LSST Camera Sensor Characterisation and pre-commissioning (LSST:UK WP 3.9)

Dan Weatherill, Ian Shipsey, Farrukh Azfar, Jeff Tseng

Oxford Physics Microstructure Detector Laboratory

Outline

UNIVERSITY OF OXFORD

- LSST camera & sensors specs recap
- Brief history of LSST:UK WP3.9 “phase A” & “phase B” contributions
  - Clock timing & optimisation
  - Measurement of Si di-vacancy
  - Effect of gate width on brighter-fatter effect
  - (ongoing) oversampled PSF measurement
  - ~~(ongoing) TCAD modelling~~ **(NO TIME!)**
- Commissioning progress & upcoming commissioning assistance (LSST:UK “in-kind” contribution)
- Other (none LSST:UK funded) Oxford “in-kind” efforts

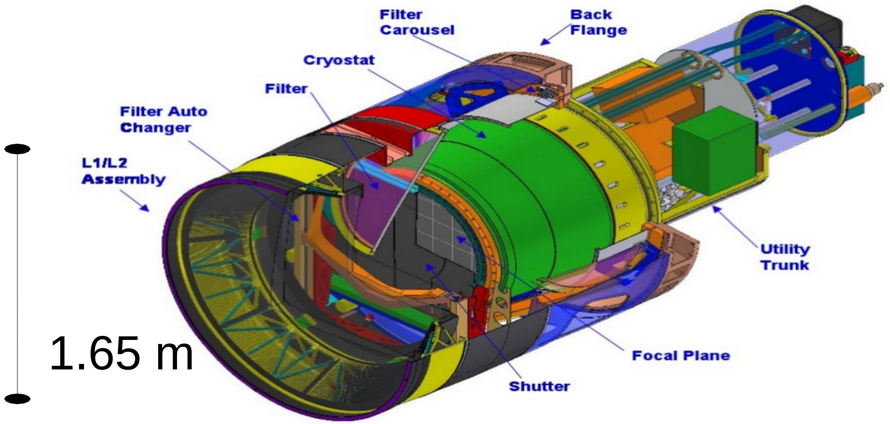


Image: LSST Science Book

The LSST Camera

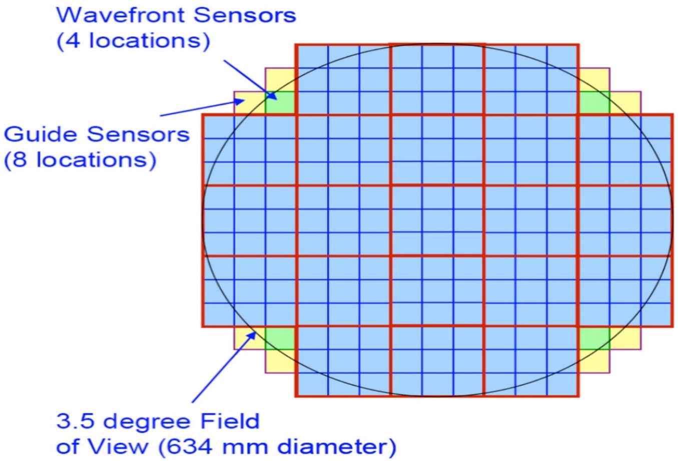


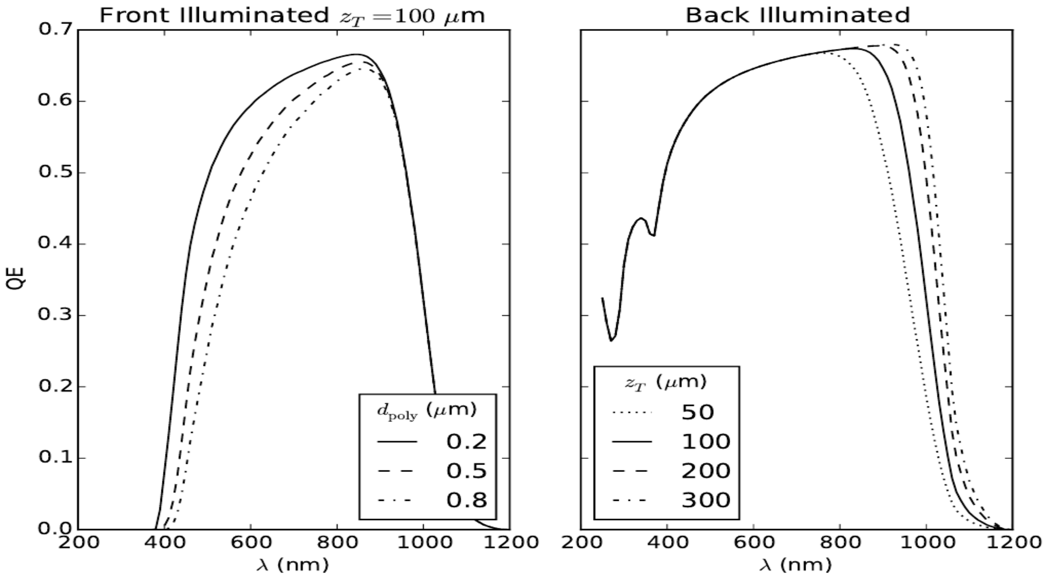
Image: LSST Science Book

- **Fast Optics needed for “fast” and “deep” survey.**
- **Small pixels – to make sure we can oversample the PSF of the optics**

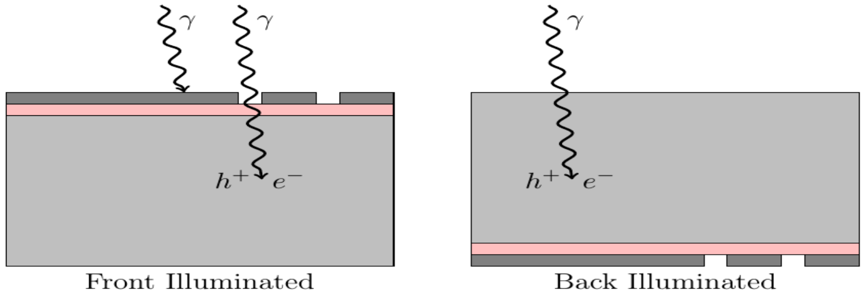
- Operating temperature: -100 Celsius
- Challenging mechanical requirements: fast (mechanical!!) shutter & filter changer
- Fast (f/1.2) optics lead to stringent flatness specification (<= 20um over whole focal plane!).
- Focal plane consists of 189 4k x 4k science sensors arranged in “rafts” of 9 (3.2 Gpix total). **Comcam is one such “raft”.**
- 10 μm pixel pitch
- 6 Filters cover wavelength range from 300nm – 1100nm
- High visit rate demands fast readout (~2s).
- To maintain reasonable noise (~4e-), CCD must be **highly segmented (16 outputs)**. This implies a **pixel rate of ~550kHz**.
- 9 * 21 * 16 = 3024 channels of video!

Achieving High QE

- LSST filter bands (below left) cover near UV to near IR. To maintain survey depth in brief exposure times, high **Quantum Efficiency** is key.
- Blue end QE is enhanced by back illumination (removing poly and gate absorption) and adding AR coating
- Maintaining high QE at long wavelengths implies a thick detector.
- LSST science detector is 100µm thick.
- Absorption length is also (slightly) temperature dependent.
- High resistivity bulk material (>10k Ω cm !!!) is used for construction

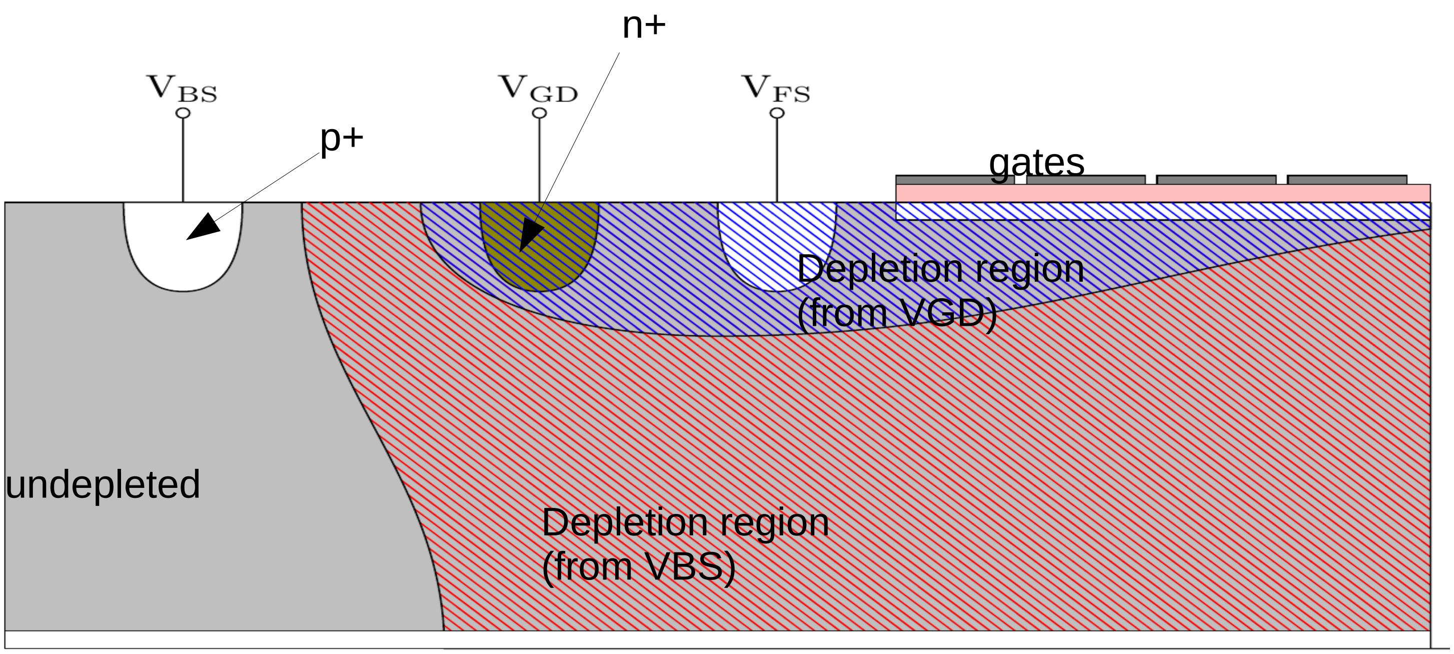


$$QE_{FI} = (1 - R(\lambda))\, e^{-\alpha(\lambda) d_{\rm poly}} \left(1 - e^{-\alpha(\lambda) z_T}\right)$$



$$QE_{BI} = (1 - R(\lambda)) \left(1 - e^{-\alpha(\lambda) z_T}\right)$$

Deep Depletion CCDs



A thick detector implies a long drift time for electron collection. This, in turn, implies a large diffusion radius

$$r_{\mathrm{diff}} = z_T \sqrt{\frac{2k_B T}{q_e V_{\mathrm{coll}}}}$$

- To reduce the collection time of charges (and thus the diffusion radius), a high bias voltage is applied to the back side of the chip. Unfortunately, unchecked, this turns the chip into an expensive resistive heater
- In order to prevent leakage currents from the front substrate to the back, guard drains are included in the design which creates a protective depletion region whilst the back bias is applied

CCD Summary

Confinement is by gates down columns, and channel stop implants along rows (as with any CCD pixel!).

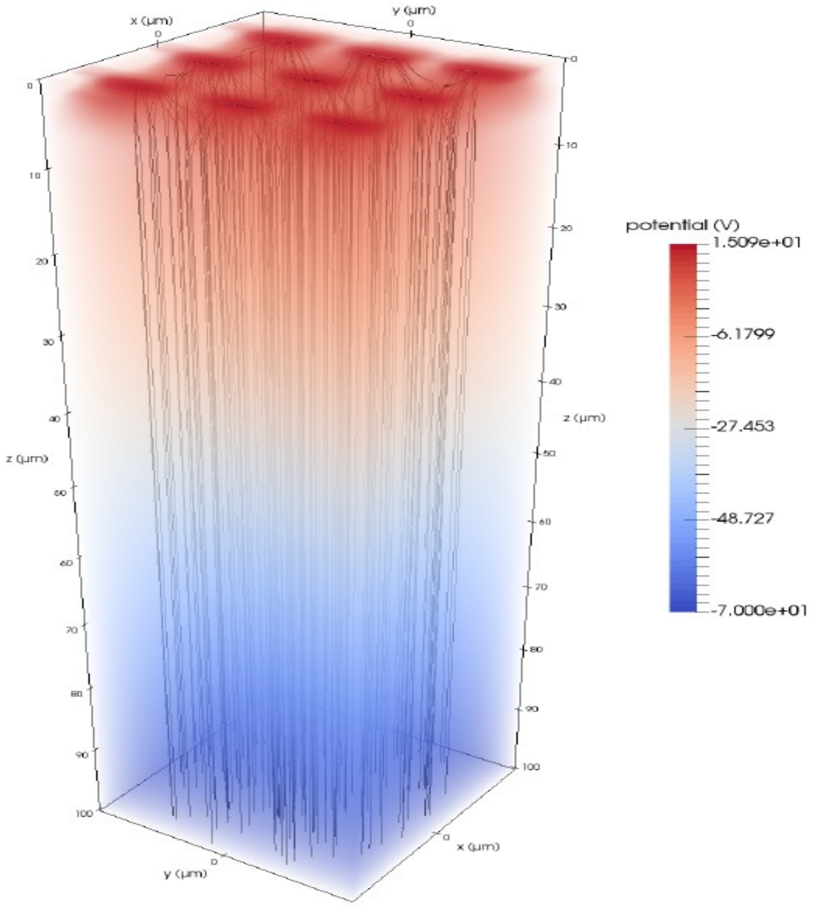
Recall LSST pixels are small in area, but very deep (right: electrostatic simulation of electron capture in CCD250 pixels).

