Characterisation of a soft X-ray optimised CMOS Image Sensor

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ABSTRACT: A prototype CMOS Image Sensor optimised for soft X-ray applications has been designed by the Centre for Electronic Imaging in partnership with Teledyne-e2v. The device features four different pixel variants (three variants of 40 µm pitch pixels, and one variant of 10 µm pixels) each covering a quarter of the 2 × 2 cm² image area. The pixel designs feature fully depleted pinned photodiodes using reverse substrate bias and have been optimised for low noise operation, high responsivity and low image lag.

The fabricated front-illuminated devices have been tested in a custom-built vacuum test setup at operating temperatures between -30 °C and -40 °C. The sensors feature less than 5 e⁻ RMS readout noise and energy resolution of 142 eV at Mn-Kα (5.9 keV). The response to soft X-ray with different sensor parameters (e.g. pixel pitch, deep-depletion extension implant depth, and back-bias voltage) is also studied.

KEYWORDS: Photon detectors for UV, visible and IR photons (solid-state). X-ray detectors

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1 Introduction

The detectors of choice for many projects over a broad spectrum ranging from the near-infra-red end of the visible spectrum to the X-ray bands are silicon image sensors. These devices can offer a combination of high detection efficiency, low noise, high uniformity over a large area, etc. For soft X-ray applications, especially for astronomy missions, the Charge-Coupled Device (CCD) has been the workhorse detector (e.g. X-ray Multi Mirror Mission (XMM) [1], Swift [2], Chandra [3], and more recently the Soft X-ray Imager (SXI) of the SMILE mission [4]). However, CCD arrays are highly susceptible to proton-induced radiation damage resulting in the increase of Charge Transfer Inefficiency (CTI) which degrades the resolution. The effects caused by the damage of the CCD arrays are usually mitigated by cooling the devices to cryogenic temperatures to lock charge in the proton-induced traps. A charge generated by an X-ray can therefore be read out with lower CTI and remain within the mission’s requirements. The typical CCD operating temperatures range from -60 °C to -130 °C.

During the study for the design of the Transient High Energy Sky and Early Universe Surveyor (THESEUS) spacecraft [5], the resources allocated would have prohibited deep-cooling of the focal plane of its own SXI instrument, limited to around -30 °C. For the anticipated levels of Total Non Ionising Dose (TNID)-induced damage, an instrument using a CCD at this temperature would progressively lose the ability to sense soft X-ray photons over the mission’s lifetime. Therefore, a solution based on CMOS Image Sensors (CIS) has been proposed for the SXI Instrument.
The CIS technology has considerably advanced over the past two decades and offers comparable or better noise performance to CCDs, lower dark current, and a linear response over a very broad dynamic range. However, new developments are required to satisfy the requirements for a back-illuminated soft X-ray optimised device, including a thick fully depleted (>35 µm) substrate for high quantum efficiency up to 5 keV, large pixels (40 µm pitch), and low-noise readout to efficiently detect most of the signal from softer X-ray within a single pixel. Optical Blocking Filters (OBF) are also required to avoid stray light contamination. The combination of these features should provide high-resolution spectroscopic capabilities on the X-ray photons. Such technologies can also find use in terrestrial applications such as synchrotron research and free electron lasers (FELs). In addition, some of these technologies can be used in other astronomy applications e.g. low noise, larger pixels which are fully depleted with improved red-response. Because there is only a single transfer from the pinned photo-diode to the sensing node, the radiation-induced degradation to the Charge Transfer Efficiency (CTE) in CIS is vastly reduced and enables the construction of large arrays. Also, CIS can be operated with very low power and at high frame rates.

