Improving the red wavelength sensitivity of CCDs

Paul R Jorden*[a], Mark Downing[b], Andrew Harris[a], Andrew Kelt[a], Pritesh Mistry[a], Pash Patel[a]
[a]e2v technologies, 106 Waterhouse Lane, Chelmsford, Essex, CM1 2QU, UK; [b]ESO, Karl-Schwarzchild-Strasse 2, 85748 Garching, Germany

ABSTRACT

The demand for higher red wavelength sensitivity is being met by various technological developments of modern CCDs. We discuss techniques for achieving higher red wavelength sensitivity by using thicker silicon to make backthinned CCDs, which combines with very low read noise for enhanced sensitivity. Thicker devices requires higher resistivity material including bulk (non epitaxial) silicon. An extended wavelength range also places more demand on the anti-reflection coatings which benefit from corresponding optimisation.

Keywords: CCD, astronomy, high-rho, bulk silicon, full depletion, Anti-reflection coating, red response

1. INTRODUCTION

Traditional CCDs have been made with modest silicon thickness (e.g. 10-16 µm) resulting in modest red wavelength sensitivity (e.g. 30% at 900 nm) because of limited photon absorption. Such devices use low resistivity silicon (e.g. 100 ohm cm) and these only allow a limited depth of depletion at normal operating voltages (e.g. 10V clocks); it is necessary for most of the silicon thickness to be depleted if good charge collection (and PSF) is to be achieved.

Use of increased resistivity has allowed use of thicker silicon with a typical thickness of 40-50 µm; these "deep depletion" devices have been widely used for astronomy and red wavelength spectroscopy. This is about the maximum thickness that is practical for epitaxial silicon which is normally used for CCDs and provides high quality devices (with about 50% QE at 900 nm).

Further increase in thickness is necessary for increased red response, especially for use close to 1 µm wavelength at cryogenic temperatures where the silicon response is falling rapidly. This requires use of higher resistivity bulk silicon. e2v has manufactured such "bulk" devices (of about 70 µm) thickness which operate at normal voltages and allow enhanced red response. Recently tested devices show excellent performance, as described in section 2 below.

Additional increase in thickness of these bulk silicon devices requires operation with a higher voltage to ensure full depletion (and charge collection); e2v calls such devices "high-rho" CCDs. Section 3 discusses this device type and introduces results of a newly manufactured high-performance "astronomical sensor".

Finally, the benefit of enhanced red response is only fully realised if the devices have optimised anti-reflection coatings. Silicon has a high refractive index and therefore signal is lost unless suitable coatings are used; developments of these are discussed in section 4.

2. "BULK" CCDS

Most standard silicon CCDs for astronomy are traditionally made on p-type epitaxial silicon. Epitaxial silicon has the benefit of an intrinsic gettering process which helps to improve device quality and yield- especially with regard to cosmetic defects. However, the maximum practical thickness of such devices is in the region of 40-50 µm since higher thickness epitaxial silicon suffers significant crystal stress and device quality deteriorates.

Thicker devices can be made from bulk silicon; the available resistivity is higher than epitaxial and the devices can therefore be fully depleted to a typical thickness up to 100 µm. e2v manufactures "bulk" devices with a nominal 70 µm thickness which operate at normal applied voltages and give enhanced red response. Prototype CCD44-82 devices (2048 X 4096 format) were made in 2008 and results presented by Downing[1] in 2009. The devices, of standard design, operated with standard clock voltages and demonstrated enhanced red sensitivity; they performed well at -120°C although white defects were more prominent than standard devices.

Very recently e2v has manufactured further bulk devices with superior defect performance, as shown below. Most other operating parameters are consistent with the previous device (ref-2) except that this device has a higher red spectral response through use of a multi-layer coating (discussed below).

Table 1. Performance summary- Bulk CCD44-82; properties at -100°C (unless indicated)

Property	Performance	Notes
Format	2048 X 4096; 15 µm pixels; full frame	1
Build standard	Bulk silicon, 70 µm thick; Backthinned	2
Spectral response	astro multi-2 AR coating (multi-layer)	See below for results
Cosmetic quality	Grade-0 quality	See below for results
Responsivity	6.0 µV/e-	Nominal
Readout noise	3.1 e- rms (at 20 kHz)	3
Dark current	0.2 e-/pixel/ hour (at -120°C)	Scaled from -100°C measurement
CTE Parallel Serial	99.9998% 99.9996%	Fe^{55} measurement (whole clock triplet)
Non-linearity	<0.3% up to 100 ke-; < 1% up to 175 ke-	220 ke- pixel full well
PSF	~ 1 pixel (400- 700 nm wavelength)	4, 5
Operating voltages	Nominal; 0 to +10V clocks; Vss= 0V; OD= 31V	5
Operating mode	Non-inverted mode operation (NIMO or non-MPP)	

Notes:

1. 2048 X 2048 (CCD44-42) format and frame-transfer (CCD44-82FT) options possible.

2. e2v adopts a nominal thickness of 70 µm, since this ensures that full depletion is obtained with nominal silicon resistivity. Thicker devices (up to 100 µm) could be made but would be prone to variability due to silicon tolerance.

