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Calibrating Teledyne-e2v's ultraviolet image sensor quantum efficiency processes

Julian Heymes^a, Matthew Soman^a, Thomas Buggey^a, Chiaki Crews^a, George Randall^a,
Alexander Gottwald^b, Andrew Harris^c, Andrew Kelt^c, Udo Kroth^b, Ian Moody^c, Xiao Meng^a,
Oskar Ogor^b, and Andrew Holland^a

^aCentre for Electronic Imaging, The Open University, Walton Hall, Milton Keynes,
United Kingdom

^bPhysikalisch-Technische Bundesanstalt, Abbestraße 2-12, Berlin, Germany

^cTeledyne-e2v, 106 Waterhouse Lane, Chelmsford, United Kingdom

ABSTRACT

Teledyne-e2v's sensors and wafer-scale processing are widely used for high performance imaging across soft X-ray and optical bands. In the ultraviolet spectral range, the combination of short absorption lengths (below 10 nm) and high reflectance (up to 75 %) can strongly limit the quantum efficiency. Direct detection capability relies on back-illumination and back-thinning processes to be applied to a sensor to remove dead layers from the optical path. As the thinning process leaves an unacceptably thick backside potential well as well as a highly reflective surface, in-house ultraviolet-specific (e.g. for WUVS) or third-party processes (e.g. delta-doping for FIREBall) are required.

We have calibrated Teledyne-e2v's latest in-house wafer-scale proprietary processes with monochromatic synchrotron radiation over a wide spectral range in the ultraviolet domain ($\lambda=40$ nm – 400 nm) at the Metrology Light Source of the *Physikalisch-Technische Bundesanstalt*. The first process is a shallow p+ implantation that permits the thinning of the backside potential well. It is available in two different levels: basic and enhanced. The second type of enhancement is a specific anti-reflective coating to increase the back-surface transmittance for distinct spectral ranges.

In this paper, we will present comparative quantum efficiency calibration of both passivation stages and of two different ultraviolet specific anti-reflective coatings (applied on enhanced passivation devices). Also, their stability after intense ultraviolet illumination will be shown. These measurements will permit Teledyne-e2v to extend the quantum efficiency data of their most recent processes across the soft X-ray to near-infrared spectrum.

Keywords: CCD, CIS, X-ray, EUV, VUV, Passivation, Coating, Quantum efficiency

1. INTRODUCTION

A large variety of scientific and industrial applications in the ultraviolet spectral range require imaging devices with optimised Quantum Efficiency (QE). This figure of merit expresses the proportion of detected photons from a known number of incoming photons ($N_{IncidentPhotons}$). The number of detected photons is obtained from the efficiently collected charge signal in electrons ($N_{electrons}$), proportional to the quantity of photo-converted photons absorbed in the sensitive volume ($N_{DetectedPhotons}$). The quantity of photons is related to the number of electrons by the Quantum Yield (QY): the charge generated for each converted photon. The quantum yield value for photons in the visible spectral range is 1 electron/hole pair and is the ratio of the photon energy by its ionisation energy in the X-ray – ultraviolet spectral range. Equation 1 gives the general relation between detected signal and photon fluence to obtain quantum efficiency:

$$QE = \frac{N_{DetectedPhotons}}{N_{IncidentPhotons}} = \frac{N_{electrons}}{QY \times N_{IncidentPhotons}}. \quad (1)$$

Further author information: (Send correspondence to J.H.)

J.H.: E-mail: julian.heyms@open.ac.uk, Telephone: +44(0)1908 655351

Thinned back-illuminated Charge Couple Devices (CCD) and CMOS Image Sensors (CIS) require spectral range or wavelength specific post-processing steps to achieve high quantum efficiency performance. The thinning process leads to the formation of a backside potential well that attracts photoelectrons generated close to the back surface and are consequently lost by recombination. The trapped photoelectrons are then lost by recombination.¹ Therefore, the first post-processing step consists of minimising the width of the backside potential well to be in the order of or smaller than the shortest absorption length to improve the wideband response. The second step consists of reducing the reflectivity of the back-surface by using anti-reflective coatings for targeted wavelength ranges. Proprietary wafer-level processes are commercially available from Teledyne-e2v as well as from third parties. Teledyne-e2v recently upgraded their ultraviolet processes that required quantum efficiency characterisation to provide useful data for the current and future space, scientific, and industrial applications. The measurements also support testing of models for understanding and for the prediction of quantum efficiency. The characterisations of the passivation processes also permit to fill the gap between the visible spectrum, routinely tested by Teledyne-e2v, and the soft X-ray results from a previous work.²