The Centre for Electronic Imaging (CEI) has developed new pixel designs to meet the performance requirements for a soft X-ray imager. These new designs have been integrated into Teledyne-e2v’s CAPELLA sensor [7]. The CAPELLA sensor is a multi-purpose scientific CIS composed of an array of 2048 × 2048 pixels with 10 µm pitch (2 × 2 cm²), a Charge-to-Voltage Factor (CVF) of 40 µV/e⁻, and approximately 6 e⁻ RMS noise with rolling-shutter readout (global shutter is also available). The column level ADCs can be used with different resolutions up to 14-bit and is designed to run at 20 fps (full-frame readout) with 12-bit ADC resolution. The HiRho variant of the CAPELLA device, named CIS220, features the Deep Depletion Extensions (DDE) technology with backside bias, successfully demonstrated with the BSB1 prototype sensor [8] and is fabricated on high-resistivity epitaxial substrates enabling fully-depleted operation.

The main features of CIS221-X are:

• **40 µm and 10 µm pixels.** Using larger pixels reduces charge splitting and improves single pixel energy resolution. Because the charge transfer relies mostly on diffusion, pixels larger than 10 µm can suffer from incomplete charge transfer from the PPD to the sense node (image lag). An additional pinning implant has therefore been implemented to concentrate the charge packet next to the transfer gate and reduce the lag.

• **A thick fully depleted sensitive volume.** A 35 µm thick sensitive volume enables high quantum efficiency for photon energies up to 5 keV and permits the rejection of any background
due to Galactic Cosmic Rays (GCR) in orbit. The depletion is achieved via reverse biasing the substrate using the DDE technology.

- **High conversion gain and low noise.** An increase of the CVF from 40 \( \mu \text{V/e}^- \) to above 70 \( \mu \text{V/e}^- \) and the use of low noise processes to reduce the noise below 5 e\( ^- \) RMS.

A schematic cross-section of the large pixel architecture is shown in figure 1.

![Schematic cross section of the pixel design. The additional pinning implant allows charge concentration in a smaller region next to the transfer gate to reduce "image lag".](image)

**Figure 1.** Schematic cross section of the pixel design. The additional pinning implant allows charge concentration in a smaller region next to the transfer gate to reduce "image lag".

Four pixel designs have been implemented in the prototype sensor: 3 variants of 40 \( \mu \text{m} \) pixels and one variant of 10 \( \mu \text{m} \) pixels each occupying a quarter of the image area. Details about the design of the pixel variants can be found in a previously released paper [9].

![A packaged front-illuminated CIS221-X. The 10 \( \mu \text{m} \) pixel variant occupies the top quarter of the image area, and the three 40 \( \mu \text{m} \) pixel variants occupy the bottom part. The area between the pixel array and the pads contain the digital architecture.](image)

**Figure 2.** A packaged front-illuminated CIS221-X. The 10 \( \mu \text{m} \) pixel variant occupies the top quarter of the image area, and the three 40 \( \mu \text{m} \) pixel variants occupy the bottom part. The area between the pixel array and the pads contain the digital architecture.

The prototype sensors have been fabricated in a 180 nm CIS process on high resistivity (>1 k\( \Omega \cdot \text{cm} \)) epitaxial substrates and feature either "medium" or "deep" DDE variants. A picture of a packaged front-illuminated device is shown in figure 2. Devices will then be back-thinned and
passivated by Teledyne-e2v [10, 11]. Some of the processed devices will have half of their area coated with an optical light-blocking filter (OBF) covering all the pixel variants from the centre to one edge of the device. The uncoated sections of the array will be uncoated silicon, to be used as a control area for characterisation of the optical and X-ray transmission.

3 Test setup

A test setup (picture and cross-section schematic shown in figure 3) dedicated to the CAPELLA family devices, and especially CIS221-X, has been designed and commissioned. As the device characterisation must be conducted at the expected operating temperatures (between -40 °C and -30 °C), the tests are conducted in a vacuum environment. The vacuum chamber has been designed to use as many off-the-shelf elements as possible to ease any modification and to allow some modularity for future tests. Selection of conflat flanges and the adoption of UHV design and commissioning techniques ensures improved vacuum quality and reduces molecular contamination that could affect the soft X-ray quantum efficiency. The setup was designed to fully automate the testing with remote access. The control of the system has been implemented with LabView.

