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NIR Large Format Sensor Array

Final Presentation

3rd April 2014 (updated 24th April 2014)

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OUTLINE OF PRESENTATION

- Phase 1 Review
  - Programme aims
  - Phase 1 results
  - PV work prior to phase 2
- Phase 2 Objectives
- ROIC
  - Design
  - Characterisation
  - Radiation test
- MCT
  - Thinning
  - MCT design
- Test results
- Summary

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PROGRAMME AIMS

Phase 1

- Demonstration of MCT with:
  - Spectral response 0.9 – 2.0 µm
  - High QE
  - Low dark current
- Using an existing small read out IC

Phase 2

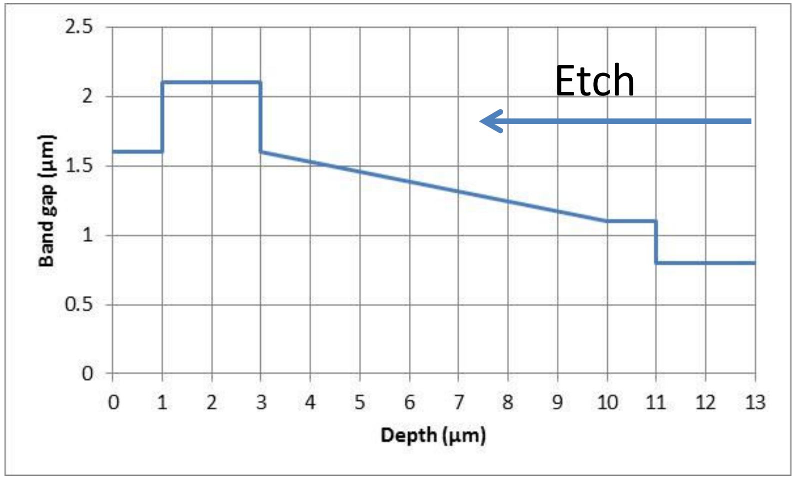
- Extension of MCT to large area and fine pitch
  - <0.1e- /pixel/s dark current at 100K
- Design and fabrication of a large area readout IC including
  - >512 x 512
  - 15µm pitch
  - Low noise
  - High gain/low well capacity

MCT DESIGN CHALLENGE

At the start of phase 1

- Standard detector design is:
  - Narrow band absorber layer, defines cut-off wavelength
  - Viewed through a wide band electrical common layer, defining cut-on
  - Effective for cut-on down to ~1.4-1.5µm
  - At wider band gaps, dopant is electrically inactive, becoming a trap

- As-grown MCT layer design illustrated
  - Designed to be etched after hybridisation to the ROIC
  - Etch through the MCT common layer
  - Etch stop within one diffusion length of the absorber
  - Low doping in the common layer, for longer carrier lifetimes
  - Composition gradient in the common, to produce an in-built field, to aid carrier collection



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PHASE 1 RESULTS

Parameter	Target Value	Comments	Achievement	
			Iteration 1	Iteration 2
Operating temperature	$80 \leq T \leq 140K$			
Cut-on wavelength	0.8 µm		1.45 µm	1.7 µm
Cut-off wavelength	1.9 – 2.0 µm	50% QE max.	1.9 µm	2.1 µm
Dark current	0.5 fA/cm^2 (0.018 e/p/s)	Over operating temperature range.	0.09 e/p/s (80K, with mux glow)	0.34 e/p/s (80K, with mux glow)
Quantum efficiency	≥ 80%	Over wavelength range. With AR coating.	H 74% J 4%	H 21% J 1.7%
Persistence	(no target)	Double saturation	3 mins	

- 24µm pitch, 320X256
- High QE in H-band (~1.6µm)
- QE degrades at shorter wavelengths (J-band is ~1.25µm)
  - In iteration 1 the shorter cut-off leads to H band absorption nearer the junction, hence the higher QE values;
  - Major issue going forward into phase 2 was how to improve response at the shorter wavelengths;
  - Thinning of MCT necessary to bring absorption to within a diffusion length of the junction.

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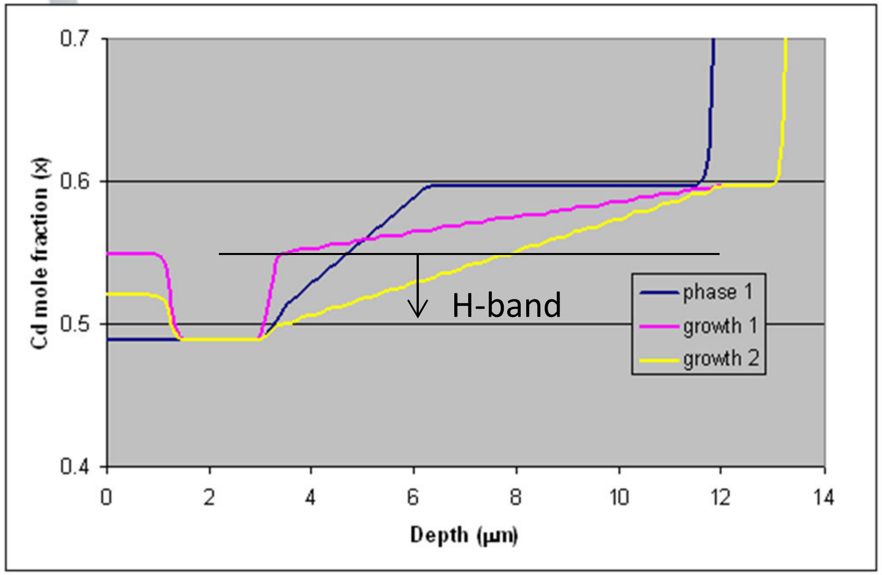
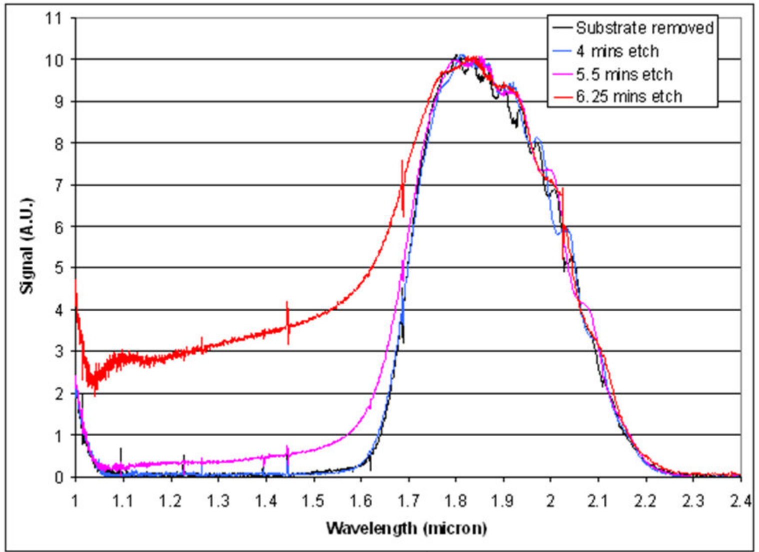
SELEX-ES FUNDED PV WORK BEFORE PHASE 2

- Two layers grown
  - Investigate shallower ramp compared to phase 1
  - Note H-band is absorbed at $x < 0.55$, J-band at $x < 0.76$
  - Higher x-contact layer to reduce generation at contact and volume of lowest x region
  - Design for low dark current
- Dry vs wet etched mesas
  - Phase 1 used wet etch, dry required for LFNIR
- Spectral assessment on test arrays – see next slide

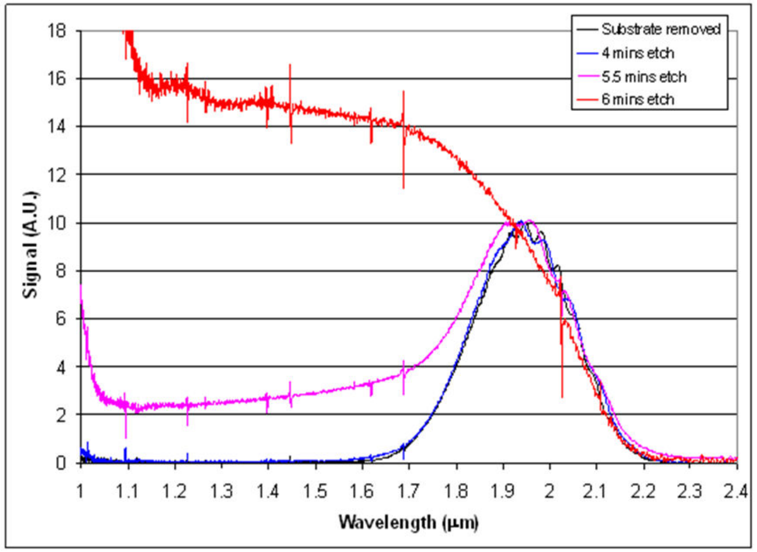
STATUS AT START OF PHASE 2

Summary of PV work before phase 2 start





Growth 1



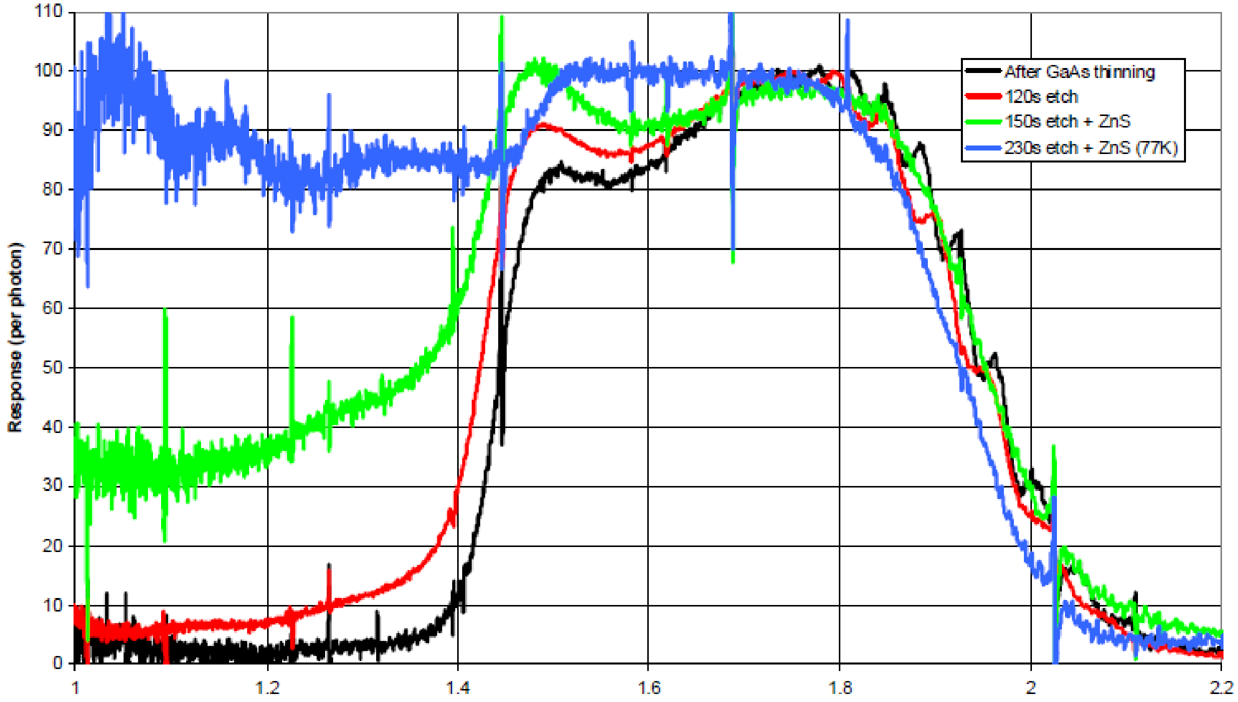
Growth 2

- Good response in growth 1 only for radiation absorbed in "well"
  - Lifetime issue still evident in high-x
- Better improvement with thinning for growth 2 but initial response poor

STATUS AT START OF PHASE 2

Summary of PV work before phase 2 start

- Best result from further thinning of a phase 1 test array
  - But we are very close to etching down to the edge of the mesas



