CMOS X-rays Microdetector Based on Scintillating Light Guides

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SUMMARY

This paper describes a pixel imaging array consisting in 400 $\mu m \times 400$ μm photodiodes fabricated in CMOS technology. Above the photodiodes, an array of scintillating CsI:Tl crystals are placed. The scintillating crystals are encapsulated in aluminum walls forming a light path to guide the produced visible light into the photodiodes. So, the x-ray energy is first converted into visible light which is then detected by the photodiode at the end of each light guide. The scintillator is 800 μm thick, absorbing almost all of 20 keV x-ray photons. Usually, the spatial resolution of the scintillating x-rays detectors is identical to the scintillator thickness. By using the light guides, the scintillator thickness can be increased, without decreasing the spatial resolution. The increase of the scintillator thickness is desirable in order to increase the x-rays absorption efficiency. Tests carried out on the system show very promising results near 20 keV.

Keywords: x-rays, scintillator, digital radiography.

Subject category: 5. Physical sensors (non-magnetic).

INTRODUCTION

The digital x-ray imaging systems are now replacing silver films (traditional radiography) in a large number of fields, enabling real time image acquisition and processing, and eliminating the costs and the pollution caused by the silver films. One of the first digital x-ray imager was based on a silicon charge coupled device (CCD). The silicon has a low x-ray absorption coefficient, but for each 1 keV of x-ray photons absorbed, about 277 electrons are excited. This enables to obtain images with sufficient quality for diagnostics with a radiation dose slightly smaller than that required for silver films. However, the small number of detected photons in CCD results in a significant quantum noise. There are two methods to reduce the quantum noise in the sensors: either the radiation dose can be increased or the quantum efficiency of the sensor can be improved. The increase of the x-ray dose is obviously not desired for medical applications.

The quantum efficiency of the sensor can be increased by adding a scintillating layer above the CCD. Since the x-rays are first absorbed by the scintillating layer, which has a high absorption coefficient, and then converted into visible (or near visible) light, the quantum efficiency of the detector is increased. The problem of this method is that the spatial resolution of the device is approximately equal to the thickness of the scintillating layer (fig. 1(a)).

In order to increase the thickness of the scintillating layer without decreasing the spatial resolution, scintillating light guides separated by reflective walls can be used, as is shown in fig 1(b) [1]. In this case, the light yield by each scintillator is guided to the corresponding CCD area by the reflective layers. The spatial resolution becomes approximately equal to the distance between the reflective layers.

A similar approach based in CMOS technology can be tried. The recent development in CMOS image detectors opens a new way to construct digital x-rays imagers. The replacement of CCDs with CMOS detec-

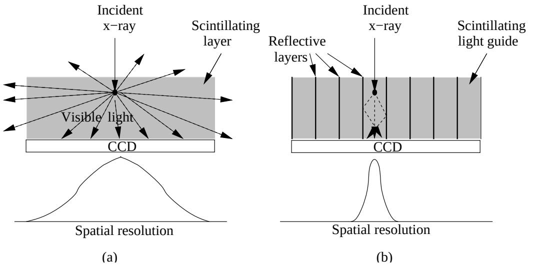

Fig. 1: Effect of reflective layers on the spatial resolution. (a) A single scintillating layer. (b) Scintillating light guides.

tors is desirable for several reasons:

- The operating power of CMOS is 5 to 10 times lower than the CCD with processing electronics.
- The CMOS is a standard fabrication process, while CCD requires special manufacturing.
- CMOS fabrication costs are 5 to 10 times lower.
- It is possible to integrate analog and digital processing electronics in CMOS.

The achievement of both low power and low cost is highly desirable for portable applications as well as situations where large x-ray imaging machines are required. The drawback is that it is difficult to match the high performance characteristics of CCD in terms of image quality [2].

SYSTEM DESIGN

In this work, a new type of detector based on scintillating guides with reflective layers and CMOS readout has been developed. The first prototype consists on an 2x2 array of photodiodes with a scintillating light guide above each one. Fig. 2 shows a schematic diagram of the detector. The scintillating light guides consist on scintillating crystals embedded into aluminum cavities. The scintillating crystal converts the x-rays into visible light, which is then converted to an electrical signal by the photodiode[3]. Each scintillator is isolated from its neighbors by the high-reflective aluminum walls, which allow multiple reflections (fig. 1) and guides the produced light through the scintillator (transparent for the visible light) to the photodiodes. Moreover, introducing a reflective layer above the scintillator (in the x-rays path) confines the light inside the light guide, increasing the efficiency. The x-ray photons interact weakly with the reflective layer placed above the scintillating crystals, since it is constituted by aluminum, a low density and low atomic number material (fig. 4).