The setup is arranged around a DN100CF 6-way cross used as the main chamber section. Vacuum is obtained with a Pfeiffer HiCube 80 Eco pumping station with a DN63 turbomolecular pump. On the opposite side, a custom-made flange connects an Oxford Instruments Jupiter 5000 series X-ray tube with a Tungsten anode to the chamber, which collimates the beam of X-rays onto a selectable fluorescence target to illuminate the device. Multiple fluorescence targets are mounted on a four-sided wheel, remotely controllable through the motorised rotary feedthrough attached to a custom flange on the top side of the 6-way cross. The position of the stage is not centred on the flange to maximise the flux onto the device. The collimated X-ray beam can hit the target to direct fluorescence photons on the device. The available targets are (main Kα energy in brackets): Aluminium (1487 eV), Titanium (4510 eV), Manganese (5898 eV) epoxied on an Aluminium plate, and Copper (8047 eV). The target selection and fine tuning of the angles (1.8°/step) is remotely controllable.

The flange directly facing the illuminated side of the tested device is holding a custom PCB with an array of LEDs. Each of the 8 available columns can be populated with 1 to 5 through-hole LEDs, depending on the required irradiance. Each column corresponds to a single wavelength and is remotely controlled from the outside of the chamber via a microcontroller board. The brightness and the wavelength are controlled using a Pulse Width Modulation (PWM) output routed to the corresponding LED column using a demultiplexer. Each wavelength line has an adjustable resistor to further control the irradiance. The selected wavelengths cover a broad spectrum from the near-UV to NIR. The microcontroller board is also used as the interface for the motorised rotational stage and for the X-ray tube trigger.

The sensor board has been procured from XCAM\(^1\), following design and development for other CEI projects. A vacuum seal is made by clamping O-rings against gold-plated rings on the PCB. The device under test is inserted on the board through a Zero Insertion Force (ZIF) socket. The camera PCB is connected to a National Instruments PCIe-1427 Frame Grabber via a Frame

\(^1\)https://www.xcam.co.uk/
Figure 3. (top) Picture of the CIS221-X test setup. The vacuum pump and recirculating water chiller can be seen on the left side. The X-ray tube’s power supply with its custom interlock system are around the vacuum chamber.
(bottom) Cross section schematics of the test setup as seen from the side (left) and from the top (right). (1) Water-cooled heat sink for the TEC cooler. (2) TEC cooler and a copper cold-finger. (3) Packaged device connected to the camera PCB (4) through a ZIF socket. (5) Vacuum gauge. (6) Electrical feedthrough or Residual gas analyser. (7) X-ray tube with W anode collimated towards a 4-sided target wheel (8) moved by a motorised rotary feedthrough (9). (A) Corrugated hose for the vacuum pump. (B) LED array controlled with an external Arduino (C) also controlling the motorised rotary feedthrough, and the X-ray interlock system.
Grabber Adapter (FGA), which converts the fibre optic transmission signal to CameraLink. The camera is controlled via a Python3 interface software. The board uses external connections to the backside bias supply line to permit measurement of the reverse current with a Keysight B2901A Source/Measure Unit (SMU). During normal operation, the reverse bias is applied with a bench power supply.

The custom tube section from the cross to the detector side of the PCB has two ports for the vacuum gauge and for an optional residual gas analyser (RGA, model: Pfeiffer QMG 220 F1). On the opposite side of the PCB, a custom chamber section contains the cooling system based on a TEC cooler. The excess heat of the hot side of the TEC is dissipated using a recirculating water-cooling system (Thermo-Fisher SC150 and A10). A copper cold finger is used to make thermal contact between the cold side of the TEC and the package of the sensor. The temperature is controlled using a bench-top power supply controlled using LabView’s PID capabilities.