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PHASE 2 OBJECTIVES

ROIC

- Design
- Procure
- Characterise

MCT

- Develop necessary processes:
  - Large area thinning trials
- Materials design aimed at improving diffusion lengths:
  - Reducing Cd mole fraction by using a shallower ramp
  - Reducing dopant concentrations
- Provide arrays for test at ATC
  - Preliminary screening at SELEX

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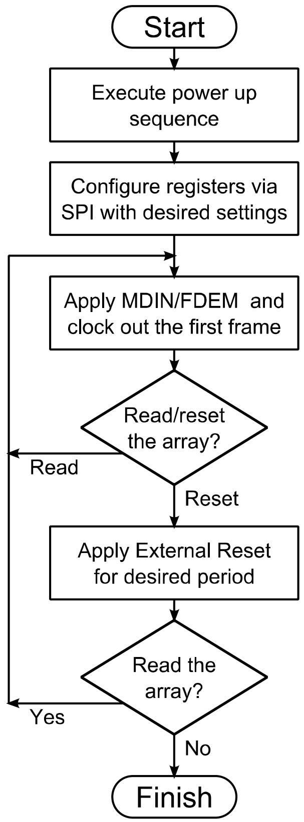
Large Format Near Infrared ROIC – Key Features

- Features:
  - 1280 x 1032 format pixel array (1276 x 1024 active pixels)
  - 4 reference rows top & bottom
  - 2 reference columns left & right
  - 15µm pixel pitch
  - Internal or external pixel array reset control
  - User programmable readout regions
  - User programmable reset regions
  - Reference output
  - On-chip array reset current limiting circuit
  - Radiation hardened digital standard cell library developed specifically for space applications
  - 3v3 CMOS SPI digital interface

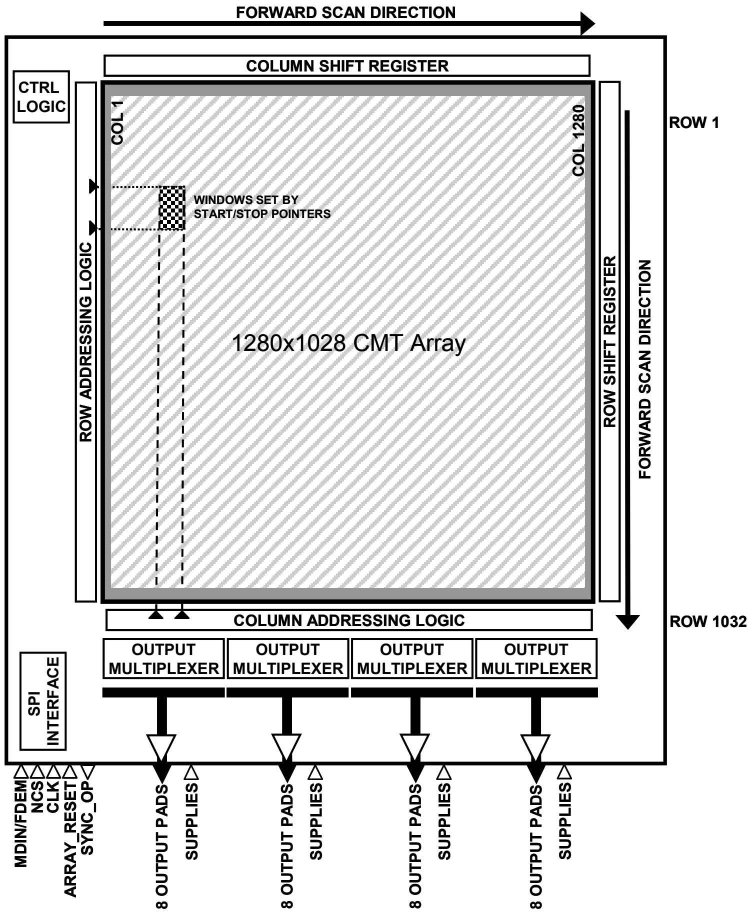
Large Format Near Infrared – Operating Modes

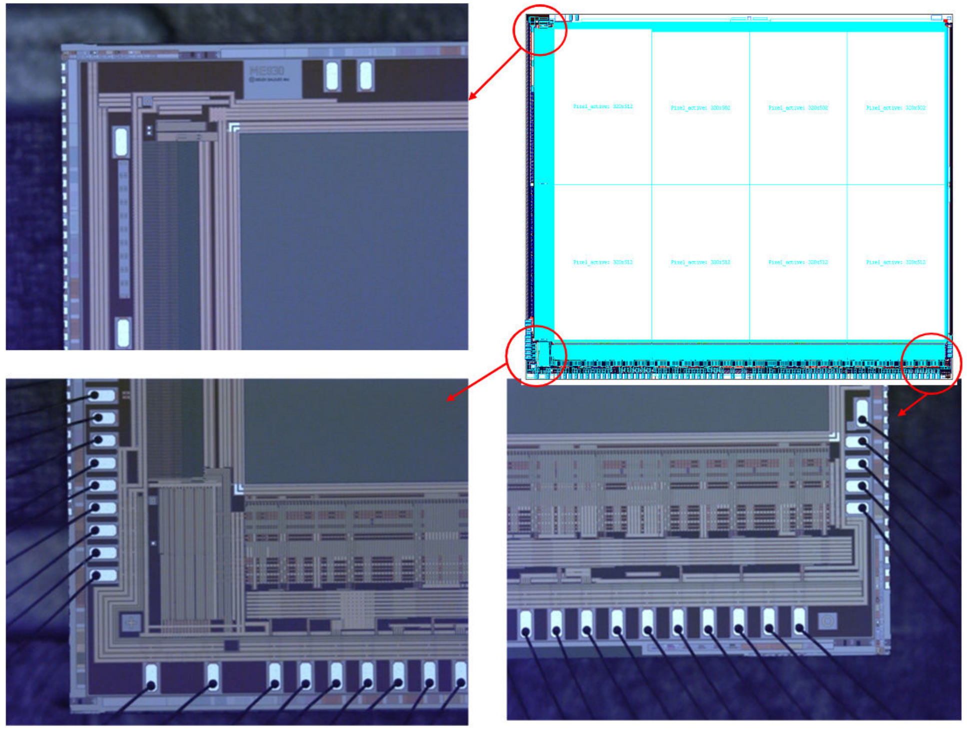
- Readout modes:
  - Non-destructive readout, Rolling Reset readout, Read-Reset-Read readout
  - Rolling Reset Readout
  - Read-Reset-Read readout
- Image capture modes:
  - Snapshot
  - Rolling shutter



Typical non-destructive readout operational flow diagram

Large Format Near Infrared – Block Diagram
Chip layout & microphotograph





Wirebonds on left and right edges are for test purposes only

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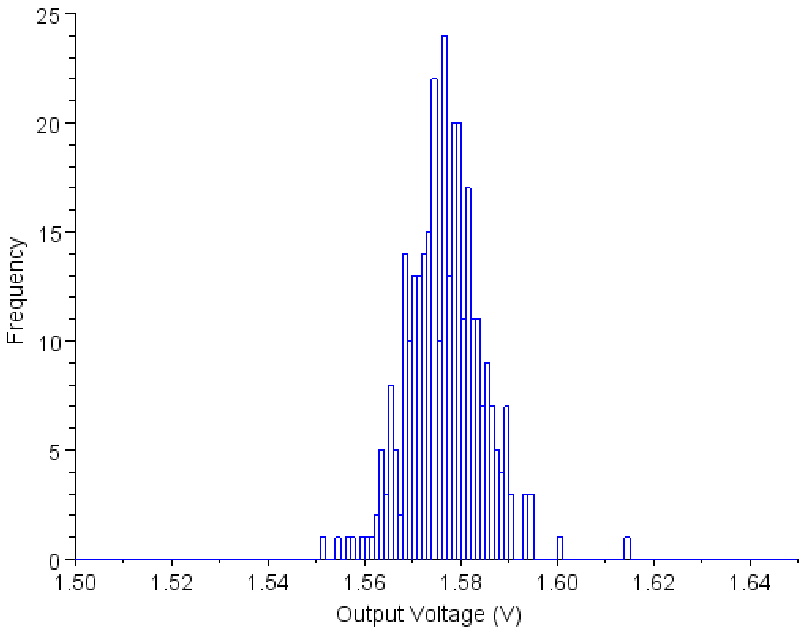
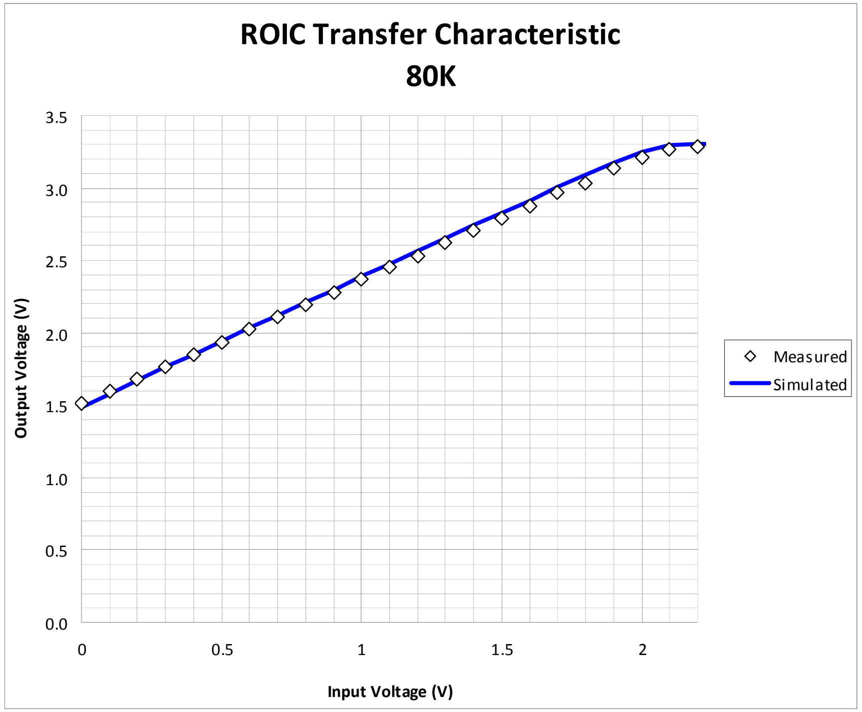
ROIC Performance Summary

PARAMETER	DESIGN	TEST	SPEC	COMMENTS/CONDITIONS
Active array size	1276 x 1024	-	512x 512+	4 reference rows top and bottom 2 reference columns left and right
Power	<120mW <40mW	55mW 35mW	Low	32 output mode (80K) to 4 output mode (80K)
Linearity	<1%	0.8%		Across maximum available pixel dynamic range (2.1V) at 80K. ROIC only
Noise	40e- input referred, <8e- excluding kTC	<7e- <20e-	<18e- (CDS), <7e- (UTR)	25 non-destructive reads (80K) Single CDS (80K)
Conversion gain	4.5µV/e-	6µV/e-		At 80K, including MCT
Transfer gain	0.85	0.853		Single Source Follower readout chain (80K)
Useful Pixel Dynamic Range	1.5V typical	1.4V		PRV = 2V (80K)
Available Charge Handling Capacity	266ke-	235ke-	>60ke-	1.2V output dynamic range and 6µV/e- conversion gain (80K)

Large Format Near Infrared – ROIC Characterisation

- Typical expected output non-uniformity (80K)
  - <65mV peak-peak, <8mV Standard Dev.
- ROIC Transfer characteristic (80K)
  - Gain=0.85, Pixel-referred DR=2.1V