The thickness of the CCD is what leads directly to effects such as: fringing, brighter-fatter effect.

It **indirectly** (via need for back biasing) leads to: complicated clocking and noise injection issues, “tearing”, “edge roll off”, “midline roll-off”, “astrometric scupper shift” etc etc.

High speed readout leads to complicated issues with clocking and timing for optimisation.

Should be emphasized: **none of the technology needed for LSSTcam sensors was new/untried. What was new was putting it *all* into one chip!**



A Tale of Two Teledyne CCDs

The devices in LSSTCam focal plane are a mixture of e2v CCD-250 and ITL/STA-3800C. Both are thick, back illuminated CCDs on high resistivity silicon.
But within that constraint, they almost couldn't be more different!
Adapting to the slight differences both mechanical and electro-optical has been challenging

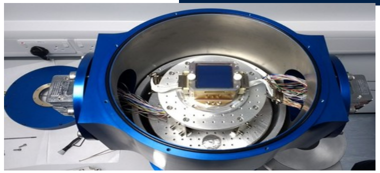
Originally 2 separate manufacturers, e2v (Chelmsford, UK) and Teledyne / ITL / STA.

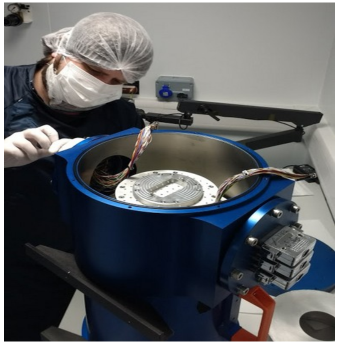
Teledyne acquired e2v in 2017, so technically these are now both Teledyne detectors

	CCD-250	STA-3800C
Imaging phases	4 (symmetric)	3 (asymmetric)
Output amp	2 stage MOSFET	1 stage JFET
construction	Back thinned, Si substrate	Glued glass substrate with lithoblack coating
Measured performance	Good noise, CTI, linearity	High FWC, better dark current

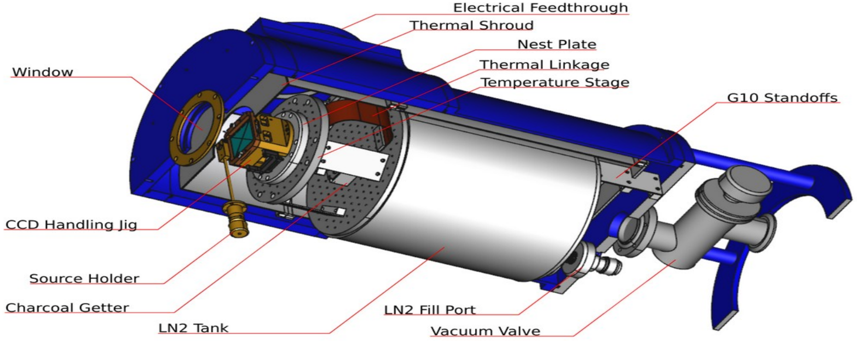
Oxford LSST Test System

UNIVERSITY OF OXFORD



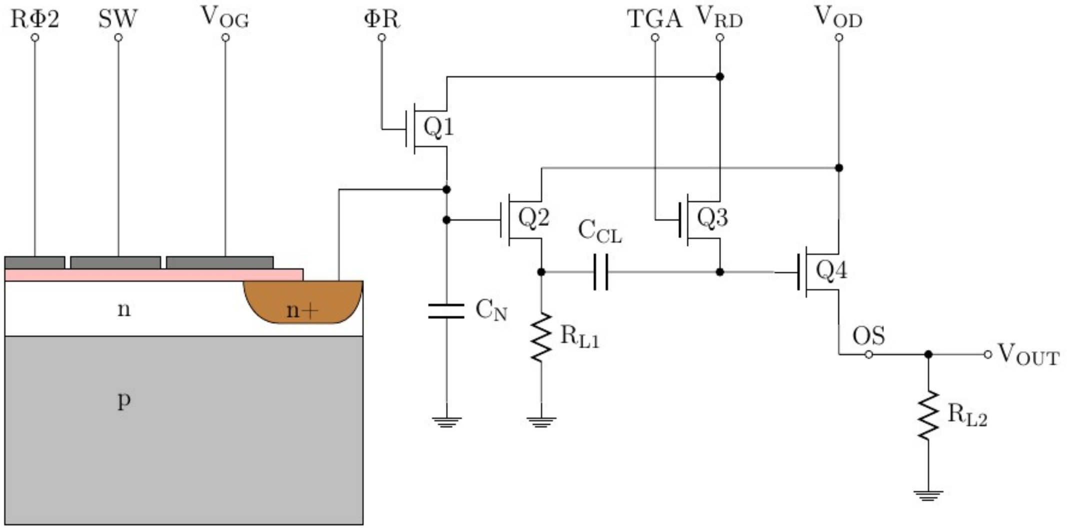


- LN2 cooling and active table for low vibration
- 250W QTH light source + monochromator (300nm – 1600nm wavelength)
- Online radiometry and spectrosopy (at integrating sphere)
- Can quickly integrating sphere with projection optics for PSF etc measurements.
- Operates at high vacuum (1E-6 mbar)
- Slightly different (but complementary) readout electronics than LSSTCam (by design!)

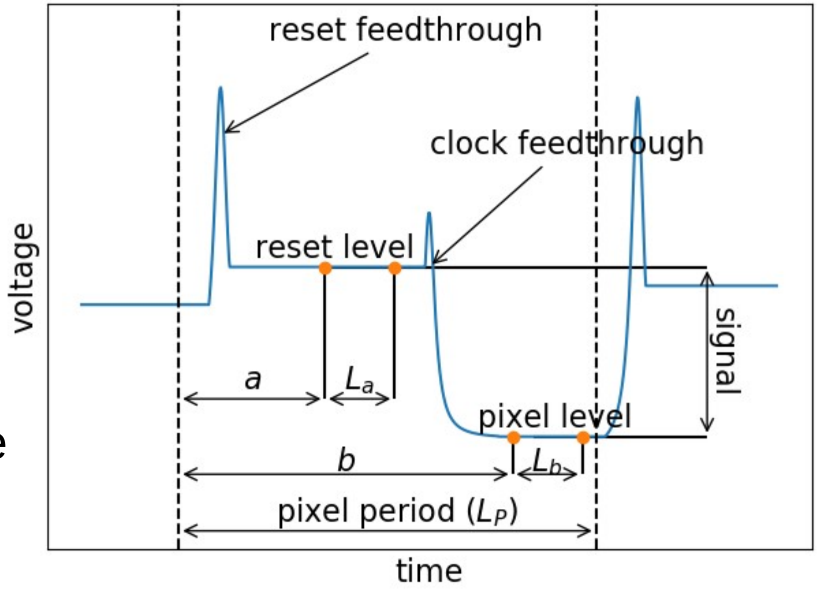


Readout Timing & Optimisation

UNIVERSITY OF
OXFORD



$$N_{\mathrm{rms}} = \sqrt{\frac{k_B T}{C_N}}$$



Correlated Double Sampling (CDS) is one of a CCD's "secret weapons".
If you don't read out and subtract the reset ("kTC") noise at each pixel, it would **completely dominate** the noise spectrum.
LSSTCam uses custom designed analog front end ("ASPIC") chips to do this (digital too power costly!)

Readout Timing & Optimisation

22 August 2019

Automatic selection of correlated double sampling timing parameters

Daniel P. Weatherill, Ian Shipsey, Kirk Arndt, Richard Plackett, Daniel Wood, Kaloyan Metodiev, Maria Mironova, Daniela Bortoletto, Nicolas Demetriou

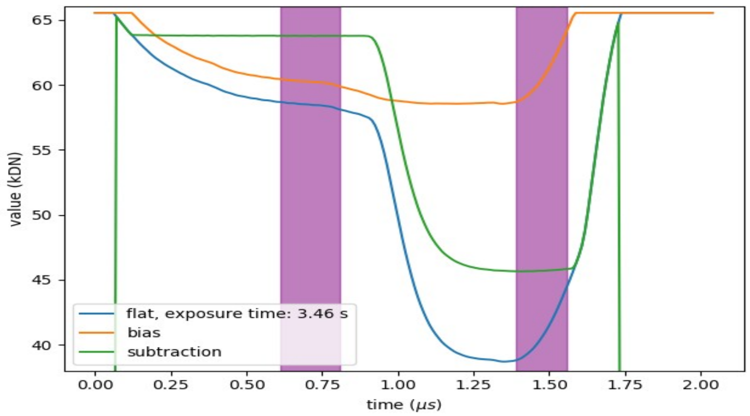
Author Affiliations +

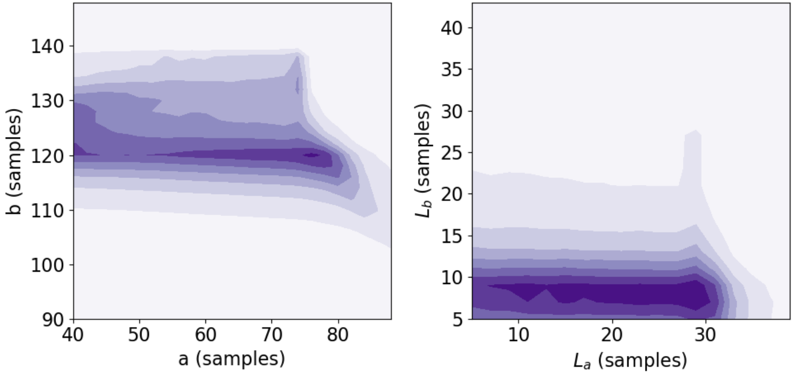
Select Language ▼

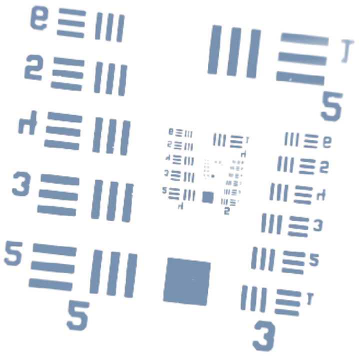
Translator Disclaimer

J. of Astronomical Telescopes, Instruments, and Systems, 5(4), 041502 (2019) https://doi.org/10.1117/1.JATIS.5.4.041502

However, using digital CDS techniques we developed a new optimisation technique for the timing parameters of the CDS (in 2018/19). Can be used to minimise noise & maximise linearity of readout





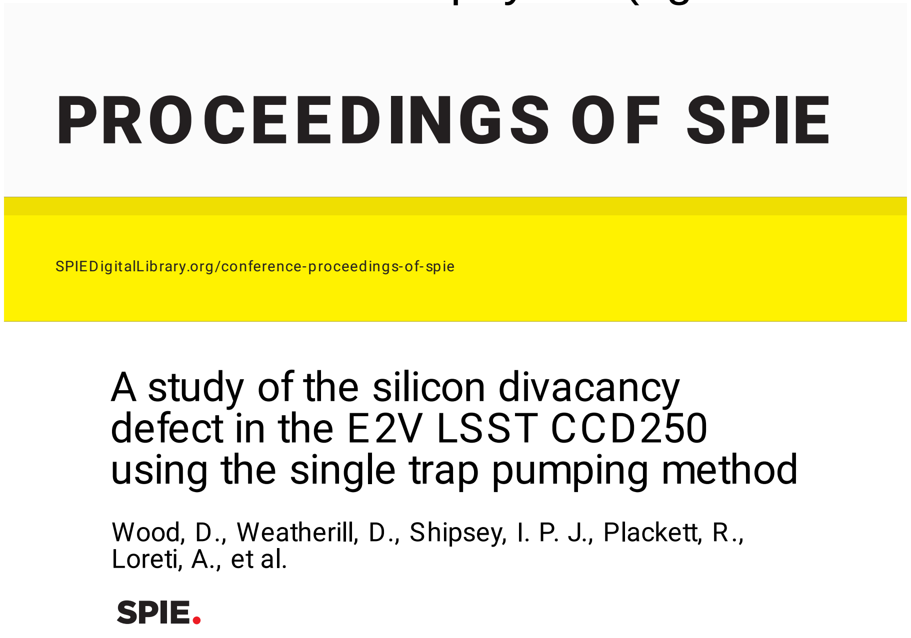


Silicon di-vacancy measurement

UNIVERSITY OF OXFORD

Charge transfer efficiency (CTE) of LSST sensors is very good, **however** we still have to worry about it because:

- We will be correcting for it anyway
- It interferes with correcting for brighter-fatter effect (ask if interested!)
- It turns out to be signal dependent in these devices, likely due to the "racetrack" device physics (again ask if interested)

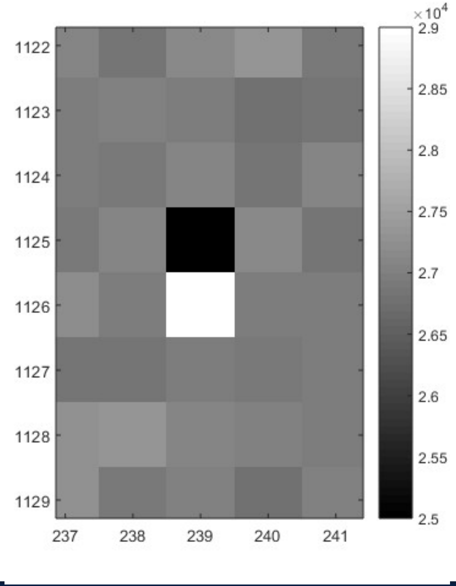

PROCEEDINGS OF SPIE

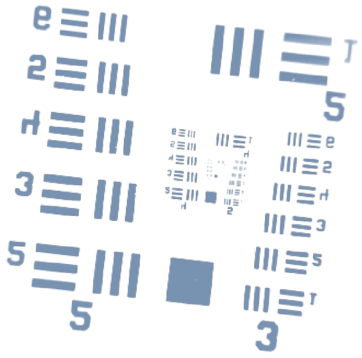
SPIEDigitalLibrary.org/conference-proceedings-of-spie

A study of the silicon divacancy defect in the E2V LSST CCD250 using the single trap pumping method

Wood, D., Weatherill, D., Shipsey, I. P. J., Plackett, R., Loreti, A., et al.

