Improving the red wavelength sensitivity of CCDs

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Introduction

CCD imagers offer very high performance for astronomical imaging and spectroscopy.

→Infrared sensors also offer very high performance but are not available in the variety (and prices!) available for CCD sensors.

→The cross-over point between the two sensor types is in the region of 1 µm wavelength.

→Traditional CCDs have finite silicon thickness and therefore limited absorption (and efficiency) at wavelengths close to 1 µm.

The range of application for CCDs can be extended by increasing the silicon thickness-

Thick silicon devices are described- for use up to the silicon cut-off of 1.1 µm

A new "high-rho" scientific sensor is introduced- the **CCD261**

Use of an extended wavelength range requires higher performance anti-reflection coatings-

Developments of wide range multi-layer AR coatings are described

Contents

- Introduction to thicker silicon CCD development
- "Bulk" CCDs
  - Intermediate thickness devices with enhanced red response
- "High-rho" CCDs
  - Fully depleted sensors with silicon thickness > 100 µm
- Anti-reflection coatings
  - Multi-layer coating developments for highest QE over a wide range
- Summary

Thick CCD sensors- 1

A progression of thickness and red wavelength response-

- Traditional CCDs- low resistivity silicon; 10- 16 µm thick; limited red QE
  Epitaxial silicon; well established; excellent performance

- e2v “deep depletion” CCDS- higher resistivity; 40 µm thick; better red QE
  Epitaxial silicon; excellent performance; risk of minor blue PSF degradation

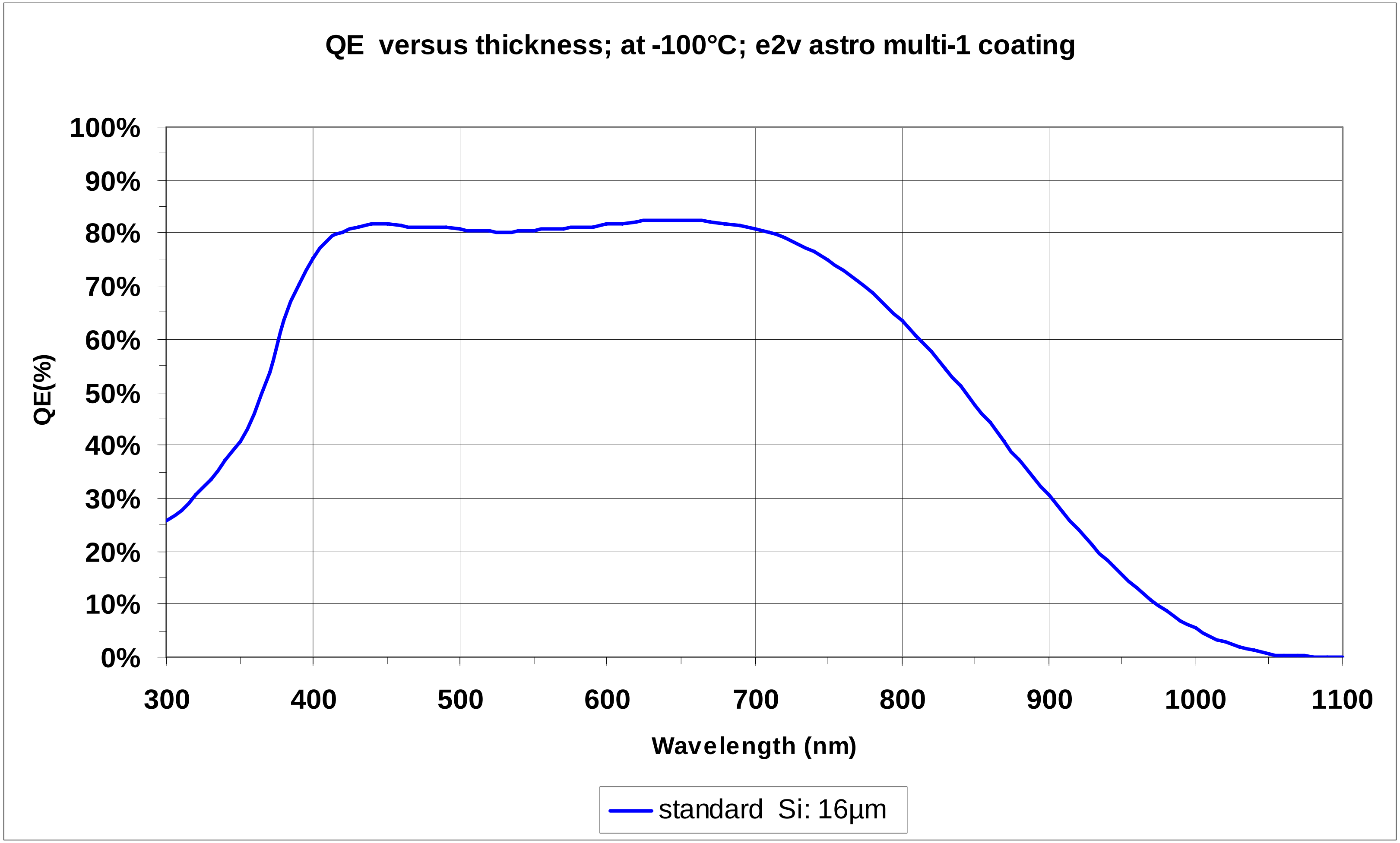
- e2v “bulk” CCDs- highest resistivity; 70 µm thick improved red QE
  Bulk silicon; good performance; any device type can be made in this material

- e2v “high-rho” CCDs- highest resistivity; > 100 µm thick; maximum red QE
  Bulk silicon; good performance; requires custom design and HV BSS operation