Examples of scientific applications in the ultraviolet spectrum requiring the use of such post-processes include space-applications:

- FIREBall-2: uses an EMCCD with δ -doping³ and anti-reflective coatings from JPL-MDL. The spectral range of interest is $\lambda=200$ nm–210 nm.⁴
- ULTRASAT: the UV focal plane array of the ULTRACam uses the developments from FIREBall-2 applied on Teledyne-e2v's CCD42-80. The spectral range of interest is $\lambda=220$ nm – 280 nm.⁵
- WSO/UV: the WUVS instrument is composed of CCD272 and uses Teledyne-e2v's proprietary processes presented in this paper. The spectral range of interest of the spectrographs are: $\lambda=102$ nm – 176 nm (VUVES), and $\lambda=174$ nm – 310 nm⁶
- EnVision is expected to use a Teledyne-e2v Capella (CIS120) for the VenSpec-U instrument. The spectral range of interest is $\lambda=190$ nm–380 nm.⁷

Other scientific examples applications benefiting from the improvements:

- Dark matter direct detection: Silicon Photomultipliers (SiPM) to be used as scintillation detectors in time projection chambers (TPC). The scintillation wavelength, in the ultraviolet spectral range, depends on which noble gas is used; LAr: $\lambda=128$ nm, LXe: $\lambda=175$ nm.⁸ For direct detection, a wavelength shifter (tetraphenylbutadiene (TPB)) can be applied to obtain $\lambda=420$ nm photons with limited efficiency.⁹ The use of anti-reflecting coatings are therefore considered.
- Any synchrotron application in the ultraviolet spectrum such as surface characterisation¹⁰ or reflectometry.¹¹

An example of industrial application is semiconductor excimer laser lithography with a typical wavelength of 193 nm.¹²

In this paper, we will first describe the limiting factors for achieving high quantum efficiency as well as the processes used by Teledyne-e2v to improve the detection performance. We will then describe the quantum efficiency calibration method we followed. The results will then be presented for different processing levels. The passivation processes calibration results have already been published¹³ and are included as a baseline reference for the anti-reflective coatings. Finally, we will assess the stability and uniformity of the processes.

2. DIRECT DETECTION OF ULTRAVIOLET RADIATION IN SILICON

2.1 Absorption and reflection

Quantum efficiency in back illuminated silicon devices is limited by three main wavelength dependent components: the thickness of the sensitive volume (transmission at longer wavelength or harder X-rays, and to minimise the

distance between the back-surface and the collection potential well), the thickness and composition of the non-sensitive layers at the back surface (e.g. coating, metallisation, backside potential well), and the reflectance of the surface.

Achieving high quantum efficiency first requires a sufficiently thin non-sensitive layer with respect to the absorption length, or attenuation length, defined as the distance after which 37 % ($1/e$) of the incoming photons are transmitted. Any photon absorbed within the non-sensitive layer (any coating or in the backside potential well) will not contribute to the signal generation.

The absorption length can be calculated in two different ways depending on the spectral range of interest. For X-rays (down to EUV), the absorption length α can be calculated from the mass attenuation coefficients μ/ρ ¹⁴ and from the imaginary part k of the complex refractive index ($\underline{n} = n_r + ik$ ^{15,16}) in the ultraviolet to the near infra-red range.

Figure 1: Absorption length in silicon and reflectivity at the air(vacuum)/silicon interface for wavelengths between 0.62 nm and 800 nm (2 keV-1.55 eV). Darker shades represent the spectral range of the quantum efficiency characterisations in this work ($\lambda=40$ nm – 400 nm)

The attenuation length for photon energies between 2 keV and 1.55 eV ($\lambda=0.62$ nm–800 nm) in silicon is shown in figure 1a as the solid line and in SiO₂ as the dashed line. In the range of interest of this study ($\lambda=40$ nm–400 nm, highlighted as the black portion of the curve), the attenuation length drops to be less than 10 nm with a minimum of 4.2 nm at $\lambda=285$ nm. An absorption length of less than 10 nm in SiO₂ can also be observed on a much smaller spectrum ($\lambda=50$ nm–100 nm). As the typical native oxide thickness is very thin (≈ 2 nm), its influence on quantum efficiency will remain small.

