X-ray interaction- induced signal and noise characteristics of edge-on silicon microstrip detectors for digital mammography

Hanbean YOUN[1], Dong-Goo KANG[2], Sangwook KIM[3], Jaechul PARK[3], and Ho Kyung KIM[1]

[1] School of Mechanical Engineering, Pusan National University, Busan 609-735, South Korea
[2] Medical Imaging Systems Group, Samsung Advanced Institute of Technology, Yongin, Gyeonggi-Do 446-712, Republic of Korea
[3] Semiconductor Device Laboratory, Samsung Advanced Institute of Technology, Yongin, Gyeonggi-Do 446-712, Republic of Korea
* Correspondence: hokyung@pnu.edu, +82 51 510 3511, fax +82 51 518 4613

Background

- Photon-counting detectors are attractive for medical imaging because of their potential low-dose imaging capabilities by suppressing additive electronic noise. There exist, however, difficulties in the realization of photon-counting detectors to large areas because of complexities in analog/digital signal processing circuitries.
- Scanning approach with one-dimensional linear-array detectors is an alternative and it has already been adapted to commercialization with silicon microstrip detectors. To maximize quantum efficiency in silicon microstrip detectors, edge-on geometry to the x-ray incidence is utilized and the application is normally limited to mammography which uses relatively lower energies.

Motivation and Objectives

- In typical x-ray imaging detector systems, useful information for diagnosis is extracted from x-ray image in the first stage only (i.e. the detection of individual x rays) and all later image-forming stages may result in the loss of information which is irecoverable. Therefore, the core component in x-ray imaging detector systems to obtain high-quality images would be an x-ray converter which is located at the first x-ray detection stage.
- Applying tilting angle to the silicon microstrip detector having edge-on geometry is inevitable due to the front dead zones for x-ray interactions. Except regarding the quantum efficiency, there has not been sufficient attention paid to the fundamental signal-to-noise performances, which are mainly responsible for the final image quality, induced by x-ray interactions in the silicon microstrip detectors.
- We investigate the signal and noise performances induced by x-ray interactions in the edge-on silicon microstrip detector designs with respect to tilting angles for mono- and poly-energetic x rays. The detector response functions are determined using the Monte Carlo methods and used to determine the signal and noise performances, such as quantum absorption efficiency (α), average energy deposition per interacting x-ray quantum (β), Swank noise factor (I), and detective quantum efficiency (DQE), based on the energy-moment theory. In addition, relative energy accuracy and imprecision in photon-energy measurements are estimated.

Materials and Methods

Theory

- It is convenient to describe the energy response function of a detector in terms of its response function $R(E, E')$ which gives the probability density of depositing energy E given an incident photon with energy E'. The nth energy moment of $R(E, E')$ is then given by

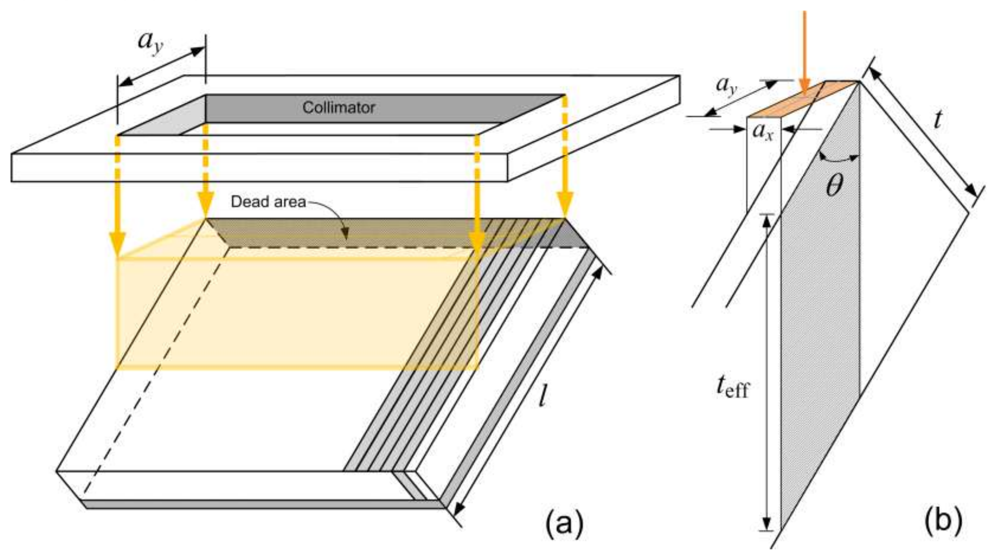
$$M_n(E') = \int_0^\infty E^n R(E, E')dE$$

