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Influence of backscattering on the spatial resolution of semiconductor X-ray detectors

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Abstract

Pixelated X-ray detectors using semiconductor layers or scintillators as absorbers are widely used in high-energy physics, medical diagnosis, or non-destructive testing. Their good spatial resolution performance makes them particularly suitable for applications where fine details have to be resolved.

Intrinsic limitations of the spatial resolution have been studied in previous simulations. These simulations focused on interactions inside the conversion layer. Transmitted photons were treated as a loss. In this work, we also implemented the structure behind the conversion layer to investigate the impact of backscattering inside the detector setup.

We performed Monte Carlo simulations with the program ROSI (*Ro*entgen *Si*mulation) which is based on the well-established EGS4 algorithm. Line-spread functions of different fully implemented detectors were simulated. In order to characterize the detectors' spatial resolution, the modulation transfer functions (MTF) were calculated. The additional broadening of the line-spread function by carrier transport has been ignored in this work.

We investigated two different detector types: a directly absorbing pixel detector where a semiconductor slab is bump-bonded to a readout ASIC such as the Medipix-2 setup with Si or GaAs as an absorbing semiconductor layer, and flat-panel detectors with a Se or a CsI converter.

We found a significant degradation of the MTF compared to the case without backscattering. At energies above the K-edge of the backscattering material the spatial resolution drops and can account for the observed low-frequency drop of the MTF. Ignoring this backscatter effect might lead to misinterpretations of the charge sharing effect in counting pixel detectors.

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1. Introduction

Pixelated, solid-state X-ray detectors have replaced conventional film-screen systems, storage phosphor plates, or image intensifier TV systems in the field of high-energy physics, medical diagnosis, or non-destructive testing. As well as scintillators coupled to a photodiode matrix, directly absorbing semiconductors are used as conversion layers. Readout is accomplished either by matrices of switches made from amorphous silicon thin-film transistors on a glass substrate, or by counting pixel chips bump-bonded to a slab of absorber material.

The whole signal generation process can be modeled by Monte Carlo simulations as has been demonstrated in a previous paper [1]. Since only part of the incident X-ray quanta are absorbed in the converting layer, the transmitted quanta can hit objects behind the converter and thus give rise to backscattered radiation. This radiation may in turn strike the converter at a remote location and induce an additional signal, deteriorating the spatial resolution of the detector.

2. Simulations

The signal-generating processes have been studied by Monte Carlo simulations by means of the program ROSI (*Ro*entgen *Si*mulation) written by Giersch et al. [2]. We implemented the detectors in all detail and had them irradiated with monoenergetic photons in the energy range from 20 to 120 keV. Some further simulations have been performed using spectra common for medical applications (mammography, radiography) with tube voltages ranging from 28 to 120 kV.

The first simulation step is the X-ray interaction of the incident radiation with the absorber, where it looses energy and fast electrons are generated. Secondary quanta can also occur and will either leave the absorber or be reabsorbed again. The second simulation step is the energy loss of the fast electrons. The signal is collected in a pixel, i.e. the signal is integrated over the active pixel area. In terms of modulation transfer function, the pixel size determines a sinc function $\sin(x)/x$ as an upper limit for an ideal detector.

In the simulations, an X-ray fan beam of infinitesimal width is directed onto the detector, irradiating a narrow line. The detector is assumed to consist of a matrix of pixels with 55 or 70 µm pitch. The beam is slightly tilted (by 5°) to produce oversampling. From this image, we determine the presampled line-spread function and in turn the dependency of MTF on spatial frequency. Details have been published elsewhere [1].

Two different kinds of detector have been studied. The first was a counting pixel detector consisting of a converter layer, bump-bonded to a readout ASIC like the Medipix-2 readout chip mounted on a chip board which was assumed to be a 1-mm piece of Perspex. The conversion layers investigated were a 300 and a 700 µm thick Si slab and a 300 µm thick piece of GaAs, respectively. The bonding layer consisted of an indium bump with 21.8 µm diameter at each pixel. As an alternative we assumed the same amount of In distributed as a homogeneous layer of 1.8 µm thickness. This speeds up simulations by a factor of 10, yielding very similar results. The readout chip was modeled as a 500 µm thick Si layer with 55 µm pixel size similar to the Medipix-2 chip [3].