3. Value to be confirmed; slightly higher than measured on other devices (e.g. Ref-1); 2.5 e- rms is typical.

4. Not measured (yet) at e2v, but expected to match previous sample (as in Ref-1).

5. Substrate (Vss) is set “low” (corresponding to clock low level) to ensure full depletion and good PSF; other settings are the same as standard devices. A negative substrate [e.g. -10V] may be used to enhance PSF if desired.

Cosmetic quality

White defects and dark defects were analysed using e2v standard test settings. Two minute dark frames were analysed and showed zero white pixel or column defects. A medium level flat field frame was analysed and showed 209 dark pixel defects and 1 partial column defect. Although this was the first sample device tested of a new batch, we have no reason to believe it to be atypical. Results are summarised below. Figure 1 illustrates (a) one dark frame and (b) the illuminated frame. The dark frame is a 120 s exposure at -100°C; most of the white points seen are cosmic rays (which are removed via multiple frames in the full analysis). The illuminated frame has a signal level of approximately 9000 e-.

Defect type	**Number measured**	**Specification level**
White pixel defects:	0	Threshold level >100 e-/pixel/hour at -120°C
White column defects:	0	At white pixel threshold; > 100 pixels long
Dark pixel defects:	209	Threshold level > 20% below local mean
Dark column defects:	1	At black pixel threshold ; > 100 pixels long
Traps:	3	Above 200 e-

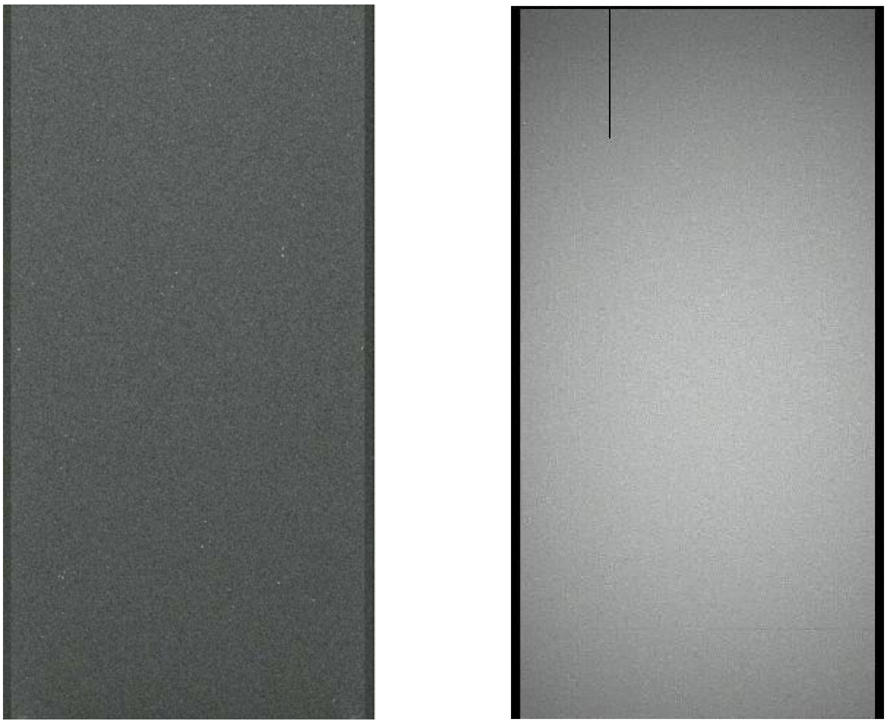


Figure 1. (a) 2 minute dark frame (b) flat field (650 nm)

Spectral response

The sample device was manufactured with the e2v “astro multi-2” AR coating; this is specifically designed to optimise the 400-900 nm response. Figure 2 below shows measured spectral response, confirming that device performance matches predicted performance closely.

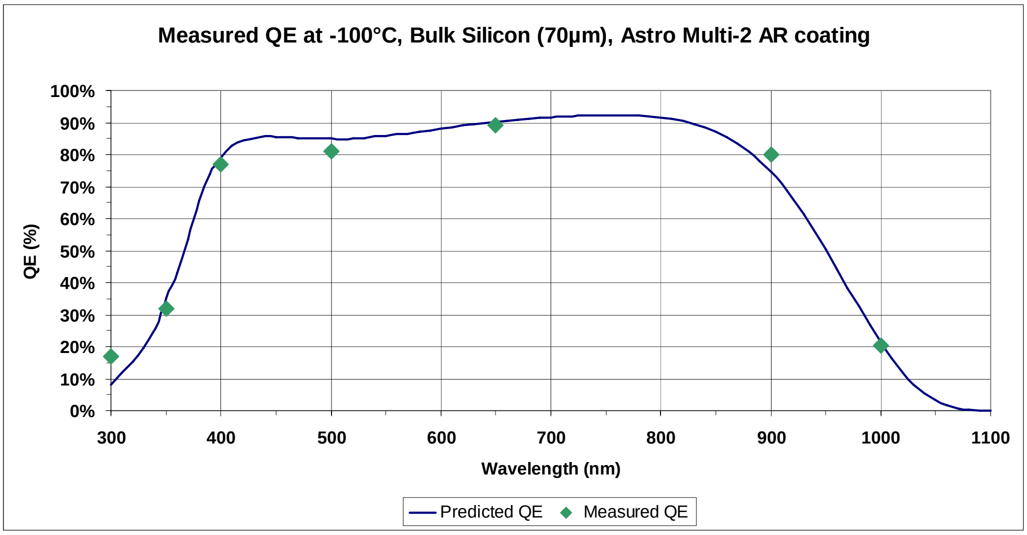


Figure 2. Bulk silicon CCD44-82 spectral response (measured and predicted)