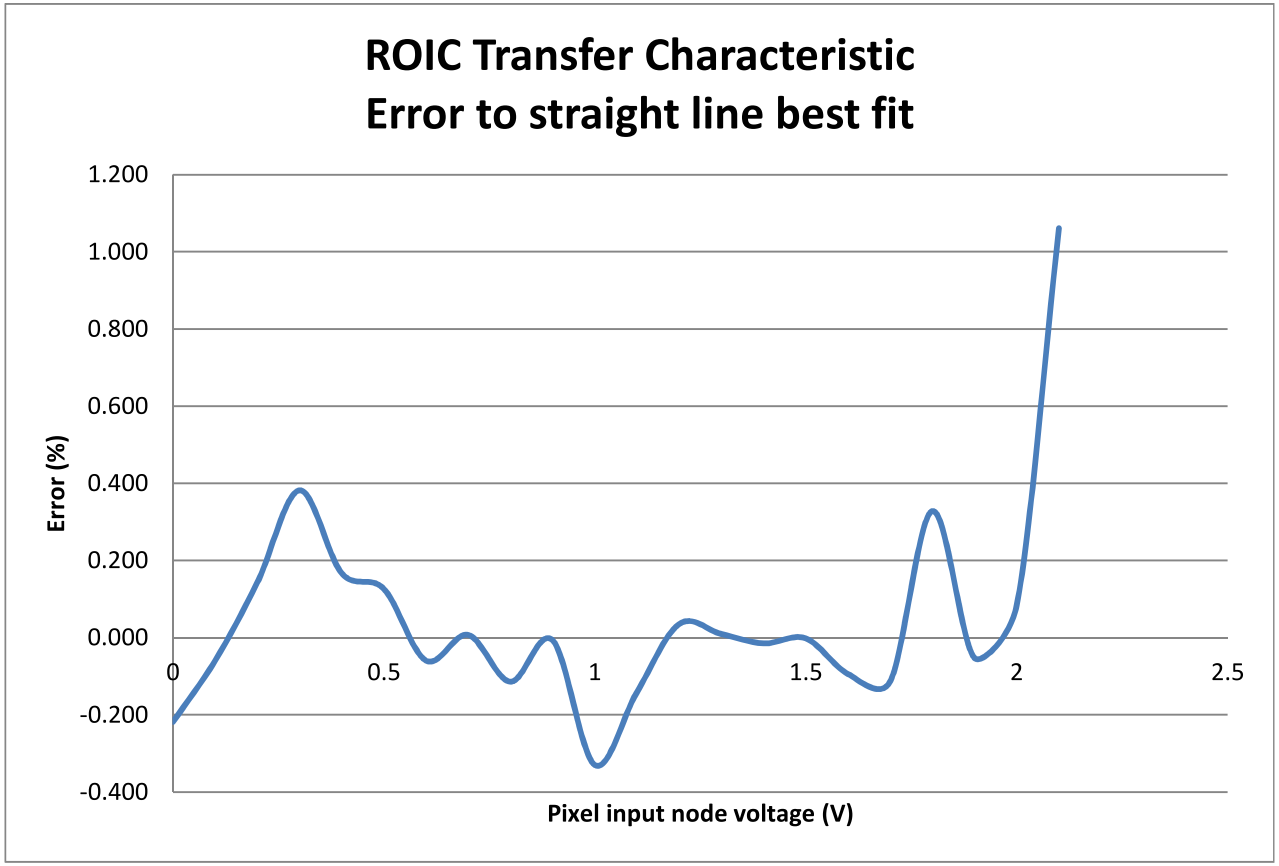




100kHz readout frequency, PRV=2V, nominal supply voltages (3.3V & 5.0V)

Large Format Near Infrared – ROIC Characterisation

- 0.8% across available pixel dynamic range (2.1V)



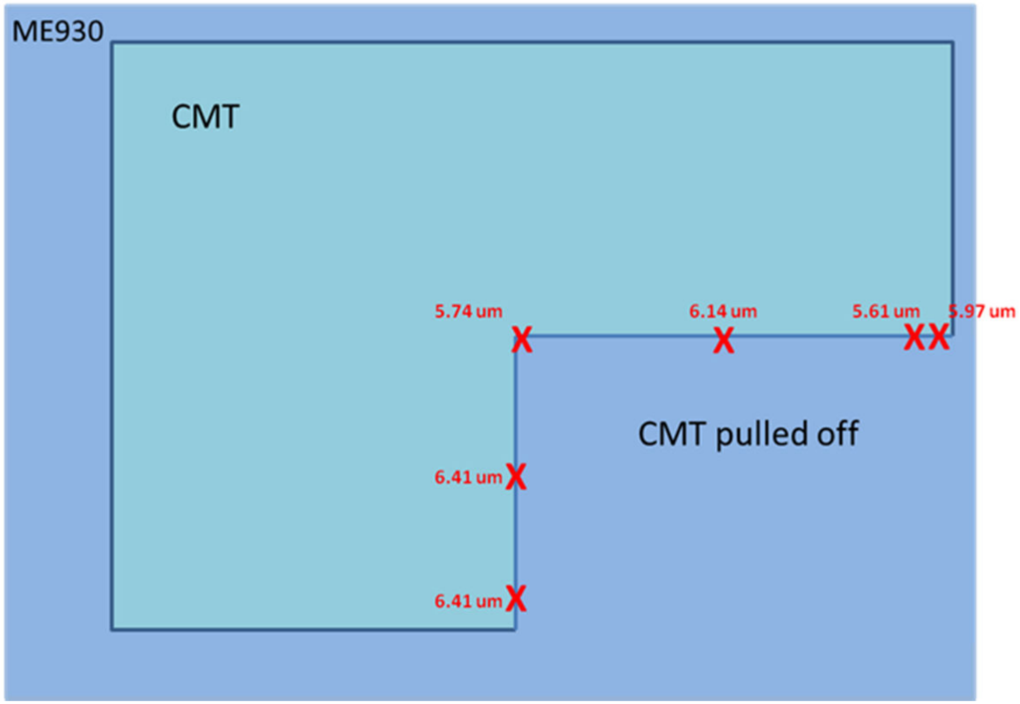
100kHz readout frequency, PRV=variable, nominal supply voltages (3.3V & 5.0V)

Large Format Near Infrared ROIC – Radiation testing

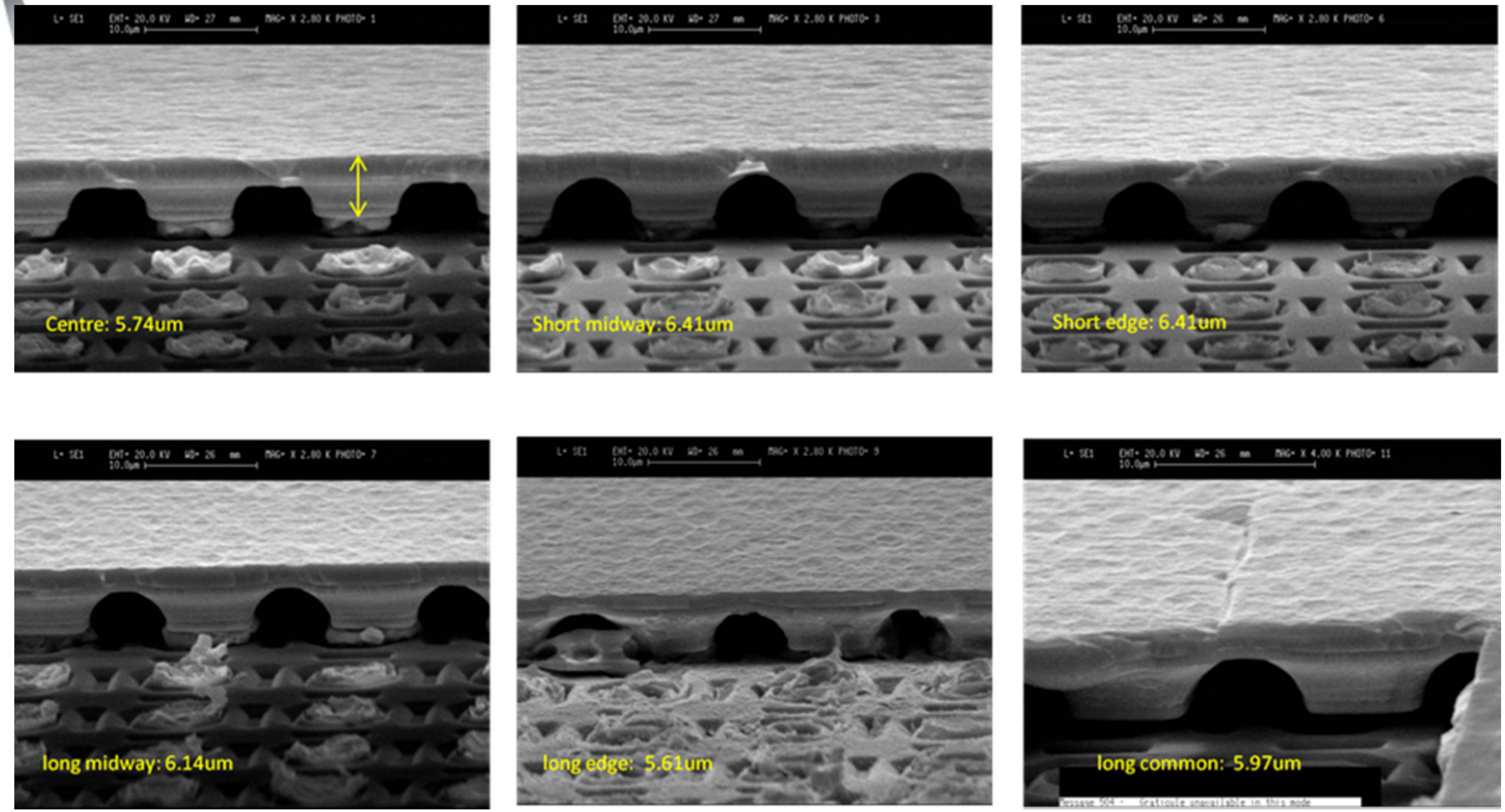
- This work was carried out under Selex ES funded PV
- Useful to help debug the test set-up
- Heavy ion test campaign
- No latch-up observed on digital supplies
- Analogue supply drew excessive current but this is expected to be due to increased leakage, not SEU effects.
- Test set-up did not allow for fast current transients on supplies to be accurately monitored
- Validated the digital library
- Testing will be repeated within the next 6 months

MCT LARGE AREA THINNING TRIALS

Used Merlin (1028 x 768 array at 16μm pitch, 16.4 x 12.3 mm active area) and Falcon (1920 x 1080, 12μm pitch, 23 x 13 mm active area)



LARGE AREA THINNING TRIALS



- Good uniformity achieved

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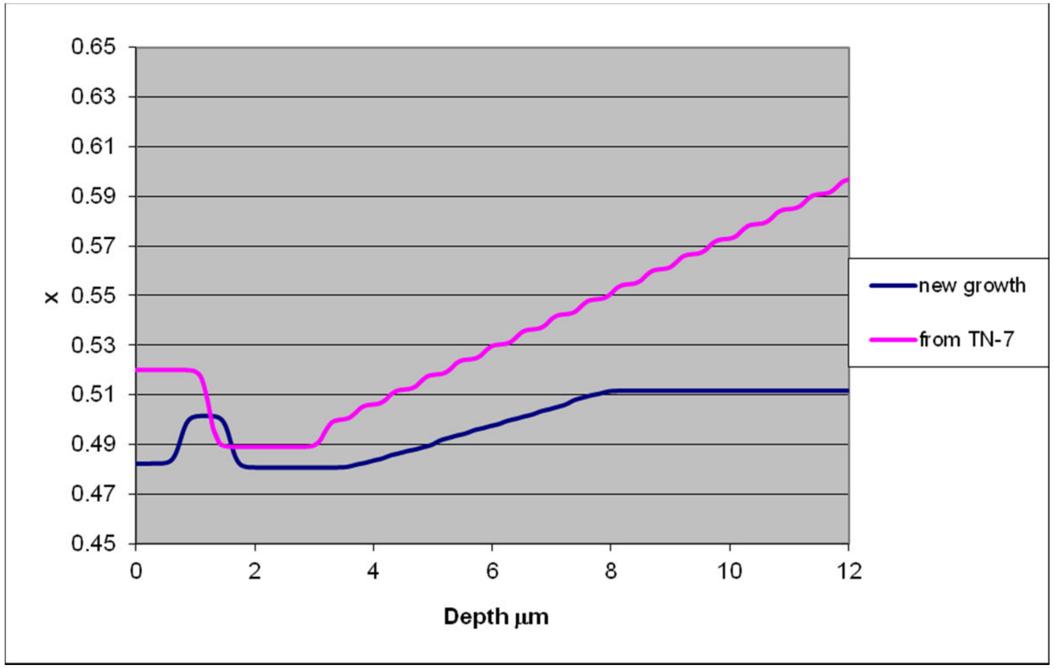
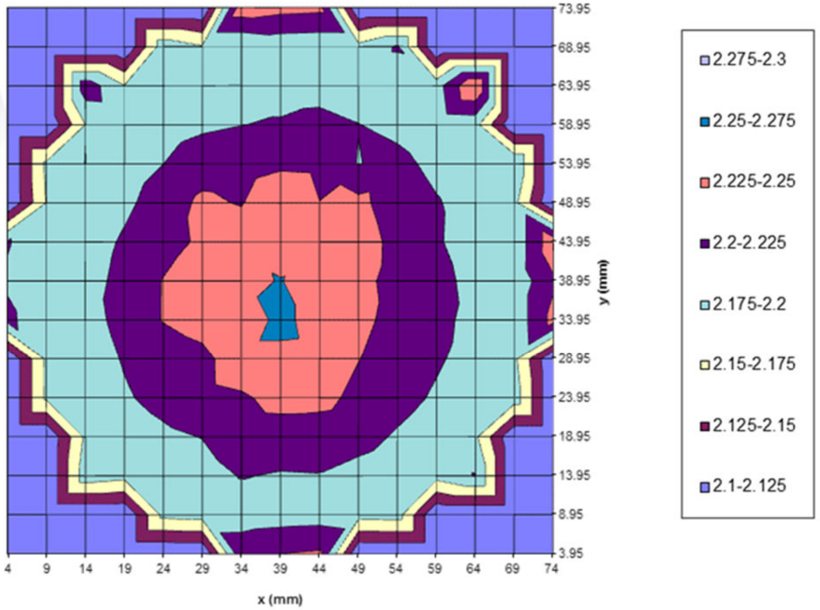
DESIGN