The flat-panel detector consisted of either a 200 µm thick Se layer as a converter, or of a 420 µm thick CsI scintillator, grown on top of an a-Si-based readout matrix with 70 µm pixels on a glass substrate. The substrate was assumed to be 3 mm Corning 7059® glass, which consists of 25% barium oxide. An additional 1-mm lead shield was assumed behind the substrate.

For each detector and energy we simulated the LSF with and without backscattering material for comparison. The corresponding MTFs were calculated and compared with the theoretical limitation given by the sinc function $\sin(x)/x$.

3. Results

The simulated MTF curves as a function of spatial frequency are plotted in Fig. 1 for a 300 µm thick Si absorber and different energies. The sinc function for the pixel size of 55 µm is given as a

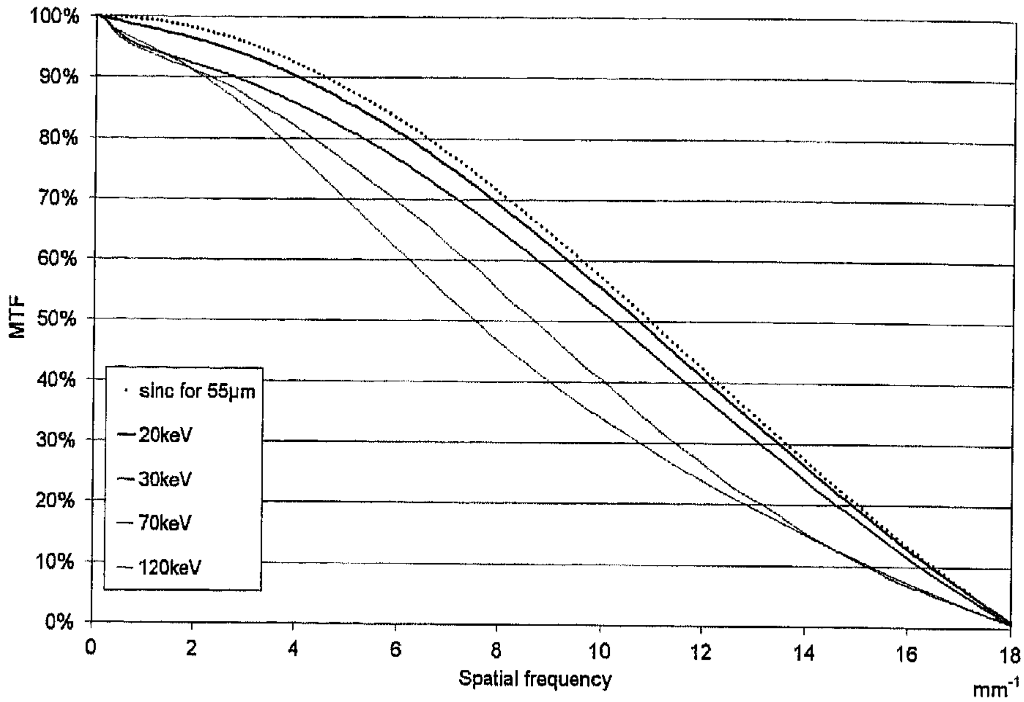

Fig. 1. Simulated MTF of a 300 μm thick Si detector bonded with In bumps to a Medipix-2 chip for different energies. Pixel size is 55 μm. The sinc function is plotted for comparison. Backscattering leads above the K-edge energy of In (27.94 keV) to a low-frequency drop.

reference value for an ideal detector. The MTF at 20 keV is close to the sinc function. At energies above the K-edge energy of indium, i.e. 27.94 keV, a drop in the MTF at spatial frequencies below 1 mm^{-1} can be seen. This is the so-called low-frequency drop which is observed in many detectors. It can clearly be seen, that with higher photon energies the impact of backscattering increases. This is because less photons are absorbed but are transmitted through the conversion layer. These photons can hit the setup behind the semiconductor and accordingly be backscattered. Most photons hitting the conversion layer from behind are fluorescence photons from the indium bonds. That explains the relatively high effect at the K-edge of In.