The back-thinning process leaves dangling bonds in the silicon crystalline structure which produces surface traps and leads to a back-side potential well caused by net positive charge in the native oxide. Any charge photo-generated within this potential well will be trapped and lost by recombination. Quantum efficiency measurements performed by Teledyne-e2v in the visible spectrum on an etched device without further processing¹⁷ allowed to estimate the width of the backside potential well to be at least 568 nm.

The second component that influences quantum efficiency is the reflectivity, which is the proportion of photons from an incident beam being reflected at the interface of different materials. It is calculated using the complex refractive indices^{15,16} of each material. The reflectivity of each interface composing the back surface (vacuum/native oxide, native oxide/Si, vacuum/native oxide/Si, and vacuum/Si for reference of a non oxidised surface) are shown in figure 1b. The vacuum/native oxide/Silicon reflectivity has been obtained using the Macleod software with published refractive indices and absorption coefficients.^{15,16}

In the ultraviolet spectrum, the reflectivity of an uncoated back surface remains above 50 % from around $\lambda=140$ nm and $\lambda=400$ nm. A maximum total reflectivity of about 75 % around $\lambda=270$ nm is the cause of low quantum efficiency. The comparison of the reflectivity of back surfaces with and without SiO_2 suggests that the presence of native oxide reduces the total reflectivity below $\lambda=200$ nm.

2.1.1 Back surface passivation

A method capable of reducing the width of the backside potential well consists of a shallow implantation of higher doping concentration to passivate the back surface. Molecular beam epitaxy has proven to be capable of forming ultra thin p+ layers of around 1 nm³ but is not widely available for industrial processing.

Two levels of wafer-level passivation, detailed in a previous publication,¹³ are available from Teledyne-e2v. The first level, referred as the basic process, is a 40 nm $\pm$ 10 nm thick p+ layer¹⁸ (the effective width of the potential well is thinner). The second consisting of an extra etching process is referred as the enhanced process.

2.1.2 Anti-reflective coatings

Further improvement of quantum efficiency in the ultraviolet spectral range requires acting on the reflectivity of the back surface. Alike for the thinning of the backside potential well, various methods exist such as anti-reflective coatings that can either be narrow-band or wide-band. Teledyne-e2v has enhanced their ultraviolet anti-reflective coating process to maximise optical transmittance at $\lambda=193$ nm and to maximise the intrinsic negative charge therefore capable of improving quantum efficiency over a wider spectral range ($\lambda=150$ nm–250 nm). Two variations of the coating are available named VUV1 and VUV2, respectively.

3. CALIBRATING THE ULTRAVIOLET QUANTUM EFFICIENCY

3.1 The normal incidence monochromator beamline

Quantum efficiency measurements require maintained standard calibration sources for comparative flux measurements. The selected facility providing reference measurements of monochromatised synchrotron radiation in the ultraviolet spectral range is the normal incidence monochromator beamline (NIM) (or M4 beamline) at the Metrology Light Source (MLS) of the *Physikalisch-Technische-Bundesanstalt* (PTB), located in Berlin (Germany).¹⁹

The available spectral range spans from $\lambda=40$ nm to $\lambda=400$ nm ($E=31$ eV – 3 eV). The photon flux is usually between 10^{10} s⁻¹ to 10^{12} s⁻¹ but can be reduced to 10^8 s⁻¹ – 10^9 s⁻¹ depending on the wavelength and on the beamline configuration. The flux can be distributed within an area of up to 3×2 mm² when in focus. The effective beam size depends on the wavelength, on the beamline configuration, and on the focus. Out of focus operation was preferred to minimize the local flux and to prevent pixel saturation.

3.2 Tested devices, camera system, and operating conditions

The quantum efficiency characterisation of the passivated, and of the anti-reflective coatings were split into two distinct calibration campaigns (the first conducted in March 2019, and the second in June 2019). A third measurement campaign was performed in November 2019 for comparative measurement of anti-reflective coatings after lifetime level of ultraviolet exposure. The procedure and results of the third set of measurements will be developed in section 5.