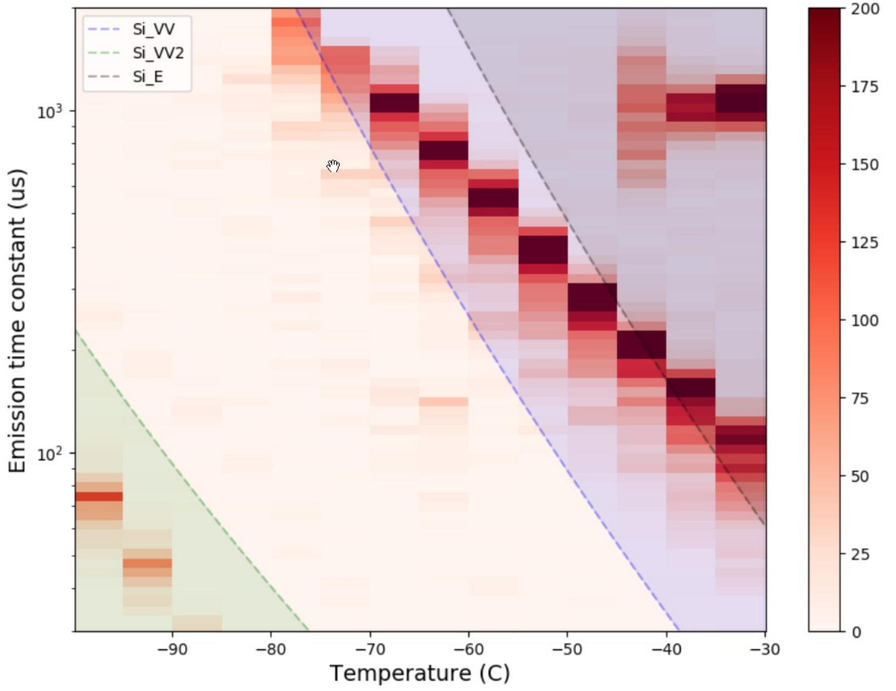
SPIE.



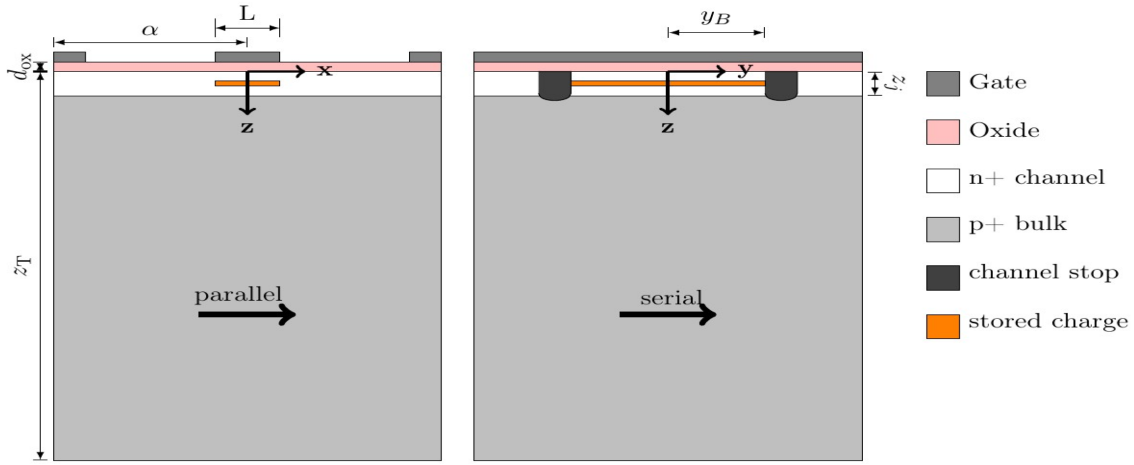


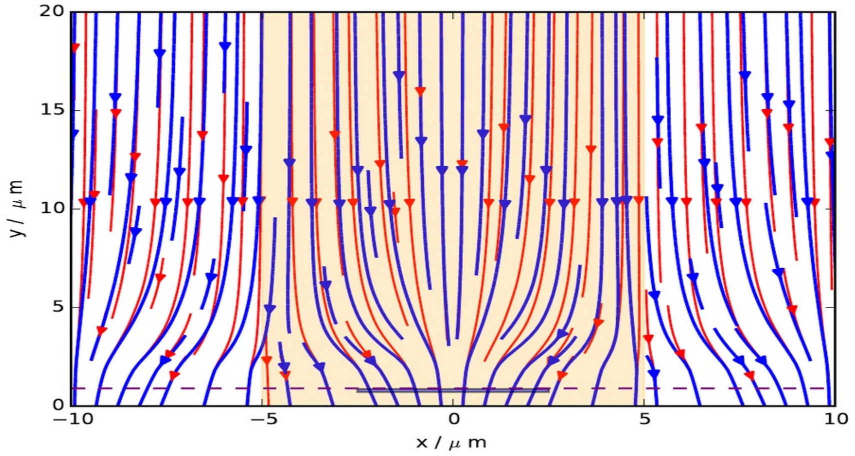
Divacancy trapping & CTI

- We used a technique called single trap pumping which can map out **individual** shallow level electron traps in the device, to survey the cause of the trapping component of the CTI (in 2019/ 2020)
- Confirmation that silicon di-vacancy traps are present at LSST camera operating conditions
- Verification that this is in addition to Roodman & Snyder's identification of "process" CTI traps in e2v CCD250 sensors
- Allows optimal readout timing conditions for minimising CTI to be determined (this has been tested!)
- **Side benefits**
  - Largest temperature range single-site trapping survey ever done on a CCD
  - First single-site trapping survey ever done on a high-rho bulk CCD
  - Interest also from other projects due to these facts (so far ESA Euclid & ESA PLATO)

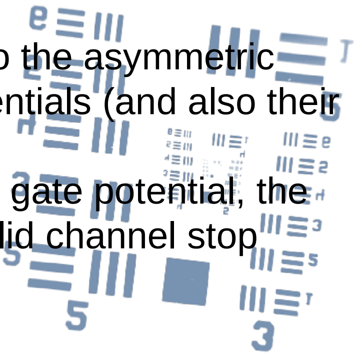


Brighter – Fatter Effect





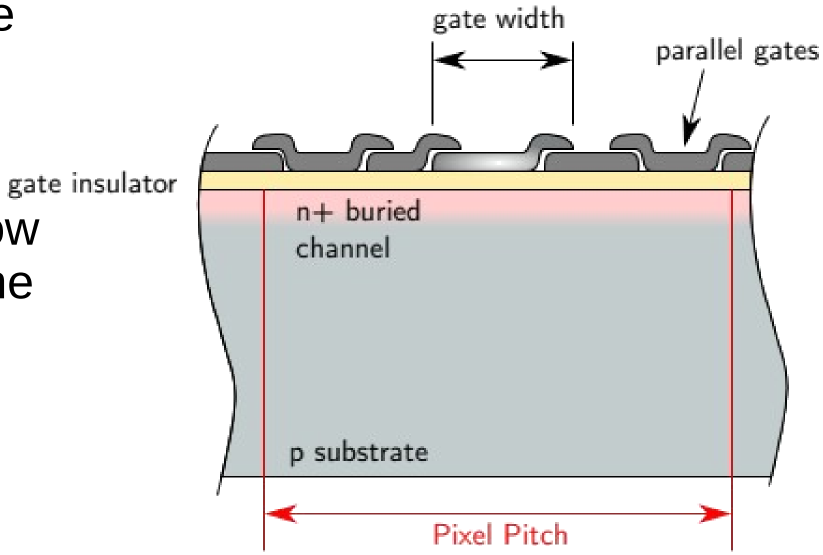
- As charge accumulates in potential wells during integration, it causes the electric field structure of the pixel to change slightly, influencing the collection of further charge.
- This introduces correlations between nearby values in a flat field, and an increase in ellipticity of point sources (possibly serious for weak lensing measurement)
- One of the main areas of research into instrument signature removal, modelling and optical testing
- Effect is **asymmetric** due to the asymmetric nature of the collecting potentials (and also their "softness" in the device.
- One direction has "squishy" gate potential, the other direction has more solid channel stop potential

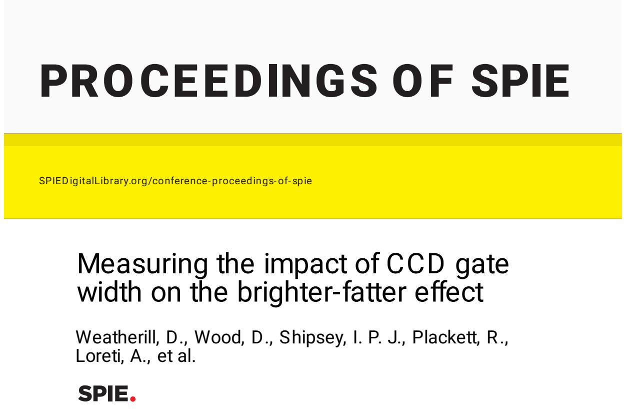


Gate Width Effect on Brighter-Fatter

UNIVERSITY OF OXFORD

- Investigation into how the width of the CCD parallel gate affects the size of the brighter-fatter effect
- Gate widths determined at manufacture time, but can choose how many are energised at integration time




PROCEEDINGS OF SPIE

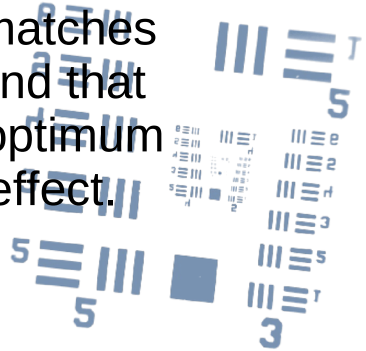
SPIEDigitalLibrary.org/conference-proceedings-of-spie

Measuring the impact of CCD gate width on the brighter-fatter effect

Weatherill, D., Wood, D., Shipsey, I. P. J., Plackett, R., Loreti, A., et al.

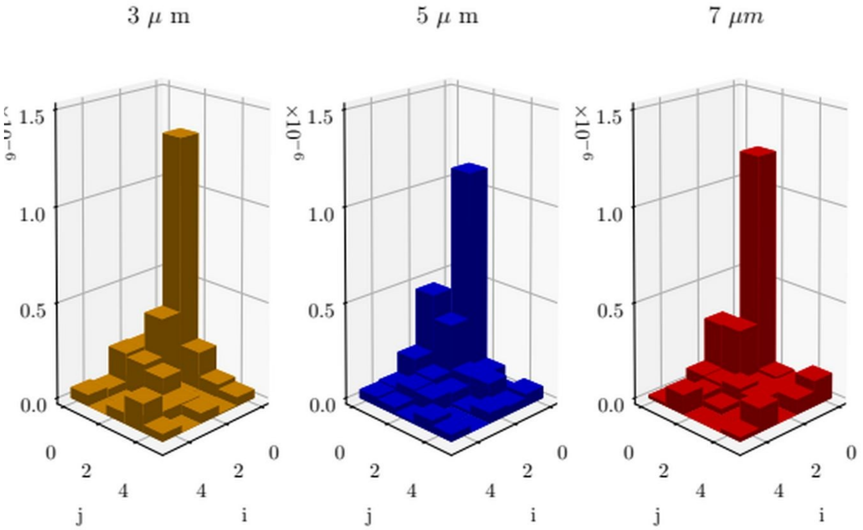
SPIE.

