Backside illumination (BSI)-scheme CMOS image sensors have been preferable for soft-X-ray sensing, which have high readout speed compared to CCD image sensor. In this regard, we recently developed a BSI CMOS soft-X-ray image sensor (SBSA) based on a commercial CMOS sensor without anti reflection (AR) coating. This sensor demonstrated a high QE, low readout noise of 2.6 e− rms, and high frame rate of 48 fps, along with a photon-energy resolution of 80–1000 eV. As regards practical application, we demonstrated fluorescence detection from highly oriented graphite and a polymethyl methacrylate film using a simple setup, wherein the samples faced our CMOS sensor without a monochromator. However, the sensor durability after soft-X-ray exposure was unsatisfactory because of the small Si-layer thickness of 3.5 μm. The QE also required further improvement, particularly for the small-absorption-length regime.

In this study, we developed a new CMOS sensor with further improvements to the backside process to afford a thicker Si layer of 9.5 μm; we called this sensor the SP3 sensor. This soft-X-ray/EUV-regime SP3 image sensor is also based on the Gpixel BSI CMOS image sensor, which incorporates minor revisions in the peripheral circuits relative to the previous sensor, the GSENSE400BSI. We made two changes to the backside fabrication process for the SP3 relative to the SBSA: the silicon thickness was changed from 3.5 to 9.5 μm to suppress radiation damage, and that the implantation energy was decreased by one digit to reduce the non-sensitive-layer thickness. Our CMOS sensor adopts a rolling shutter and a high dynamic range (HDR) scheme using the double-mode conversion gain method, and has 2048 (H) × 2048 (V) 11 μm pixels. In the low-gain mode, the conversion gain is 1/18 that of the high-gain mode, and all saturated electrons can be read out. The high- and low-gain-mode readout time and frame rate are 21 ms and 48 fps, respectively, and the HDR-mode frame rate is 24 fps. Dark current was 3.7 e−/s/pixel at −7 °C.

The sensor’s QE was measured at the BL-10 beamline of the NewSUBARU synchrotron facility (University of Hyogo) same as previous paper. We set the exposure time to 2 ms, for which the signal was not saturated even in the high-gain mode. The sensor temperature was 42 °C as measured by a vacuum-operating embedded temperature sensor. The SBSA and SP3 sensor QEs are shown in Fig. 1. The standard electron–hole pair creation energy of 3.66 eV was used for QE calculations. The high-gain-mode conversion gains were calculated as 1.85 and 1.27 for the SBSA and SP3 sensors, respectively. It can be observed that the SP3 sensor QE is >100% at several photon energies due to measurement errors. Importantly, the 80–1000 eV range QE is >90%. The solid curve denotes the fitting of the simplest dead-layer model omitting the cloud size and transient region. The Si thickness of the SBSA and SP3 sensors were estimated as 3.5 and 9.5 μm, respectively, as per the QE drop above 700 eV and the backside process condition. Importantly, we note that the SP3 sensor exhibits the highest recorded QE for the energy range of 80–1000 eV to the authors’ knowledge.

Figure 2 shows the energy resolution measurement results of the SBSA and SP3 sensors. In the measurement, we used the photon-counting event called the single-event, which is widely used for the hard-X-ray regime to obtain the energy resolution. The experimental setup was same as that for practical application, we demonstrated fluorescence detection from highly oriented graphite and a polymethyl methacrylate film using a simple setup, wherein the samples faced our CMOS sensor without a monochromator. However, the sensor durability after soft-X-ray exposure was unsatisfactory because of the small Si-layer thickness of 3.5 μm. The QE also required further improvement, particularly for the small-absorption-length regime.