The two levels of post-thinning passivation processes, basic (S/N: 15051-12-44) and enhanced (S/N: 15051-07-07), have been tested on uncoated back-illuminated CCD97s. The specificities of those devices have been detailed in a previous publication¹³ and the results are shown here to provide a baseline for the coated devices.

The ultraviolet anti-reflective coatings, optimised for $\lambda=193$ nm with improved efficiency for $\lambda=150$ nm – 250 nm, have been tested during the second campaign, with back-illuminated enhanced passivation (thinned to 16 μm) CCD30-11 taken from the standard production line as well. Most of the anti-reflection coated devices tested for lifetime stability (3rd campaign) were different from the reference measurements of the second campaign.

A summary of the selected devices are listed in table 1.

Table 1: List of the characterised devices.

S/N	Type	Passivation	Coating	Campaign	Lifetime Exposure	Temp. [K]
15051-12-44	CCD97	Basic	None	Soft X-ray, 1	None	228
15051-07-07	CCD97	Enhanced	None	Soft X-ray, 1	None	228
14421-13-11	CCD30-11	Enhanced	VUV 1	2, 3	Medium	288
14421-13-12	CCD30-11	Enhanced	VUV 1	2	None	288
14421-11-11	CCD30-11	Enhanced	VUV 2	2	None	288
14421-11-12	CCD30-11	Enhanced	VUV 2	3	Medium	288
14421-11-32	CCD30-11	Enhanced	VUV 2	3	High	288

Each device has been operated using the same electronics and was tested (^{55}Fe laboratory characterisation, and at the beamline) following the methods presented in our previous work.¹³ The differences between each type of device are the operating temperature: 228 K for CCD97 and 288 K for CCD30-11, the number of rows readout: 5000 for CCD97 and 8000 for CCD30-11, as well as the row readout time: 700 μs for CCD97 and 590 μs for CCD30-11.

As the devices were readout in TDI mode while the beam was continuously on, the obtained images have a smeared aspect as shown for each type of device in figure 2. The data in each row outside the integrated spot area (e.g. the parallel overscan region) corresponds to the spot signal integrated for the row readout time.

Figure 2: Left: image obtained with an enhanced passivation CCD97 readout in TDI mode, resulting in a smeared aspect, following a 500 ms integration to observe the shape of the $\lambda=190$ nm spot at the centre of the image area. Right: same image obtained with an anti-reflection coated CCD30-11. The total number of rows shown are reduced to 2000 for display purposes.

3.3 Quantum Yield correction

The light grey points in figure 3 show the computed quantum efficiency of the enhanced passivation process for each tested wavelength using the method presented in our previous work.¹³ However, for $\lambda < 70$ nm the quantum

efficiency values are above 100 %. This non-physical outcome is due to the assumption that the quantum yield, the charge generated by a single photon, is 1 electron/photon as in the visible spectrum.

Figure 3: Example of quantum yield correction of the quantum efficiency for a passivated device.

In the soft X-ray regime, the quantum yield is the ratio of the photon energy with the ionisation energy in silicon (3.66 eV). This relation allows the calibration from a known source.

The same relation also exists in the ultraviolet spectral range but the ionisation energy, and therefore the quantum yield, is wavelength dependent. Published ionisation energy²⁰ (W_{Si}) data completed by the soft X-ray ionisation energy at shorter wavelengths have been used to determine the quantum yield using equation 2:

$$QY(\lambda) = \frac{hc}{\lambda W_{Si}}. \quad (2)$$

The quantum yield calculated points are shown on figure 3 as the circle and diamond markers. An 8th order polynomial fit was applied to the point to obtain the quantum yield correction function valid for wavelengths between 40 nm and 400 nm. This corrective function was then applied to the calculated quantum efficiency points resulting in the corrected quantum efficiency shown as the black points ($QE_{corr} = QE/QY$). At the shortest wavelengths, the quantum efficiency remains below 100 %.

4. RESULTS

The quantum efficiency of the passivation processes, and the anti-reflective coatings available from Teledyne-e2v have been characterised in two distinct campaigns following the methods previously presented.