At a wavelength of 1000 nm QE is almost proportional to device thickness

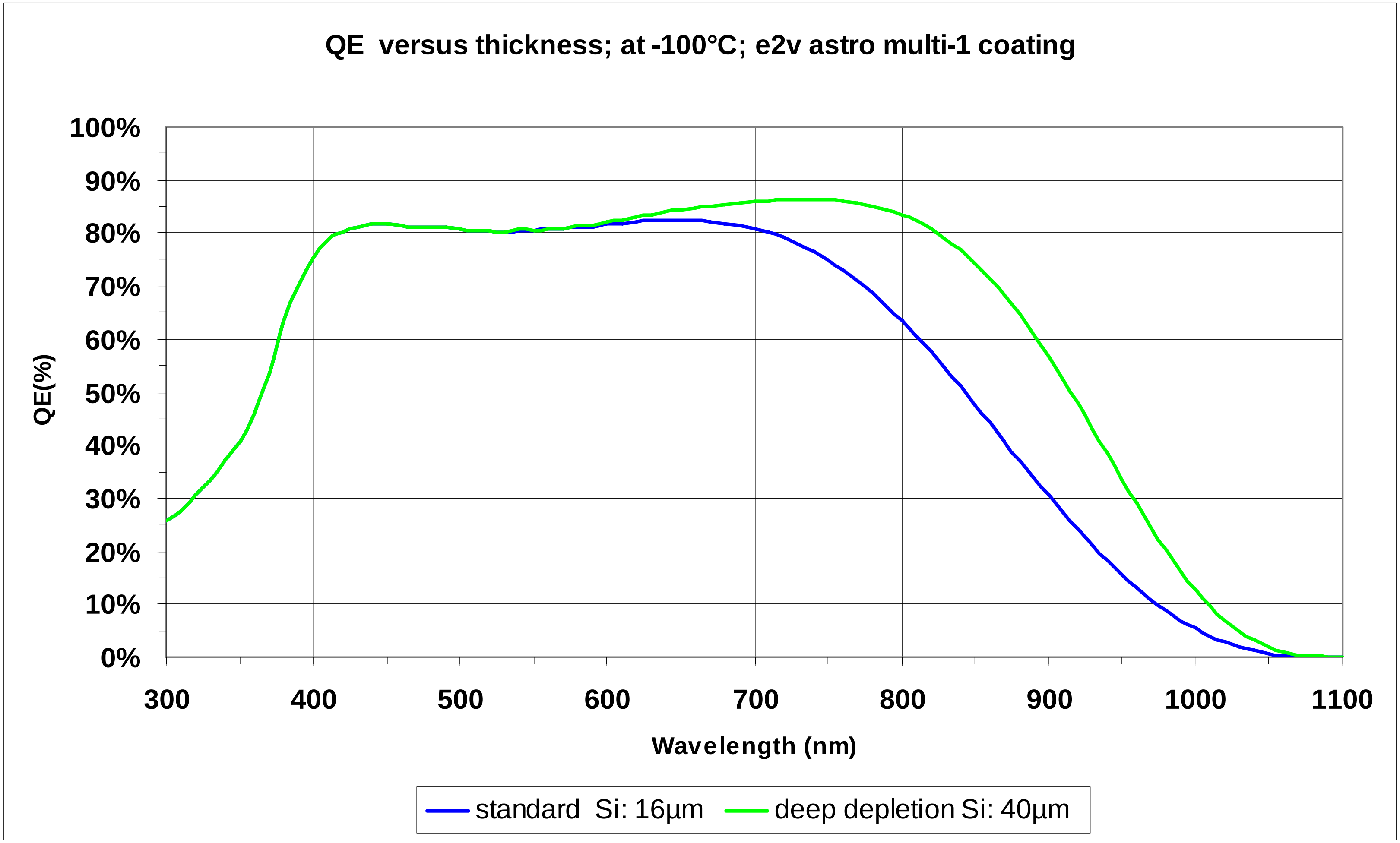
Thick CCD sensors- 2

A progression of thickness and red wavelength response-



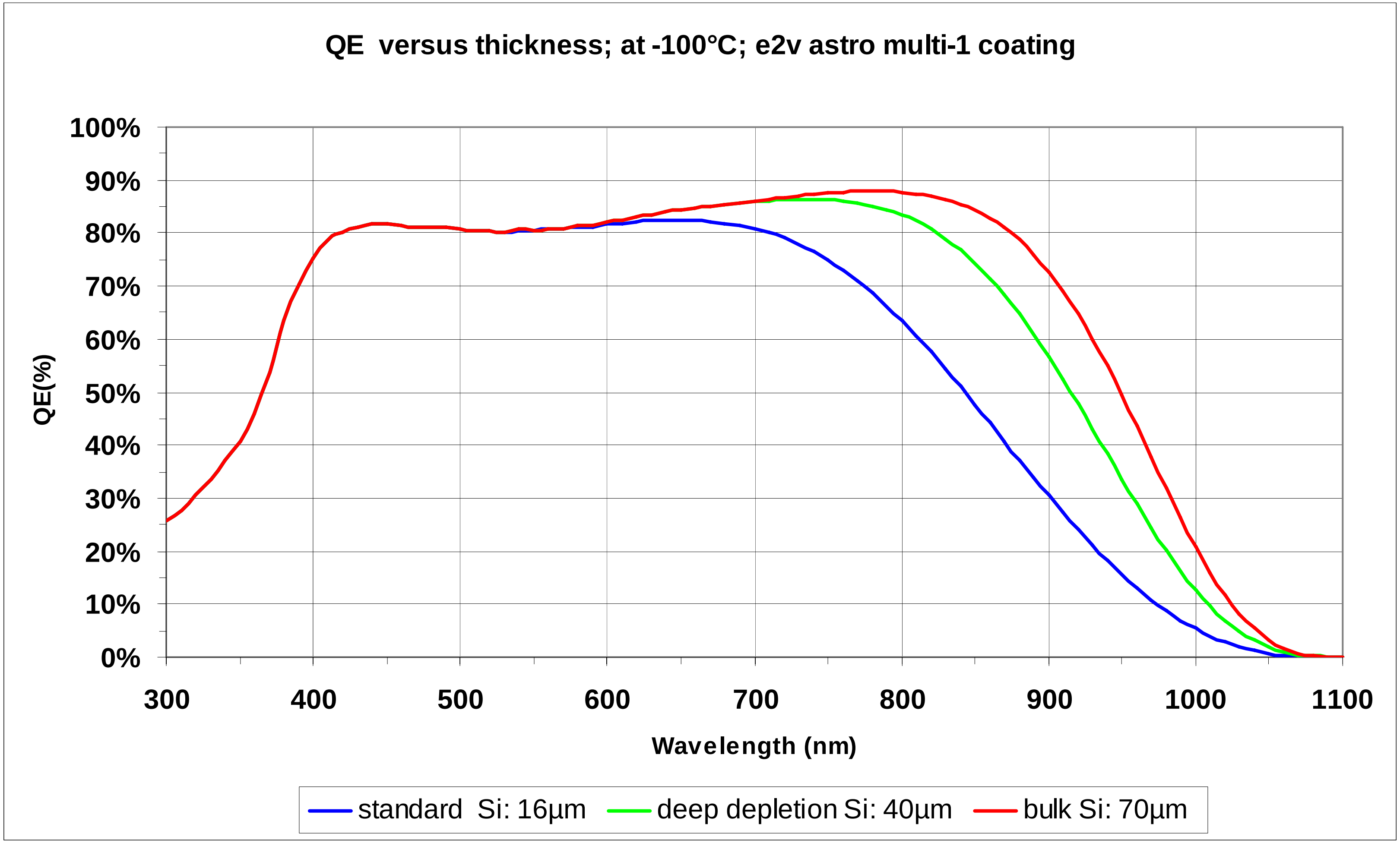
Thick CCD sensors- 3

A progression of thickness and red wavelength response-



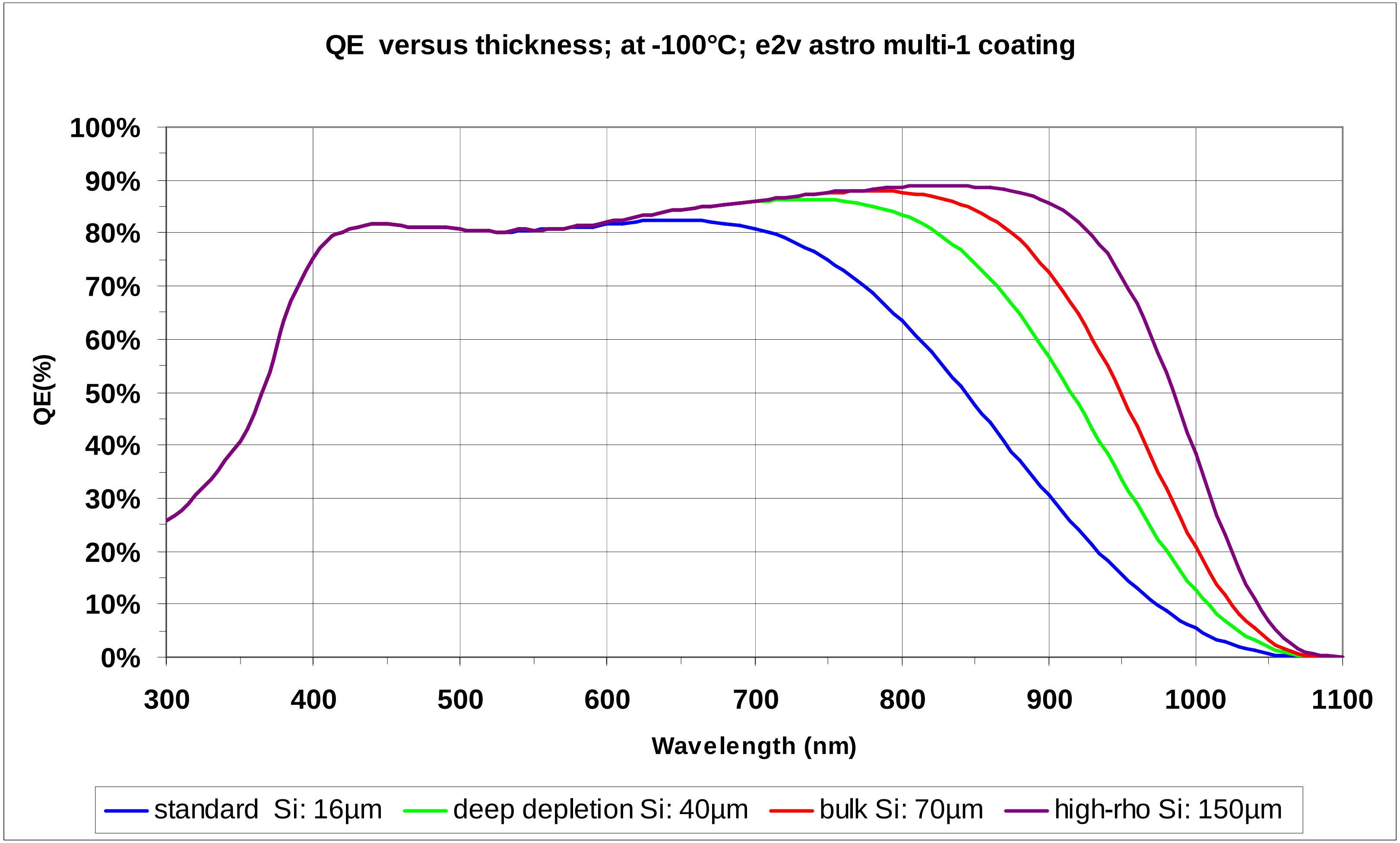
Thick CCD sensors- 4

A progression of thickness and red wavelength response-



Thick CCD sensors- 5

A progression of thickness and red wavelength response-



“Bulk” CCD devices- 1

•Bulk silicon (non epitaxial) offers higher resistivity and therefore larger depletion depth and thicker silicon thickness.

•Any existing device could be made using this material- offering better QE than standard epitaxial devices.

•Operation at normal voltage levels (eg 10V clocks and 0V substrate) limits depletion depth and therefore limits device thickness- to about 70 µm for typical bulk silicon

•Bulk silicon does not benefit from intrinsic gettering of epitaxial silicon and can have poorer cosmetic quality.

•Bulk silicon CCD44-82 devices (2k X 4k) have been previously evaluated.
See Downing et al, “Bulk silicon CCDs…”, http://www.eso.org/sci/meetings/dfa2009/
Devices worked wll, but required -120°C operation for best white defect performance.

•Here, we report on latest refinements to the manufacturing quality of these devices- which now demonstrate improved cosmetic performance- this allows lower white defect levels and an elevation of operating temperature → -100°C increases red QE