The cooling system of the initial iteration of the test setup was based on a Stirling cooler and a heating element to raise and control the temperature above the baseline of the cooler. The change to a TEC-based cooler was motivated by the presence of high electromagnetic noise on the sensor by the Stirling cooler which negatively-impacted the noise and resolution measurements that will be discussed in the following sections.

4 Characterisation results

The initial characterisation of CIS221-X have been conducted on two front-illuminated devices: a medium DDE variant (SN: 21094-02-16) and a deep DDE variant (SN: 21094-11-09). Each electro-optical characterisation was conducted under vacuum (<10⁻⁵ hPa) and cooled to temperatures between -40 °C and -30 °C, and with the protective glass window removed.

An image obtained with a CIS221-X device under very low illumination is shown in figure 4. The sub-arrays labelled from $1$ to $3$ are 40 µm pixel variants, and the sub-array $4$ is the 10 µm variant. The signal in the 40 µm pixels is more than 16 times larger than in the 10 µm pixel due to its larger area and of proportionally less metal coverage in the optical path. The image exhibits a large amount of defects in the larger pixel variants only and has been observed on multiple devices (both tested in this study as well as devices tested for functionality by Teledyne-e2v). Additional testing and observations with back-thinned devices will be conducted to confirm the source of defects.

Initial testing have shown that all the pixel designs except the 40 µm labelled as $3$ suffer from excess lag despite the design considerations. In the following characterisation, we have used the X-ray performance as a way to quantify the image lag. The pixels showing excess lag all feature the same small transfer gate while the third large variant has a larger gate design. The effects of lag can be mitigated by increasing the transfer gate voltage. In the following sections, the characterisation will remain focused on the 40 µm variant $3$ and the 10 µm ($4$) variant and will only be labelled by their respective pitch. The transfer gate voltage was adapted to mitigate the image lag.

4.1 Reverse bias

The application of the reverse bias was tested by measuring the reverse current. The obtained curves shown in figure 5 permit to determine the maximum reverse bias that can be applied for normal operation. The calculation for the depletion depth [12] of a pn-junctions indicates that the substrate
should be fully-depleted over 35 µm with a minimum reverse bias of -11 V. However, to guarantee a non-zero electric field at the very back of the device, over-depletion operation is preferred and requires a back bias of approximately -20 V.

For the deep DDE variant, reverse biases down to -25 V can be applied which permits over-depleted operation. A reverse bias of about -20 V can be applied on the medium variant with leakage current for the whole device of about 1 µA, beyond the knee point visible around -12 V. For both DDE variants, the back bias can be increased further as the current remains acceptable beyond the breakdown limit, as long as the total reverse current in the whole 2 × 2 cm² array remains below 1 mA.

4.2 Readout noise

The readout noise was measured in the 40 µm pixel for both DDE variants without charge transfer from the PPD (V_TG=0 V) and with charge transfer (V_TG=3.8 V). The noise measured without charge transfer is the readout noise with the dark current contribution removed. The measurement with the deep DDE device was conducted 10 °C warmer than with the medium DDE and both variants were operated over-depleted at around 18 fps. A set of 100 dark frames were acquired for each condition and the standard deviation of signal in each pixel was computed to obtain the noise. The noise distributions, and the cumulative pixel noise are shown in figure 6.

Figure 4. Image obtained with a front-illuminated CIS221-X under low illumination. 1 40 µm variant #1, 2 40 µm variant #2, 3 40 µm variant #3, 4 10 µm variant.
Figure 5. Reverse current in both CIS221-X variants: medium and deep DDE.