4.1 Passivation processes

The measured quantum efficiency of both passivation levels, completing the soft X-ray ones² and already presented in a previous work,¹³ are shown on the right side of figure 4 to provide a baseline for the characterisation of the anti-reflective coatings. For wavelengths between 75 nm and 320 nm, where the thickness and composition of the backside non-sensitive layers as well as the reflectivity are the most critical, the characterized quantum efficiency remains below 10 % with a minimum of $3.86 \% \pm 0.23 \%$ at $\lambda=100$ nm for the basic passivation.

Slightly higher efficiencies, below 15 %, are observed for the enhanced passivation device with a minimum of $7.91 \% \pm 0.41 \%$ at $\lambda=105$ nm. The enhanced passivation process offers more than 50 % improvement over the basic one for wavelengths between 70 nm and 370 nm and is even doubled in the range 80 nm – 115 nm.

Figure 4: Top: Quantum Efficiency measured for the two backside passivation processes applied on back-thinned CCD97 (basic: black diamonds; enhanced: red triangles). Bottom: ratio between the enhanced and the basic versions of the passivation process. The red dashed line delimits the data from the soft X-ray calibration² on the left side with the logarithmic x-axis, and from the ultraviolet characterisation¹³ on the right side with the linear x-axis. The discrepancy at the junction is due to higher errors at the shortest wavelengths tested in the ultraviolet spectral range.

4.2 Anti-reflective coatings

The results for the anti-reflection coated devices are shown in figure 5. For wavelengths above 130 nm, the quantum efficiency increases substantially with respect to the uncoated device. Below, the added coating material reduces the efficiency by absorbing almost every photon, leading to about 0 % quantum efficiency in the VUV2 variant. The efficiency of the VUV1 coating is higher for wavelengths up to 310 nm peaking at $60.27 \% \pm 2.63 \%$ at $\lambda=210$ nm. A minimum of $5.45 \% \pm 0.42 \%$ is observed for $\lambda=100$ nm.

The quantum efficiency is more stable for the VUV1 version between $\lambda=200$ nm and $\lambda=400$ nm than for the VUV2 coating. Within this wavelengths range, the minimum quantum efficiency of the VUV1 coating is observed for $\lambda=280$ nm (due to shorter attenuation length): $37.67 \% \pm 1.2 \%$. The VUV2 coating allows detection of photons above $\lambda=130$ nm. The quantum efficiency is lower than with the VUV1 coating for $\lambda < 320$ nm ($53.95 \% \pm 1.74 \%$ for $\lambda=200$ nm, and $27.95 \% \pm 0.85 \%$ for $\lambda=270$ nm). Above this wavelength the quantum efficiency increases drastically to reach $80.87 \% \pm 2.51 \%$ for $\lambda=400$ nm.

Figure 5: Quantum efficiency measured for the two anti-reflective coatings applied over an enhanced passivation processed CCD30-11.

5. PROCESSES STABILITY

The tested processes can be used in a broad range of applications, with different operating conditions and with different lifetime levels of exposure. The stability of the quantum efficiency of each processes after lifetime levels of exposures have been tested. The thermal stability and the uniformity of the quantum efficiency of the anti-reflective coatings have also been assessed.

5.1 Effects of lifetime UV exposures on the passivation processes

During the first characterisation campaign, after the acquisition of the data presented in section 4.1, the tested devices were exposed, while running, for several hours to a high flux of 200 nm photons to observe the effects of intense high flux UV exposures. The results presented in a previous work¹³ have shown that the long exposures may have affected the reflectivity properties of the back surface by adding or removing contamination at the surface or may have improved the internal quantum efficiency by negative charging of the oxide layer (QE-pinning¹). The rapid change followed by stable performance with continuing exposure tends to rule out accumulating contamination material. Negative charging is considered the most likely cause, but the reflectivity change cannot be ruled out without additional measurements.

5.2 Effects of lifetime UV exposures on the anti-reflective coatings

For the lifetime test of the anti-reflective coatings, a different exposure method was used before their quantum efficiencies were measured during a third campaign at the M4 beamline.