Alternate coating designs are available for other spectral ranges (e.g. 320-1000 nm) where higher UV response is desirable. See section 4 (fig 9) also for a description of a high-rho device with an enhanced UV performance. Figure 4 of ref-1 also shows an "astro broadband" response (with higher UV QE), which is not repeated here.

Summary

The latest tests of a recent bulk e2v CCD44-82 show that it offers full scientific grade performance with high red quantum efficiency. Bulk silicon can be used to manufacture most device types which can then be operated at standard clock and bias voltage settings. Other device types from the e2v family are planned for manufacture in this "bulk" silicon material particularly for use where high red wavelength sensitivity is required.

3. "HIGH-RHO" CCDS

As discussed above, devices made of high resistivity bulk silicon can only be fully depleted with normal voltages up to a thickness of order 70 µm. For highest red sensitivity an increased thickness is required with consequent higher operating voltage to avoid loss of spatial resolution through sideways diffusion of charge.

Hi-Rho Device Technology

The depth of depletion is proportional to square root of the operating voltages and the silicon resistivity, but there is a practical limit to both and possibilities for maintaining full-depletion with increasing thickness are therefore limited. The Hi-Rho technology is a way of overcoming this limitation.

In standard devices the bulk of the silicon substrate is all at the same bias voltage V_{SS}. It is possible to take V_{SS} to negative voltages to increase depletion, but the limit is generally set by the onset of avalanche breakdown in the p-n junctions of the output circuit components.

The Hi-Rho technology allows the use of a larger negative substrate bias on the back of the silicon V_{BS} to increase the depth of depletion under the electrodes, whilst still maintaining a bias on the front-surface of the silicon V_{FS} at a voltage level normally used for V_{SS} such that the output circuits function normally. However, for this to be possible, current flow between the front (FS) and back (BS) bias connections [Figure 3a] must be avoided. This is achieved using an additional "guard diode" at bias V_{GD}, as shown below.

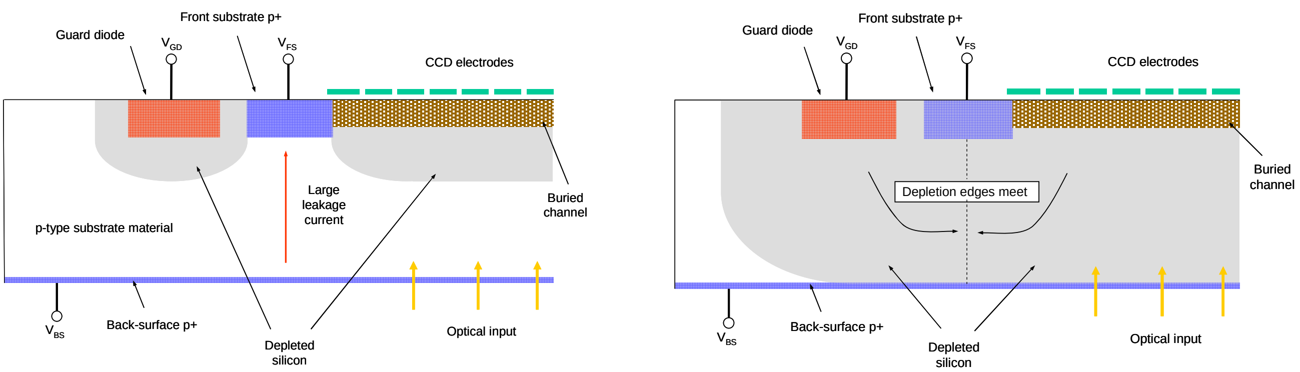


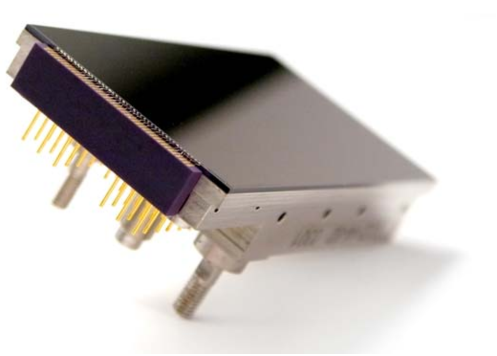
Figure 3. High-rho device (a) with leakage from back to front (b) with FS and BS isolated by depletion regions

With correct bias conditions the depletion regions from the CCD channel and the guard diode merge to block the conductive path, rather like the operation of a JFET, as shown above [Figure 3b]. If incorrect, then there is a direct resistive path between the front and back contacts and excessive currents can flow.

e2v has been actively developing several generations of such devices which we term "high rho"; previous developments were described by Jorden et al[2]. Very recently test samples of the new CCD261-84 "high-rho" device have been evaluated and are discussed here. These devices are fabricated from bulk silicon (> 3000 ohm-cm resistivity), back-illuminated, and designed to operate with increased back bias voltage. It should be emphasised that results are presented from the first sample that has been tested.