In Fig. 2, MTF curves are compared for differently thick Si samples at 50 keV. Ignoring backscattering, the thinner Si conversion layer delivers the better spatial resolution. With backscatter taken into account, all curves display a rather similar shape. It turned out that simplifying the In bumps by a contiguous layer of the same amount of In leads to comparable results.

The corresponding MTF curves at 120 keV are shown in Fig. 3. At this energy, the MTF without backscatter is markedly lower than the sinc function due to the long range of the fast electrons generated in the absorber. The backscattering effect by the bumps turns out to be slightly stronger than that from a contiguous layer which can be seen from the lower MTF. This can be explained by the fact that the gaps between the bumps allow for most of the quanta backscattered from the chip board to reach the converter. In contrast, an In layer attenuates all backscattered quanta which results in a higher MTF.

For the flat-panel detector the results are quite similar. Barium as a constituent of the substrate glass has the same effect like the In bumps in the first setup. For energies above the K-edge of barium, i.e. 37.44 keV, the spatial resolution decreases, as can be seen in Fig. 4.

GaAs and CsI as conversion layers have little influence on backscatter. This is mainly due to their efficient absorption of the primary radiation which leaves only few quanta over for transmission.

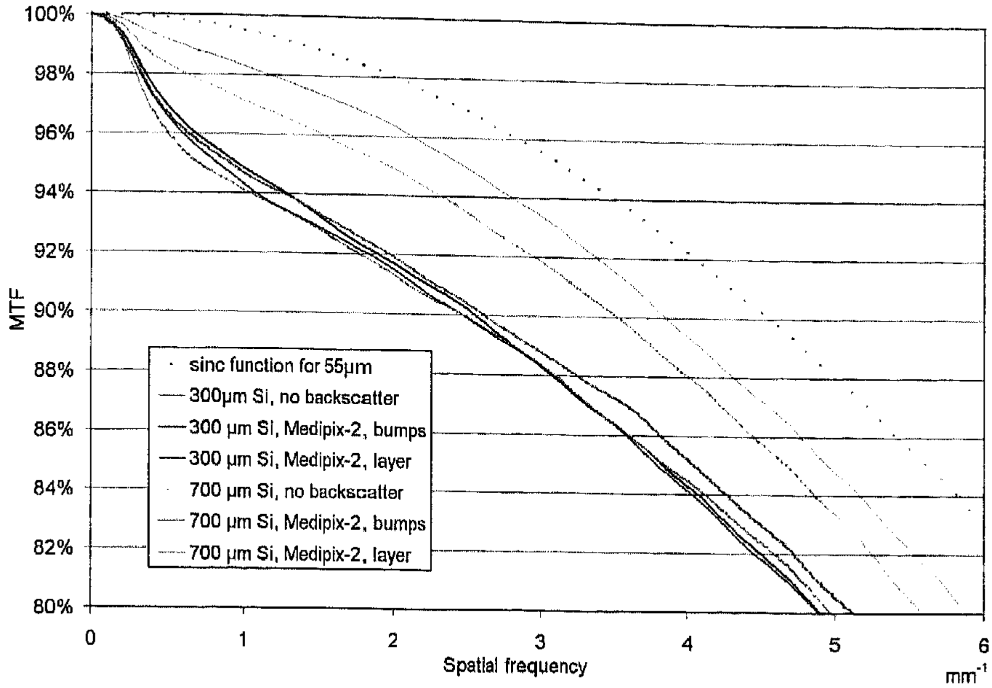

Fig. 2. Simulated MTF of a 300 μm and a 700 μm thick Si detector bonded with In bumps to a Medipix-2 chip at 50 keV. Pixel size is 55 μm. The sinc function is plotted for comparison. Backscattering leads to a low-frequency drop. Simplifying the In bumps by a contiguous layer leads to similar results.