Figure 6. (left) Noise distributions, (right) Cumulative pixel noise. TG off ($V_{TG}=0$ V): readout noise contributions only, dark current excluded. TG on ($V_{TG}=3.8$ V): all noise contributions.
The readout noise performance is similar in both variants and irrespective to temperature as observed by the dashed lines. Despite the cooling, the sensors appear to have substantial dark current that will be studied further. Some of the noise increase might be caused by the large amount of defects observed in the image (figure 2) and observed as the tail in the noise distributions (solid line). The main noise requirement for CIS221-X is less than 5 e\(^{-}\) RMS for the 90\(^{th}\) percentile with the dark current contribution excluded. Both variants achieve this performance with about 3.2 e\(^{-}\) RMS noise without the dark current contribution. With dark current, the noise is 4.65 e\(^{-}\) at -40 °C and 5.36 e\(^{-}\) at -30 °C, at 18 fps.

4.3 Linearity

The linearity measurement was conducted by illuminating the device using low gain settings with increasing illumination using a blue LED. The response was studied in the 10 µm variant which is common for all the pixel designs as they share the same sense node, the limiting factor for linearity and full-well capacity (FWC). The measured signal against the light intensity is shown in Figure 7, and has been converted to electrons using a soft X-ray calibration. The linear portion of the slope was fitted using an affine function over the range 1 – 50 a.u., and the residuals were computed to obtain the non-linearities.

![Figure 7](image_url)

**Figure 7.** Linearity of the CIS221-X architecture and affine fit constrained in the 1–50 a.u. range (top). Non-linearities (residuals) against the signal level (bottom).

In the interval 300 eV – 5 keV (82 e\(^{-}\) – 1370 e\(^{-}\)), less than 1 % non-linearity can be observed. Less than 1 % non-linearity is achieved up to 23.7 keV, and 2 % up to 32 keV (CIS221-X is transparent
to such energetic photons as the sensitive substrate is 35 \( \mu \text{m} \) thick). The 5 % non-linearity point, defining the FWC is reached at approximatively 14.5 keV.

### 4.4 Response to soft X-rays

The response of CIS221-X has been characterised using characteristic X-rays from different targets. However, additional lines can be observed due to the composition of the stainless steel of the vacuum chamber. The majority of the presented data was obtained with the Mn target. Data from the other targets were used for the study of the energy resolution. For the data acquisition, the X-ray tube was set to 20 kV and 10 \( \mu \text{A} \) providing sufficient photons per frame without significant superposition. The medium DDE device variant was cooled to -40 °C using the Stirling cooler, and the deep DDE variant was cooled to -30 °C using the TEC-based cooling system. For each dataset acquisition, a large number of frames with X-rays were acquired and the background subtracted using the median dark frame. An algorithm was used to extract pixel events to produce the isolated events spectra, the average events, the gradings and the energy resolutions. The threshold for detection was set to 5 times the 90\textsuperscript{th} percentile noise value. The parameters were extracted for both DDE variants, the large and small pixel, and across multiple back-biases.

#### 4.4.1 Pixels and variants comparison

The spectral response to X-ray of both pixel variants in the deep DDE variant is shown in figure 8. A similar response has been observed with the medium DDE variant with worse energy resolution as the noise was higher due to the Stirling cooler.

![Figure 8. Isolated events spectra for the large and small pixel with the deep DDE variant.](image)
Overall, more X-rays were collected in a single pixel in the 40 µm variant than in the 10 µm variant. In the large pixel, the spectral peaks are far more defined showing the improved single-pixel charge collection. Each event found by the algorithm has been graded following the XMM-Newton/EPIC event grade terminology [13]. The threshold for grading has been set to 5 times the 90th percentile noise value. The gradings for both pixel size in each DDE variant is shown in figure 9.

On average, more than 65 % of the X-rays have been collected in a single 40 µm pixel variant whereas less than 30 % were collected within a single 10 µm pixel. The single pixel collection is slightly better in the medium DDE variant. In the 10 µm pixel variants, the charge are mostly collected as split events irrespectively to the DDE variant. Finally, the grading process in the deep DDE returned a very large number of ungraded events, especially in the 10 µm variant.