The CCD261-84

The device has been designed to complement the widely used CCD44-82 standard silicon astronomical sensor, which has a 2048 X 4096 15 µm pixel format in a buttable precision package. The CCD261-84 has the same format and package design and very similar operation apart from the requirement of a back bias high voltage (BSS) for full depletion. Figure 4 illustrates the device package and architecture.



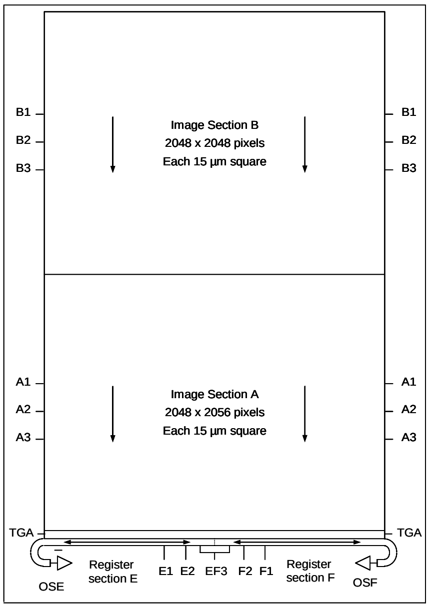


Figure 4. CCD261-84 device (a) illustration (b) architecture (not to scale)

Table 1 below lists the key features of this device which are discussed further in following sections. Only some parameters have been measured so far, but device performance (where measured) corresponds to design.

Table 1. Key parameters of CCD261-84

Item	**Parameter**	**Notes**
Format	2048 X 4104 pixels; 15 X 15 µm size; 30.7 X 61.6 mm image	
Package	32 X 66 X 14 mm buttable; 40 pin PGA connector; 20 µm flatness	
Outputs	2; split register- may be read out from one or both outputs	
Responsivity	12 µV/ e-	See discussion below
Read-noise	3.5 e- rms at 500 kHz	See discussion below

Item	Parameter	Notes
Pixel capacity	200,000 e- expected from design	1
Dark signal	Non-inverted operation mode	See discussion below
CTE	99.9995% typical (for 3-phase triplet)	2
QE	40% typical QE at 1000nm wavelength and -100°C operation	See discussion below
Cosmetics	Grade-1 scientific quality achieved at -100°C	See discussion below
Operating temperature	-100°C typical for extended integration times	See discussion below

Notes

1. Camera gain range did not allow full-range test yet; measured (so far) as > 100ke-.
2. X-ray CTE test not yet performed; cosmic rays and white pixel defects appear sharp.

Read noise and responsivity

Responsivity has been confirmed by two measurement techniques: (a) Photon transfer curve (values at low signal were used; see Downing[3]) and (b) reset drain current at fixed readout frequency.

System noise has been measured and subtracted in quadrature from measured total noise. System noise was comparable to detector noise (and therefore introduces slight inaccuracy). Detector read noise = 3.5 e- rms at 500 kHz and -120°C. Both outputs showed the same noise, with negligible change in noise as backside bias was changed from 0V to -70V.

See figure 5 below for predicted and measured noise; output circuit details are also shown.

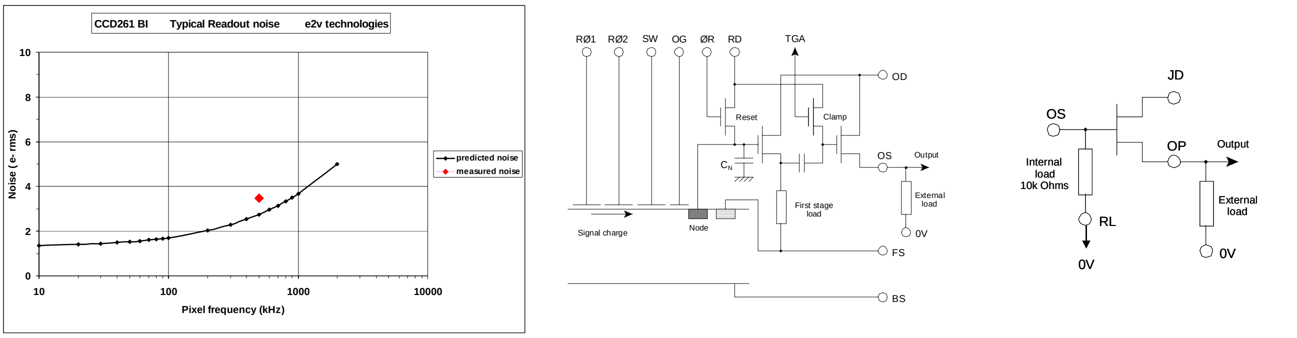


Figure 5. (a) Readout noise (b) output circuit (c) optional FET buffer

Dark current

Dark current was measured over the range -20°C to -120°C, at 0V BSS and -70V BSS. Unfortunately the test camera had some light leakage, and so results are only considered valid at temperatures above -80°C where the leakage was small. Figure 6 below shows measured dark signal (points) which confirm that signal does not change appreciably with back bias voltage. A trend line is fitted to the -70V BSS measurements from -20°C to -80°C; with an exp(-6600/T) dependence. We believe that true dark current at low temperatures will correspond to the trend line shown and give a dark current of 5 e-/pixel/hour at -100°C; this is very similar to that seen on lower resistivity e2v standard devices. This is due to be confirmed as soon as possible.