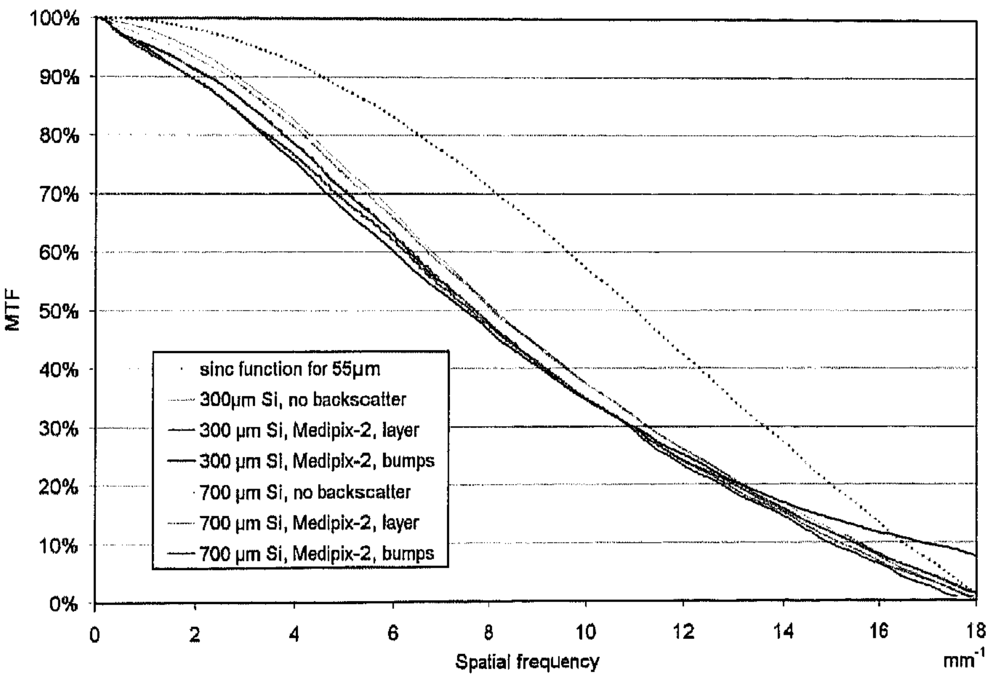

Fig. 3. Simulated MTF of a 300 μm and a 700 μm thick Si detector bonded with In bumps to a Medipix-2 chip at 120 keV. Pixel size is 55 μm. The sinc function is plotted for comparison. Backscattering leads to a low-frequency drop. Simplifying the In bumps by a contiguous layer leads to a slightly higher MTF.

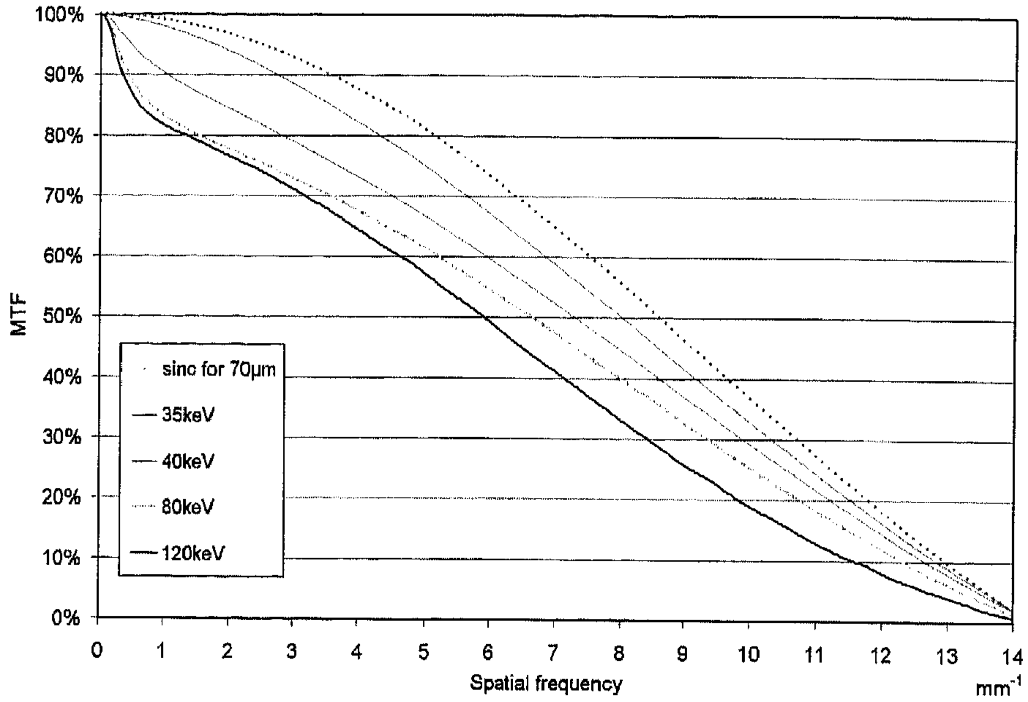

Fig. 4. Simulated MTF of a 200 µm thick Se detector on a glass substrate. Pixel size is 70 µm. The sinc function is plotted for comparison. Above the K-edge of Ba (37.44 keV) backscattering leads to a low-frequency drop.