- This energy-moment approach can be utilized to determine x-ray interaction-induced signal and noise performances such as α, β, I, and DQE. These performance parameters can be further utilized for the estimation of relative energy accuracy and imprecision in energy measurements as derived in a previous study [J. Tanguay *et al*., "The role of x-ray Swank factor in energy-resolving photon-counting imaging," Med. Phys. 37 (2010) 6205]. Table summarizes the calculations of signal and noise performances based on the energy-moment method.
- The signal and noise performance parameters for poly-energetic x rays can easily be estimated by weighting the energy-moment formula by the poly-energetic spectra.

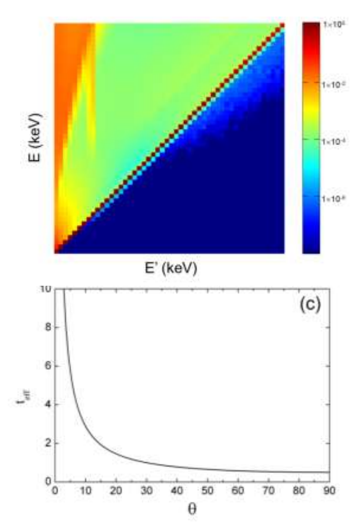
Signal and noise performances	Description
Quantum efficiency	$\alpha(E') = M_0(E')$
Energy deposited	$\varepsilon(E') = M_1(E')$
Energy deposited per x-ray interaction	$\beta(E') = \frac{M_1(E')}{M_0(E')}$
Swank factor	$I(E') = \frac{M_1^2(E')}{M_0(E')M_2(E')}$
Detective quantum efficiency	$\mathrm{DQE}(E') = \frac{M_1^2(E')}{M_2(E')}$
Relative accuracy in energy measurement	$\varepsilon_{rel}(E') = \frac{\beta(E')}{E'}$
Relative imprecision in energy measurement	$\sigma_{rel}(E') = \sqrt{\frac{1}{I(E')} - 1}$

Detector geometry

- Geometric parameters of the hypothetical silicon microstrip detector investigated in this study for the Monte Carlo simulations are taken from those of the prototype detector (See the poster ID 112 at this conference: "Detective quantum efficiency of photon-counting detectors having edge-on geometry under mammography imaging condition").
- $a_x = 0.095$ mm; $a_y = 0.1$ mm; $t = 0.5$ mm; $l = 100$ mm; $t_{eff} = a_y/\sin\theta$
- The detector response function is determined by virtual pulse-height spectroscopy using Monte Carlo N-Particle transport simulation (MCNP version 5, RSICC, Oak Ridge, TN, USA) to simulate the coupled photon-electron transport within the silicon microstrip detector for momo-energetic photon incidence. A photon beam is incident normal to the collimator plane at the center point of an effective pixel defined by $a_x \times a_y$ located at the center of the linear array. We considered interacting photon energies in the range 1 – 50 keV with 10^8 photons per simulation.



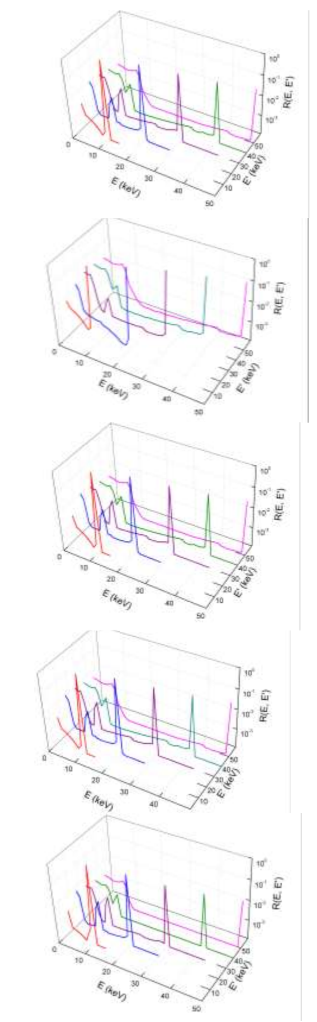
Sketches describing the hypothetical silicon microstrip detector for Monte Carlo simulations