“Bulk” CCD devices- 2

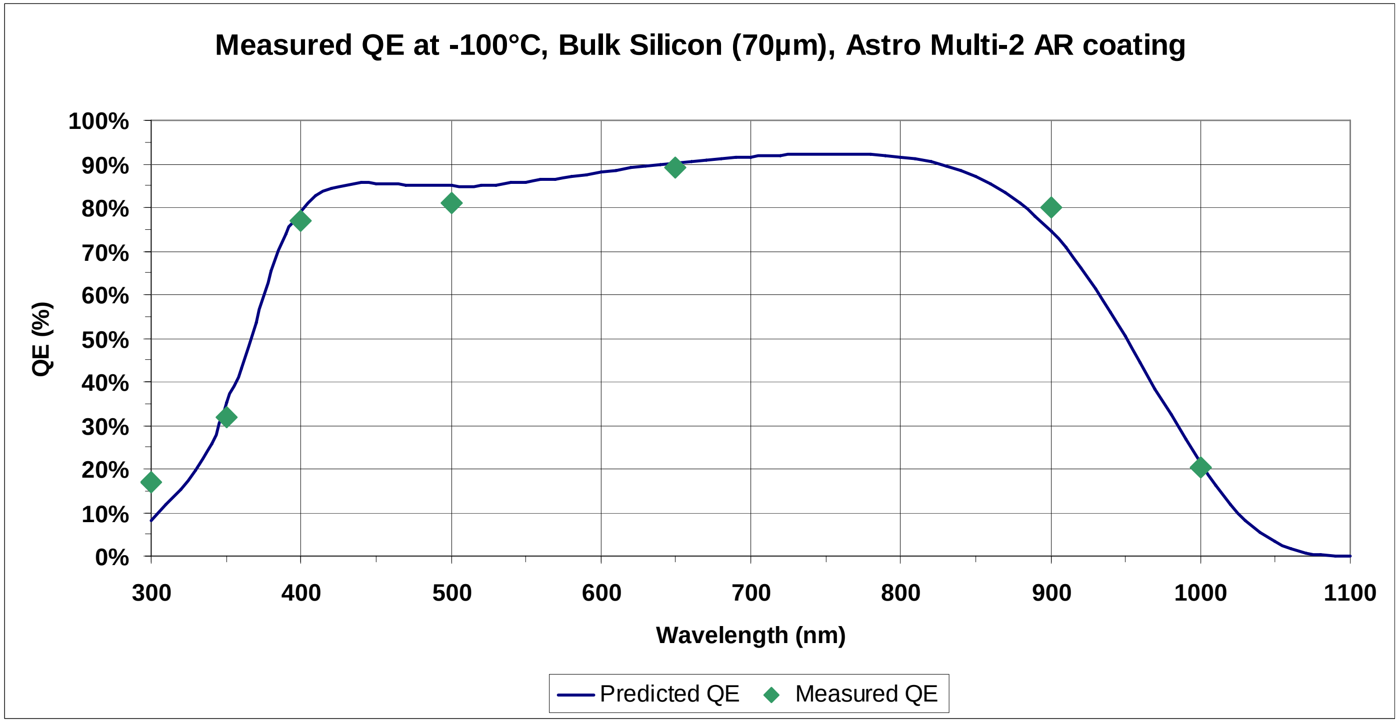
Performance summary of bulk CCD44-82 tests

Property	Performance	Notes
Format	2048 X 4096; 15 µm pixels; full frame	Other formats possible
Build standard	Bulk silicon, 70 µm thick; Backthinned	
Spectral response	astro multi-2 AR coating (multi-layer)	See figure
Cosmetic quality	Grade-0 quality	See below
Responsivity	6.0 µV/e-	Nominal
Readout noise	3.1 e- rms (at 20 kHz)	
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)	Not measured on this sample [See Downing et al; 2009]
Operating voltages	Nominal; 0 to +10V clocks; Vss= 0V; OD= 31V	
Operating mode	Non-inverted mode operation (NIMO or non-MPP)	

Full scientific quality demonstrated

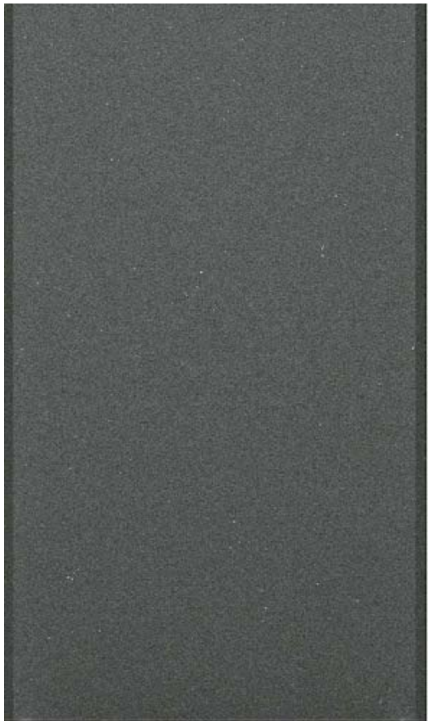
"Bulk" CCD devices- 3

Sample manufactured with e2v astro multi-2 AR coating (see later also)