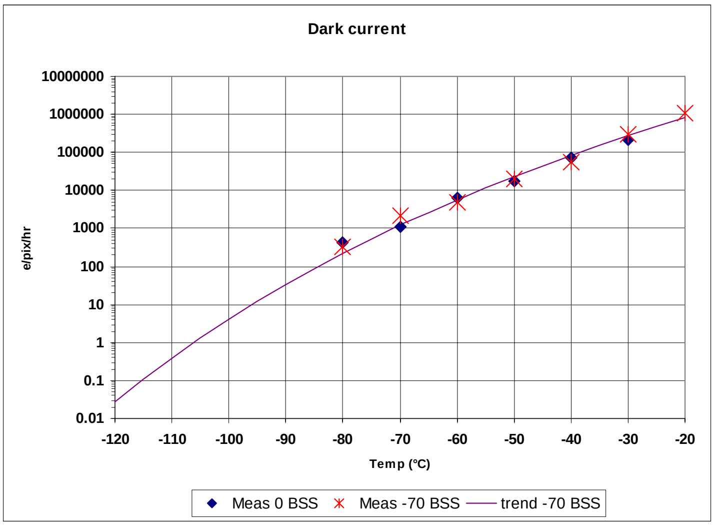


Figure 6. CCD261 Dark current

Quantum Efficiency

Quantum efficiency has not yet been measured for the sample device, however it is e2v experience that QE normally matches design closely- depending on device thickness, operating temperature, and coating design; an example of measured and predicted performance is shown in section 2 above. Anticipated spectral response for a 150 µm thick device at cryogenic temperature is shown in figure 8 (of section 4); we consider that the astro multi-1 response is likely to be of most interest for wideband astronomical use.

Cosmetic quality

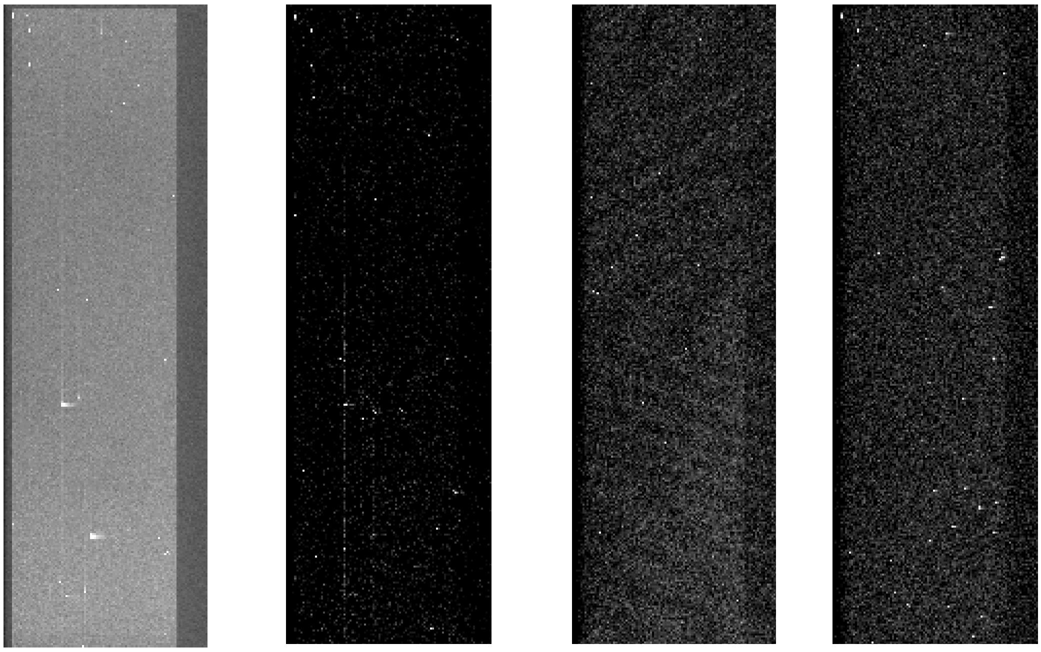
White defects were analysed using e2v standard test settings. Five minute dark frames, taken at -120°C, were analysed at two back bias settings (0V BSS and -70V BSS). BSS= -70V corresponds to full depletion of the silicon (over-depleted in fact). Results are summarised below.

Defect type	Number of defects BSS = 0V	Number of defects BSS = -70V	Specification level
White pixel defects:	8	9	Threshold level >100 e-/pixel/hour at -120°C
White column defects:	0	3	At white pixel threshold; > 100 pixels long

It can be seen that the defect level is low (full scientific quality) and that this is obtained with low back bias and full back bias (-70V). A limited number of dark frames were also analysed at -100°C (and BSS= -70V) and the number of column defects increases to 6 but remains acceptable.