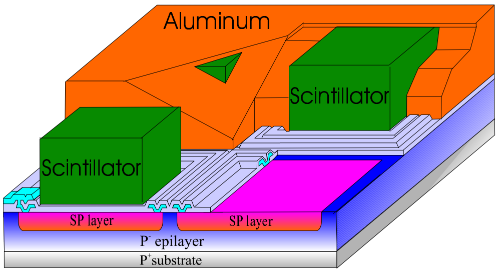

Fig. 2: Sensor structure for 2x2 pixels.

The scintillator thickness is 800 μm, absorbing almost all of the 20 keV x-ray photons, as it is shown in fig. 3.

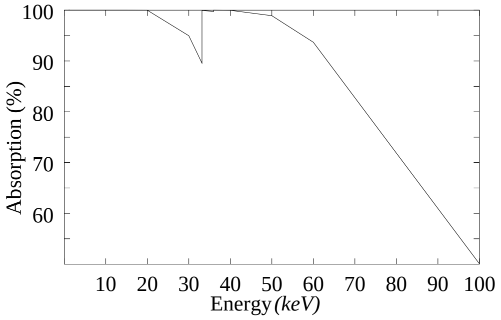

Fig. 3: Absorption of a 800 μm thick CsI scintillating crystal from 1 to 100 keV.

The aluminum top wall of the light guide is 10 μm thick. The x-ray intensity absorbed at 20 keV is only 1%, as it is shown in the graphic of fig. 4.

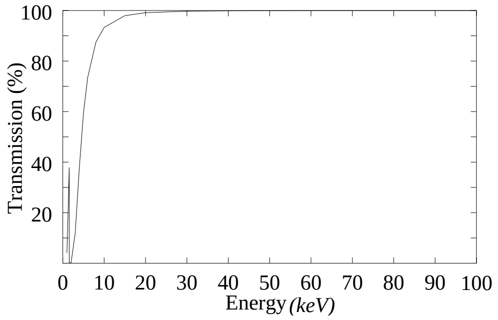

Fig. 4: Transmission of a 10 μm thick Al from 1 to to 100 keV.

FABRICATION PROCESS

The photodiodes are fabricated using a standard CMOS n-well 1.6 μm process. This technology allows the accomplishment of four different types of photodiodes: three vertical structures and a lateral one [4]. Among the vertical diode structures, the junction n+ substrate has the highest quantum efficiency and it has a better response for green wavelengths. The diode p+ n-well has a better response for blue wavelengths relatively to the n-well substrate diode, because its junction is closer to the surface and it can absorb more photons of short wavelength, where silicon has an high absorption coefficient. The lateral diode structure has a good response for the blue wavelengths, because the electron hole pairs generated by these wavelengths contributes in a significative way to the output current. This is due to the fact that in this photodetectors, the junction goes to the surface, and the blue light is absorbed near it. The chosen photodiode structure was the n+ substrate due to its highest quantum efficiency and to its spectral response in the green region of the spectrum. As it will be shown later, the light yield by the scintillating crystal used in this work is green. A picture of the 2x2 photodiode array is shown in fig. 5.

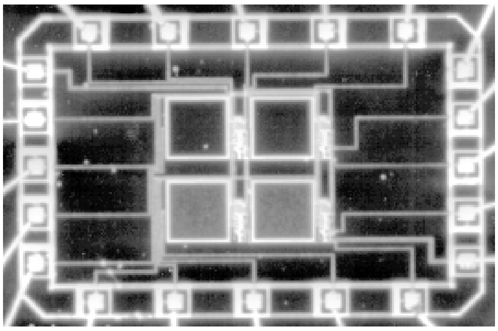

Fig. 5: Picture of a 2x2 photodiode array.

In order to fabricate the light guides, 400 μm diameter holes were drilled in a 800 μm thick aluminum sheet. The scintillating crystal was then placed in the holes by a clamping pressure (about 10 MPa). The chosen crystal was the cesium iodide doped with thalium (CsI:Tl) due to its high light yield, reasonable decay time and wavelength of emission in the green region. Table 1 shows some of the properties of CsI:Tl.

Table 1: Properties of CsI:Tl.

Crystal class and space group	Cubic Pm3m (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
Effective Atomic Number	54
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
Light yield $(phot/MeV)$	65900
Emission wavelength (nm)	560
Decay time (ns)	10^3

Fig. 6 and fig. 7 show the CsI:Tl crystals inside the aluminum holes.

Fig. 6: CsI:Tl inside the aluminum holes: 2x2 array.

