintillating crystal used in this work (CsI:Tl) is green ($\lambda = 560$ nm). For some specific applications, other type of photodiode can be combined with scintillator materials which produce light of different colors, e.g. $Bi_3Ge_4O_{12}$ combined with a p^+/n-well junction for the detection of the 511 keV photons in the PET imaging.

In order to fabricate the cavities, an 800 μm thick aluminum sheet is used. The 400 μm diameter cavities were drilled and filled with a scintillator material by means of a clamping pressure of about 10 MPa (Figure 5). Finally the set was placed above the CMOS photodetectors [6] as is shown in Fig. 6. Fig. 7 shows a picture of the CMOS device before the placement of the aluminum dye with the scintillating material.

In this case, the walls of the cavities avoid losses of the visible light by guiding the light to the photodiode.

Fig. 5. CsI:Tl inside the aluminum holes: 2 × 2 array. The diameter of each hole is 400 μm.

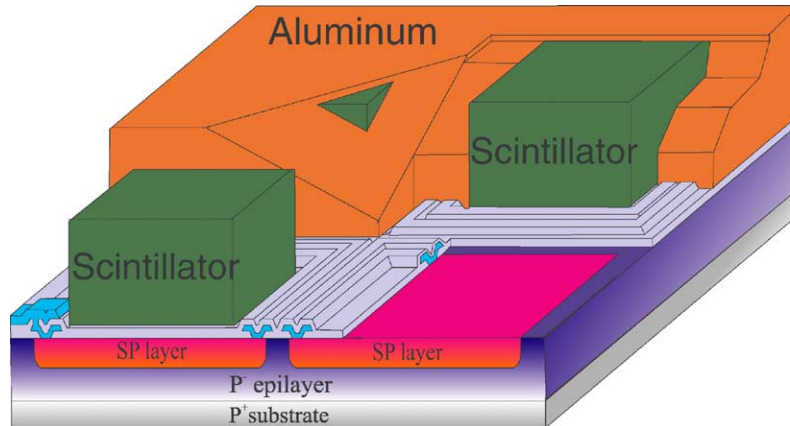

Fig. 6. Structure of a 2 × 2 CMOS X-ray detector array. The scintillator dimensions are 400 μm × 400 μm and 790 μm high.

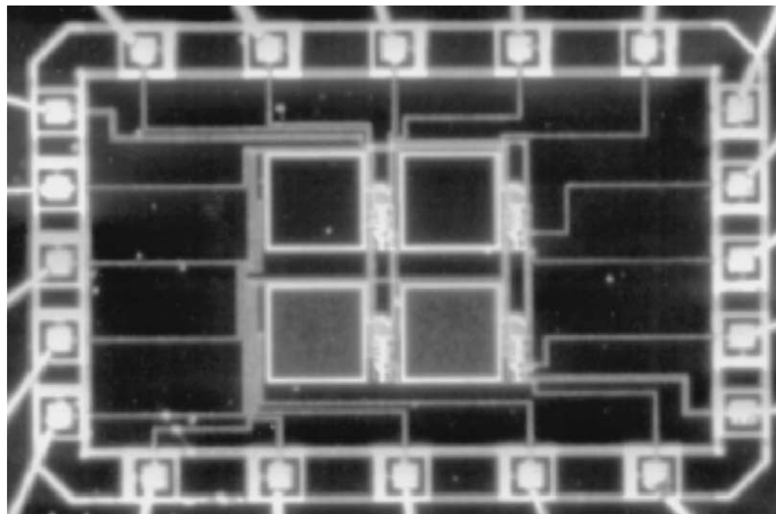

Fig. 7. Picture of the 2 × 2 CMOS photodetector array before the placement of the CsI:Tl layer. The size of each of the squares is 400 μm.

4. Efficiency of the reflective layers

For the BMM detector, the area of the bottom of the cavity, a_1 (Fig. 3) is 2.056 mm^2 and the area of the cavity wall, a_2 is 0.859 mm^2, so the total area of the photodetector surface is 5.492 mm^2. The area of the scintillator surface is 9.492 mm^2. Eq. (1) relates the light that reaches the photodiode (L_{pd}) with the one emitted by the scintillator (L_R) [4],

$$\frac{L_{pd}}{L_R} = \frac{R_A}{1-(1-R_A)(1-R_{loss})} \quad (1)$$

where R_A is the ratio between the area of the photodiode and the area of the scintillator, and R_{loss} is the percentage of losses in each reflection. In this case, $R_A = 5.492/9.492 = 0.579$. Assuming that the efficiency of each reflection in the mirror is 80%, $R_{loss} = 0.2$, and $L_{pd}/L_R = 0.873$. In the case in which the reflector does not exist, $R_{loss} = 1$ and $L_{pd}/L_R = 0.579$.