MCT Baseline Design

- X ≤ 0.51 throughout:
  - attempt to improve lifetimes;
  - H-band absorbed throughout structure.
- Reduced x at contact:
  - Ensure good dopant ionisation for reliable contact;
  - Barrier between contact and active part reduces influence of contact generation;
- 2 layers provided for processing
  - 5vg260 and 5vg292

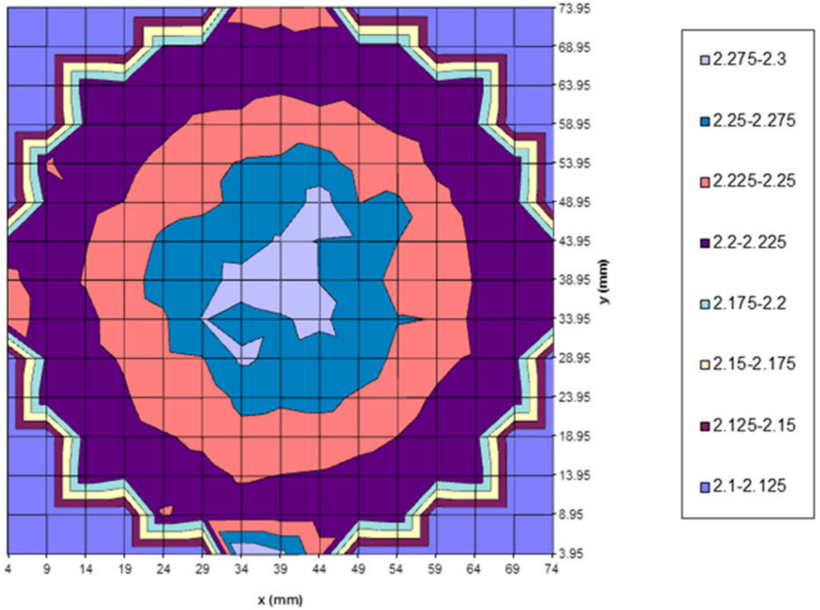


PREDICTED CUT-OFF MAPS



5vg260

5vg292



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TEST

Test capability

- Selex ES
  - ROIC transfer function;
  - Spectral response;
  - Functional temperature range;
  - Operability.

- The UK ATC
  - System gain;
  - Detector conversion gain;
  - Full well capacity;
  - Non-linearity;
  - Read noise;
  - Inter-pixel capacitance;
  - Dark current;
  - Reset effect;
  - Readout glow;
  - Persistence;
  - Electrical crosstalk;
  - Intra-pixel sensitivity measurement;
  - Modulation transfer function;
  - Quantum efficiency.

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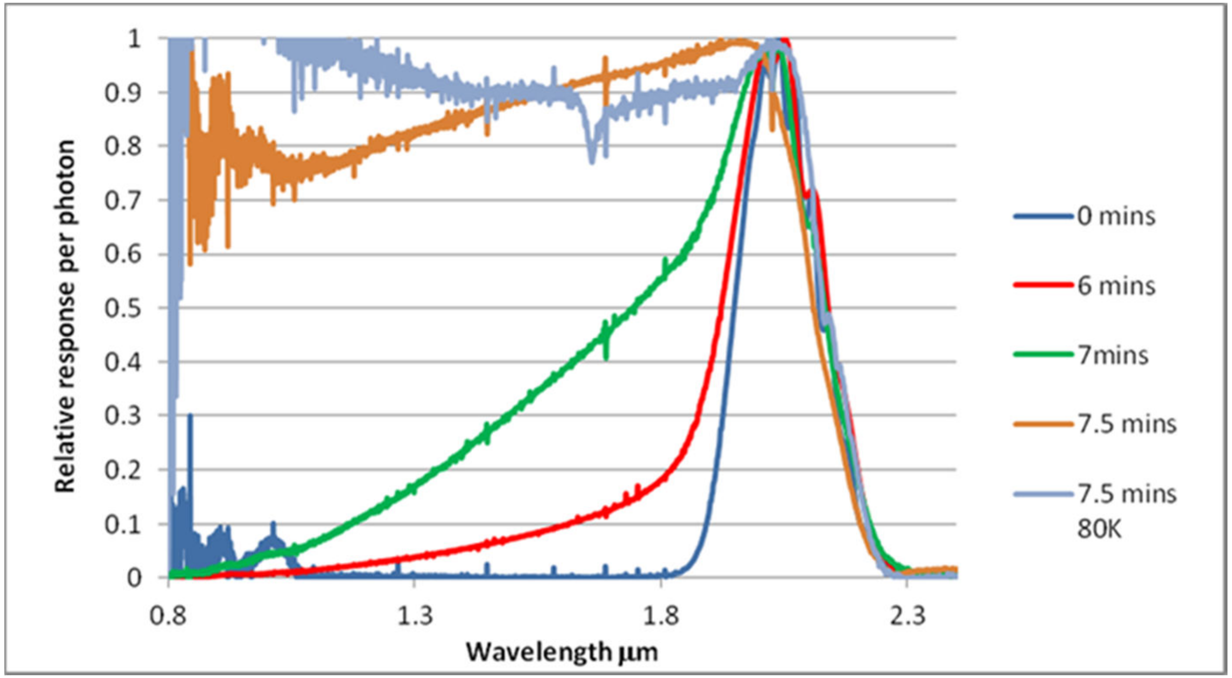
RESULTS

Spectral response and Thinning – small area test array

- As expected, initial response only from bottom of x-ramp;
- Thinning still required to ~7µm to achieve shorter wave response.

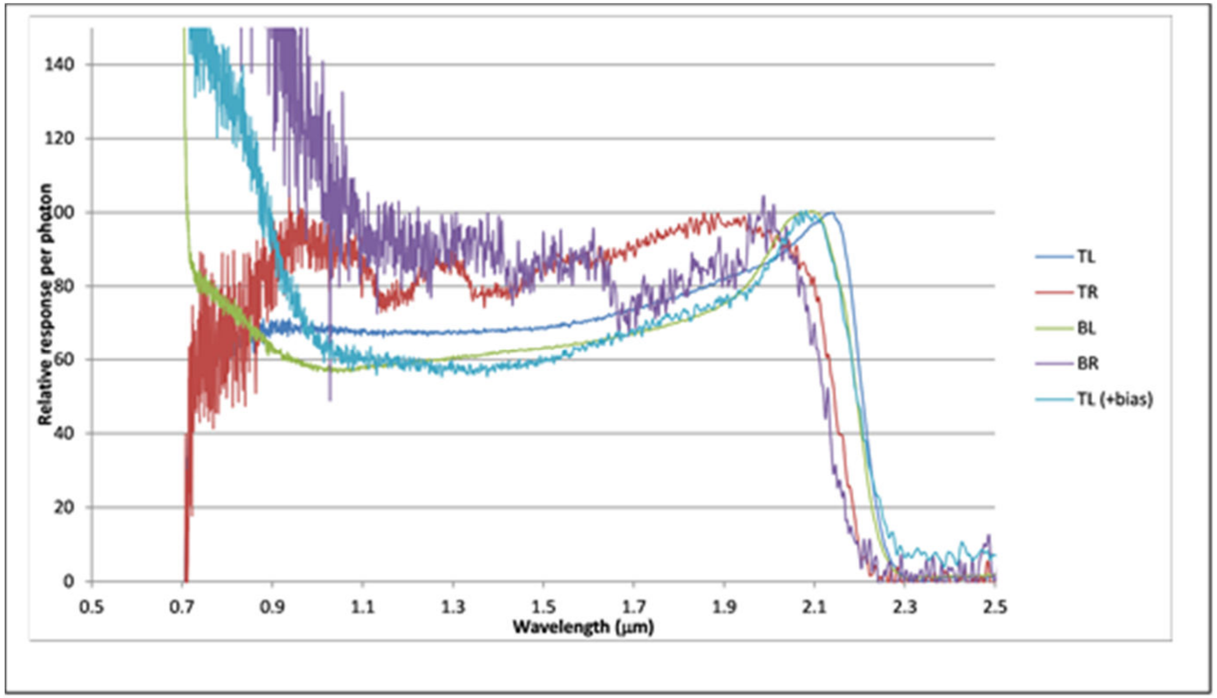


5vg260 test array at various stages of thinning

RESULTS

Spectral response and Thinning –corner diodes of full sized arrays

- Initial results showed insufficient thinning
  - Misinterpretation of thinning guides
  - Thinning assessment by FTIR interference fringes developed
- 02605-04 supplied to ATC. Response after thinning to ~ 7µm

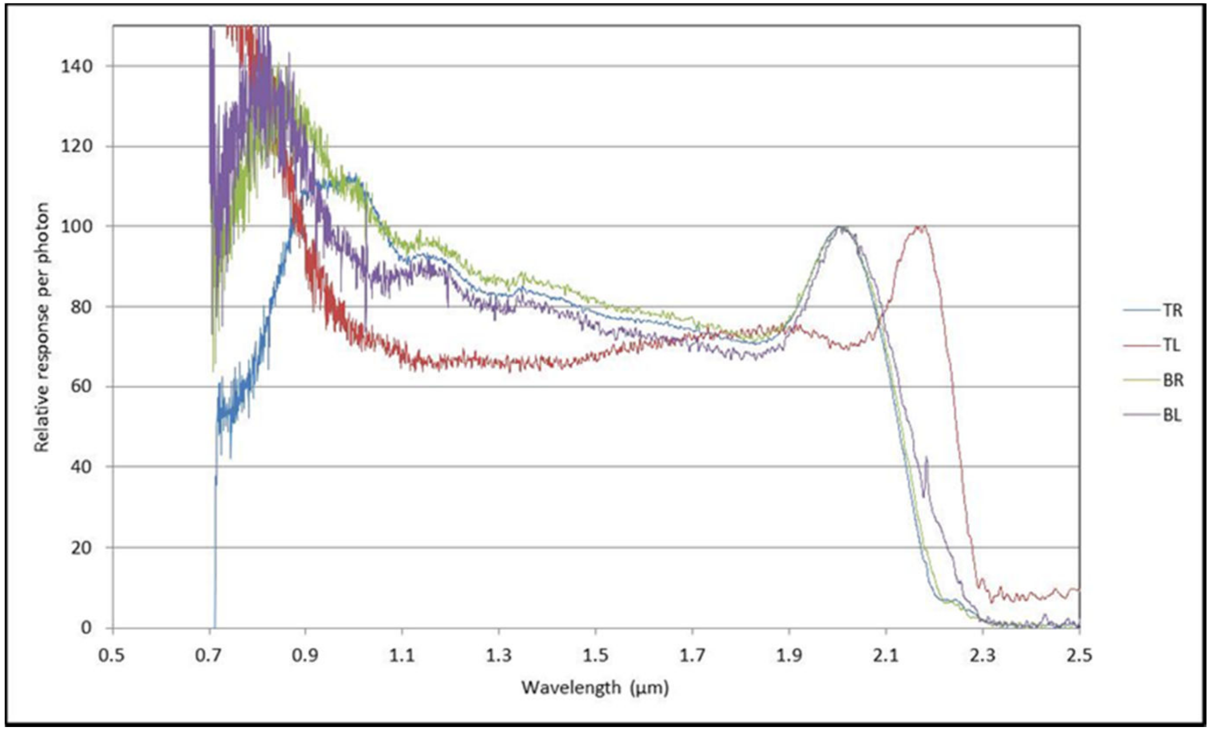


- ATC array assessment:
  - 12.6% H-band,
  - 7.6% J-band;
- Possibly enhanced thinning near corners