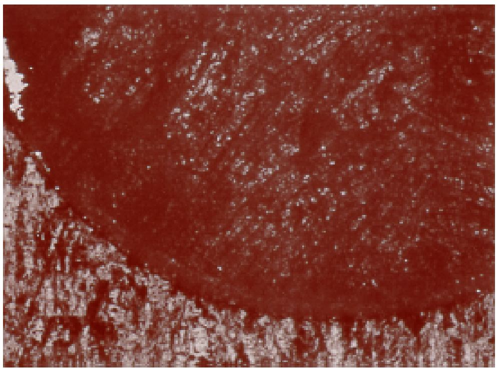

Fig. 7: CsI:Tl inside the aluminum holes: Aluminum/CsI:Tl interface.

A film of aluminum (10 μm) is then placed on the top of the aluminum holes filled with CsI:Tl. As a final step, the light guides setup is placed on the top of the photodiodes (fig. 8).

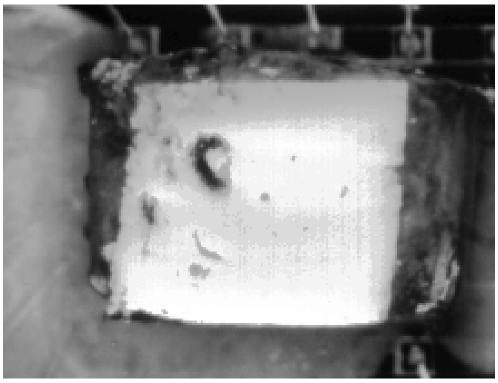

Fig. 8: Picture of the final prototype.

EXPERIMENTAL SETUP AND RESULTS

Spectral response of the photodiodes

The spectral response of the photodiodes was measured using an Oriel spectral analyzer system motorized monochromator UV VIS. The output current was measured using a Keithley 487 picoamperimeter / voltage source. To perform this test, no bias was applied to the photodiode. Fig. 9 shows the measured current for each wavelength.

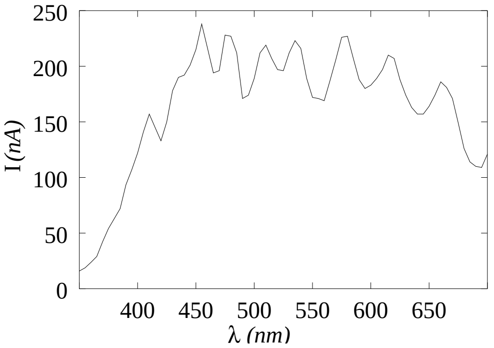

Fig. 9: Spectral response of the photodiodes.

X-ray detection

The experimental test was performed using an x-ray tube (Leybold) with molybdenum anode. The x-rays produced in this tube are composed by [5]:

- *Braking radiation:* According to the classic electrodynamics, an electron whose speed suffers a sudden reduction, emits radiation, preponderantly perpendicular to the direction of the acceleration.
- *Characteristic radiation:* When the energy of the electrons is high enough, the spectrum of the braking radiation is overlapped by a relatively simple structure of lines. This lines are characteristic of the anode material and are due to electronic transitions from the L and M shells to the K shell.

The molybdenum anode has a characteristic short wave radiation of $K_\alpha = 17.4\ keV$ and $K_\beta = 19.6\ keV$. The tube was powered with a voltage of $35\ kV$, and a current ranging from $0\ mA$ to $1\ mA$. Fig. 10 shows the measured values for one photodiode. The other ones have similar results.

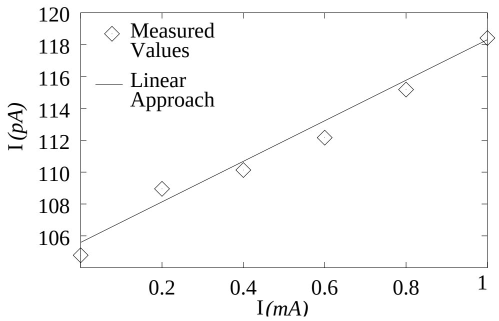

Fig. 10: Current detected for the photodiodes with a x-ray tube input of 35 KV and different currents.

CONCLUSIONS

This approach, scintillating light guides plus CMOS photodiodes, reveals to be suitable to x-rays imaging applications. The scintillating light guides allow to increase the scintillator thickness with low cross-talk and good spatial resolution. CMOS technology allows to implement x-ray detectors which reveals advantages relatively to the CCD technology. As a future work photodiodes and readout electronics will be integrated in the same device.

ACKNOWLEDGMENTS

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