For the CMOS detector (Fig. 6), the area of the photodetector is 0.16 mm^2 and the area of the scintillator is 1.584 mm^2. The ratio between both areas is $R_A = 0.101$. As the reflector in this case is constituted by aluminum, its efficiency is 86%, and $R_{loss} = 0.14$. In this case, $L_{pd}/L_R = 0.445$. Once again, if the reflector at the top of the scintillator is removed, $L_{pd}/L_R = 0.322$.

5. Experimental results and comparison between the two X-ray detectors

The experiments on the two devices were performed using a didactic X-ray tube with a molybdenum anode from Leybold. In this setup, the maximum voltage of the tube is 35 kV and a current can be changed from 0 mA to 1 mA. Under these experimental conditions, the tube produces X-rays with an energy peak near 20 keV. The results of these measurements are shown in Fig. 8 for the BMM detector and in Fig. 9 for the CMOS detector.

- The BMM detector do not use a standard fabrication process in the construction of the photodetector. This fact allows the optimization of the junction depth in order to

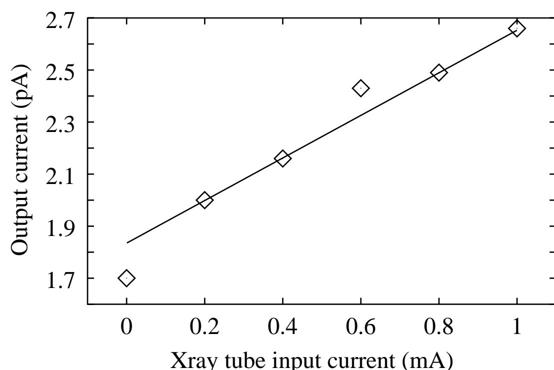

Fig. 8. Output current of the BMM X-ray detector with a X-ray tube input voltage of 35 kV.

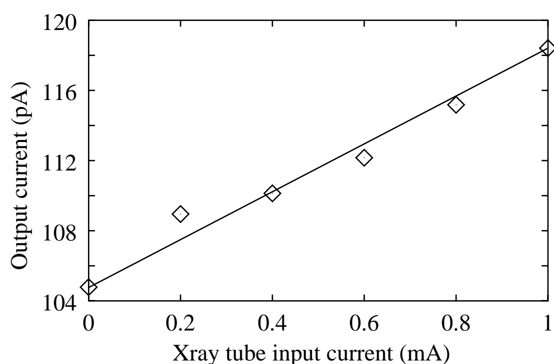

Fig. 9. Output current of the CMOS X-ray detector with a X-ray tube input voltage of 35 kV.

obtain a spectral response that matches the emission peak of the scintillator. Nevertheless, the fabrication of the CMOS detector is cheaper as it make use of a standard fabrication process.

- The fabrication of the cavities in the BMM detector is easier due to the use of anisotropic chemical etching of the silicon instead of the mechanical methods used for the CMOS detector.
- The dimensions of the pixels in the CMOS detectors can be smaller than in the BMM detector due to the fact that the side walls of the cavities fabricated with KOH etching in the BMM detector are not vertical (Fig. 2).
- For the applications of these detectors for digital radiography, a pixel size of about 200 μm is required. With the BMM technology this limit is very difficult to achieve, whereas CMOS detectors with dimensions below 200 μm are easily achieved.
- Due to the standard fabrication of the CMOS prototype, it is possible to integrate the electronics with the photodetectors without additional fabrication steps. This integration is more difficult in the BMM detector.
- The BMM structure is more efficient than the CMOS detector in terms of light emitted by the scintillator that reaches the photodetector (Section 4).
- Both detector prototypes show a linear response up to 1 mA of X-ray tube input current (Figs. 8 and 9).
- The CMOS detector has a higher sensibility, but a larger offset (Fig. 9).

6. Conclusion

Two X-ray detector prototypes for digital radiography were fabricated using two different technologies: one is based on a bulk micromachined silicon photodetector and other is based on a standard CMOS photodetector. The fabrication process and the performance of the two prototypes were presented and discussed comparatively. Whereas the CMOS detector has advantages in the integration of the photodetectors with the electronics and the detection sensibility, the BMM detector shows advantages in the fabrication of the cavities and the lower offset. Miniaturization down to the limit of 200 μm, which is necessary for practical purposes, is easier to achieve for the CMOS detectors. Further, even when the tests were performed for X-rays energy of 20 keV, larger energies are more easily detected by this kind of devices.

Acknowledgements

This work was supported by the Foundation of Science and Technology, Portugal, FCT-CTM/POCTI/33751/1999; Grant-BD SFRH/BD/1296/2000.

References

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

[2] P. Kleymann, J. Linnros, C. Fröjdh, C.S. Petersson, An X-ray imaging pixel detector based on a scintillating guides screen, IEEE Trans. Nucl. Sci. August (2000).

[3] C.P. Allier, R.W. Hollander, P.M. Sarro, M. Boer, C.W.E. Eijk, Scintillation light read-out by low-gain thin avalanche photodiodes in silicon wells, IEEE Trans. Nucl. Sci. August (2000).