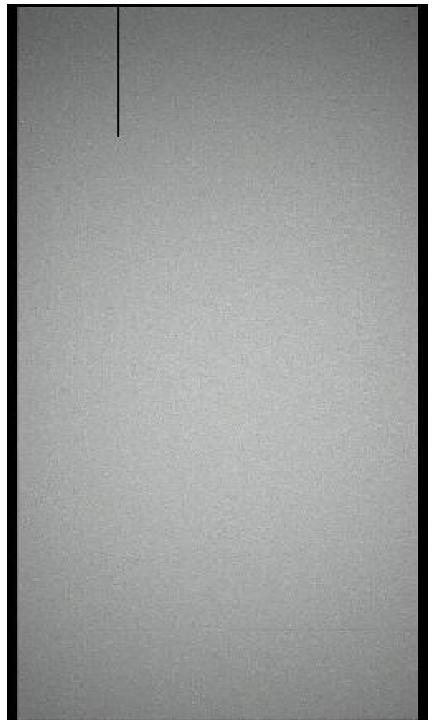
QE matches expected value

"Bulk" CCD devices- 4



2 minute dark frame

At -100°C



650 nm flat field

Cosmetic 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-

Excellent cosmetics: Standard scientific defect specs achieved

"High-rho" fully depleted CCD development- 1

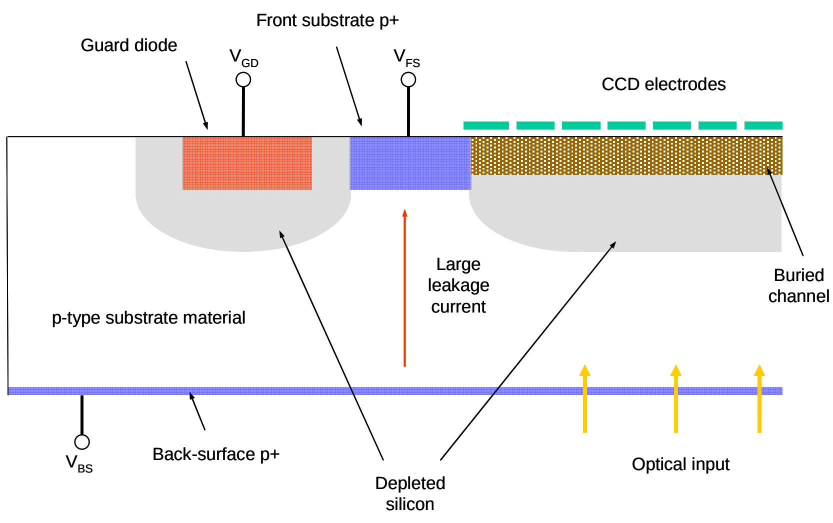
High rho technology

Depletion region needs to extend from front to back to ensure no PSF degradation

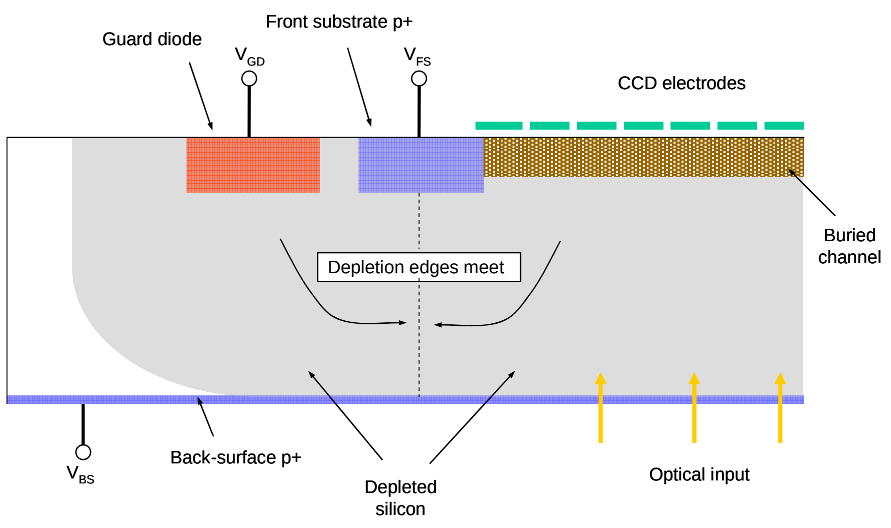
High voltage back bias (BSS) needed to create full depletion

Front side (output circuits) need to operate at normal low voltage (FSS)

No leakage current must flow from BSS to FSS; guard diode is important



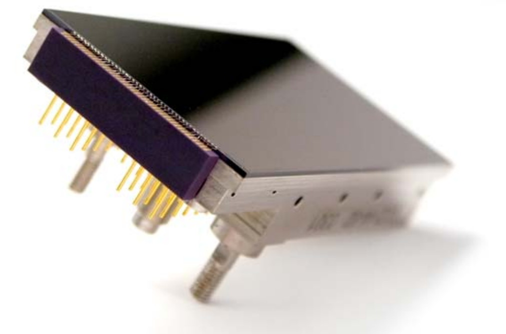
(a) Leakage current

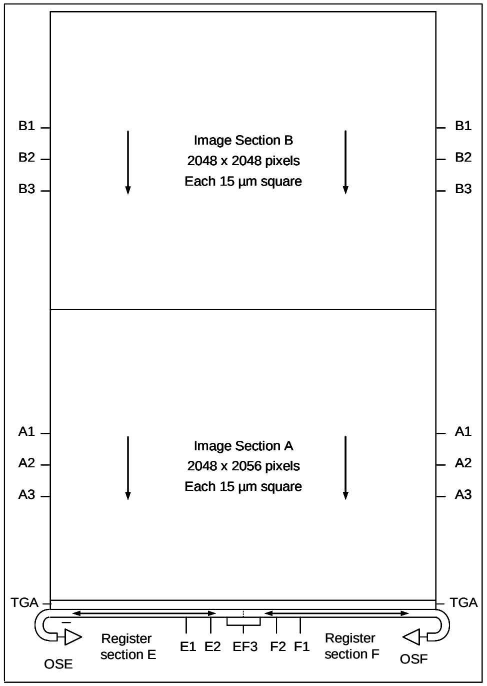


(b) Guard diode depletion isolates front and back

"High-rho" CCD development- 2

e2v





The CCD261-84 high-rho device

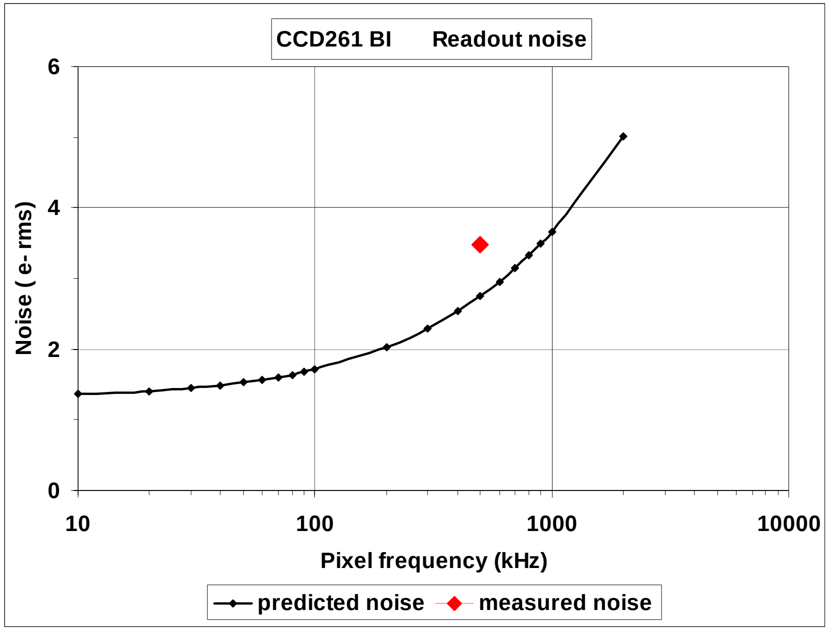
An evolution of previous e2v high rho sensors-

see Jorden et al, Proc SPIE **6276** (2006)

First Sample Results (June 2010)

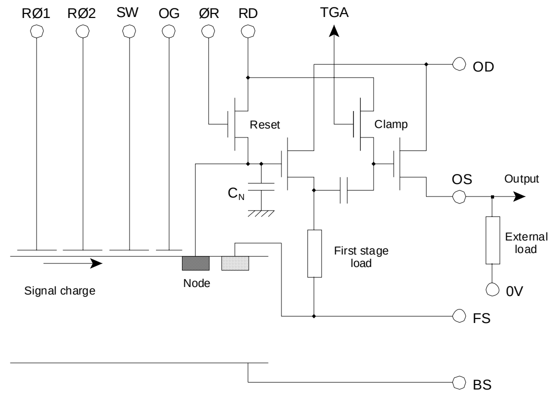
Item	**Key Parameters**
Format	2048 X 4104; 15 X 15 µm ; 30.7 X 61.6 mm image
Package	Buttable; 40 pin PGA connector; 20 µm flatness
Outputs	2; split register- read from one or both outputs
Responsivity	12 µV/ e-
Read-noise	<2 e- noise floor
Pixel capacity	200,000 e- (design; measured to 100ke- so far)
Dark signal	Same as standard silicon devices (Non-inverted operation mode)
CTE	99.9995% expected (for 3-phase triplet)
QE	40% QE at 1000nm wavelength
Cosmetics	Grade-1 quality achieved at -100°C
Operating temp.	-100°C typical