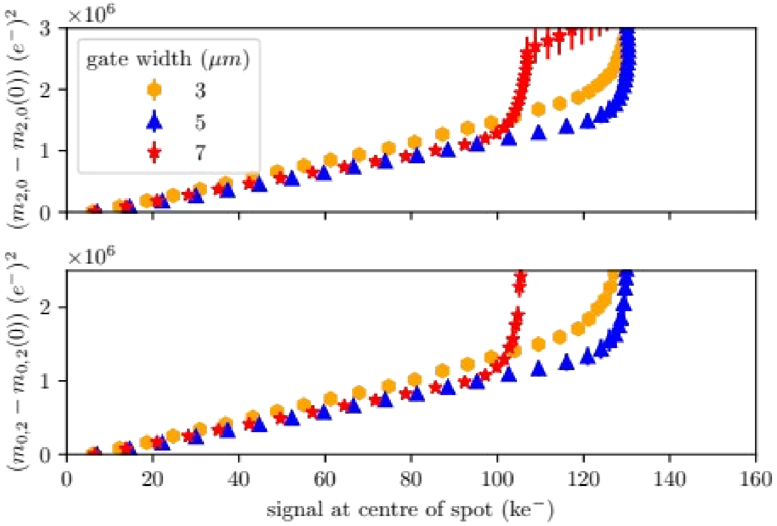
- Verified that this effect is there, that it matches the size expected due to simulations, and that the lsst camera is operating using the optimum gate widths to minimize brighter-fatter effect.

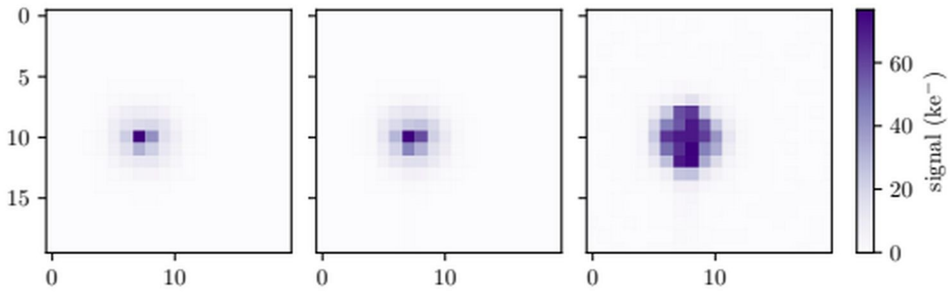


Gate width effect on brighter-fatter effect

UNIVERSITY OF OXFORD

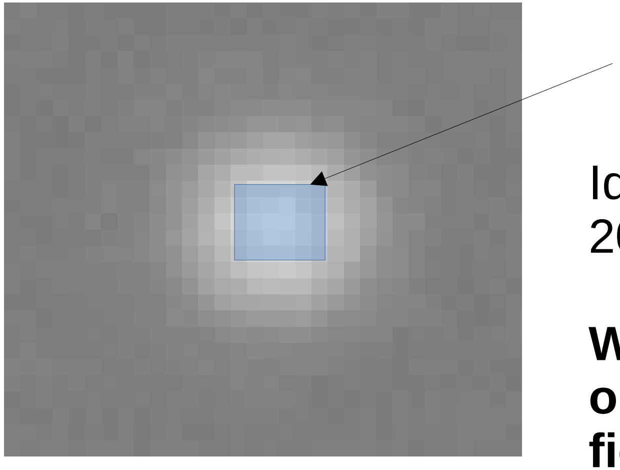






Accurate flat field correlation measurements (**above left**) correctly matched with direct spot projection measurements **(above right, right)**

Interferometric PSF Measurement



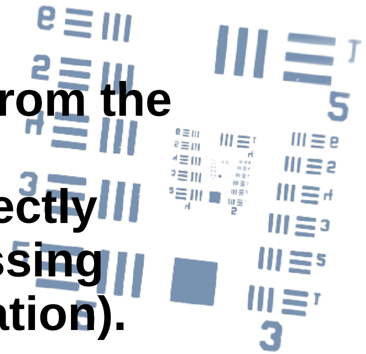
Idea we first had in 2016 , and first seriously contemplated in 2018:

What if we could simultaneously project the same spot onto two detectors, such that we *know* that the optical field is close to identical?

Then we could:

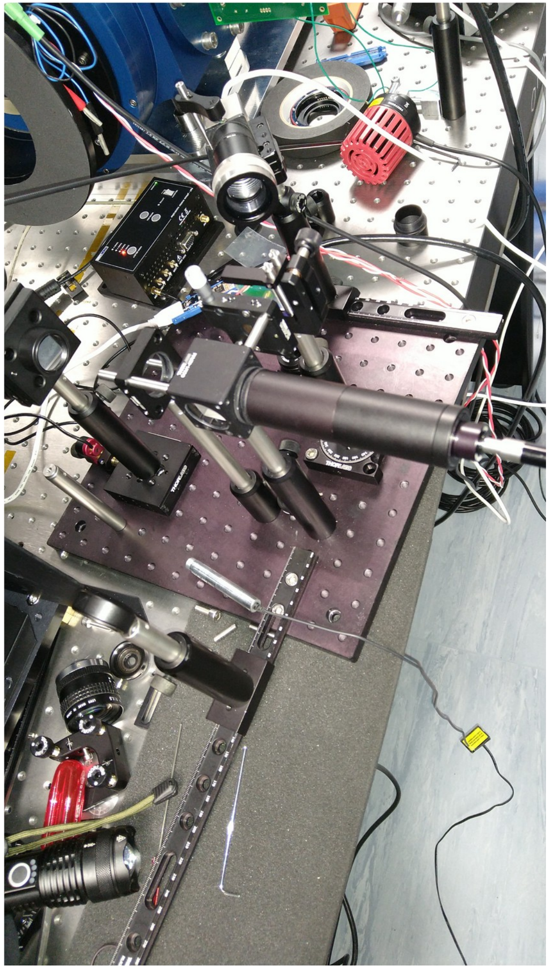
1) easily de-convolve the optical spread from the device under test

2) carefully do a lateral scan and do a directly oversampled measurement of its PSF! (bypassing Shannon-Whitaker-Nyquist limits on interpolation).



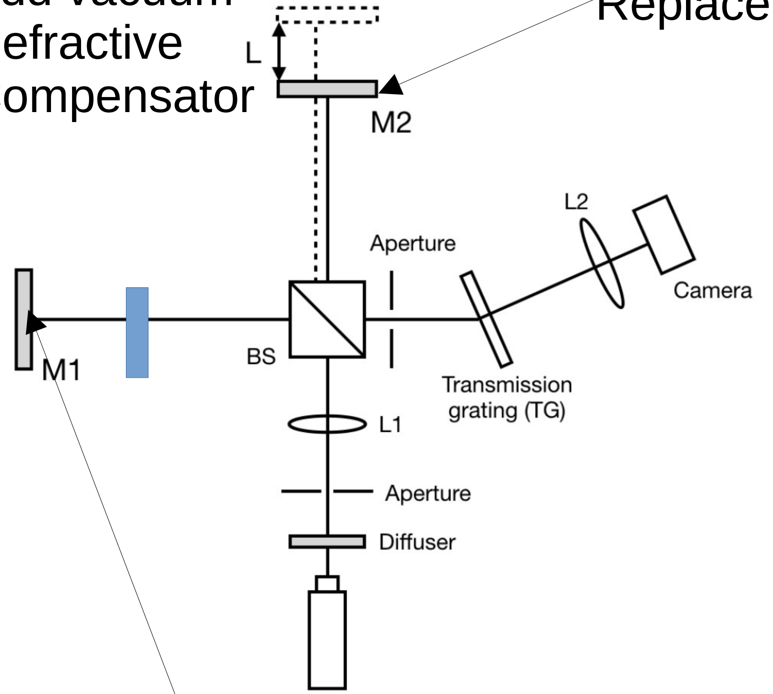
Above: a way we checked the size of our optics spot projection early on!

Interferometric Alignment



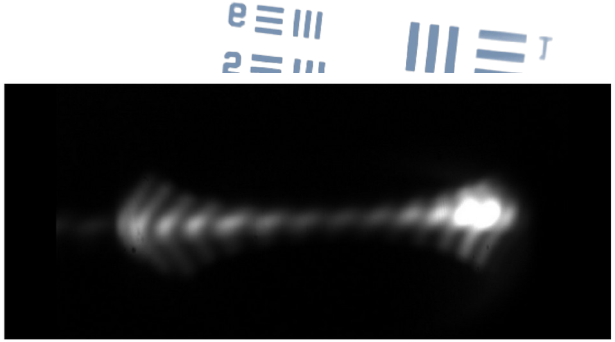
Add vacuum Refractive Compensator

Replace with aux camera!



Replace with CCD!

Building a White Light Spectrally Channeled Interferometer, to do absolute optical path difference measurement between two arms`

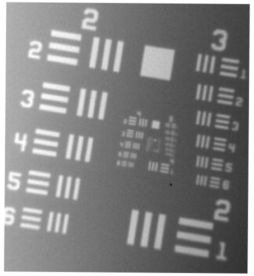


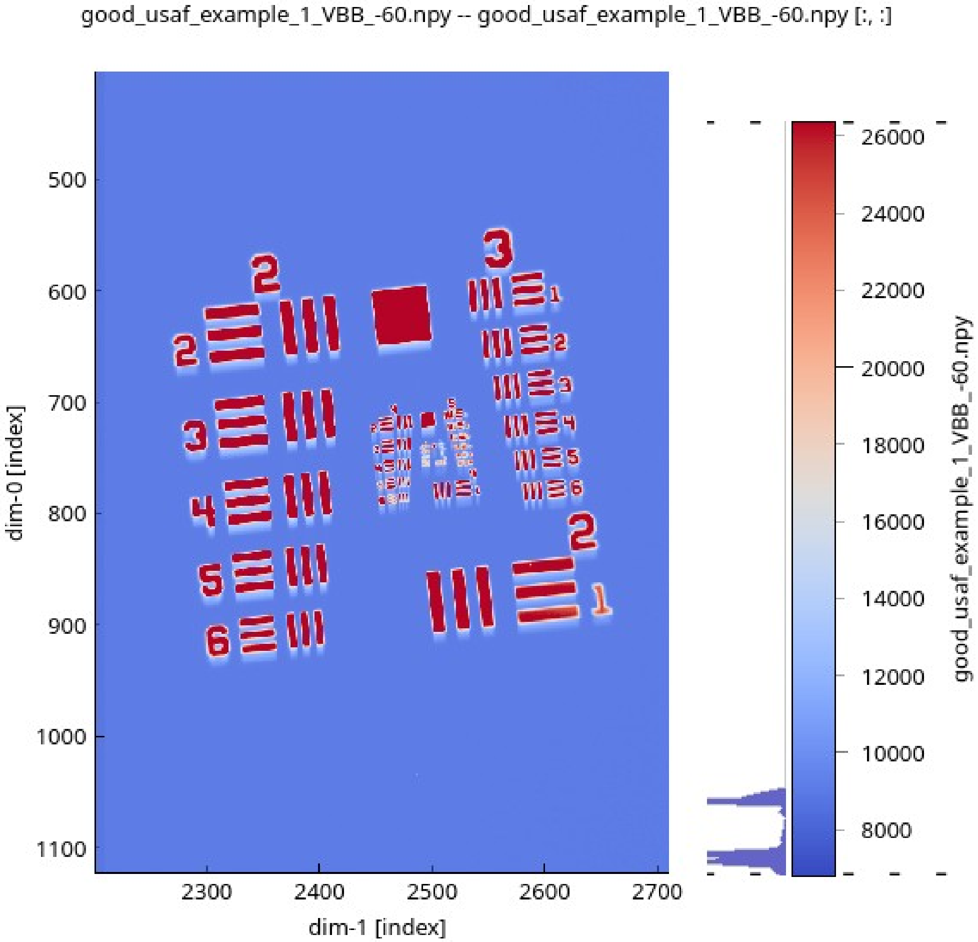
First Relative Projections

Early Results, don't take too seriously yet (work still in progress)!

Test images of a USAF test pattern projected through our interferometer imaged on LSST CCD (below), and aux test camera (right). Images shown at roughly relative pixel scale.

Note "trails" on test camera image, not 100% sure what the problem is yet, may be tilt though.



