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Optical coupling between scintillators and standard CMOS detectors

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Abstract

In the digital X-ray imaging systems, one of the main problems to be solved is the efficiency of the optical interfaces between scintillators and photodetectors. This article presents the theoretical analysis, simulations, and experimental results on two different optical interfaces (SiO_2 and Si_3N_4), in order to maximize the X-ray detection efficiency. The working principle is the following: the X-ray photons reach the scintillator, which produces visible light. The visible light is then absorbed by the CMOS photodetector. Due to the fact that the refractive indexes of the scintillator and the photodetector are different, the visible light produced by the scintillator is partially reflected by the surface of the photodetector. In order to minimize this problem it is necessary to cover the photodetector with an anti-reflective filter. The anti-reflective filters were fabricated using two different dielectric layers available in a standard CMOS process, with no increase of the production time and costs of the devices.
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1. Introduction

The digital X-ray imaging systems are now replacing silver films (traditional radiography) in a large number of applications, enabling real time image acquisition and processing, and eliminating the costs and the pollution caused by the silver films. One of the simplest methods of constructing a digital X-ray detector consists in the placement of a scintillator above a CMOS photodetector [1–6], as it is shown in Fig. 1. In this case, when the X-ray photons reach the scintillator, visible light is produced, which is then detected by the photodetector. As the main goal of the set-up device is to maximize the light transfer between the scintillator and the photodetector, it is necessary to introduce an anti-reflective filter between the two elements. Usually, the refractive indexes of the scintillators and the silicon photodetectors are very different, as a consequence, without the anti-reflective filter, a percentage of the light produced by the scintillator would be reflected at the photodetector interface, not being detected. Another relevant characteristic of this anti-reflective filter should be that it could be constructed from a standard CMOS dielectric, without additional costs and/ or processing time. For these reasons we have tested the performance of SiO_2 and Si_3N_4 as interface materials.

2. Interface reflectance

In a standard CMOS process, there are several layers upon a photodiode that can influence its absorbicity or spectral response, namely the gate oxide, TEOS, BPSG, plasma oxide and passivation layer (Si_3N_4). In order to simulate and optimize the response for the scintillator/ photodiode interface, these layers must be taken into account [7].

For a theoretical analysis of this problem, a film stack with two interfaces, i.e. three films will be considered (Fig. 2). The behavior of the film stack can be calculated from the electromagnetic theory and the boundary conditions at each interface. The boundary conditions at each

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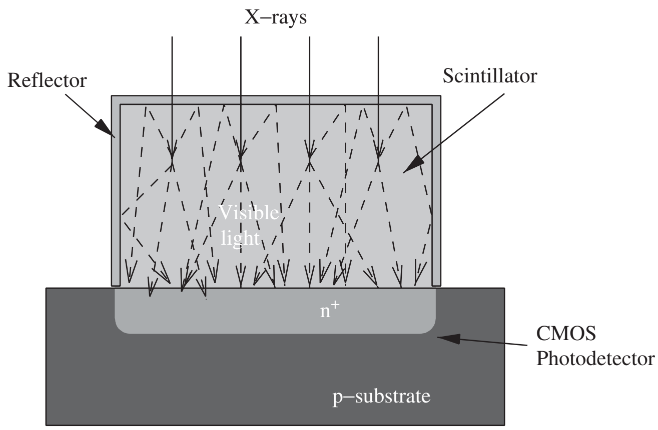

Fig. 1. Schematic design for a digital X-ray sensor: scintillator placed above a photodetector.

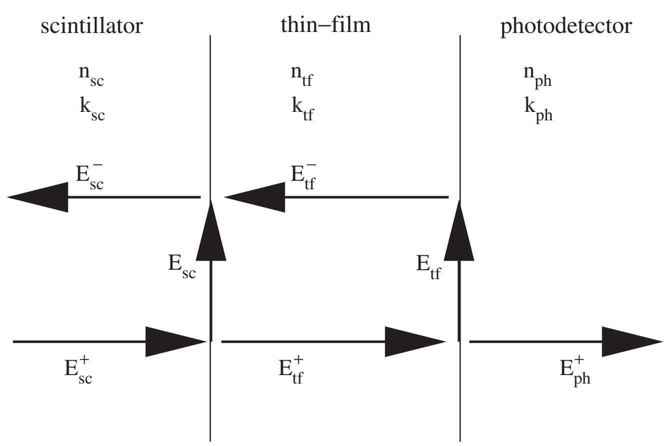

Fig. 2. Parameter definition for a stack of three films. In order to simplify, the angles (θ_i) and the film thicknesses (d_i) are not shown in the figure.