"High-rho" CCD development- 3

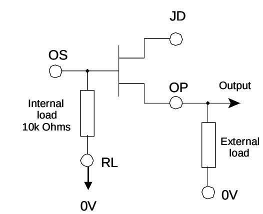


Read-noise: 3.5 e- rms at 500 kHz

System noise (3.5 e-) subtracted in quadrature



2-stage output circuit



optional JFET buffer

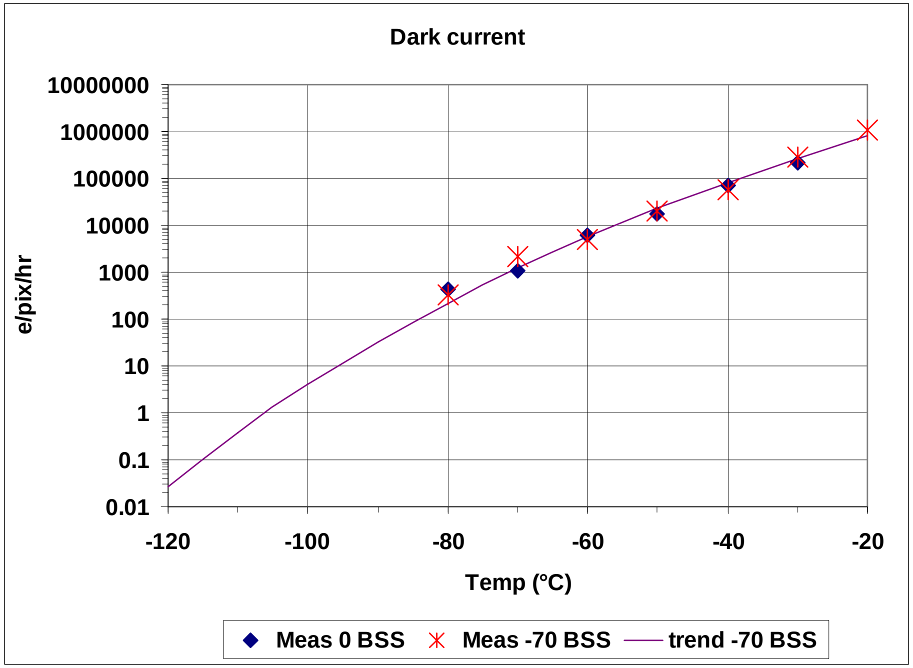
Responsivity: 12 µV/ e-

Measured by photon transfer- with care to use low signals see Downing et al, Proc SPIE **6276** (2006)

Reset drain current measurement gives same result

< 2 e- noise floor design **high responsivity, very low noise amplifier**

"High-rho" CCD development- 4



Dark current

Measured from -20°C to -80°C

0V BSS & -70V BSS- <u>no significant change in dark current</u>

Trend line drawn; exp (-6600/T) : 5 e-/hr expected at -100°C

I.e. very similar dark current to standard silicon devices

Lower temperature tests in progress

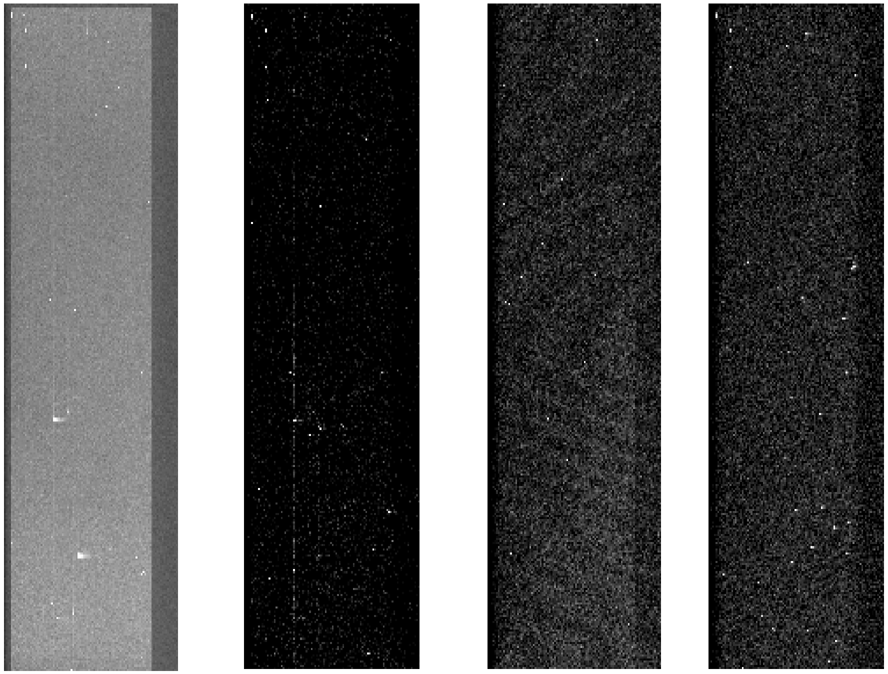
Dark current follows typical scale law; no change with HV back bias; 5 e-/hr expected at -100°C

Quantum Efficiency

Not measured yet. QE expected to correspond to device design (thickness & coating)

See later

“High-rho” CCD development- 5



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

300 s dark images- showing effect of temperature and BSS voltage

Cosmetics

White defects analysed (below)

Dark defects not yet analysed

Defect type	Number of defects		Specification level
	BSS = 0V	BSS = -70V	-120°C frames
White pixels	8	9	>100 e-/pix/hr @ -120°C
White columns	0	3	> 100 pixels long

White defects

Small change with full BSS voltage

(d → b): Minor change of white defects as BSS increases

(c→b→a): Modest progression of white defects with temperature

(b): High scientific quality even at high BSS and -100°C

Cosmic rays dominate white defects in long exposures

"High-rho" CCD development- 6

Summary

Full operation of new CCD fully depleted sensor

Demonstrated with-

- **2048 X4096 format device CCD261-84**
- **-100°C operation typical**
- **Good cosmetic performance**
- **Low read-noise and low dark current**
- **Performance to design parameters**