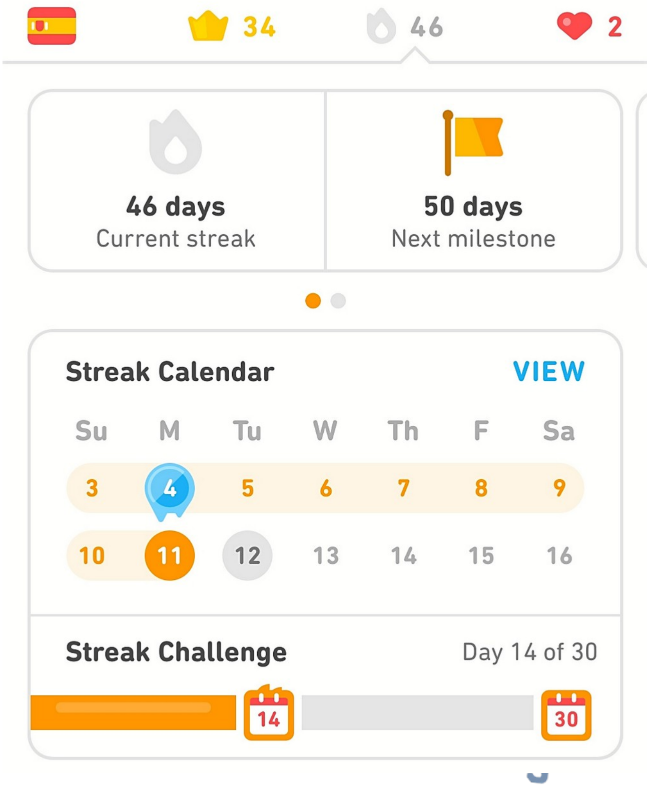


Summit / Camera Progress

UNIVERSITY OF OXFORD

- Recently, LSST project decided to go ahead with “plan B” LSST camera cooling. This means, there will be no more BOT data runs from SLAC (though there is still much interesting to analyse from what we already have)!
- LSST project have indicated more CCD expertise is needed on the summit soon to help with commissioning & tuning auxtel, and comcam during its commissioning
- Thus, DPW is going to be on summit from August 23rd – November 2022 to help out with this effort on site

- Preparations underway (see right + diptheria vaccine)



Oxford Contribution to CCS/OCS

OCS – "Obvervatory Control System"

CCS – "Camera Control System"

From Colleage Farrukh Azfar:

-LSST/Rubin camera- team member since 2016, "builder" status, activity: Camera Control System (CCS) & bridge between CCS Observatory Control System (OCS-CCS Bridge)

- 2016-2022: Temps Atomique International, (TAI) time stamping for CCS, provided automated software generation and test, & major portion of bridge, Auxiliary Telescope - now deployed to summit with Commissioning Camera, AuxTel - doing telemetry right now - it works ! (*)

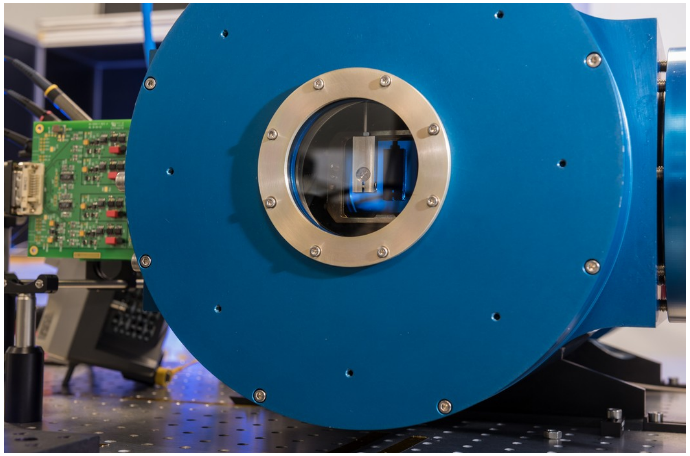
- Current : Extending CCS, OCS-CCS Bridge to actual camera and maintenance and operational support

Thanks

Daniel.weatherill@physics.ox.ac.uk

special thanks to all our 3rd year / summer project students on LSST instrumentation over the years:
- Nicholas Demetriou (Summer 2018)
- Sergio Garcia (Summer 2019)
- Mingyu Liu (2019/20)
- Esther Hung (2019/20)
- Fiona Zhang (2021/22)

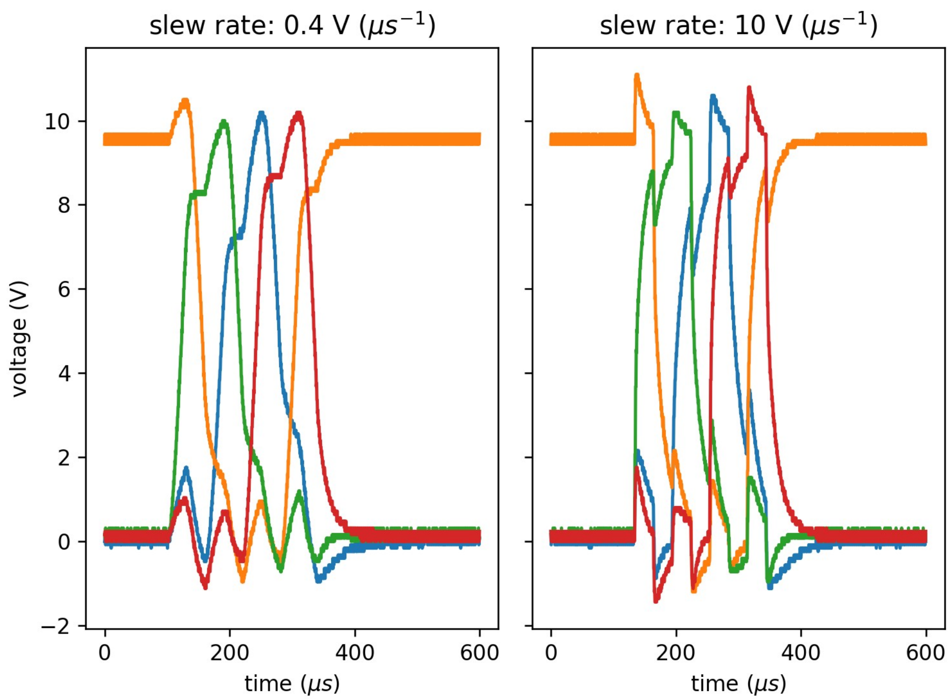
Any questions, comments, discussions you wish to have about LSST instrumentation please do not hesitate to get in touch (before February 2023 ideally!)

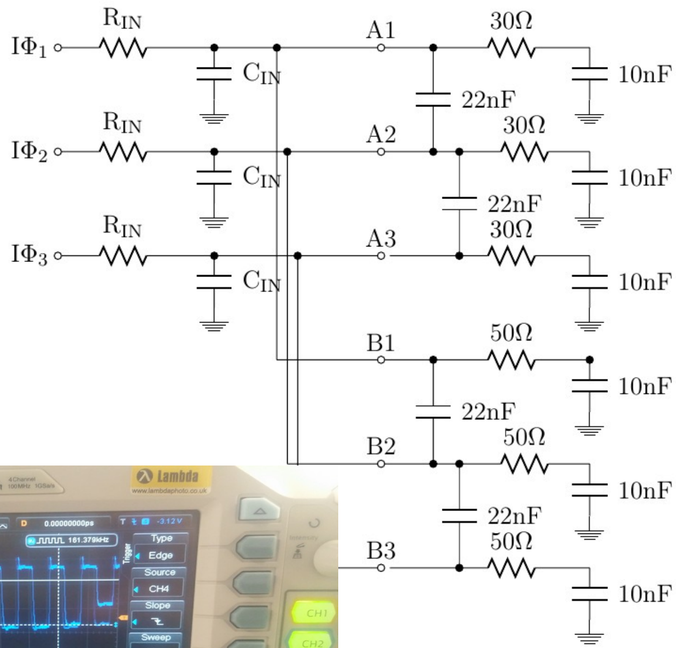


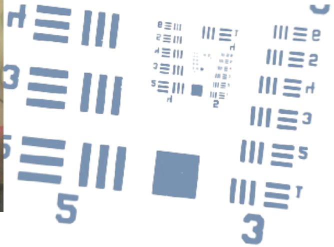
UNIVERSITY OF OXFORD

BACKUP

CCD Clock Optimization







Astier's Photon Transfer Curve Model

UNIVERSITY OF OXFORD

Image mean

Conventional PTC

Quadratic Fit

Relationship between BFE coefficients

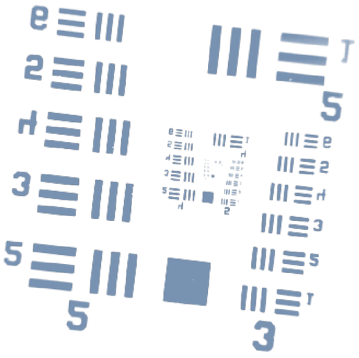
Noise / offsets

$$C_{ij} = \frac{\mu}{g}\left(\delta_{i0}\delta_{j0} + a_{ij}\mu g + \frac{2}{3}\left[\mathbf{a}*\mathbf{a}+\mathbf{a}\circ\mathbf{b}\right]_{ij}(\mu g)^2 + \frac{1}{6}\left[2\mathbf{a}*\mathbf{a}*\mathbf{a}+5\mathbf{a}*(\mathbf{a}\circ\mathbf{b})\right]_{ij}(\mu g)^3\right) + \frac{n_{ij}}{g^2}$$

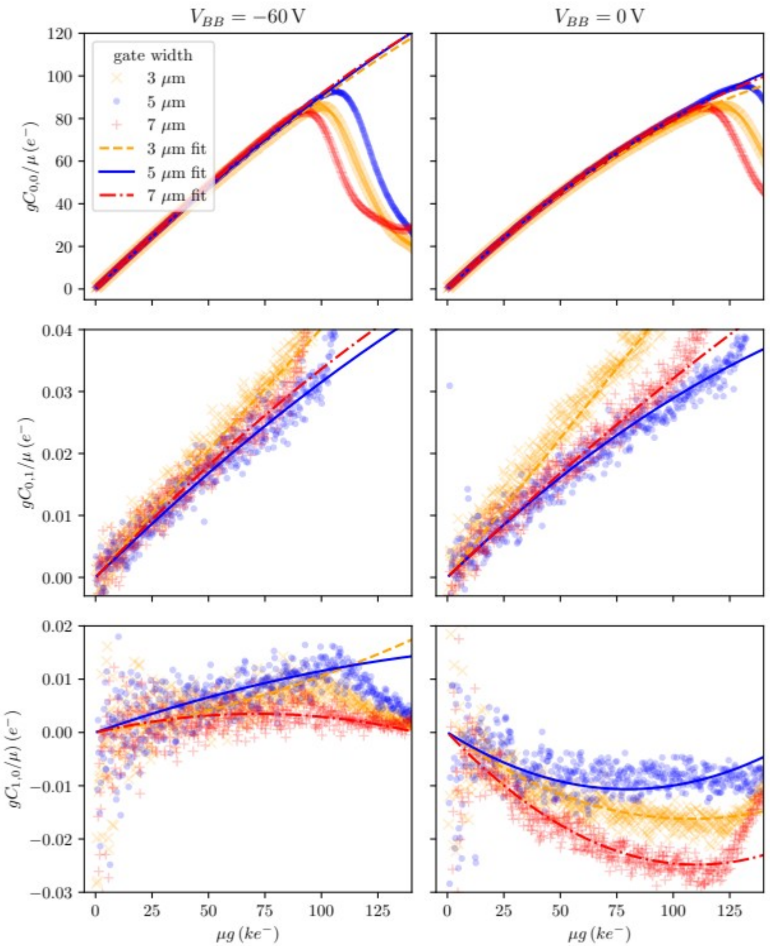
Camera Gain

Measured Covariances

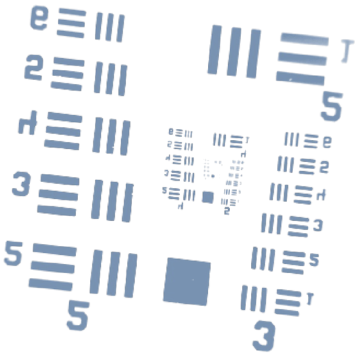
Next to leading order BFE relationships



Equation from work of Astier et al (2019)

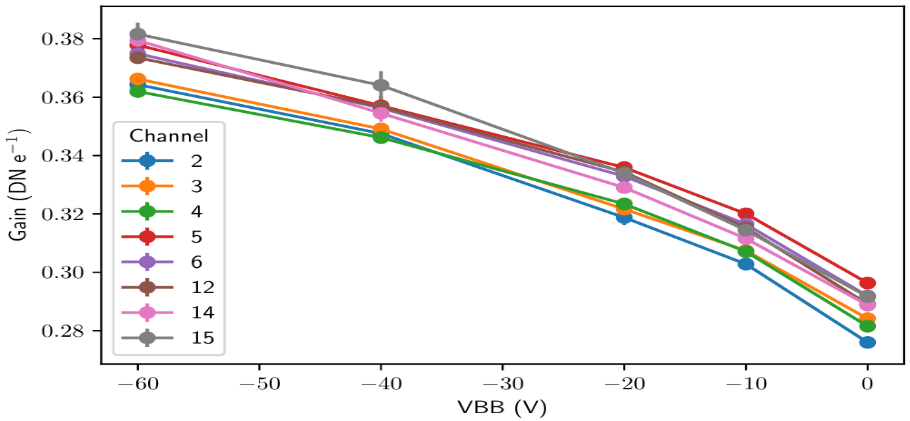


$V_{BB} = -60\,\mathrm{V}$
$V_{BB} = 0\,\mathrm{V}$
gate width
3 μm
5 μm
7 μm
3 μm fit
5 μm fit
7 μm fit
$gC_{0,0}/\mu\,(e^-)$
$gC_{0,1}/\mu\,(e^-)$
$gC_{1,0}/\mu)\,(e^-)$
$\mu g\,(ke^-)$



Clock Voltage Optimisation

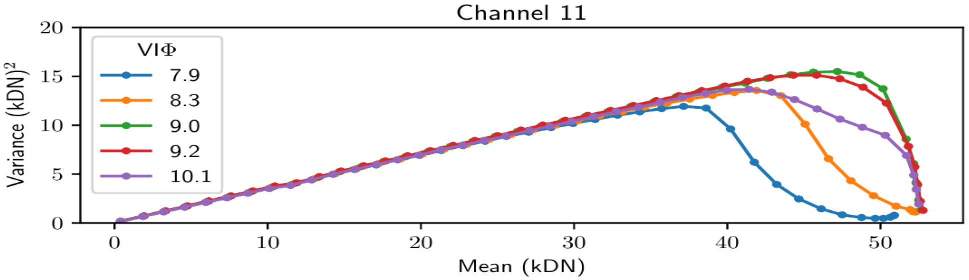
UNIVERSITY OF OXFORD

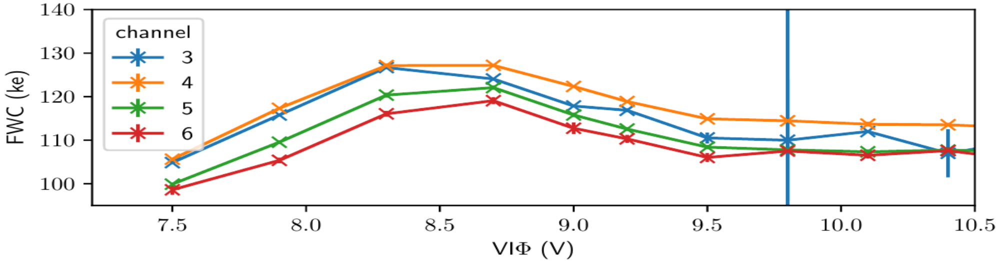


Back-side biasing means that gain and full well capacity change with applied voltage (unlike a regular CCD!). This is because the sense node capacitance is influenced by the biasing field

In 2017, investigated these relationships with a view to optimising both the back and front side clock voltages.