4.4.2 Back bias comparison

The study of the response has also been conducted against different back-bias values from 0 V to an over-depleted regime depending on the DDE variant. The isolated events spectra at different back bias voltages in the deep DDE variant for the 40 µm variant is shown in figure 10.

Without any back-bias, very few events have been collected in a single pixel, but the Mn-Kα and Mn-Kβ lines can be seen and used for calibration. The poor single pixel response is due to diffusion of charge in the large non-depleted regions in the device. The spectra with an applied back bias appear very similar and allow to determine all the spectral lines from the target and chamber components. The energy peaks from the target (Mn-Kα, Mn-Kβ, and Al-Kα) are easily
discernible. The silicon fluorescence and escape peaks from the Mn lines can also be seen. Many different components from the fluorescence of the chamber’s stainless steel are observable (Cr-Kα, Fe-Kα that slightly broadens the Mn-Kβ, Fe-Kβ, Ni-Kα, and Cu-Kα). The W L-lines from the X-ray tube can also be discerned at the higher energies.

By using the average event, the proportion of charge present in the central pixel and in their two neighbouring rings have been extracted for various back-bias voltages for the 40 µm pixel variant to compare the DDE implant types. The influence of the size of the pixel in each variant has also been compared at a similar back-bias voltage of -20 V. The results are shown in figure 11.

With back-bias as low as -5 V, the response in the large pixel variant is similar in both DDE variant with a slightly lower performance in the deep DDE variant, but operating with 0 V back-bias would not be expected for these devices. Without back-bias, the performance of the medium DDE is by far superior than the deep DDE. At the same back-bias voltage, the charge collection performance of the medium DDE appears to be better than in the deep DDE for both pixel variants with more signal being in the central pixel on average. The grading of each event against the back bias has been conducted for each DDE variant in the 40 µm pixel structure and is shown in figure 12.

A similar trend as for the average event is seen with the event gradings: better single pixel performance in the medium DDE with the lowest voltages. At a similar bias (e.g. -20 V), more events have proportionally been collected by a single pixel in the medium DDE variant. Pushing the back-bias voltage in the deep DDE variant to -30 V is not sufficient to achieve the same performance as in the other variant with a lower bias. The deep DDE variant appears to have some negative effect on charge collection such as a potential pocket caused by partial depletion [8]. The medium
DDE variant therefore appears to be the best candidate for the design of a large soft X-ray CIS.

4.4.3 Energy resolution

The energy resolution was computed using the spectral lines in the reconstructed isolated spectra. The energy peak has been fitted using a non-centred non-normalised Gaussian function to obtain the standard deviation ($\sigma$). The energy resolution is determined by calculating the full-width-half-maximum (FWHM) of the peak:

$$\Delta E(FWHM) = 2.355\sigma$$  \hspace{1cm} (4.1)

The energy resolution for the Mn-K$\alpha$ spectral line (5.898 keV) for the 40 µm pixel variant using the deep DDE implant against different back-bias values ranging from 0 V to -30 V is shown in figure 13. Without any supplied bias, the energy resolution is 172 eV FWHM and decreases with the increase of the back-bias and depletion in the sensitive volume. Below $V_{bb} = -10$ V, the energy resolution is below 145 eV FWHM and plateaus around 142 eV FWHM below -20 V.

The energy resolution was also probed for other spectral lines from fluorescence of other targets and from the components of the stainless steel. The probed energies are ranging from Al-K$\alpha$ (1.487 keV) to Cu-K$\beta$ (8.904 keV). The resulting resolutions with each type of DDE with the 40 µm pixel are marked in figure 14.