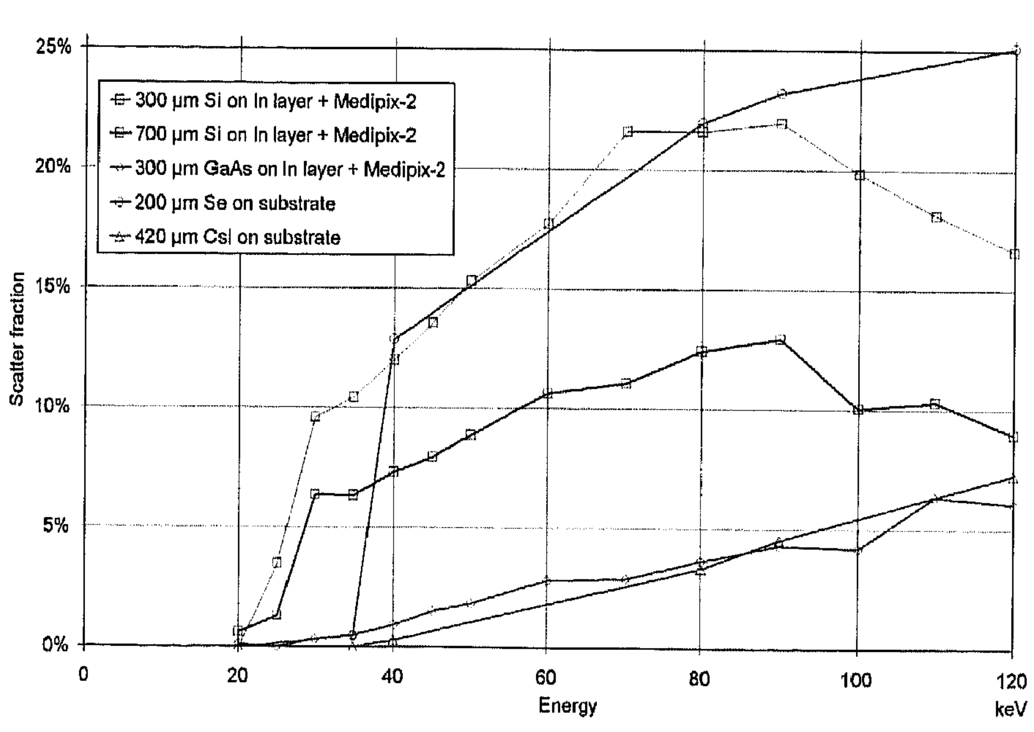

Fig. 5. Fraction of scattered quanta as a function of energy. Scattering rises strongly above the K-edge energies of In and Ba, i.e. 27.94 keV and 37.44 keV, respectively. GaAs and CsI absorb most of the quanta leading to little backscatter.

Fig. 5 shows the fraction of the scattered quanta for all samples investigated as a function of energy. Scattering rises strongly above the K-edge energies of the major scattering elements In and Ba, i.e. 27.94 and 37.44 keV, respectively. The 700 µm thick Si layer exhibits less scatter since compared to the 300 μm thick layer, a higher fraction of the incident radiation is absorbed. The GaAs and CsI converters absorb most of the quanta leading to only little backscatter.

4. Conclusions

Our results show, that there can be a strong effect of backscattering on the spatial resolution of an X-ray detector. This is especially important in the case of conversion layers that absorb only a small fraction of the incident radiation. Depending on the material behind the converter, backscattering increases strongly above the respective K-edge energy. Since backscattered quanta can be reabsorbed far away from the first interaction site, the MTF at low spatial frequencies will also be reduced leading to the so-called low-frequency drop.

It should be noted that the interpretation of charge sharing experiments can be wrong due to the backscattering effect, which can be tested at energies below and above the K-edge energy.

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