Dark defects have not been analysed but an illuminated test frame shows no dark column defects in the sample device. White defects are considered more critical for long exposure applications (such as astronomy) because severe ones tend to limit exposure duration due to charge blooming. Bulk silicon devices tend to have more severe white defects than epitaxial silicon and so we have paid particular attention to these. Dark defects are often surface effects (which do not change significantly with silicon type).

Figure 7 illustrates 300 second dark frames taken under different conditions. Frames (a) to (c) show how white defects reduce as temperature is lowered; some system pick-up noise is seen in the contrast stretched frame (c). Most of the visible white defects are cosmic rays in these frames- which are removed by our multiple-frame analysis. Frames (b) and (d) illustrate the influence of changing back bias from 0 to -70V. White defects are low at all temperatures below -80 °C although dark current considerations would normally dictate an operating temperature of -100°C or lower.



(a) -70V, -80C (b) -70V, -100C (c) -70V, -120C (d) 0V, -100C

Figure 7. 300 s dark images at different test conditions- a, b, c, d; see text for description.

Operating temperature

The white defect results show that good science-grade performance is possible at temperatures of -80°C or below. We consider that temperatures in the range -120°C to -100°C are likely to be used to ensure low enough dark current for long exposures. The long wave quantum efficiency will be best at the highest possible temperature.

Operating voltages

The device is designed to operate at “standard” operating voltages- i.e. 0V front substrate (FSS), clocks in the range 0 to +12V, DC levels in the range 0 to +30V, and a back substrate (BSS) in the range 0 to -60V typical. We have demonstrated that normal operation is available with BSS voltages in the range 0 to -70V. The exact value used will depend on the thickness of device and degree of depletion required. The sample tested had a thickness of 150 µm and appears to be fully depleted at a BSS voltage close to -20V; to be confirmed. We anticipate manufacturing thicker devices and these will require an increased (negative) voltage.

“High-rho” devices have been described previously by LBNL (Holland[4] and previous papers) where the effects of increased dark current and cosmetic defects have been noted. The e2v devices described here show equivalent effects although at levels low enough to allow commercial production of scientific quality devices of large format.

Future plans

Remaining parameters are planned for full characterisation in the following months (July-2010 onwards). The sample presented here was fabricated with 150 µm thickness. Increased thickness devices are also possible (as discussed above).

Other devices are planned, including a 4096 X 4096 pixel format: a CCD261-88 (4k4k) would be a natural complement to the popular CCD231-84 standard silicon 4k4k e2v sensor.

4. ANTI-REFLECTION (AR) COATING

The extended red sensitivity offered by thicker silicon devices increases the demands on high performance anti-reflection coatings. An example is the desire for many projects to use wide-band sensors from U to Z bands covering the 320 to 1000 nm wavelength range. Single layer coatings (usually of Hafnia) offer good midband response and can have their thickness tuned for other wavelength peaks. e2v has been active in developing advanced coatings to ensure highest sensitivity; one specific example is the graded AR coating as described by Kelt[5], which has significant benefits for fixed format spectroscopy. However, here we discuss further refinements of coating, particularly multi-layer types for broad wavelength range application (including imaging/photometric use).

It should also be noted that there are several secondary benefits of efficient AR coatings- minimised reflectivity (a) which reduces ghost images & scattered light and (b) minimised red-wavelength fringe amplitude- although this is naturally reduced with increased thickness devices; both were discussed also in ref-5.

Section 3 discussed the high-rho (thick silicon) sensor, where a sample of 150 µm thickness was evaluated. This thickness gives QE of close to 90% at 900 nm and -100°C operation. Figure 8 illustrates the effect of using different anti-reflection coatings on a device of this thickness. Four coatings are shown- (a) "broadband", an e2v standard single layer coating, (b) "multi-1", a multi-layer coating designed for astronomical wide-range use, (c) "multi-2", a multi-layer coating designed for highest 400-900 nm response, (d) "multi-3", a multi-layer coating designed for highest NIR response. Coating (c) was also shown in section 2 for the 70 µm thick bulk device.