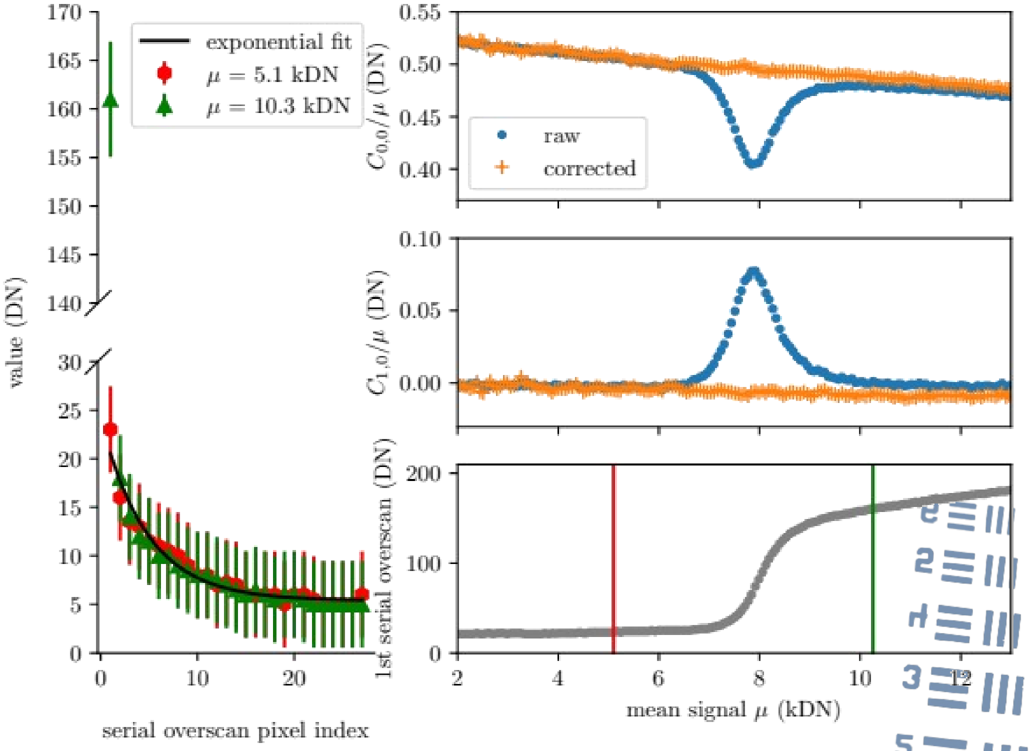
Discovered it is quite easy to operate the LSST devices in a surface transport regimen. Much has moved on since then, including the introduction of bipolar clocking to combat “tearing” issue





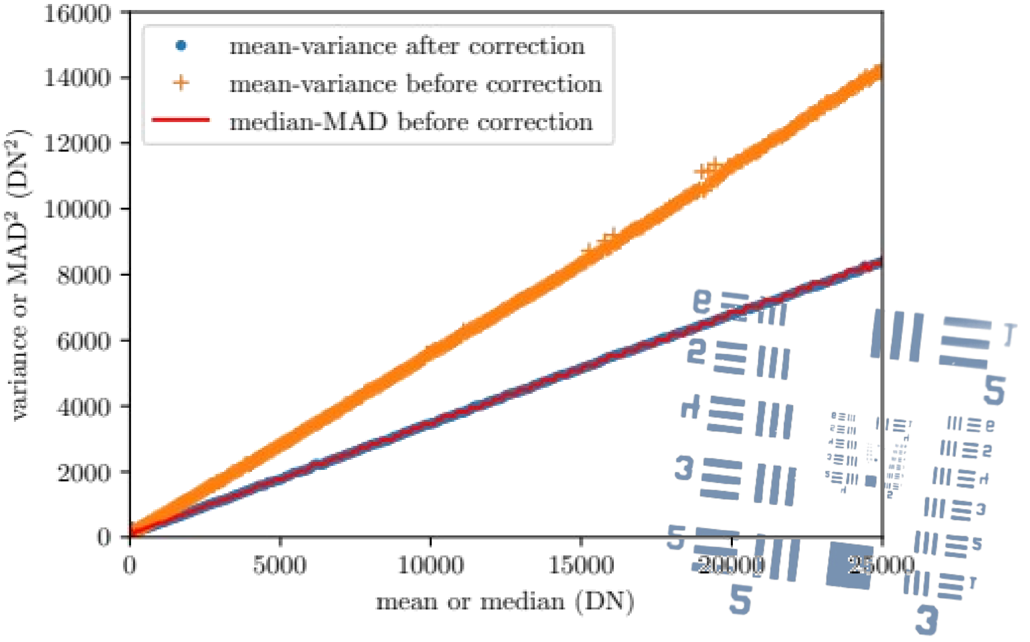
CTI Correction for ISR

- Signal dependent CTI causes peaks in first serial correlation (and dip in variance)
- Correction using iterated simulated image trailing after fitting EPER measurements (c.f. Massey et al)



Tearing Correction

- Time varying “tearing” patterns cause excess variance due to incomplete cancellation on subtraction (left)



- We mask these using iterative sigma clipping of the absolute value of the difference image
- After correction, mean variance curve lines up well with median-MAD curve, not affected by outliers (right)

Trap Pumping Theory

UNIVERSITY OF OXFORD

Integer prefactors can change depending on the clocking scheme used to pump

Electron density

$$I = N_{\mathrm{pump}} P_c \left(\exp\left(\frac{-2t_{\mathrm{ph}}}{\tau_e}\right) - \exp\left(\frac{-3t_{\mathrm{ph}}}{\tau_e}\right) \right)$$

$$\tau_c = \frac{1}{\sigma n v_{th}}$$

$$\tau_e = \frac{1}{X \chi \sigma N_c v_{th}} \exp\left(\frac{E}{kT}\right)$$

Final measured signal includes prefactor for Number of pumps and probability of capture (we assume instant capture)

$$N_c = 2 \left(\frac{2\pi m_{dos} kT}{h^2}\right)^{\frac{3}{2}}$$

$$v_{th} = \sqrt{\frac{3kT}{m_c}}$$

Theoretical emission time comes from Shockley – Reed- Hall theory. Depends on:

- Trap cross section (reciprocally)
- Temperature (exponentially + polynomially)
  Local electron density (reciprocally)

$$P_x = 1 - exp\left(\frac{-t}{\tau_x}\right)$$

Single trap-pumping

Temperature range -30°C to -100°C , in 5°C intervals.

Capture 5 bias and 5 flat-field images per temperature.

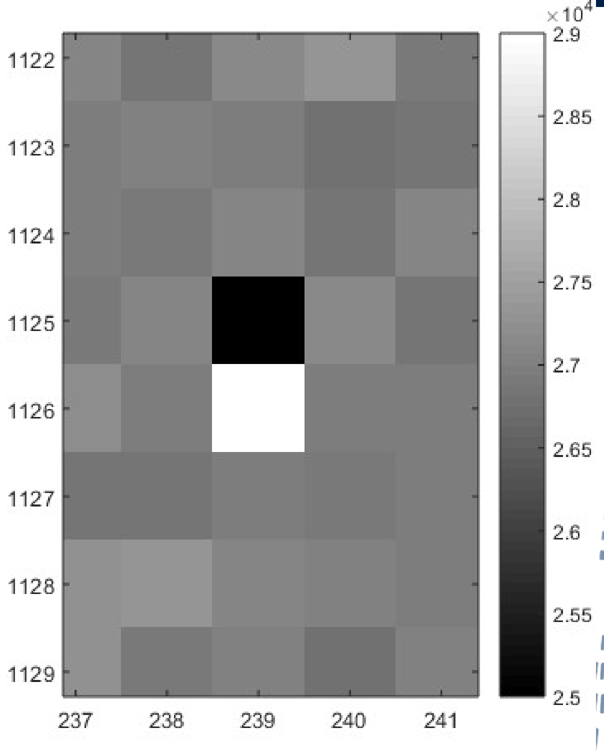
Capture 5 trap-pumped images with N=50000 at each phasetime, from 10µs to 1000µs.

Average and background subtract, then locate dipoles through thresholding on signal level.

Plot dipole intensity simply as ½ * (bright pixel signal – dark pixel signal) across entire phasetime range.

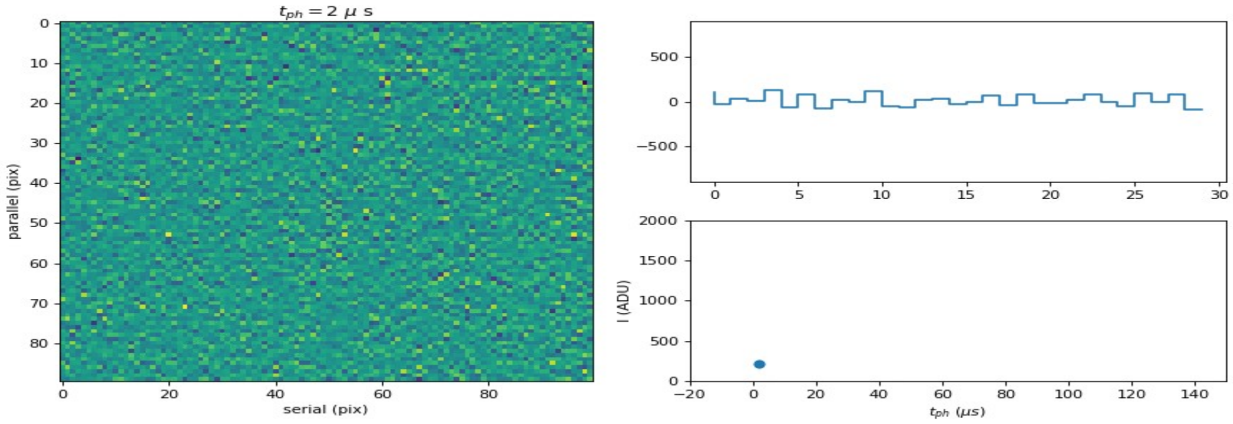
Fit intensity curves based on SRH to determine capture and emission time constants.

$$\frac{I}{N} = A\left(\left(1 - e^{\frac{-t}{\tau_c}}\right)\left(e^{\frac{-2t}{\tau_e}} - e^{\frac{-3t}{\tau_e}}\right)\right) + d$$



Trap Pumping In Practice

If animation not working try here – http://users.ox.ac.uk/~phys1463//trappump.gif



Procedure: expose to light, then pump a large number of times, varying dwell time. We also take unpumped flats for reference.

Find traps by simple sigma thresholding (with a goodness of fit cut after fitting emission time curve).

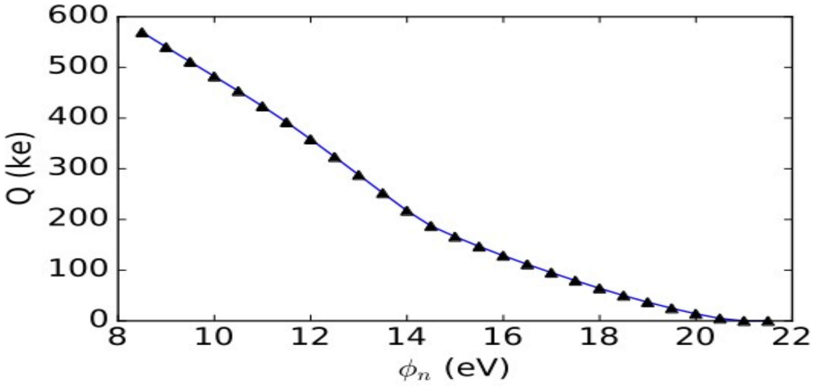
We typically can get away with 4 sigma exclusion.