Future plans

Complete characterisation of CCD261-84

Commercial supply of devices

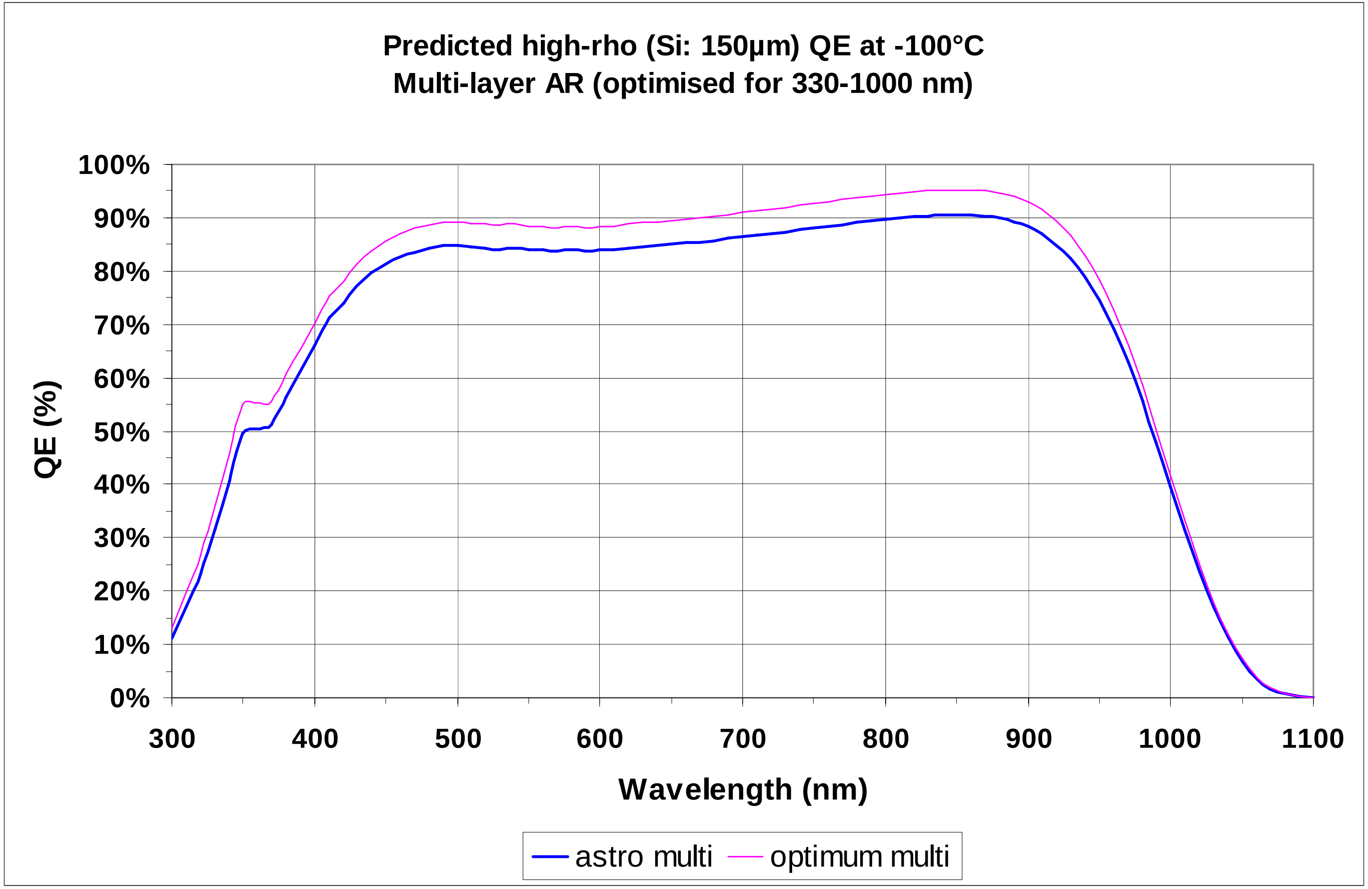
Intended 4096 X 4096 format variant

Alternate thickness and AR coating variants

“High-rho” QE

Quantum Efficiency

A multi-layer AR coating optimised for 330 to 1000 nm



Designed for very high red wavelength response and maintaining high UV QE

“astro multi”:

Using existing process

“optimum multi”:

Optimised process

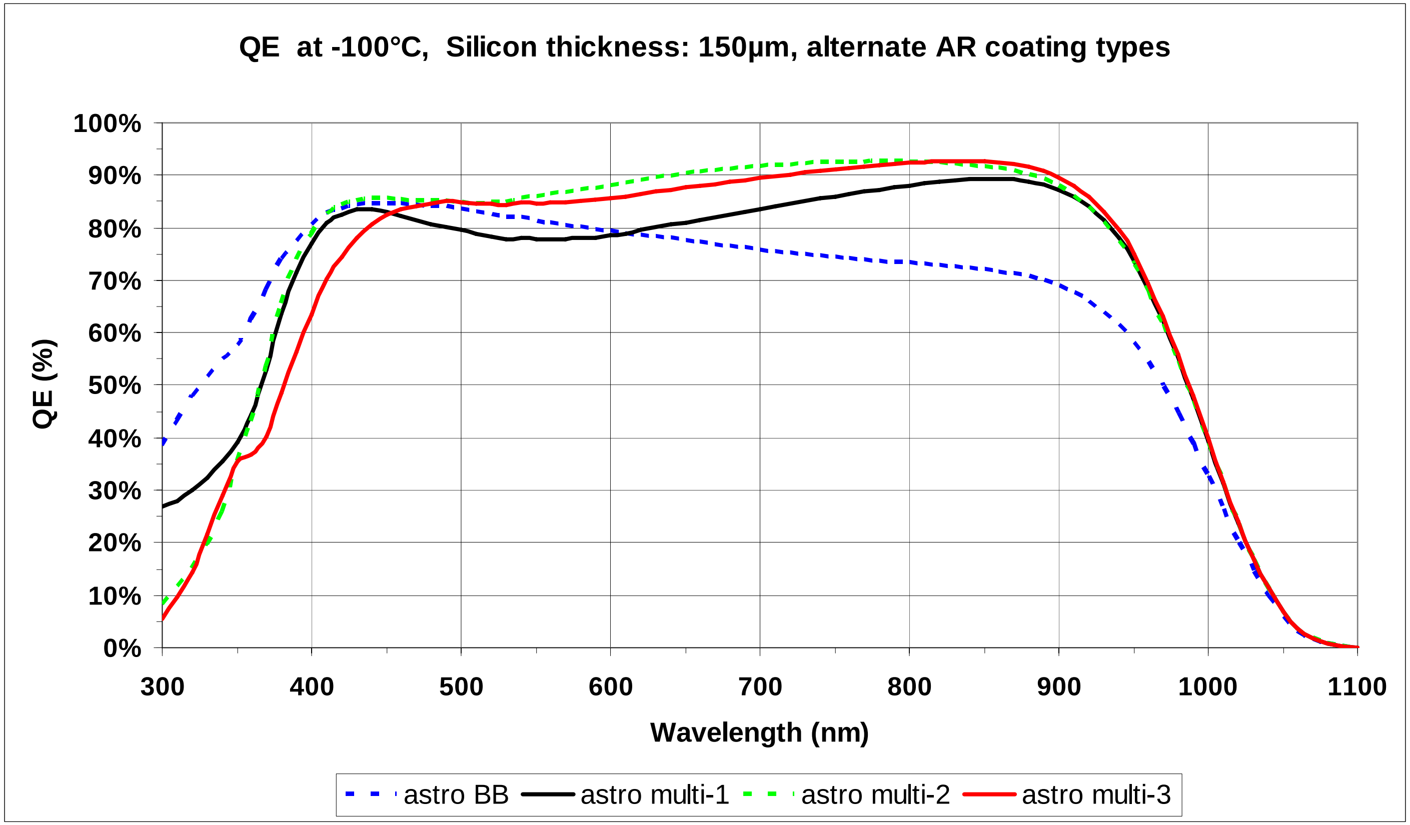
QE at -100°C

>40% for 330 - 1000 nm

>70% for 400 - 950 nm

Anti-reflection coating refinement- 1

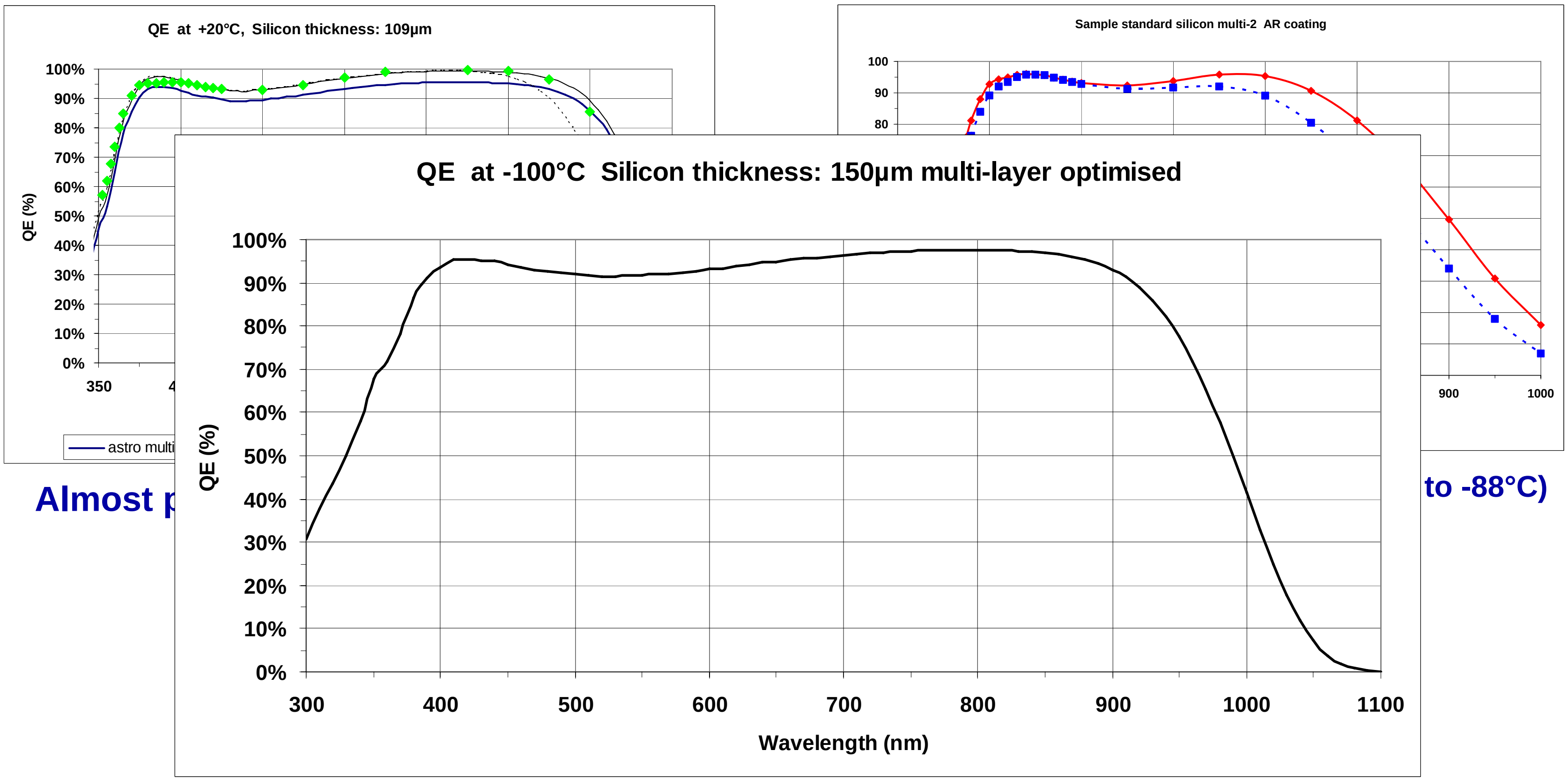
Extended red response and desire for blue response (U-Z bands) requires wider-range anti-reflection coatings



Spectral response of single layer (BB) compared to three e2v multi-layer coatings

Anti-reflection coating- 2

Enhanced coatings designs tested with new materials and multi layers



Almost p ... **to -88°C)**

Predicted performance of optimised coating

Anti-reflection coating- 3

AR Summary

- Wide wavelength range (U-Z) benefits from multi-layer coatings

- e2v has developed advanced multi-layer coatings:
High performance at red wavelengths together with maintained UV response

- Multi layer AR coatings have advantages over single layer Hafnia (traditional) coatings:
Single layers give good peak response; multi-layers broaden range (with slight dip in middle)

- Latest coatings show close to theoretical performance

- Coating design is adjusted for application area

- Secondary benefits-
  - Minimised reflectivity (ghosts/ scattered light)
  - Minimised fringing

Summary

Progression of development towards thicker CCDs for higher red QE

- Commercially available device types

Standard “Bulk” CCD44-82 (2K X 4K) shows excellent performance

- Operates at standard voltages; drop-in upgrade path

New “high-rho” CCD261-84 (2K X 4K) shows scientific performance

- Highest red response; good performance with one HV bias

Multi-layer AR coatings

- Enhanced performance for wide wavelength range

Acknowledgements

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