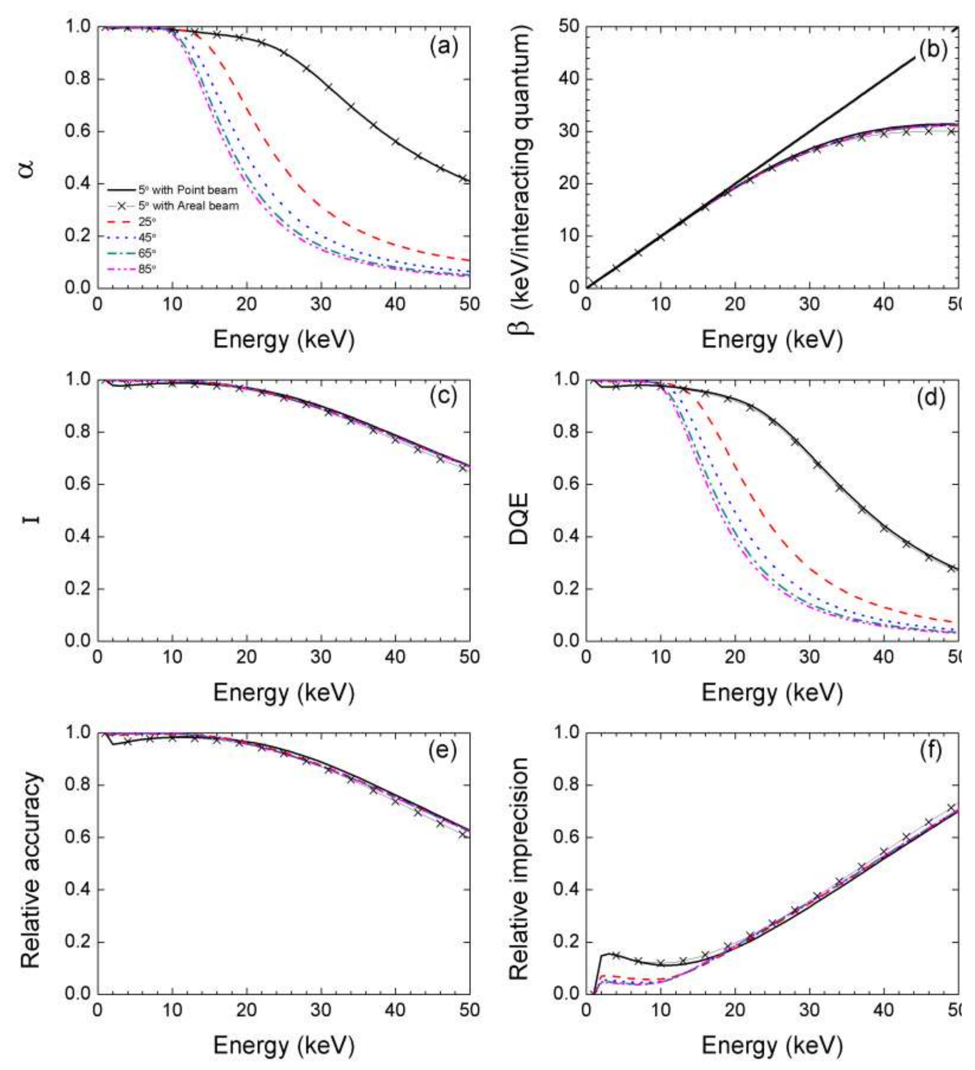
R(E,E') matrix and Effective detector thickness as a function of tilting angle