RESULTS

Spectral response and Thinning –corner diodes of full sized arrays

- Array 02925-4 was returned from ATC for further thinning, target 6μm;



- ATC array assessment after extra thinning:
  - 55% K-band* (~2.2μm)
  - 33% H-band
  - 36% J-band
  - 14% Z-band (~0.9μm)

* Cut-off 2.17μm

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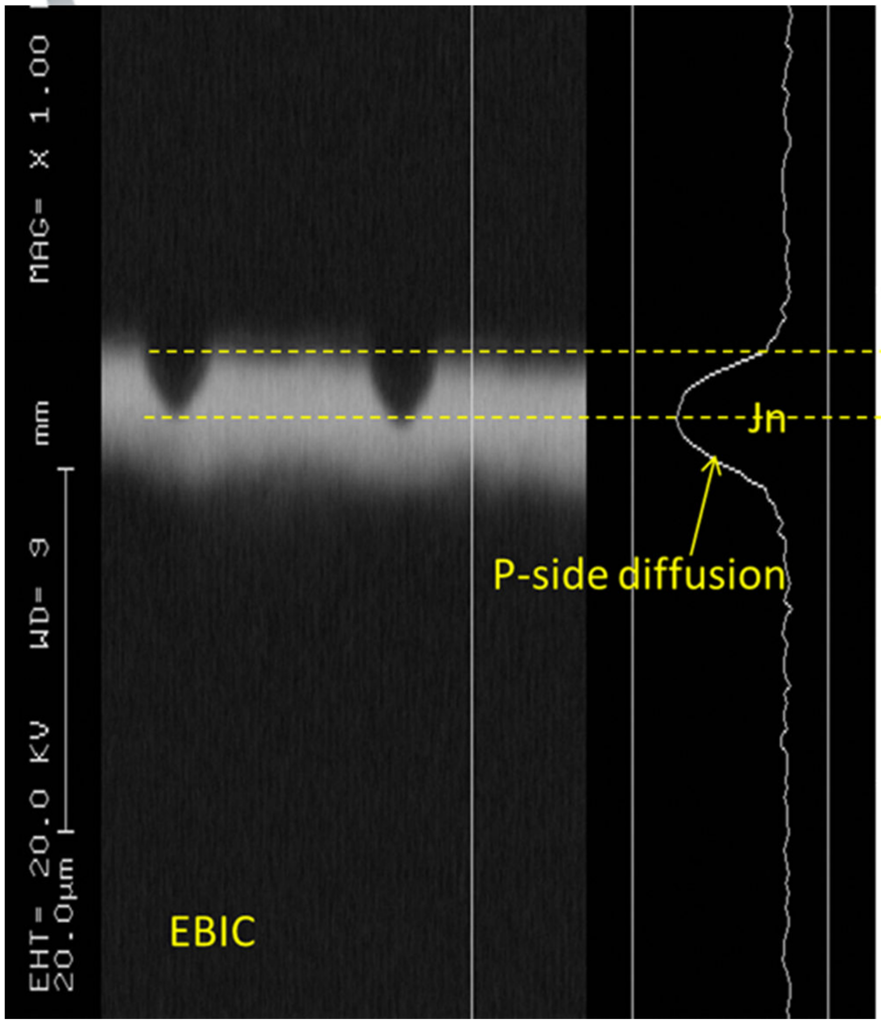
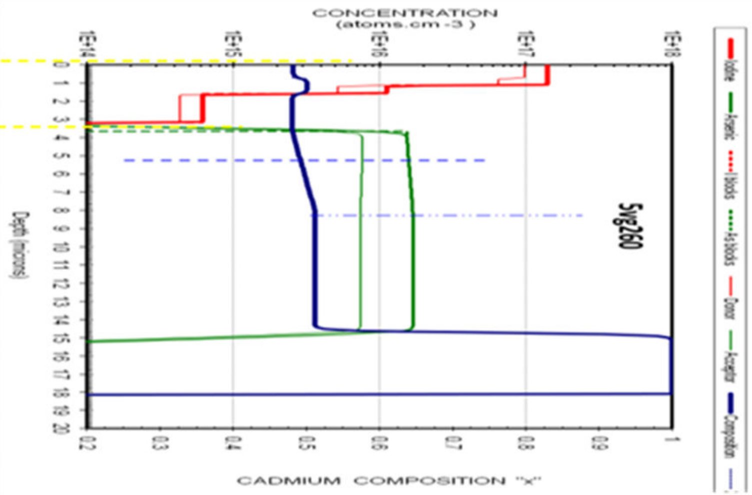
EBIC ASSESSMENT



- These arrays aimed at detecting radiation from 0.8um to 2.1um. Need to thin the CMT down to ~7um by ferric chloride etching to get SW response.
- EBIC carried out to see if p-diffusion length is consistent with this CMT thickness.



- EBIC and SIMs plot scales adjusted to match.
- Junction location from EBIC coincides with that expected from SIMS plot.
- Diffusion length in p-region consistent with CMT thickness removal required to get short wave response.

RESULTS

Summary of Array Assessment at the ATC

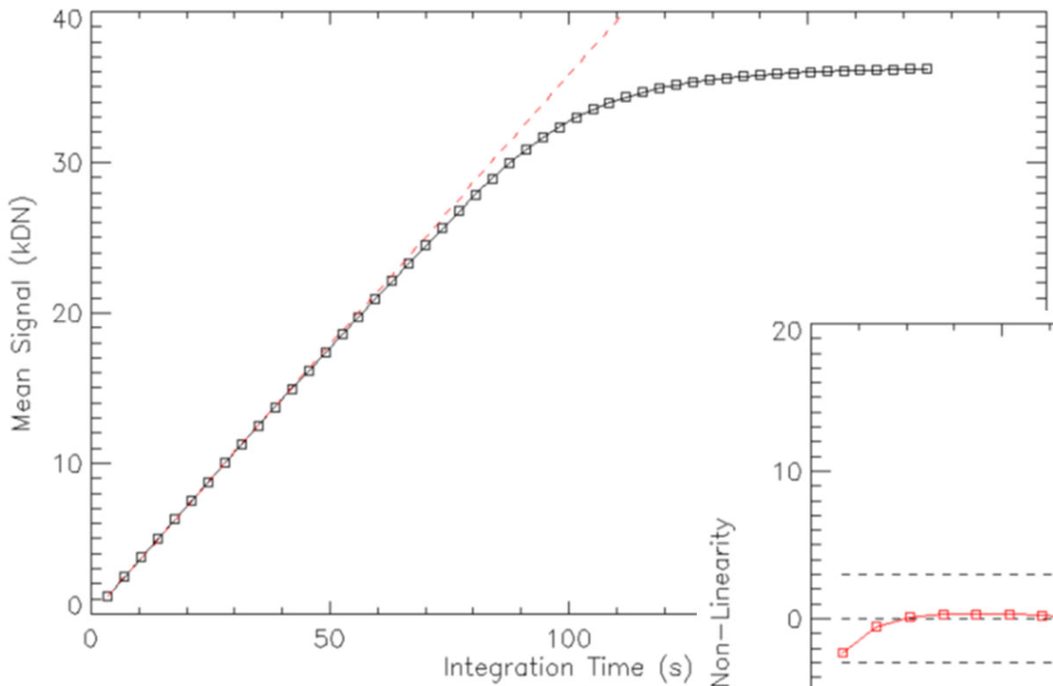
Array	2605-05	2605-03	2605-04	2925-04	2925-04 reworked
QE K (%)	24[1]			36[1]	55[2]
QE H (%)	0.55	Low	12.6	1.2	33
QE J (%)			7.6	0.4	36
QE Z (%)					14
80K Idk (e/p/s) [3]	0.02		0.43	0.1	
Idk (e/p/s) at (T)	230 (150K)			0.25 (100K)	
C (fF) [4]	37		30	26	23 (13[5])

1. Estimate 1.95 – 2.15µm;
2. Estimate K-band filter and 2.17µm cut-off;
3. Screening test, stray light potential;
4. Ballast capacitors enabled;
5. Ballast capacitors disabled

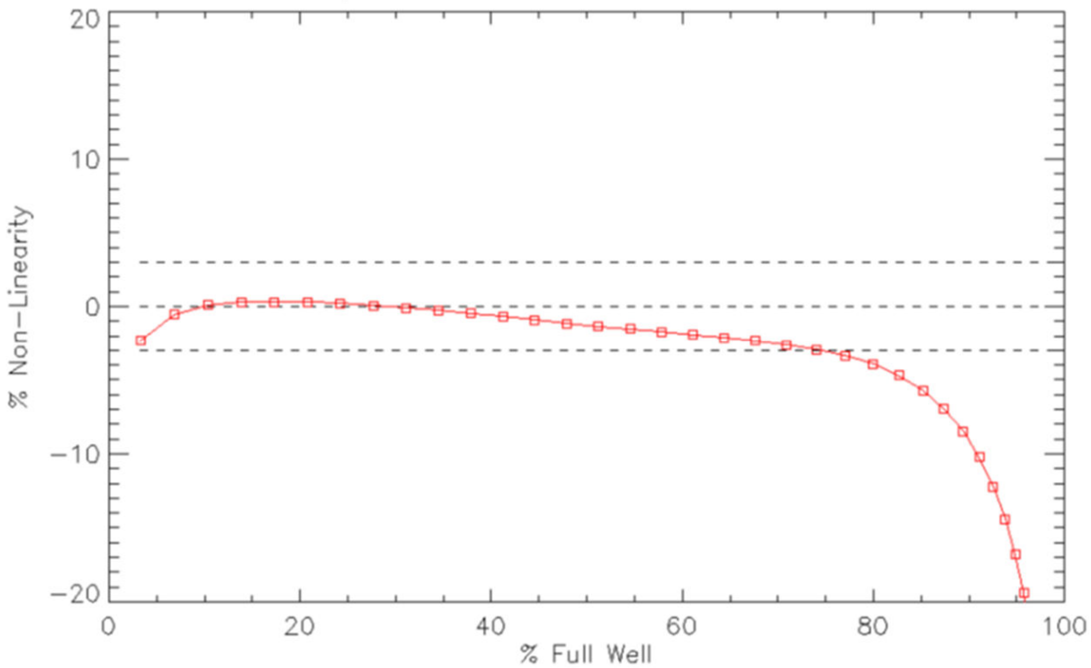
- Insufficient thinning given to 2605 -03 and 05;
- 2605-04 was thinner;
- 2925-04 returned for further thinning.

