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Signal and noise characteristics in radiation-damaged CMOS detector

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1. Introduction

Recently, an active-pixel sensor based on COMS (complementary metal-oxide-semiconductor) technology is greatly investigated as digital x-ray imaging detectors, because of its unique advantages, such as very low image lag and lager pixel fill-factor compared to conventional flat-panel detectors based on amorphous silicon thin-film transistor technology [1, 2]. In this study, we have investigated the long-term stability of signal and noise characteristics as a function of the accumulated dose at the entrance surface of the CMOS detector, which employs a phosphor screen to convert x-ray into light. Bare CMOS sensor was also considered in the experiment.

2. Methods and Results

2.1 Experimental

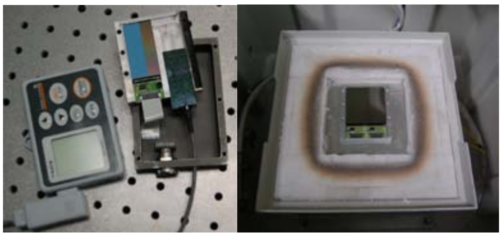

Fig. 1. The photographs of the experimental layout for the irradiation (left) and annealing (right) for the CMOS sensor.

We configured a sample detector with a commercial phosphor screen (Min-R2000^{TM}, Carestream Healthcare, Inc., USA) and a CMOS photodiode array (RadEye^{TM}, Rad-icon Imaging, Corp., USA)[1, 3, 4]. As shown in Fig. 1, half of the CMOS photodiode array was covered by the phosphor screen, which is the typical configuration as an x-ray imaging detector, and the other region was kept as bare. Two-different x-ray sources were employed for the irradiation. To provide a heavy irradiation dose, a relatively high-power source (max. 810 watts; EXG-6^{TM}, E-Woo Technology, Co., Ltd., Korea) was used with a source-to-detector distance (SDD) of 300 mm. On the contrary, images for the analysis of signal and noise characteristics were obtained with a small-power x-ray source (max. 80 watts; Ultrabright^{TM}, Oxford Instruments X-ray Technologies, Inc., USA) with a SDD of 400 mm to reduce additional radiation damage during analysis. The applied energy was set to 50 kVp for both x-ray sources. The total irradiated dose was about 50 Gy.

2.2 Dark current analysis

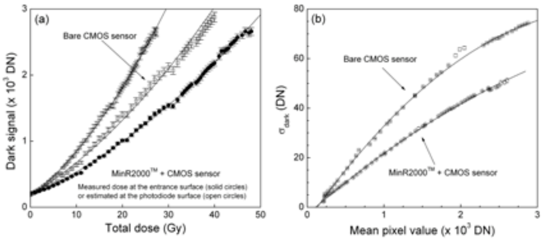

Fig. 2. (a) Dark signal levels as a function of total irradiated dose for two different detector configurations. (b) Standard deviation of dark signal values as a function of mean pixel value.

The effect of accumulated total dose on the signal and noise characteristics is summarized in Fig.2. The error bars indicate the standard deviations of the average dark values calculated for 20 images. As expected, the level of dark signal is increased as the total dose increases as shown in Fig. 2(a). The increase of dark signal follows quadratic-dependence on the total dose. Interestingly, if we replot the result of the CMOS sensor having a phosphor screen considering the total dose at the surface of CMOS photodiode array, the trend of increase of dark signal is higher than that of bare region in the CMOS sensor. This phenomenon may be explained by the beam hardening through the phosphor screen. Although the noise characteristic quadratically depends on the dark signal level, the dependency is gradually reduced as the dark signal increases as shown in Fig. 2(b). This result implies that the fixed-pattern noise (FPN), which increases the standard deviation linearly with the signal, is negligible in this investigation

2.3 Dynamic range

Dynamic range of detector in this study is defined as

$$\Gamma(X) = \frac{S_{max} - \overline{S_{dark}(X)}}{\overline{\sigma_{dark}(X)}} \qquad (1)$$

where X denotes the accumulated total dose, and S_{max} and $S_{dark}(X)$ are the maximum signal and the dark signal at the given total dose, respectively. $\sigma_{dark}(X)$ is the standard deviation of the dark signal at the given total dose X. The upper bar denotes the mean value. The increase of dark signal level for the total dose definitely consumes a significant part of the total dynamic range. The dynamic ranges in decibels of the CMOS sensor with and without the overlying phosphor screen drop to ~40% and 17%, respectively, of the starting dark signal status of detector over the course of the experiment.

2.4 Imaging performances

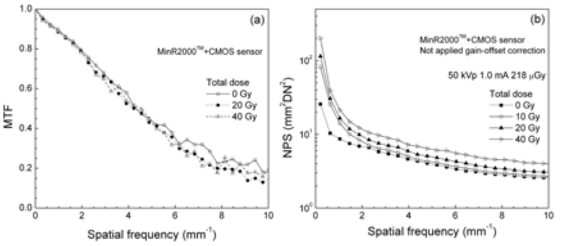

Fig. 3. Measured MTFs (a) and NPSs (b) of the CMOS detector with respect to various total irradiated dose levels. In the measurements of NPS, gain-offset correction was not applied.

Fig. 3 shows the measured results of MTF and NPS of the detector with respect to total dose. While there is no significant change in MTF performance with total dose, the noise-power spectral densities are gradually increased as the accumulation of total dose increases. In the NPS measurements as shown in Fig. 3(b), however, we cannot observe any sign of the existence of FPN components in spatial frequencies even with no application of the gain-offset correction procedure. These measured NPSs would largely degrade the DQE performances. Therefore, gain-offset correction is essential to avoid the effect of the increase in dark signal and noise on the DQE evaluation.

2.5 Annealing effect

We have annealed the aged detectors in a vacuum furnace with temperature. We found that the application of thermal energy of 100°C over 50 hours worked on the reduction of dark signal level. This recovery is based on the hypothesis that positive ions built in the SiO_2 layer by irradiation are neutralized with electrons, which have enough energy to jump back into the SiO_2 layer, from the silicon substrate. During this experiment, however, we observed the increase of malfunctioned or dead lines in the CMOS detectors, which may be due to the disconnection between photodiode pixel arrays and the peripheral control/readout electronics at higher temperature.

3. Discussion

The noise components contributing to dark images consist of electronic noise, statistical quantum noise, and structured fixed-pattern noise. Therefore, for an image obtained at a certain total dose level the noise characteristic can be analyzed as

$$\sigma^2 = k_e^2 + k_q^2 x + k_s^2 x^2 \qquad (2)$$

where the coefficient k_j describes the dependency between the level of dark signal x and the corresponding noise component, and the subscript j denotes each noise component; e, q, and s for electronic, statistical, and structural noise, respectively. The electronic noise term is dependent on total dose, but the others are almost independent on the total dose. In addition, the structural noise term is negligibly related to the total dose compared with other noise terms, which may explain the observations in this study. Two different detector configurations show the same trend.

4. Summary

In this study, we have systematically investigated the aging of signal and noise characteristics of CMOS photodiode array detectors. While the increase of dark signal showed quadratic-increasing form along the accumulated total dose, that of noise showed saturating form. In the noise characteristics, electronic noise was dominant and structural FPN was negligible in this study. These phenomena result in significant reduction of dynamic range as the total dose increases. With the proper gain-offset correction procedures, MTF, NPS, and DQE evaluations were not significantly changed at any total dose level.

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