5.2.1 254 nm lifetime exposure

A set of four anti-reflective coated CCD30-11 devices, two of each type (VUV1 and VUV2), have been exposed at room temperature to lifetime levels of ultraviolet light (at $\lambda=254$ nm). Half of the active area were covered with adequate aluminium shielding to perform comparative measurements of exposed and unexposed areas. The shielding was similar on each device: the side of pin 1 remained exposed.

The light source used was a low pressure mercury vapour lamp with fused silica envelope emitting UVC light at $\lambda=253.7$ nm. The 184 nm component was blocked to suppress ozone production. Longer wavelengths (i.e. blue light) were stopped by a long cut filter, and appropriate interlocking permitted safe operation. The monochromaticity and the photon flux stability for the full exposure period were confirmed with a set of different reference photodiodes (a wideband Hamamatsu S1337-1010BQ, and a 254 nm narrowband Hamamatsu S12742-254). The temperature on the focal plane was monitored throughout the illumination and remained stable.

A device of each type of anti-reflective coating was removed during the exposure to test two different lifetime exposure levels: $1.41 \times 10^{19} \text{ cm}^{-2}$, and $6.25 \times 10^{19} \text{ cm}^{-2}$ referred as medium and high, respectively.

The devices were tested in laboratory for basic functions after exposure and the VUV1 device exposure to the high level did not respond and was removed from the list of devices to be characterised at the beamline. The first characterisation at the beamline started 11 days after the end of the exposure.

5.2.2 Stability after lifetime exposure

Figure 6: Quantum efficiency measured for the two anti-reflective coatings applied over an enhanced passivation processed CCD30-11 after lifetime levels of exposure to $\lambda=254$ nm ultraviolet light.

The quantum efficiency of the three devices exposed to lifetime levels of ultraviolet light was characterised in the exposed and covered areas following the same method as before. The measured quantum efficiencies are shown in figure 6. No major difference can be observed between each side and the results are very similar to the devices that have not been exposed (figure 5).

The absolute difference from the reference measurement (section 4.2) is shown on the left plot in figure 7, and the difference between each side (exposed and covered) on the right plot. Both figures have been limited to a range of wavelength comprised from $\lambda=150$ nm, the minimum targeted range of the anti-reflective coatings, to $\lambda=400$ nm.

The absolute difference between each sides remains stable for both type of anti-reflective coating and remains within the error bars. A similar trend is observed when comparing the exposed side to the unexposed reference measurement of the second campaign: less than 2 % absolute relative variation is observed and widely remain

Figure 7: Left: absolute quantum efficiency difference between the exposed and covered sides of the lifetime anti-reflective test devices. Right: absolute quantum efficiency difference between the devices exposed to lifetime levels of 254 nm ultraviolet radiation and the reference unexposed devices (2nd campaign).

within the error bars. Therefore, no noticeable difference can be observed after lifetime levels of ultraviolet light on the anti-reflective coatings and can be considered as stable.

6. CONCLUSIONS

In this work, a method to measure the quantum efficiency in the ultraviolet range has been established. Along with previous work reported in the soft X-ray range reported² and more common measurements available in the visible range characterisation of quantum efficiency response across a very wide wavelength has been established and will be useful in characterising manufacture baseline performance and potential process improvements and to test physical models of quantum efficiency.

The measurements have been applied to two passivation process types available from Teledyne-e2v. The basic passivation process consists of a low-energy boron implantation at the back-surface followed by ultraviolet laser annealing providing a thin p+ layer. The enhanced process consisting of an additional etching of the implanted back-surface provides an even thinner p+ layer.

The measurements were conducted with wavelengths ranging from 40 nm to 400 nm. An efficiency up to 15 % at the most challenging wavelengths close to $\lambda=285$ nm where the absorption length is short, and the reflectivity is high has been measured for the enhanced process. Overall, in the most critical spectral range ($\lambda=70$ nm–370 nm), the enhanced passivation process offers more than 50 % higher quantum efficiency compared to the basic process. The devices were exposed to long high flux ultraviolet exposures to observe any change. An increase of the quantum efficiency has been observed with both processes. The determination of the cause would require additional measurements and studies such as reflectivity measurements as well as carrier lifetime measurements.