RESULTS 2605-04

Photon Transfer curve

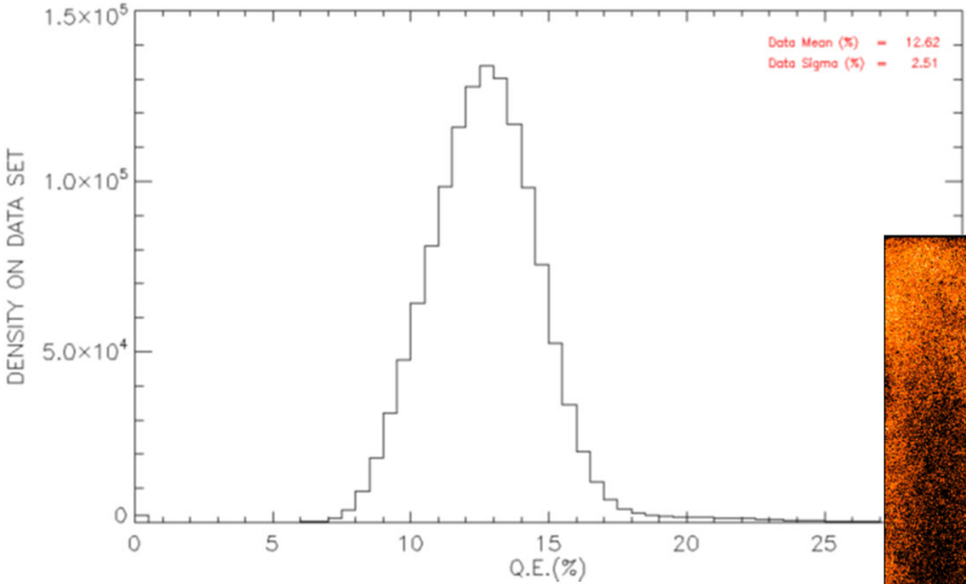


- System gain 2.74e/DN
- Non-linearity < 3%
- 75ke^{-} well capacity

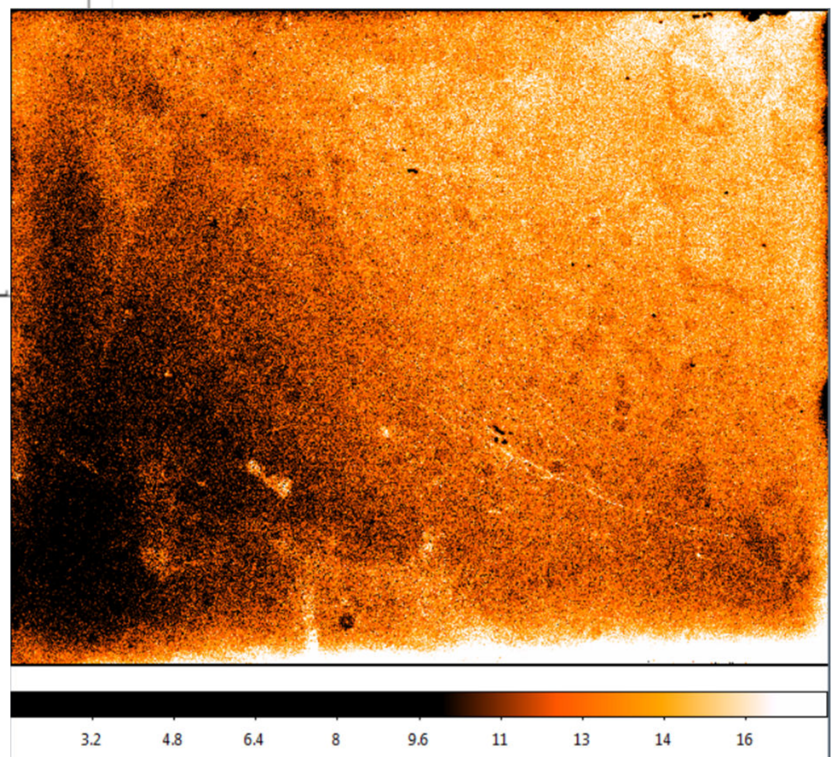


RESULTS 2605-04

H-band QE

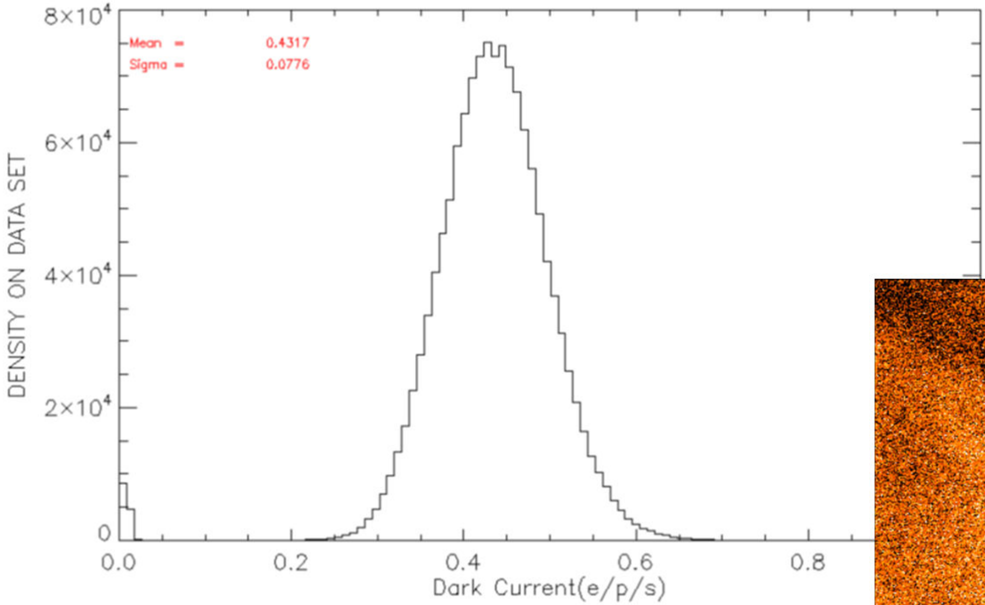


- J-band had similar distribution

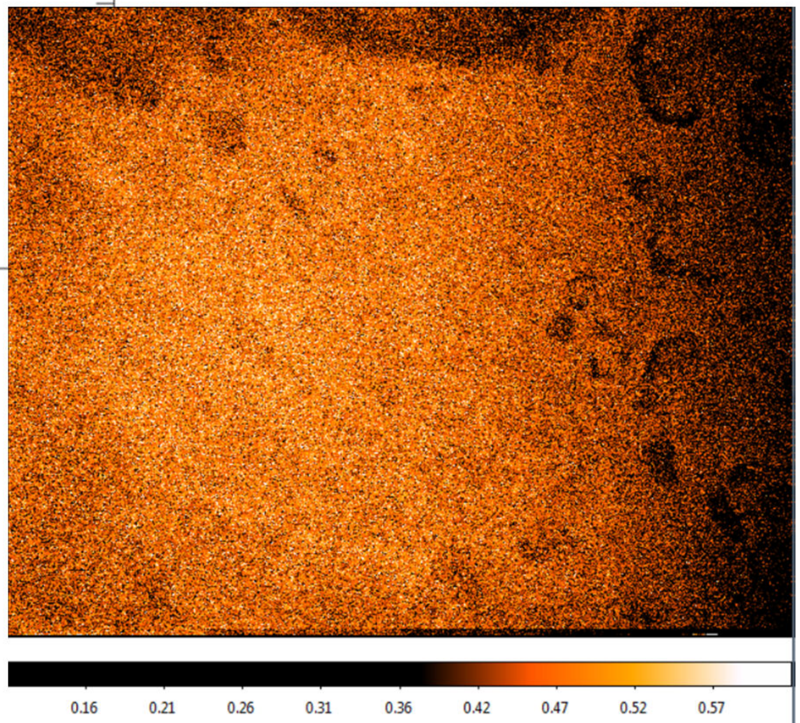


RESULTS 2605-04

Dark current at 80K

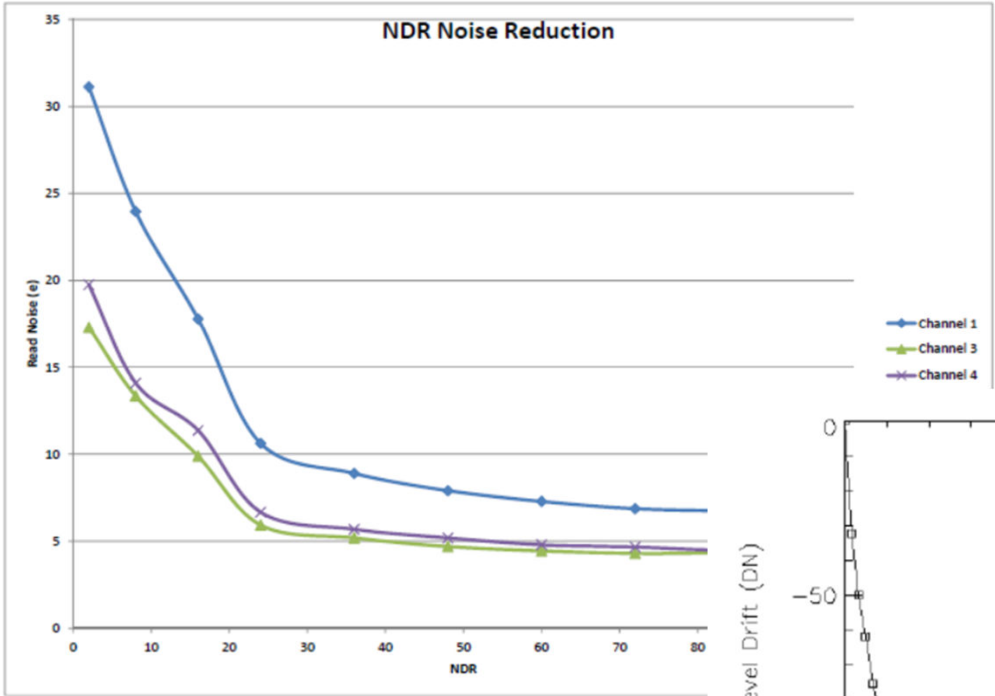


- Blank in filter wheel
  - Not optimum test set up
  - Some stray radiation expected