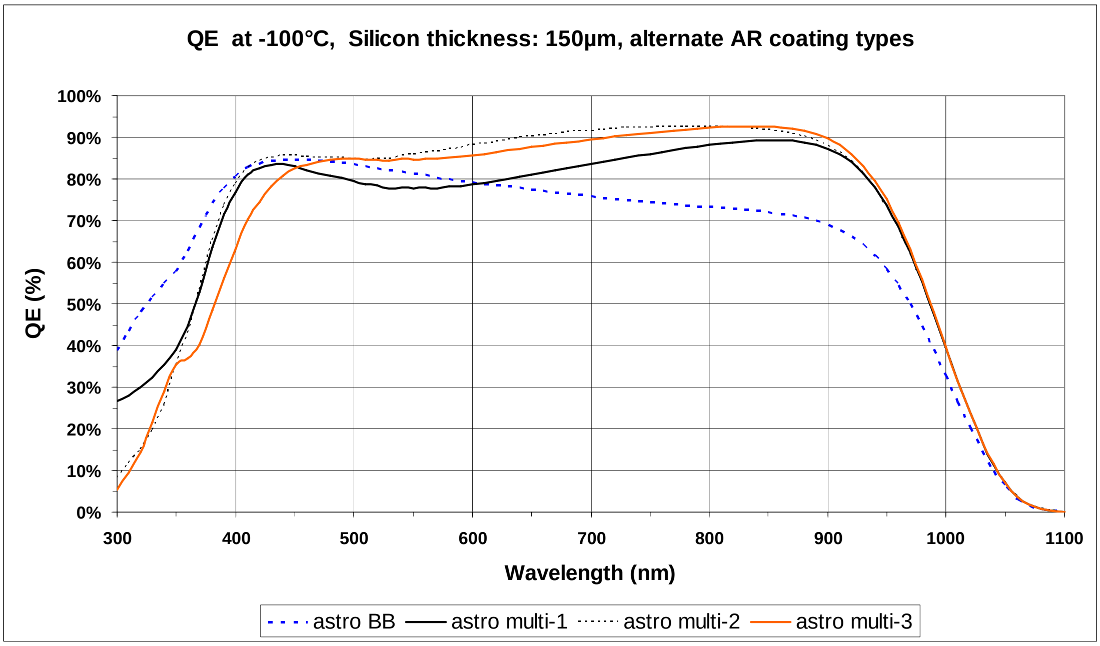


Figure 8. Predicted QE for alternate AR coatings on 150 µm thick silicon CCD

It is worth noting that single layer coatings generally offer the highest response close to the wavelength of optimisation but fall off on either side. Two layer (or more) coatings offer broader response although often with slight reduction from the highest peak- it is usually considered acceptable to lose a little signal in the midband region where signals levels are often high so that the extreme ends of the range are optimised (e.g. <400 nm and > 900 nm).

Further improvements to spectral response can be obtained by utilising multiple layers (e.g. four) and multiple materials in the AR coating. These offer extra degrees of freedom, including high and low indices as well as better matches to silicon refractive indices at some wavelengths than the traditional Hafnia alone). The next two figures illustrate some recent developments at e2v that are expected to lead to further enhancements in spectral response beyond that illustrated in figures 2 and 8 of this paper.

A sample high-rho device (of 109 µm thickness) was constructed with the “multi-2” coating design. Figure 9 shows predicted and measured performance; measurements have so far only been made at +20C on this device. We note that in this device we observed higher QE than predicted by our normal models (astro multi-2) which make some allowance for internal losses and that QE is very close to the theoretical maximum (theory multi-2).

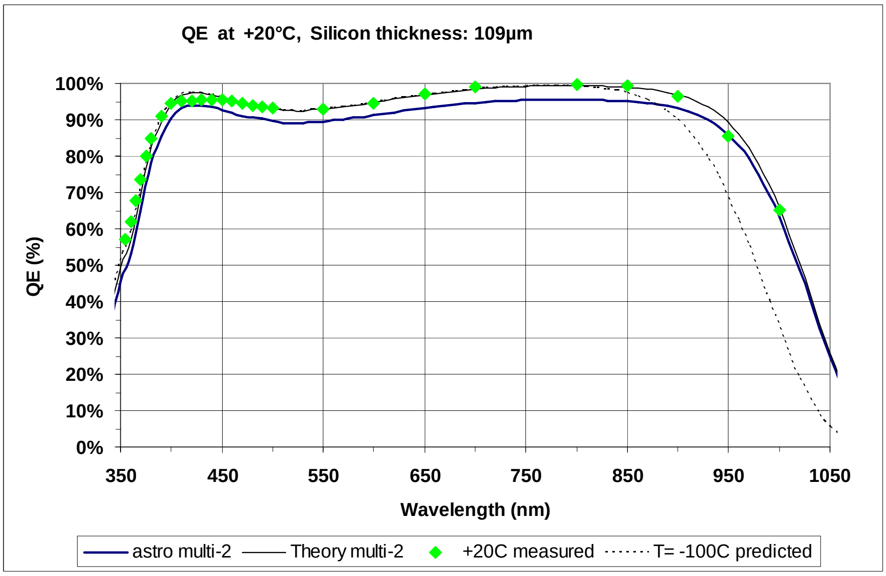


Figure 9. QE of high-rho multi-2 coated sample

The same coating type was applied to a standard thickness sample, as shown in figure 10. The red response here is limited because the sample thickness was only 16 µm. However, the purpose of this sample was to confirm that no significant change to the response occurs at UV short wavelengths (where surface losses can occur).