In an unirradiated device, traps are rare!

Animation on left – some of our earliest (2018) attempts at getting this working on the CCD250

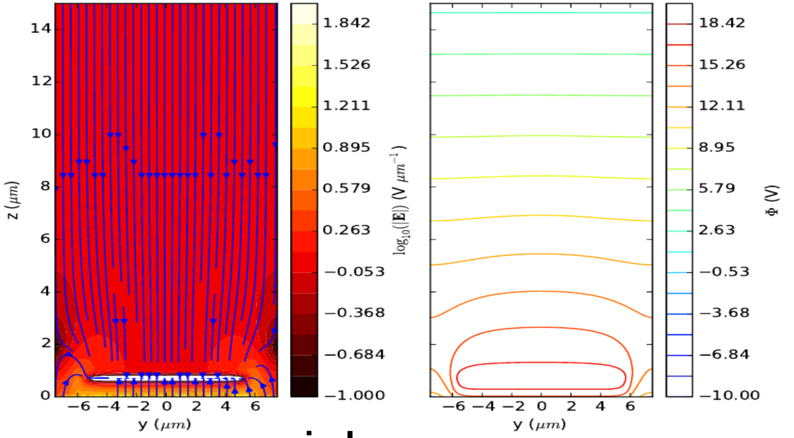
UNIVERSITY OF
OXFORD

Charge Storage: TCAD modelling

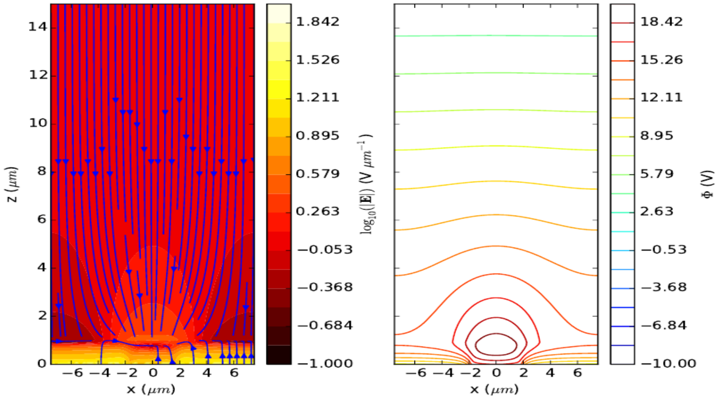


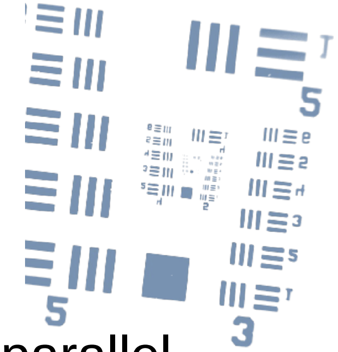
Procedure for modelling charge storage in TCAD:

1) solve equilibrium PE
2) solve applied bias PE
3) force (“Hand of God”) a small change in electron QFL
4) solve continuity & do small transient timestep
5) solve steady state continuity & PE
6) repeat 3-5 until desired electron QFL is reached



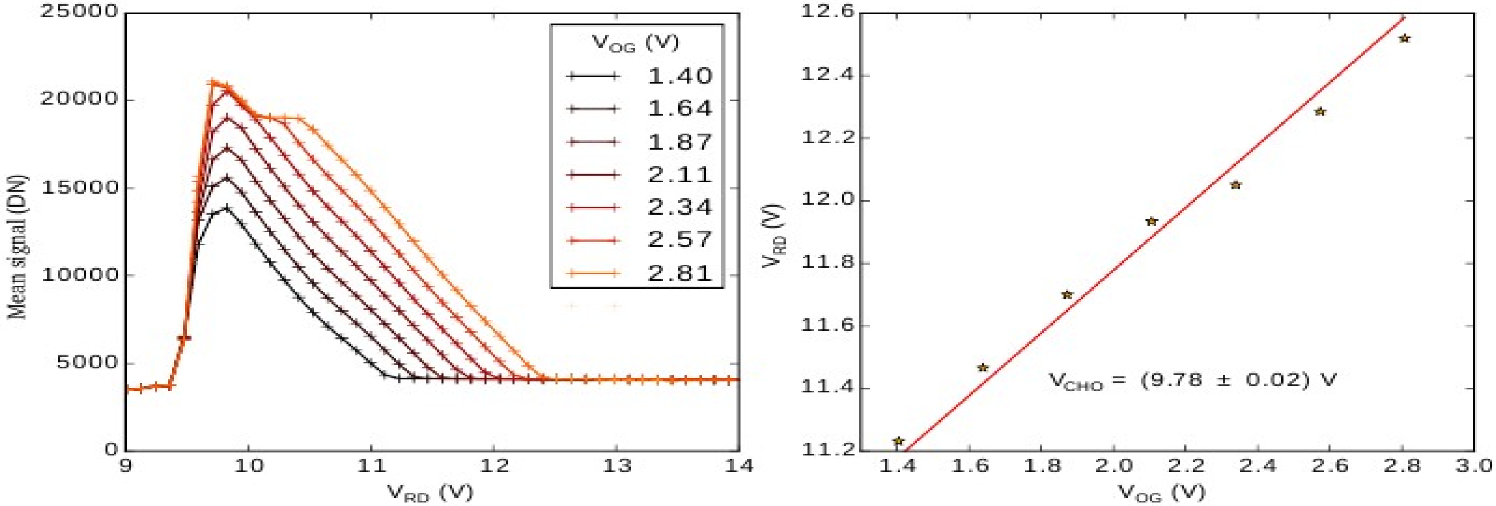
serial





parallel

Estimating parameters for TCAD simulation

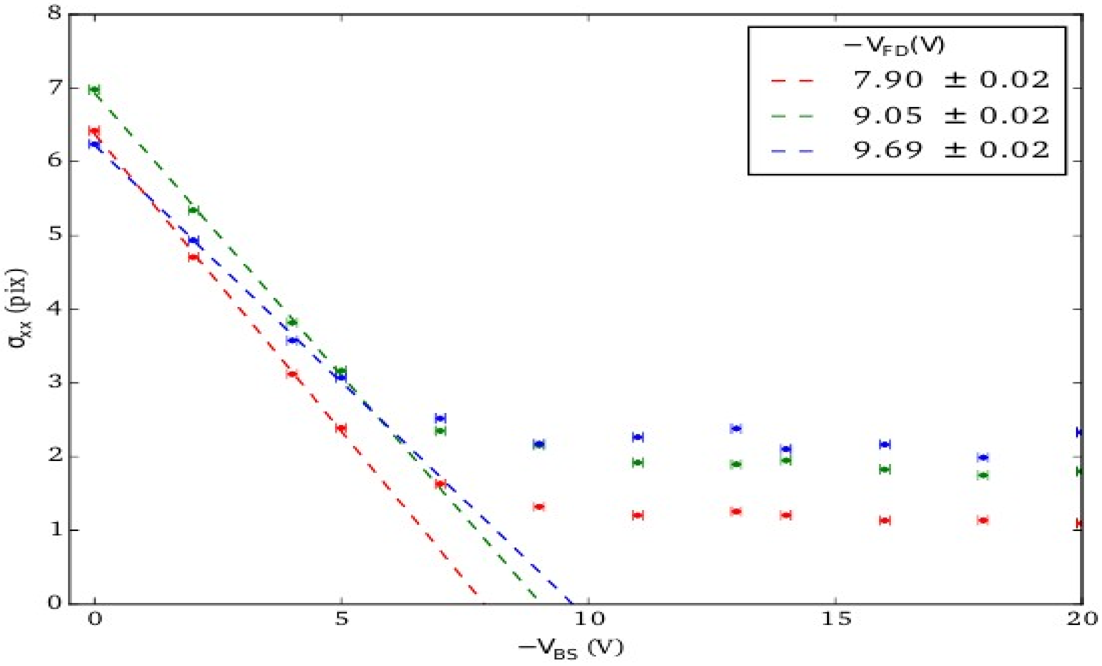


1) measure the channel parameter using a standard method of finding the reset drain and output gate potentials which cause the onset of charge injection from the reset transistor to the output node.

All TCAD simulations sanity checked against this number (i.e. check that empty channel gives correct potential extremum)

Estimating parameters for TCAD simulation

Estimate substrate acceptor density using the full-depletion voltage:

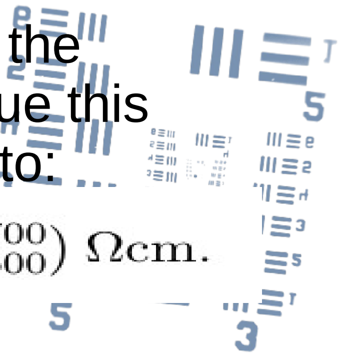


$$V_{\mathrm{BS}} = V_{\mathrm{max}} + \frac{q_e N_A}{2\varepsilon_{\mathrm{si}}\varepsilon_0}\left(z_T - \sigma_{xx}\right)^2 .$$

$$N_A \quad = \quad (2.0 \pm 0.2) \times 10^{12}\,\mathrm{cm}^{-3}$$

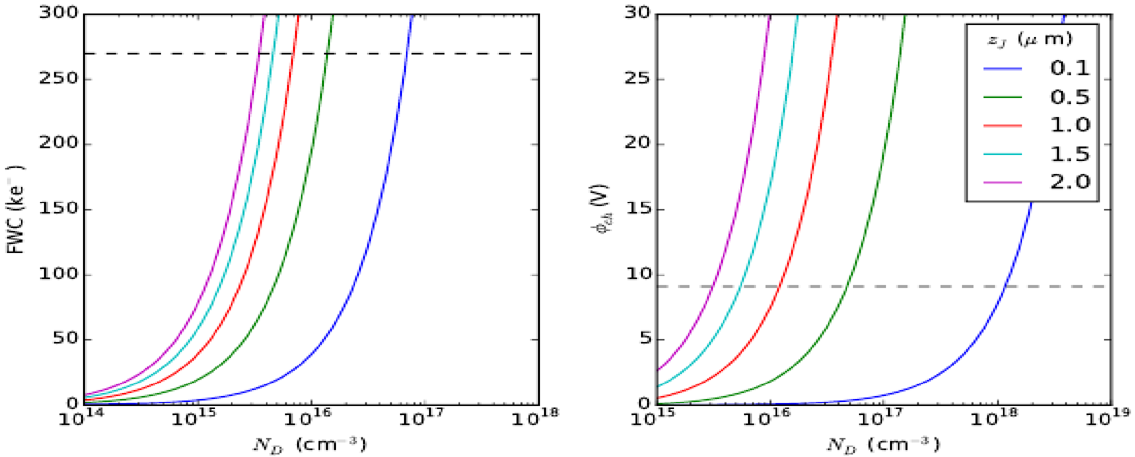
- Sanity check the resistivity value this corresponds to:

$$\rho = \left(6600^{+700}_{-600}\right)\,\Omega\mathrm{cm}.$$



Estimating parameters for TCAD simulation

- Use the (approximate) 1D analytic solutions to Poisson's equation to construct constraints on donor density and junction depth against measurements of (maximum) full-well and channel potential



$$z_j' = z_J - \frac{Q}{2N_D y_B L}$$

$$z_0 = z_J' - \sqrt{\frac{2\varepsilon_{si}\varepsilon_0 N_A V_m}{q_e N_D (N_A + N_D)}}$$

$$z_1 = z_J - \sqrt{\frac{2\varepsilon_{si}\varepsilon_0 N_A V_m}{q_e N_D (N_A + N_D)}}$$

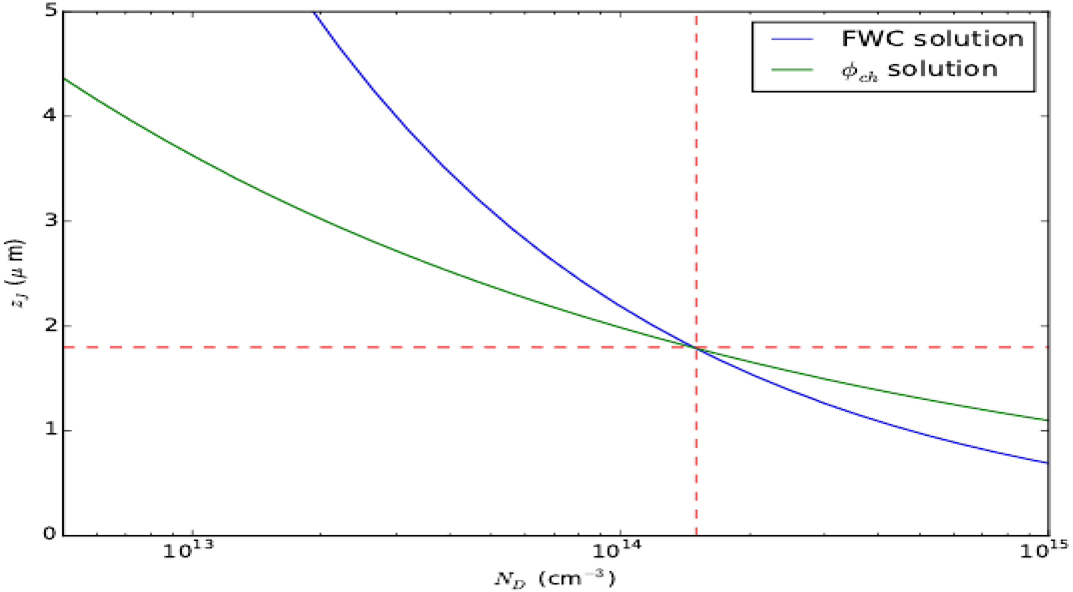
$$V_m = \left(1 + \frac{N_A}{N_D}\right)\left(V_G + V_1 + V_2 - \sqrt{V_2^2 + 2V_2(V_1 + V_G)}\right)$$