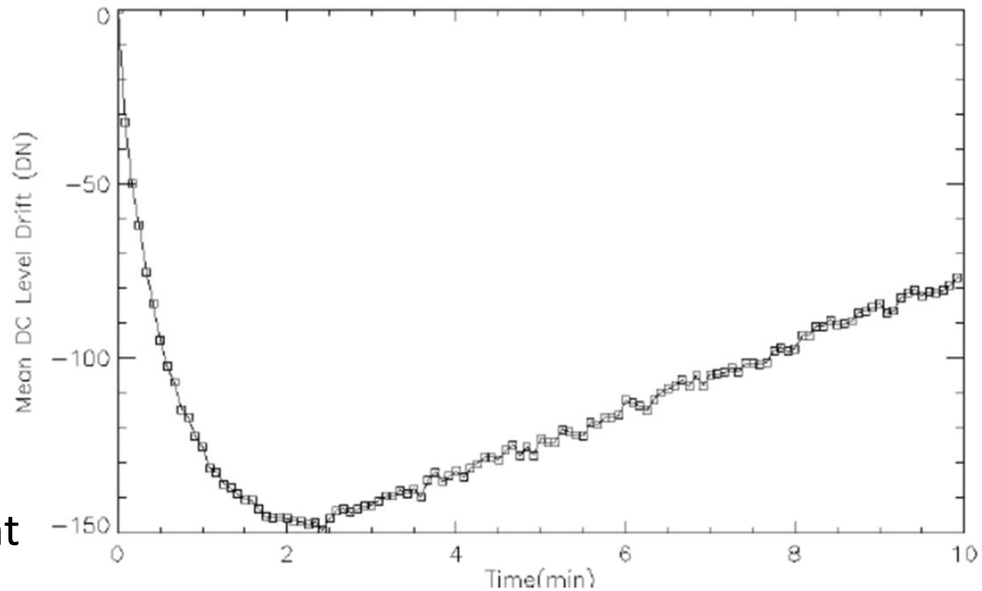


RESULTS 2605-04

Multiple NDR – dark scene



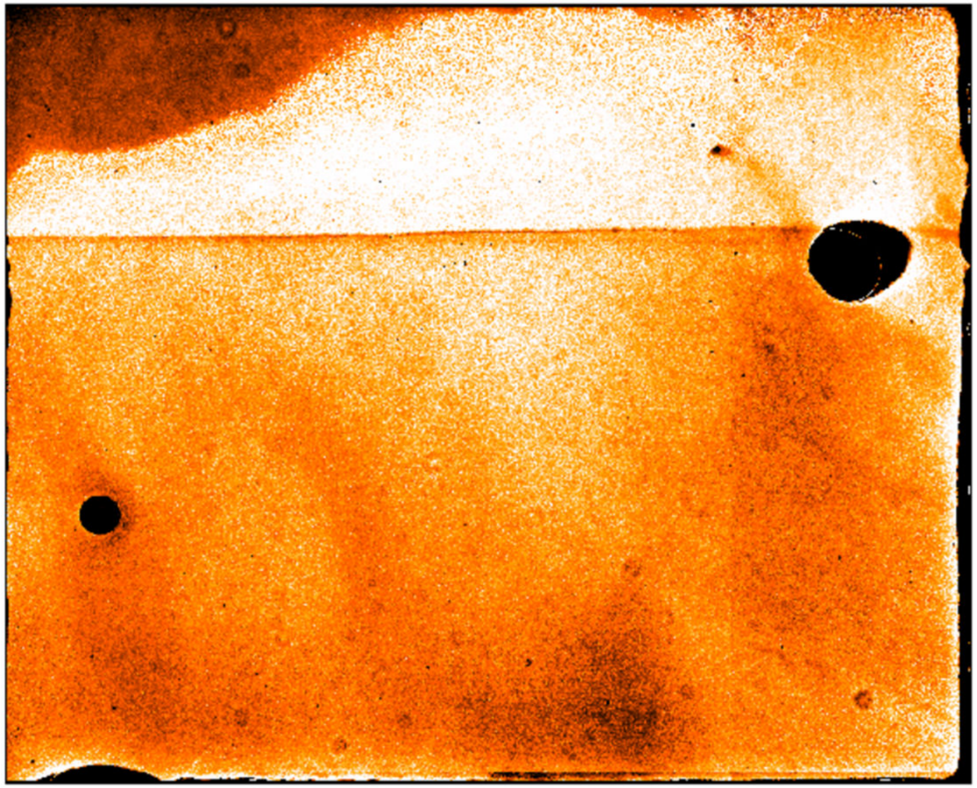
Noise reduction achieved with a sequence of non-destructive reads



Reset effect on measured dark current

RESULTS 2925-04 (after rework)

Flat field response



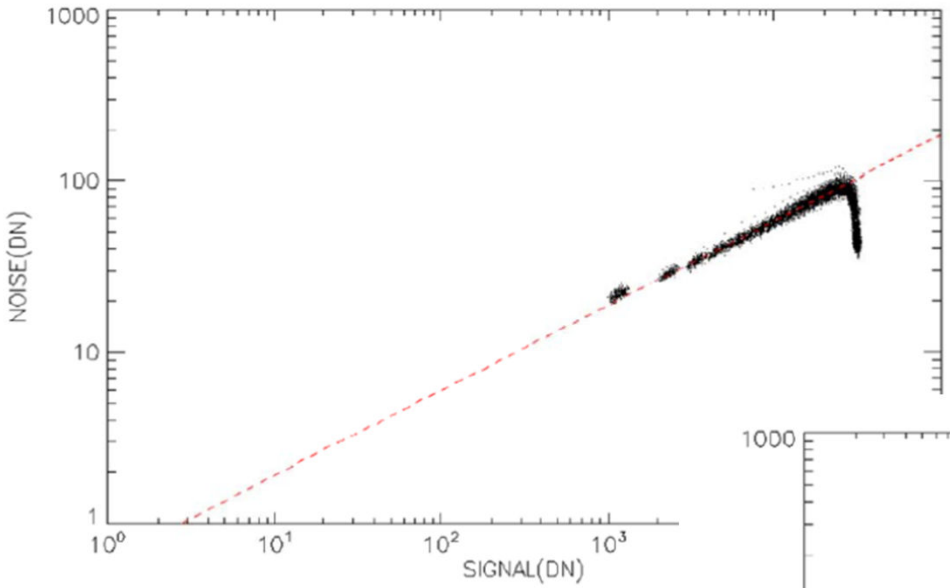
Un-coated

AR coated

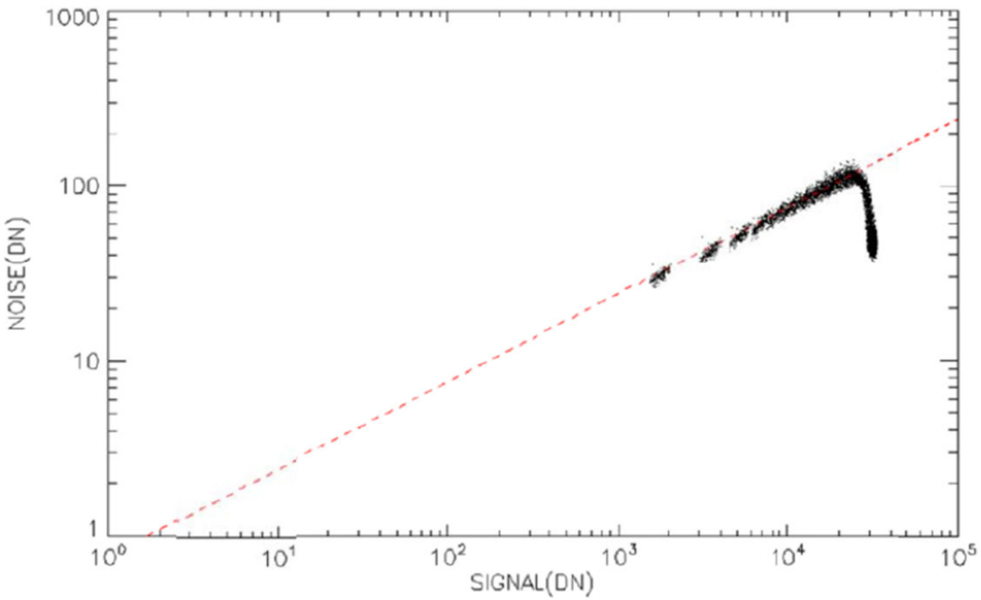
- Mid-band quarter wave coating;
  - Becomes reflective near cut-off

RESULTS 2925-04 (after rework)

Photon transfer curves – high gain observed



- Ballast enabled;
  - 23 fF.



- Ballast disabled;
  - 13 fF.

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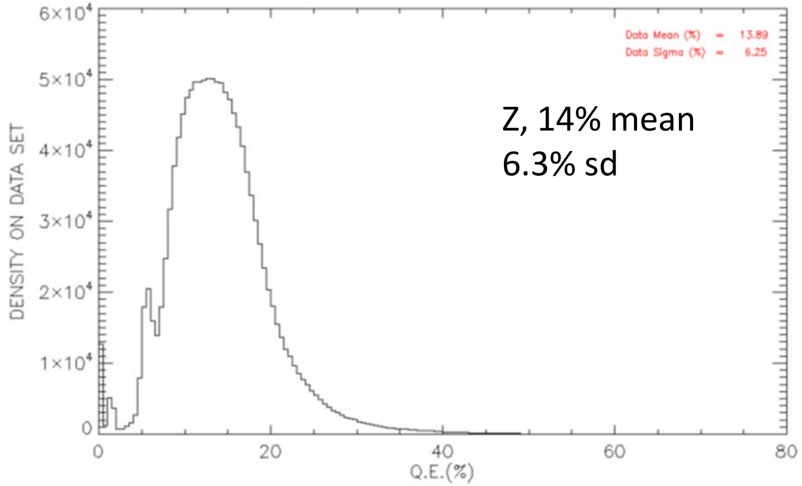
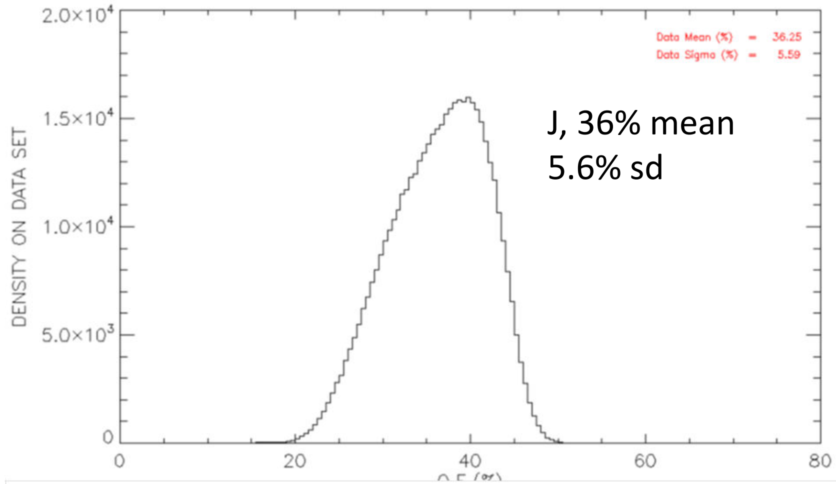
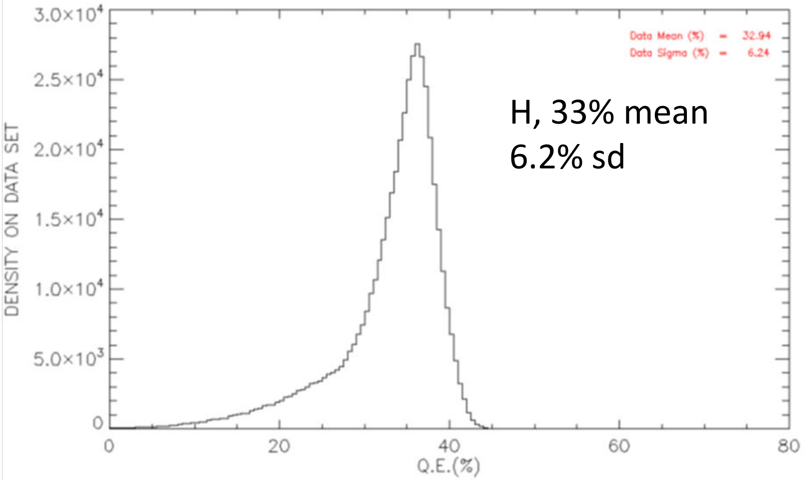
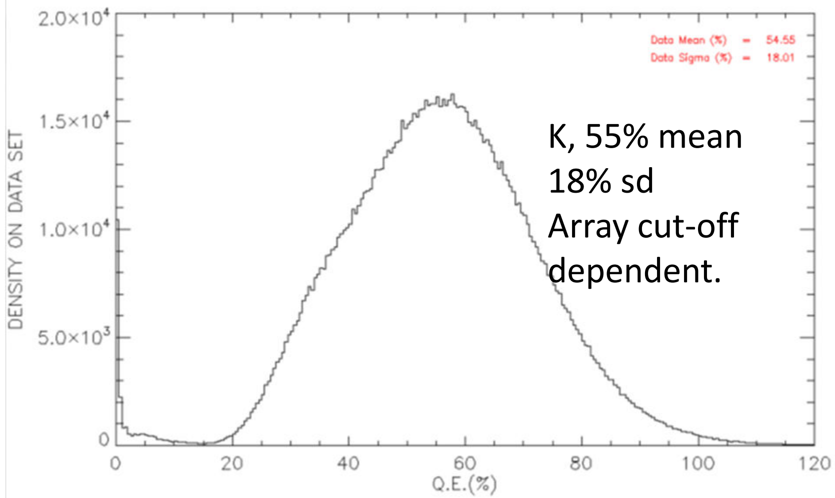
RESULTS 2925-04 (after rework)