The test anti-reflective coatings have provided a large improvement of the quantum efficiency beyond their targeted wavelength range ($\lambda=150$ nm – 250 nm). The VUV1 coating provides an overall better response above $\lambda=130$ nm and the VUV2 coating shall be considered for applications closer to the visible spectrum (above $\lambda=300$ nm) but still provides better response than the uncoated devices. The results were used as a baseline to compare the change of the quantum efficiency of coated devices that have been exposed to lifetime levels of

254 nm light. No noticeable variation beyond the errors have been observed. The stability was also confirmed from comparing exposed and covered part of the devices.

The measurements conducted in this work were at normal incidence. Further work could include quantum efficiency characterisation of the processes at various incident angles to provide reference values for applications with isotropic illumination.

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REFERENCES

- [1] J. R. Janesick, *Scientific Charge-Coupled Devices*, SPIE, Jan. 2001.
- [2] I. Moody *et al.*, “CCD QE in the Soft X-ray Range,” *e2v Technologies white paper*, 2017.
- [3] M. E. Hoenk *et al.*, “Delta-doped back-illuminated CMOS imaging arrays: progress and prospects,” in *Infrared Systems and Photoelectronic Technology IV*, E. L. Dereniak, J. P. Hartke, P. D. LeVan, R. E. Longshore, and A. K. Sood, eds., SPIE, Aug. 2009.
- [4] K. Hoadley *et al.*
- [5] S. Nikzad *et al.*, “High-efficiency UV/optical/NIR detectors for large aperture telescopes and UV explorer missions: development of and field observations with delta-doped arrays,” *Journal of Astronomical Telescopes, Instruments, and Systems* **3**(3), pp. 1 – 24, 2017.
- [6] K. Werner *et al.*, “HIRDES – the high-resolution double-echelle spectrograph for the world space observatory ultraviolet (WSO/UV),” *Advances in Space Research* **41**, pp. 1992–1997, Jan. 2008.
- [7] J. Helbert *et al.*, “The VenSpec suite on the ESA EnVision mission to Venus,” in *Infrared Remote Sensing and Instrumentation XXVII*, M. Strojnik and G. E. Arnold, eds., **11128**, pp. 18 – 32, International Society for Optics and Photonics, SPIE, 2019.
- [8] F. Acerbi *et al.*, “Silicon photomultipliers: Technology optimizations for ultraviolet, visible and near-infrared range,” *Instruments* **3**, p. 15, Feb. 2019.
- [9] C. E. Aalseth *et al.*, “DarkSide-20k: A 20 tonne two-phase LAr TPC for direct dark matter detection at LNGS,” *The European Physical Journal Plus* **133**, Mar. 2018.
- [10] M. Kolbe *et al.*, “Surface Characterization with Vacuum UV Radiation,” *PTB-Mitteilungen* **124**(3), pp. 69–72, 2014.
- [11] M. Krumrey *et al.*, “Reflectometry with Synchrotron Radiation,” *PTB-Mitteilungen* **124**(3), pp. 35–41, 2014.
- [12] M. Rothschild *et al.*, “Photolithography at 193 nm,” *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena* **10**(6), pp. 2989–2996, 1992.
- [13] J. Heymes and others, “Comparison of Back-Thinned Detector Ultraviolet Quantum Efficiency for Two Commercially Available Passivation Treatments,” *IEEE Transactions on Nuclear Science* **67**(8), pp. 1962–1967, 2020.
- [14] “NIST X-Ray Form Factor Attenuation and Scattering Tables.”
- [15] E. D. Palik, *Handbook of Optical Constants of Solids*, Elsevier, 1985.
- [16] E. D. Palik, *Handbook of Optical Constants of Solids, Vol. 2*, Academic Press, 1991.
- [17] Teledyne-e2v. Private communication.
- [18] P. Jerram *et al.*, “Back-thinned CMOS sensor optimization,” in *Optical Components and Materials VII*, S. Jiang *et al.*, eds., **7598**, pp. 298 – 309, International Society for Optics and Photonics, SPIE, 2010.
- [19] A. Gottwald *et al.*, “Ultraviolet and vacuum-ultraviolet detector-based radiometry at the Metrology Light Source,” *Measurement Science and Technology* **21**, p. 125101, oct 2010.
- [20] P. Kuschnerus *et al.*, “Characterization of photodiodes as transfer detector standards in the 120 nm to 600 nm spectral range,” *Metrologia* **35**, pp. 355–362, aug 1998.