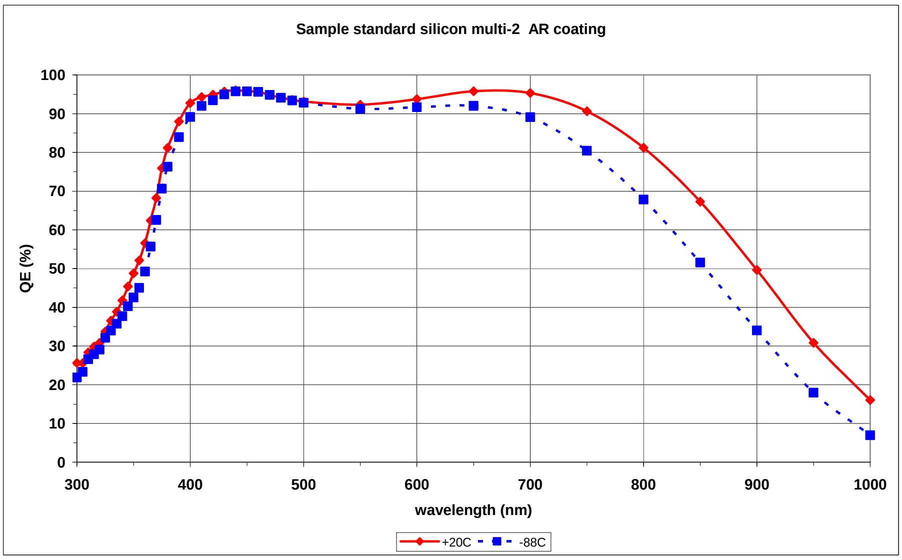


Figure 10. Sample device measured at ambient and cryogenic temperature

The developments described above have led us to anticipate making high-rho devices with a spectral response as indicated in figure 11. This utilises a multi-layer coating with materials and designs that are currently being tested at e2v. A QE above 90% should be obtained from 400 to 900 nm at cryogenic temperature, with >50% from 330 to 900 nm.

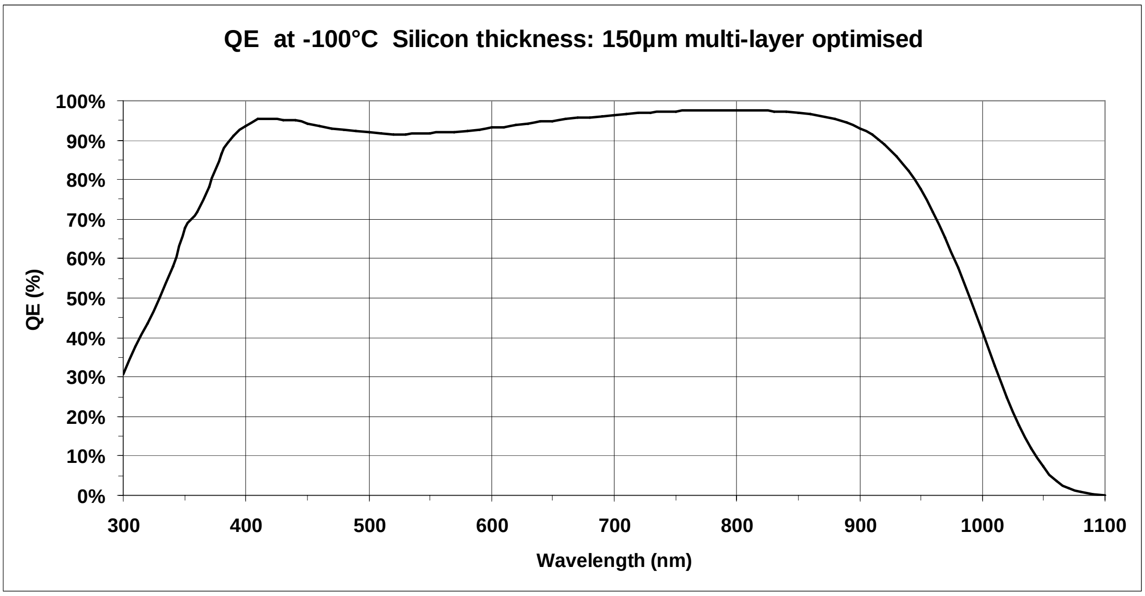


Figure 11. Spectral response of e2v multi-layer coating design for wide-range high-rho use.

5. SUMMARY

Sample devices have been constructed and tested utilising bulk silicon of differing thickness. A new "high-rho" device type has been shown to work well in fully-depleted mode, with excellent red wavelength response and scientific quality performance. Developments in anti-reflection coating have been shown to give wide-range spectral response to complement the enhanced intrinsic performance of these thicker silicon sensors.

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REFERENCES

[1] Downing M, Baade D, Deiries S, Jorden P, "Bulk Silicon CCDs, Point Spread Function and Photon Transfer Curves: CCD Testing Activities at ESO", DfA Garching http://www.eso.org/sci/meetings/dfa2009/, (2009).
[2] Jorden, P., Ball, K., Bell, R., et al., "Commercialisation of full depletion scientific CCDs", Proc. SPIE **6276,** (2006).
[3] Downing, M., Baade, D., Sinclaire, P., Deiries, S., Christen, F., "CCD riddle: a) signal vs time: linear; b) signal vs variance: non-linear", Proc. SPIE **6276,** (2006).
[4] Holland, S., E., et al, "Fabrication of back-illuminated, fully depleted charge-coupled devices", NIMPhysResA **579**, p653 (2007).
[5] Kelt, A., Harris, A., Jorden, P., Tulloch, S., "Optimised CCD antireflection coating", Springer Proc of Scientific Detectors for Astronomy 2005 (eds J E Beletic, J W Beletic, P Amico), p369 (2006).