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QE measurements. The sensor exposure time was 2 ms, and the irradiated photon number in the central region was made too large (>100 photon/pixel) to record single events. Thus, weak scattered photons around the center were counted as single events. The photon-counting-event threshold was set as 4 e⁻, corresponding to 7 and 5 DN for the SBSA and SP3 sensors, respectively. This threshold was 1.6 times the readout noise. In some cases, the single events were found to “share” their electrons among neighboring pixels. As the DN of these electron-sharing events indicated smaller energy than the photon-energy, these events were omitted as per the threshold. The vertical axis in Fig. 2 represents the normalized DN frequency of these photons. The single events in ~100 image frames were counted under each photon-energy condition. The obtained energy resolution was 70 eV at the photon-energy of 1000 eV for both the SBSA and SP3 sensors. We note that below 450 eV, the SBSA-sensor energy distribution exhibits a large low-energy tail. In contrast, that of SP3 exhibits no low-energy tail at 200 eV because the dead-layer thickness is reduced from 27 to 5 nm. Thus, the SP3 sensor is able to resolve low-energy fluorescences corresponding to carbon (284 eV) and boron (188 eV). Here, we note that EUV photons (92 eV) are also resolved by the sensor.

Next, we evaluated the sensor durability against EUV and soft-X-ray photons. In general, sensor displacement damage⁶,¹⁷ can be ignored because the irradiated photon-energy is <1000 eV. Because the peripheral circuits are not X-ray-irradiated and the pixel array has only N-type MOS transistors and no PNPN structure, single-event latch-up is also not a problem. Because there are no memory components and dynamic circuits in the pixel array, the occurrence of a single-event upset⁶,¹⁹ is also negligible. Therefore, only the total ionizing dose (TID)⁶,²⁰,²¹ needs to be considered. The TID measurement results for various soft X-ray energies are shown in Fig. 3. The dark-current increases with the TID, corresponding to the number of irradiated photons per pixel. Again, in this case, the experimental setup was almost identical to that for QE measurements. The monochromator exit slit was opened to a 1 mm width from 0.001 mm for QE measurement to increase the dosage. The irradiated intensity profile was evaluated using a low-gain-mode image with the minimum sensor exposure time (36 μs). The irradiation time of this durability test was set as 10–2000 s. The TID (photon/pixel) was calculated using the intensity profile and irradiated time. The applied energies were 92, 108, 600, and 1000 eV. The dark-current increase was measured as a function of the dosage. Here, we note that silicon dioxide and silicon nitride insulator/dielectric layers can undergo charge-up, trapping photogenerated holes. These deplete the Si–SiO₂ layer interface and activate its generation-recombination centers. Subsequently, the dark-current increases along with the dark-current shot noise. This phenomenon can occur at both the Si rear and front sides.

Figure 3 shows the durability evaluation results for three CMOS sensors: AR-coated VIS, SBSA, and SP3. Here, we recall that the SBSA and SP3 sensors do not use any AR coating. The Si-layer thicknesses of the SP3, SBSA, and VIS sensors were 9.5, 3.5, and 4 μm, respectively. As per the results, the sensors were classified into 3 groups (Groups 1–3) as a degree of their durability (Fig. 3). The VIS sensor can be classified under Group 1, corresponding to low durability. The SBSA and SP3 sensors at 92 and 1000 eV, respectively, are categorized under Group 2 (medium durability). The SBSA sensor at 108 eV and SP3 sensor at 92–600 eV fall under Group 3 (high durability). In these devices, charge-up occurs in three regions: illuminated-surface layer, MOS-transistor gate insulator, and oxide layer on the photodiode’s front side. The VIS sensor used had a thick AR coating (several 100 nm), causing strong charge-up. On the other hand, because the SP3 and SBSA sensors had only a native-oxide layer instead of AR coatings on the illuminated (backside) surface, the illuminated-surface charge-up is possibly small. The charge-ups at the gate insulator and oxide layer on the photodiode’s front side are caused by photons penetrating the silicon layer. These charge-ups can be reduced with the use of thicker silicon layers to suppress photon penetration.