interface between two different optical media allows the establishment of the relationship between the electromagnetic fields of one side of the interface with the ones of the other side. These conditions derive from the electromagnetic theory and establish that the values of the electric and magnetic field components parallel to the interface are the same at both sides.

Considering Fig. 2, each film i can have a light wave traveling to the right, whose electric field is E_i^+, and another traveling to the left, E_i^-. The light waves also have the magnetic fields (H_i^+ and H_i^-) not represented in the figure. These waves make an angle θ_i relatively to the normal of the interface. Each film is characterized by a refractive index n_i, an extinction coefficient k_i, and a thickness d_i (not shown in the figure). In the figure, the subscript ph refers to the substrate (the silicon photodiode in this case), the subscript sc indicates the input medium, constituted by the scintillating material (CsI:Tl in our case), and the subscript tf indicates the optical interface constituted by SiO_2 or Si_3N_4, which is the main object of this study.

Taking into consideration the set of film interfaces, the electrical fields of incident, reflected and transmitted waves are, respectively, E^+_{sc}, E^-_{sc} and E^+_{ph}, which are the fields that have practical interest in order to calculate the stack behavior.

The phase thickness of film i is given by

$$g_i = \frac{2\pi u_i d_i \cos\theta_i}{\lambda} \tag{1}$$

where λ is the wavelength of light in the free space, θ_i is given by

$$u_{sc}\sin\theta_{sc} = u_{tf}\sin\theta_{tf} = u_{ph}\sin\theta_{ph}, \tag{2}$$

and

$$u_i = \begin{cases} (n_i - jk_i)/\cos\theta_i & \text{for } p \text{ polarization} \\ (n_i - jk_i)\cos\theta_i & \text{for } s \text{ polarization} \end{cases} \tag{3}$$

is the complex refractive index (n_i and k_i are the refractive index and the extinction coefficient of the medium, respectively, and $j = \sqrt{-1}$ is the complex operator). The phase thickness represents the change in the phase of the wave when it travels through the film [8]. The light that travels in a given direction can present two independent polarizations. The light that falls upon a surface, forming an angle θ with its normal, can have either the electric field or the magnetic field parallel to the plane of incidence. In the first case, the polarization is p, and in the second is s. In a general case, the electric field vector forms an angle ϕ with the plane of incidence. In this case, it can be separated into two components with p polarization, and s polarization, respectively,

$$\begin{aligned} E_p &= E\cos\phi\cos\theta && \text{for } p \text{ polarization} \\ E_s &= E\sin\phi && \text{for } s \text{ polarization.} \end{aligned} \tag{4}$$

In a similar way, the magnetic field vector can be separated into two components

$$\begin{aligned} H_p &= H\cos\phi && \text{for } p \text{ polarization} \\ H_s &= -H\sin\phi\cos\theta && \text{for } s \text{ polarization.} \end{aligned} \tag{5}$$

Notice that in a scintillating light source the light travels in all directions with equal probability. Also all the angles of the electric and magnetic fields occur with equal probability. Since each light wave can be decomposed into two vectors, with p and s polarizations, in average half of the light is p polarized and the other half is s polarized.

By using the boundary conditions derived from the electromagnetic theory [9], the reflectivity of the stack of Fig. 2 is given by

$$R = \left|\frac{E^-_{sc}}{E^+_{sc}}\right|^2 \tag{6}$$

where

$$E^-_{sc} = \frac{1}{2u_{sc}u_{tf}}[(u_{sc}u_{tf} - u_{tf}u_{ph})\cos g_{tf} + (u_{sc}u_{ph} - u_{tf}^2)j\sin g_{tf}]E^+_{ph} \tag{7}$$

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