QE histograms









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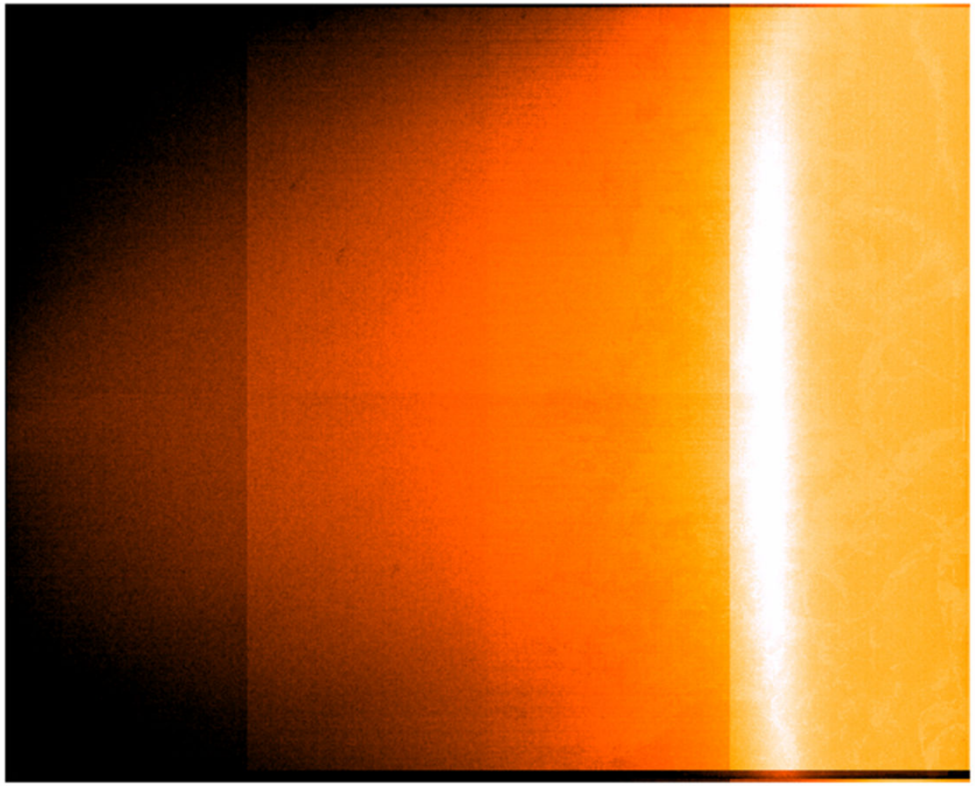
RESULTS - ISSUES

Single raw read

- Subtracted out in CDS
  - Not integrated signal
  - Not glow
- Effect ~35ke$^-$



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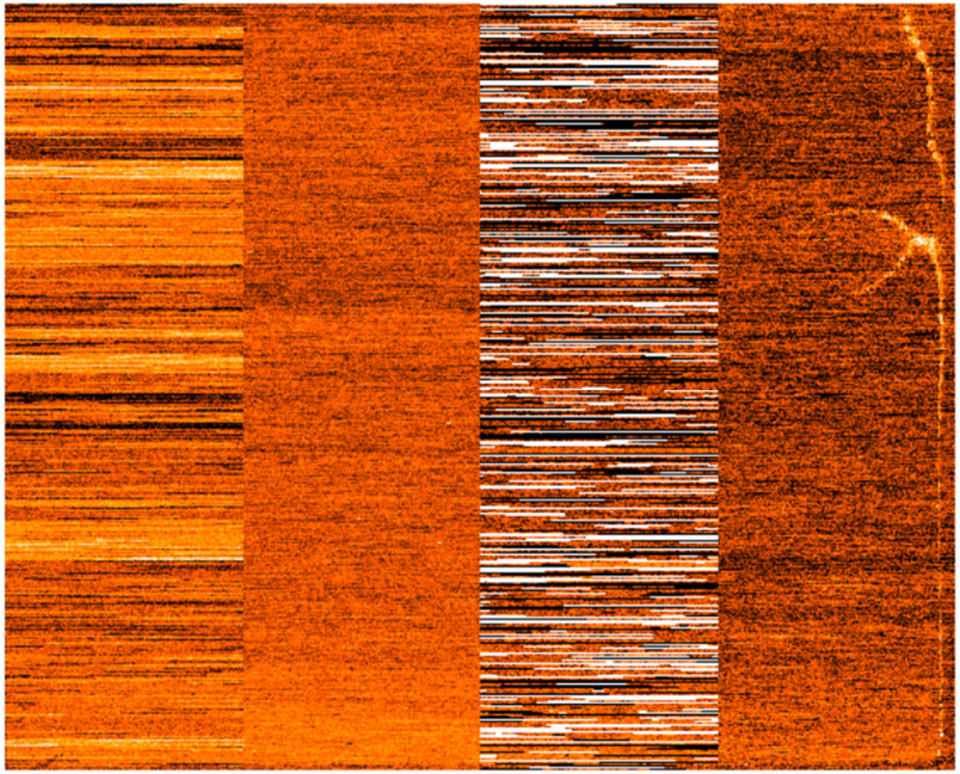
RESULTS - ISSUES

CDS

- Noise levels
  - O/p1, 21DN (61 e rms)
  - O/p2, 12 DN (35 e rms)
  - O/p3, 102 DN (296 e rms)
  - O/p4, 15 DN (44 e rms)

- 2605-04 for comparison had 14, 112, 8 and 9 DN respectively.



2925-04

RESULTS - ISSUES

CDS noise

This variation between outputs has been investigated further:

- Exchanging outputs has shown that it is not an effect in the proximity electronics
- Different devices have shown different patterns, but none have had 4 quiet outputs
- This effect has been seen in the test array supplied to the ATC, which was a ROIC with no MCT hybridised
- There is some spatial non-uniformity on all four outputs, suggesting that the effect is present on all 4 outputs, but with a different characteristic frequency, as well as amplitude
- 2605-04 which showed a similar variability between columns had significant noise reduction associated with multiple non-destructive reads (at least on its 3 quieter outputs)

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SUMMARY

Deliverables - status

- Reports:
  - TN5 Preliminary design report – issued;
  - TN6 Detector Test Plan – issued;
  - TN7, TN7a Detailed Detector Design Report – issued;
  - TN8 – Detector Test Bench Description – to be issued;
  - TN9 – Detector Manufacturing Report – draft;
  - TN10 – Detector Test Report – draft.
- Hardware
- Software

SUMMARY

Successes

- Low nodal well capacitance, ~25fF with ballast capacitors on, ~15fF off
- High pixel yield – almost all pixels are responsive
- Linear well capacity target met (75ke- compared with >60ke- target) with ballast capacitors enabled.
- Low dark current measured (<~0.1e^-/pixel/s at 80K, 2.1µm cut off)
  - Possibly degraded by straylight
- CDS noise only slightly above specification (22e- cf 18e-) on best measurement, higher on other outputs. Some reduction is expected from a measurement with the ballast capacitance disabled. The excess low frequency noise from the ROIC may also be having an impact, even on the quietest channel.
- Non-destructive reads can reduce the noise of the best channels to below 5e-
- A new method of monitoring the etch depth, by FTIR, has been demonstrated and it gave the best results in terms of QE
  - Thinned structures have survived several cryogenic temperature cycles
- Flatter response in J-, H- and K- bands than achieved in phase 1

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SUMMARY

Issues

- A mask design issue, that connects device supplies via the MCT common, fixed for future devices by a mask change. A ‘corner fix’ has been used to break this connectivity on two of the existing devices
  - **A revised ROIC processing mask design is already complete**
- Excess low frequency noise on the ROIC outputs, varying greatly between ROIC outputs
  - **New work package for ROIC noise to understand and identify the noise source**
- Non-uniform output level on a single raw read. It isn’t present in forced reset or after CDS
  - **New work package to understand and identify cause**
- Variable level and duration of a temporary drift following reset, in the opposite sense to the dark current. This measurement has not been made with the corner fix in place
  - **New measurements will be undertaken as part of the CCN test programme**
- Levels of QE achieved are at best about half the specification level in the J- and H-bands and lower in Z-band and achieving these levels requires very precise control of etch depth and uniformity
  - **The main objective of the CCN is to improve the QE – see separate presentation**
- Although dark current result is above the specification, an alternative test method can be used to minimise straylight for tests at 100K
  - **Testing at 100K is included in the CCN programme of work**

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SUMMARY

Approach to Industrialisation

- Growth on large area low cost substrates
- Wafer scale MCT processing:
  - Up to 8 die per 75mm wafer;
  - Potential for 150mm processing in future.
- 150mm ROIC processing:
  - 30 die.
- Bump bonding individual die - up to 10/day
- Batch processing for GaAs substrate removal (x5)
  - MCT thinning currently as individual die, could develop batch process;
  - Look at alternative structures which do not require MCT thinning for response down to 0.8 μm. Morphology and interface issues to be resolved.
  - Option for Multi-Layer AR coating by external supplier in large batches
- Packaging
  - In a separate collaboration with e2V, we have demonstrated a development of their assembly approach for close-packed CCDs suitable for use with our detector chips
  - <3mm gaps between active areas on 3 sides

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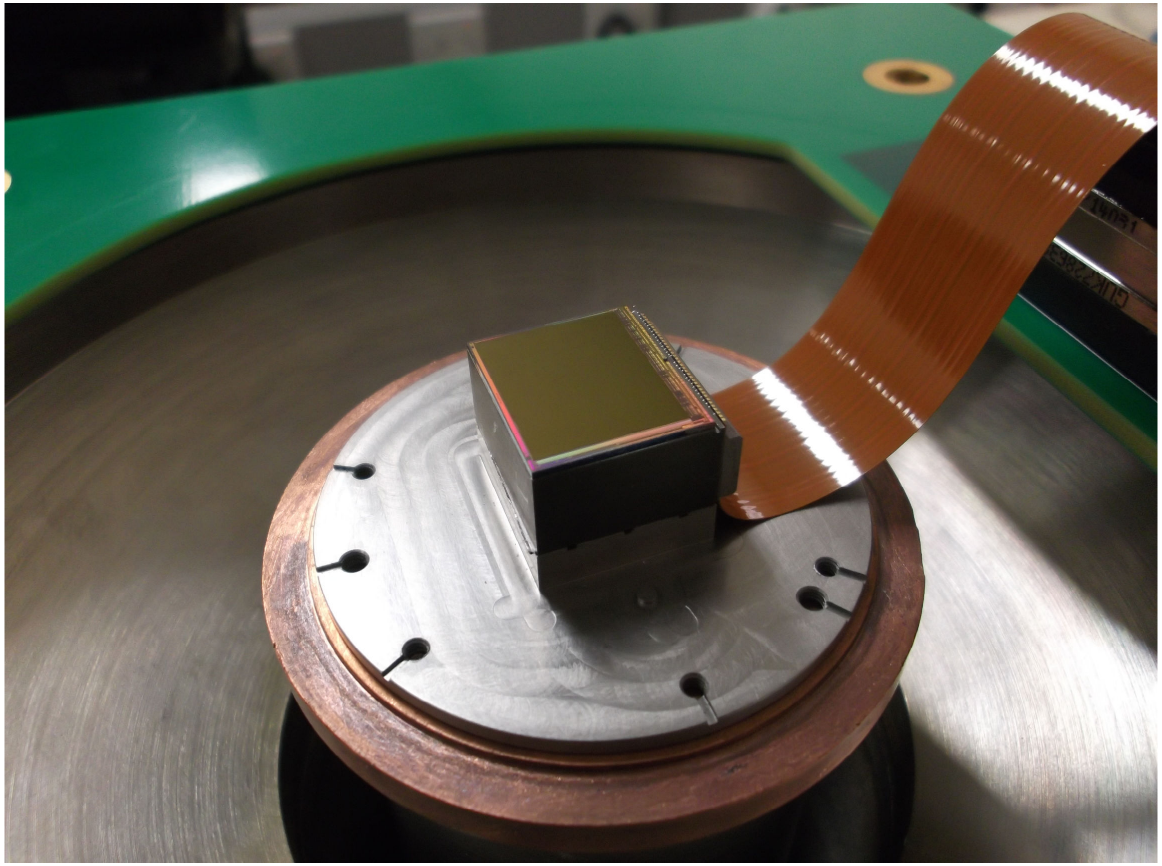
SUMMARY

Approach to Industrialisation

- Three-side close-buttable array packaged and assembled on a test card



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SUMMARY

Contract Change Note Work

MCT

- Growth and processing of 0.8μm to 2.1μm devices
  - Alternative approach proposed to remove the MCT thinning step
  - First wafer grown, processed and tested – no improvement in QE
- Growth and processing of 0.8μm to 2.5μm devices
- Thinning of 2.5 um devices for response down to 0.4um
- Screening and characterisation testing at the UKATC
- Option for growth and processing of a 24um on Saphira ROIC

ROIC

- ROIC noise investigation