[4] J.G. Rocha, J.H. Correia, A high performance scintillator-silicon-well X-ray Microdetector based on DRIE techniques, Sens. Actuators A 92 (2001) 203–207.

[5] J.G. Rocha, C.G.J. Schabmueller, N.F. Ramos, S. Lanceros-Mendez, A.G.R. Evans, R.F. Wolfenbuttel, J.H. Correia, X-ray detector based on bulk micromachined photodiode, in: Proceedings of the MME'2002, pp. 323–326.

[6] J.G. Rocha, N.F. Ramos, S. Lanceros-Mendez, R.F. Wolfenbuttel, J.H. Correia, CMOS X-rays detector array based on scintillating light guides, Sens. Actuators A, 2003, in press.

[7] C.J. Crannell, R.J. Kurz, W. Viehmann, Characteristics of cesium iodide for use as a particle discriminator for high-energy cosmic rays, Nucl. Instrum. Methods 115 (1974) 253–261.

[8] G. Vieux, H. Rougeot, Input screen scintillator for a radiological image intensifier tube and a method of manufacturing such a scintillator, US Patent 4803366 (1989).

[9] J.G. Rocha, C.G.J. Schabmueller, N.F. Ramos, S. Lanceros-Mendez, M.F. Costa, A.G.R. Evans, R.F. Wolfenbuttel, J.H. Correia, X-ray detector based on bulk micromachined photodiode combined with a scintillating crystal, J. Micromech. Microeng. 13 (2003) S45–S50.
[10] M.J. Weber (Ed.), Handbook of Laser Science and Technology, vol. IV: Optical Materials, CRC Press, Boca Raton, 1986.
[11] K.H. Hellwege, A.M. Heliwege (Eds.), Landolt–Börnstein Numerical Data and Functional Relationships in Science and Technology, vol. 11: Elastic, Piezoelectric, Electrooptic Constants and Nonlinear Susceptibilities of Crystals, Springer-Verlag, Berlin, 1979.
[12] G. Simmons, H. Wang (Eds.), Single Crystals Elastic Constants and Calculated Aggregate Properties, MIT Press, New York, 1971.
[13] J.D. Valentine, D.K. Wehe, G.F. Knoll, C.E. Moss, Temperature dependence of absolute CsI(Tl) scintillation yield, IEEE Trans. Nucl. Sci. 40 (1993) 1267–1274.

Biographies

J.G. Rocha graduated in industrial electronics engineering in 1995, obtained his MSc degree in 1999 and the PhD degree in 2004. All titles were obtained at University of Minho, Portugal. Since 2004 he has been assistant professor at the Department of Industrial Electronics, University of Minho, Portugal and he is involved in the research of radiation sensors.

N.F. Ramos graduated in industrial electronics engineering in 2001 at University of Minho. Since than he works in the Department of Industrial Electronics, University of Minho, Portugal and he is involved in research of radiation sensors.

S. Lanceros-Mendez graduated in physics at the University of the Basque Country, Leioa, Spain in 1991. He obtained his PhD degree in 1996 at the Institute of Physics of the Julius-Maximilians-Universität Würzburg, Germany. He was research scholar at Montana State University-Bozeman, MT, USA from 1996 to 1998. Since September 1998 he has been assistant professor at the Physics Department of the University of Minho, Portugal, where he is involved in experimental investigations in the area of condense matter physics and its applications. He was a visitor at the A.F. Ioffe Physico-Technical Institute, St. Petersburg, Russia in 1995 and at the University of Porto, Portugal, in 1996.

R.F. Wolffenbuttel received the MSc and PhD degrees from the Delft University of Technology, Delft, The Netherlands, in 1984 and 1988, respectively. Between 1986 and 1993, he was an assistant professor, and since 1993, an associate professor, at the Department of Microelectronics of the Delft University of Technology, where he is involved in instrumentation and measurement in general and on-chip functional integration of microelectronic circuits and silicon sensor, fabrication compatibility issues, and micromachining in silicon and microsystems, in particular. He was a visitor at the University of Michigan, Ann Arbor, in 1992, 1999, and 2001, at Tohoku University, Sendai, Japan, in 1995, and at EPFL, Lausanne, Switzerland, in 1997. Dr. Wolffenbuttel was the recipient of a 1997 NWO pioneer award. He served as general chairman of the Dutch National Sensor Conference in 1996, Eurosensors in 1999 and The MME workshop in 2003.

J.H. Correia graduated in physical engineering at University of Coimbra, Portugal in 1990. He obtained his PAPCC (equivalent to MSc degree) in 1994 at University of Minho, Portugal and his PhD degree in 1999 at Delft University of Technology, The Netherlands. He is an associate professor at the Department of Industrial Electronics of the University of Minho and he is involved in instrumentation and measurement in general and on-chip functional integration of microelectronic circuits and silicon sensors. He served as general chairman of the Eurosensors conference in 2003.