Figure 4 shows the calculated device transmittances for Si thicknesses of 3.5, 9.5, and 40 μm using IMD software.²² The transmittances significantly change at ∼100 eV and 1840 eV due to the silicon L- and K-absorption edges, respectively. For the Si thickness of 3.5 μm, the Si layer can only block 100–500 eV photons (transmittance of <0.1%). Adversely, photons with energies of <100 and >500 eV can penetrate the silicon layer to cause damage. In contrast, transmittance with the 9.5 μm thick silicon layer...
is <0.1% below 800 eV, which indicates the possibility of a small amount of charge-up on the front side.

The above discussion focuses on the photodiode dark-current, but we note that MOS transistor damage also occurs; the reference signal level shifts negatively after X-ray illumination of the Group 1 and 2 devices. The negative-shift amount is \( \sim 10 \) DN in the SP3 sensor for 1000 eV photons for an irradiation amount of \( 1.6 \times 10^8 \) photon/pixel. Because these sensors were measured using correlated double sampling (CDS),\(^{23}\) a simple threshold-voltage shift of the source follower amplifier transistor might have been compensated, and the reference-level shift may have been suppressed. However, if radiation damage slightly degrades the CDS, such a reference-level shift can occur. Here, we emphasize that this reference-level shift was not observed in Group 3 devices.

In summing the X-ray TID results, we note that Group 3 devices exhibit a slight dark-current increase due to native-oxide-layer charge-up. This dark-current increase is negligible for most applications, particularly when the sensor is cooled. The Group 2 devices show a non-negligible dark-current increase because the front-surface oxide of the photodiode is charged up by penetrative X-ray photons. The Group 1 devices suffer from a severe dark-current increase due to charge-up of the AR dielectric layers.

As regards durability, for EUV ptychography\(^{24,25}\) for EUV lithography mask inspection for example, a durability of \( 6 \times 10^{10} \) EUV photon/pixel is normally required, assuming that the incident photon number at the sensor center is \( \sim 10,000 \) photon/pixel/s and that the device is operated 8 h d\(^{-1}\) and 200 d yr\(^{-1}\). In our study, SP3 exhibited a dark-current increase of 300 electron/pixel at 42 °C when subjected to \( 6 \times 10^{10} \) EUV photon/pixel (Fig. 3). This dark-current value is acceptable for EUV ptychography. In addition, we also measured the dark-current–temperature dependence of the devices. The dark-current decreased by half for every temperature reduction of 5.7 °C. Thus, the dark-current increase at \(-10°\)C was \(<1/560\) times smaller than that at 42 °C, corresponding to 0.5 electron/pixel/s for 1 y of usage at \(-10°\)C; this increase is negligible for most practical applications.

In summary, our SP3 sensor exhibits the highest QE among all devices in the 80–1000 eV energy range. The device dead-layer thickness is only 5 nm, and its energy-resolving performance indicates that oxygen, nitrogen, carbon, and boron fluorescences can be identified. EUV photons can also be resolved. The device tolerance to soft-X-ray photons is also improved due to the thick Si layer of 9.5 \( \mu \)m. Importantly, the dark-current increase after 1 y usage for EUV ptychography is also negligible. The SP3 sensor also affords a high frame rate of 48 fps and low readout noise of 2.5 e\(^{-}\)rms, which are practical for general soft-X-ray experiments,\(^{26-34}\) indicating a potentially wide range of applications as it affords a high QE in the vacuum–ultraviolet regime and efficient low-energy electron sensing. This sensor could provide high-sensitive soft-X-ray imaging with low-readout-noise and high frame-rate condition. In future, we plan to develop a vacuum cooling system and apply the sensor in actual synchrotron experiments, and evaluate line spread function, which is an important parameter for spatial resolution.

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Fig. 3. (Color online) Exposure durability of VIS, SBSA, and SP3 sensors. The vertical axis represents dark-current increase and the horizontal axis the exposure dose. The dark-current is observed to increase with the dosage.

Fig. 4. (Color online) Calculated result of soft-X-ray transmittance of Si for various thicknesses.
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