Results

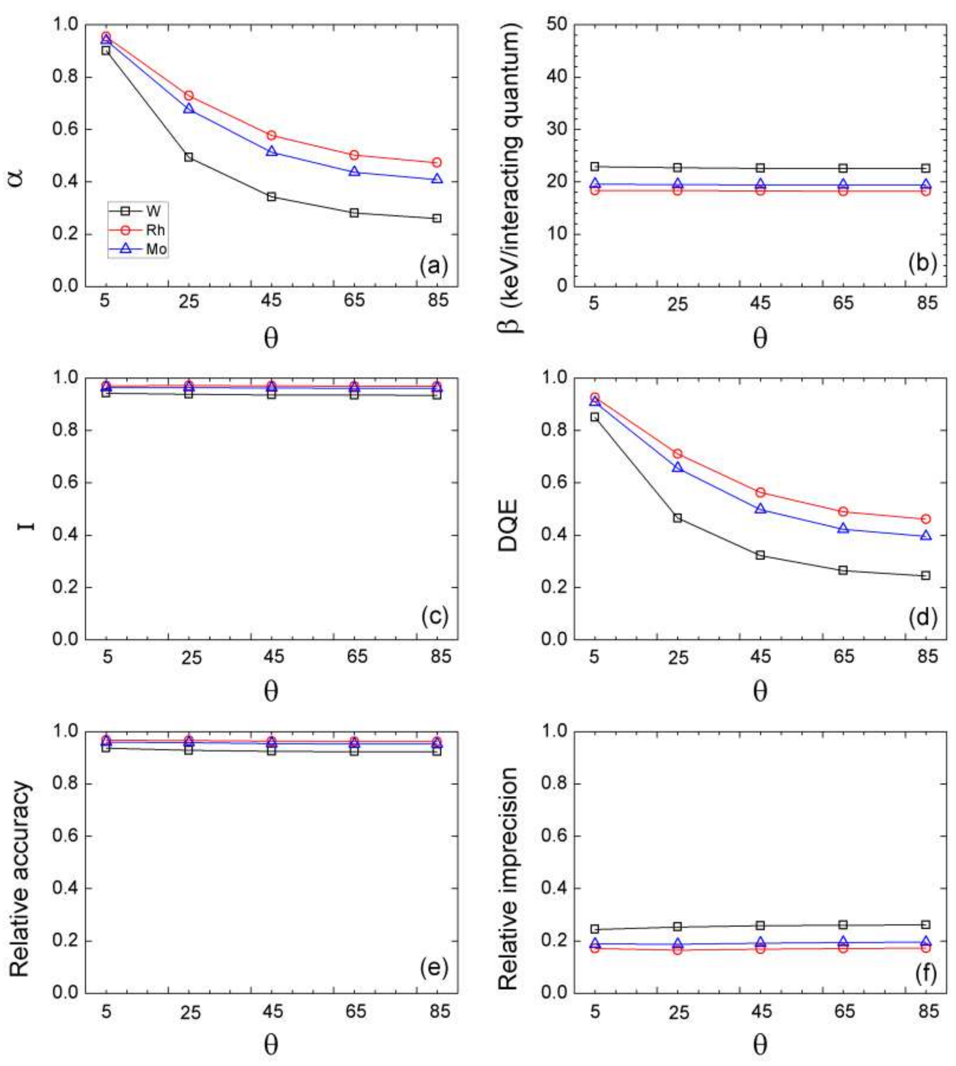
- The unique peak around 8 keV in the response functions is due to the absorption of fluorescence x-ray from the copper electrode which is located at the back of detector.
- "Cross (×)" symbol plots in the mono-energy analyses designate the results based on the detector response functions obtained for areal ($a_x \times a_y$) beam incidence instead of the point-like beam. The areal beam incidence affects the average energy absorption per interacting quantum and the Swank noise factor, thus the DQE, the relative accuracy and imprecision in the energy measurements. This is due to the loss of energy deposition in a given pixel by escaping Compton-scattered photons.
- For θ = 5°, which is the minimum angle we can achieve in the prototype detector to avoid the dead-zone effect, the overall signal and noise performances rapidly degrades at energies greater than about 20 keV. While the quantum absorption efficiency and DQE deteriorate as θ increases, degradations in other performances are negligible.
- From the results of poly-energy analyses, the Rh spectrum provides the best signal and noise performances for the silicon microstrip detector except the average energy deposition per interacting quantum.



Examples of R(E,E') when E' = 10, 20, 30, 40 and 50 keV for θ = 5, 25, 45, 65 and 85°



Signal and noise performances for mono-energetic x rays



Signal and noise performances for poly-energetic x rays

Discussion and Conclusions

- The DQE due to x-ray interactions in the silicon microstrip detector is mainly governed by the quantum absorption efficiency.
- Except the quantum absorption efficiency and thus the DQE performance, the other signal and noise performances, such as the average energy absorption per interacting quantum, the Swank noise factor, the relative accuracy and imprecision in energy measurements, are nearly independent upon the tilting angle θ or the x-ray interaction volume.
- For energies less than about 20 keV, relatively small interaction volume or large tilting angle θ provides a higher DQE performance and a better energy measurement performance (e.g. imprecision) because of the better Swank noise performances.
- The Rh spectrum relatively well matches to the silicon microstrip detector rather than Mo and W spectra.
- This study suggests an upper limit of the signal and noise performances which we can achieve with the silicon microstrip detector. The real signal and noise performances in images obtained from the silicon microstrip detector would be unfavorably compromised due to further image degradation stages, such as charge sharing, noise aliasing and others.

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