The energy resolution in the medium DDE appears worse than in the deep DDE which is caused by the higher readout noise when using the Stirling cooler. For both variants, the points
Figure 12. Event grading for the 40 µm pixel variant for each type of DDE against back-bias voltage.

have been fitted using their individual components. The first main contributor is the sensor readout noise component used is the 90th percentile noise ($\sigma_N [eV] = \epsilon \sigma_n [e^{-}]$, with $\epsilon$ the ionisation energy in silicon). The Fano-limited shot noise ($\sigma_F = \sqrt{\epsilon FE}$) is the second contributor (Fano factor: $F=0.11$ and $E$ the photon energy). The final considered component ($\sigma_x = \sigma_g E$) is proportional to the photon energy and can be attributed to inter-pixel gain differences ($\sigma_g$) that can be reduced by thorough calibration. The total energy resolution is given by the following equation [14]:

$$\Delta E = 2.355 \sqrt{\left(\sigma_g E\right)^2 + \epsilon FE + (\epsilon \sigma_n)^2}$$  (4.2)

The data points for each DDE variant have been fitted with equation 4.2 with a free parameter ($\sigma_g$). Both fit results (with different noise contributors) have provided the same value for the inter-pixel gain variation: 0.52 %. The noise with the Stirling cooler turned-off was measured for the medium DDE device. The energy resolution was then re-estimated with this lower noise and is shown as the dashed black line. The expected energy resolutions against the photon energy are very close to the ones measured with the deep DDE device. As the measured noise of the medium DDE variant with the Stirling cooler off (4.65 e⁻) is even slightly lower than the deep DDE device’s noise (5.36 e⁻), the medium DDE should be able to provide slightly better energy resolution performance than the deep DDE.

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Deep DDE

Medium DDE

Gradings

Gradings

Events proportion [%]
Figure 13. Energy resolution at 5.898 keV (Mn-K\(\alpha\)) of the 40 \(\mu\)m pixel variant with the deep DDE implant against back-bias.

Figure 14. Energy resolution and their components for both DDE variants (40 \(\mu\)m pixel pitch) against photon energy.
5 Conclusions and future work

A prototype CIS optimised for soft X-ray applications has been developed and fabricated. The device features a $2 \times 2$ cm$^2$ pixel array composed of 4 pixel types occupying each a quarter of the area (three 40 µm pitch variants and one 10 µm pitch variant). All the pixels have been designed to reduce the noise, be fully-depleted and to minimise image lag. The calibration results of the front-illuminated devices have shown that the noise has been reduced but that some pixels suffer from excess image lag which can be mitigated by increasing the transfer gate bias. Despite a large number of cosmetic defects, the most promising 40 µm pixel variant (#3) has been thoroughly tested and compared to the 10 µm variant for X-ray performance.

The devices have been fabricated in two variants consisting of different DDE implants ("medium" and "deep"). Both DDE variants have shown excellent performance within the expectations. The X-ray events study has shown that the most suitable DDE implant variant is the "medium" as the single pixel charge collection performance appears superior with lower applied back-bias voltages. The improved charge collection and smaller charge sharing with the 40 µm pixels has also been demonstrated.

The energy resolution was assessed for both DDE types with the 40 µm pixel variant over a broad spectral range. Both implant levels have demonstrated similar results. At 5.9 keV, energy resolutions of 142 eV FHWM have been demonstrated. This performance can be improved further by thorough calibration and subtraction of the pixel-to-pixel gain spread. The total readout noise is also higher than anticipated because of high dark current which is under investigation.

Devices are being back-thinned and post-processed by Teledyne-e2v to be operated back-illuminated. Some devices will also be half-coated with an optical light blocking filter. Back-illuminated devices will undergo full characterisation to assess their performance. Devices will also be tested at a synchrotron light source to assess their quantum efficiency with and without OBF. Back-illuminated sensors will also be irradiated with both protons and gamma rays to assess their performance at typical end-of-life doses during a space mission. Heavy-ion irradiation of devices of the CAPELLA family will provide results about their single event effect immunity.

Acknowledgments

This programme is funded by ESA under the E/0901-01 Technology Development Element "CMOS Image Sensor for X-ray Applications".

References