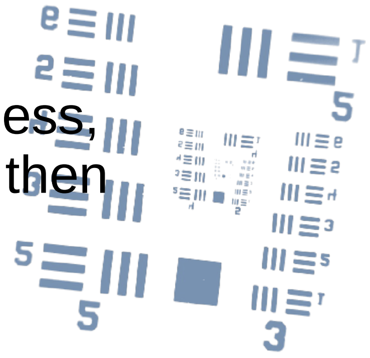
with

$$V_1 = \frac{q_e N_D (z_J')^2}{2\varepsilon_{si}\varepsilon_0}\left(1 + \frac{2\varepsilon_{si} d_{ox}}{\varepsilon_{ox} z_t}\right)$$

$$V_2 = \frac{q_e N_A (z_J')^2}{\varepsilon_{si}\varepsilon_0}\left(1 + \frac{\varepsilon_{si} d_{ox}}{\varepsilon_{ox} z_t}\right)^2.$$

Estimating parameters for TCAD simulation



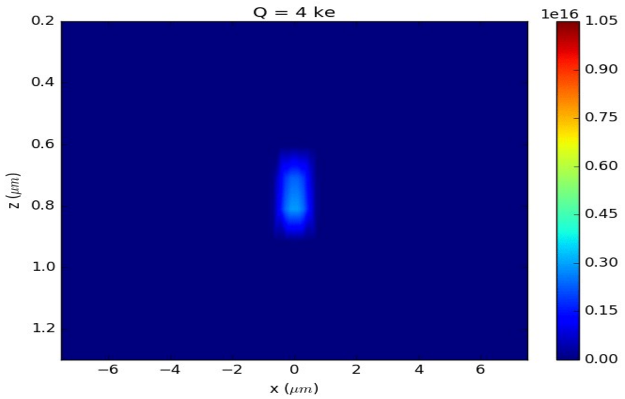


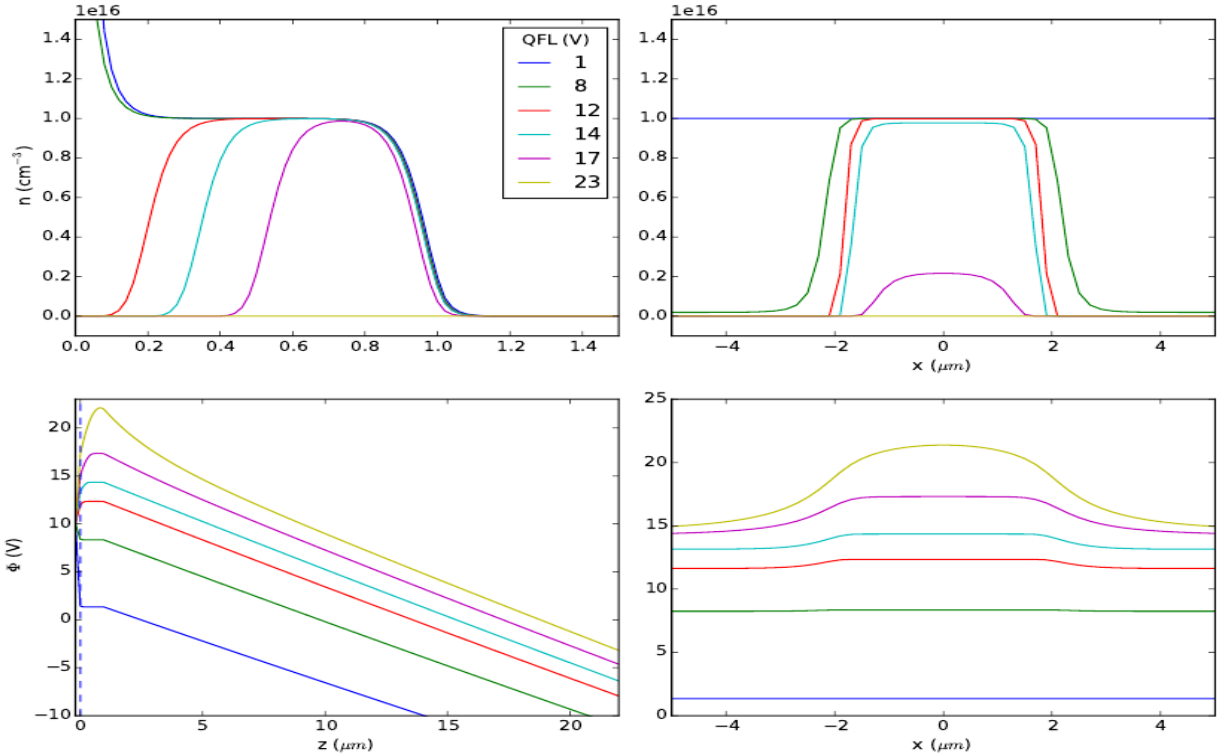
- The numerical parameters needed for the simulation (oxide thickness, device thickness, donor density, acceptor density, junction depth) then all have estimates consistent with measurements
- Use these parameters as starting point and make sure channel potential is consistent

Charge Storage: TCAD modelling

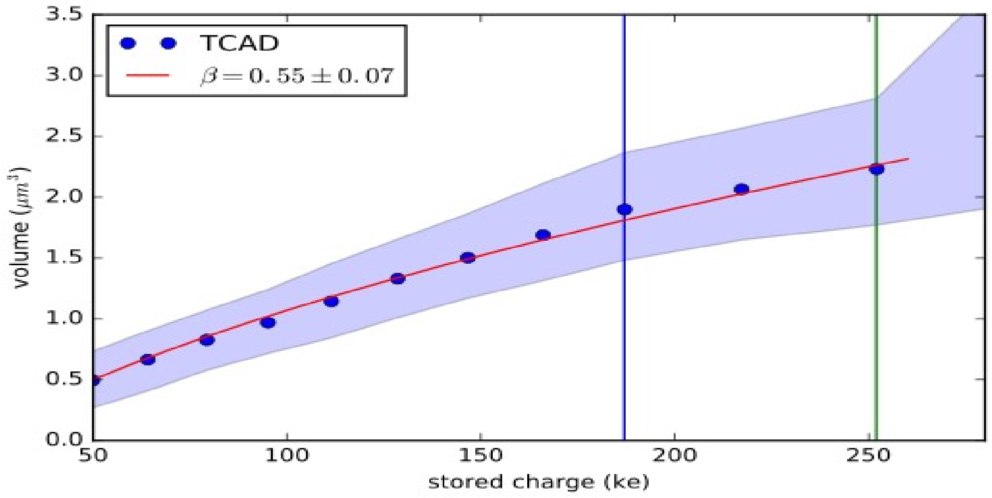
Changing QFL this way allows modelling of reset pixels without the inclusion of a drain contact in the pixel

Blooming and surface contact effects both clear – junction depth = 1 μm, Oxide interface @ z=0.2 μm



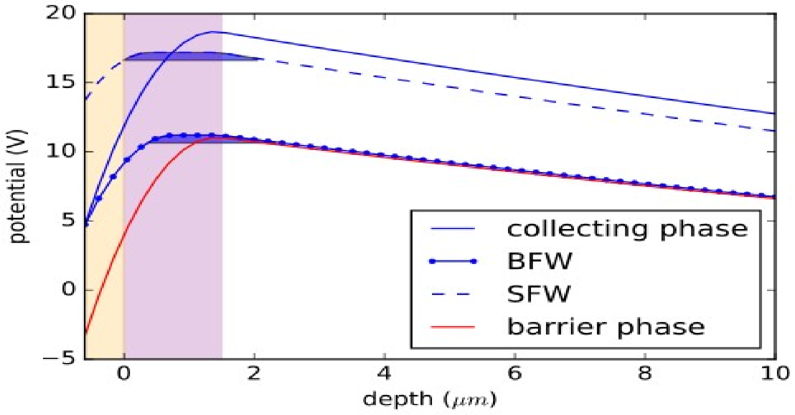


TCAD Charge-Volume calculation



- By drawing contours around electron concentration solutions, volume can be estimated without resorting to rectangular assumptions
- Shaded area represents bound of taking 99.9% charge contour (upper bound) to 90% charge contour (lower bound)
- Note reasonably good power law fit to β= (0.55 ± 0.07)
-

Full Well Capacity - Background



- Important to have full-well characteristics matched by charge storage model (because they are linked via the density)
- Full well transfer usually used to optimize collecting phase potential

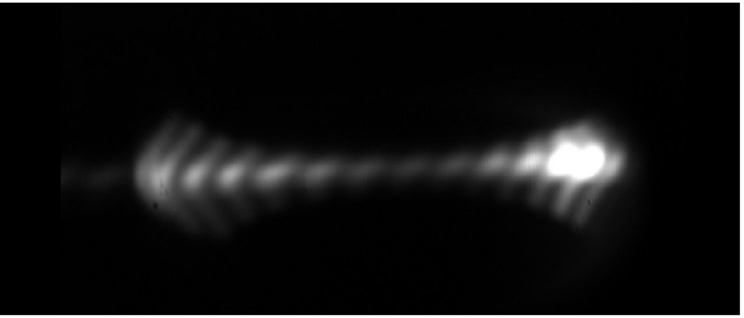
- Bloomed Full Well (BFW) → clock level becomes low enough that the collecting phase potential overlaps the barrier phase potential causing blooming
- Surface Full Well (SFW) → charge packet begins to interact with surface traps before charge can spill into barrier phase

"Optimum"* Full Well when Image clocks set such that

BFW ≈ SFW

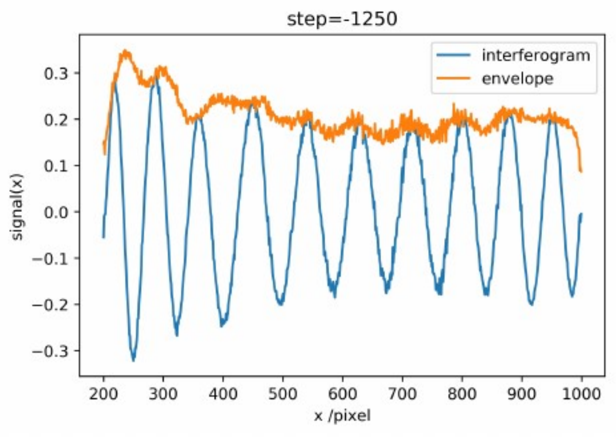
*Jim Janesick's word

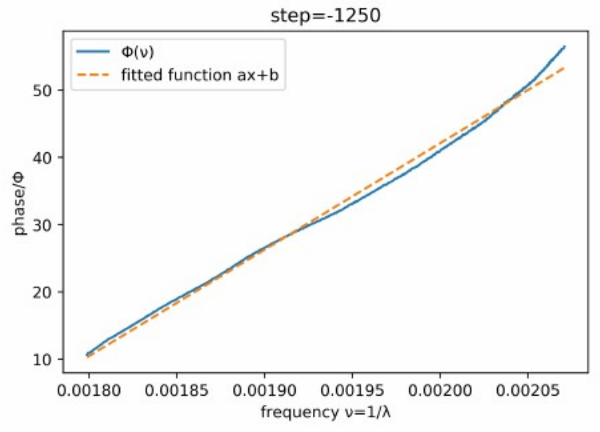
Steps so far

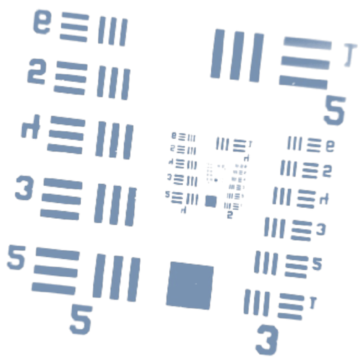


We carefully calibrated the interferometer using two arms with mirrors (to be replaced with cameras later).

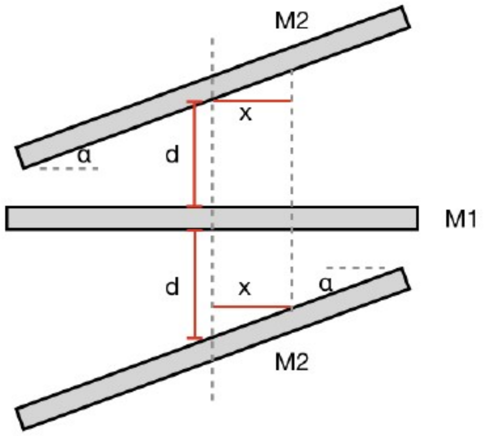
We produce interferograms on white light (left) from which we can extract a phase function(below) and from that, a distance measurement (more details in previous update talk!)

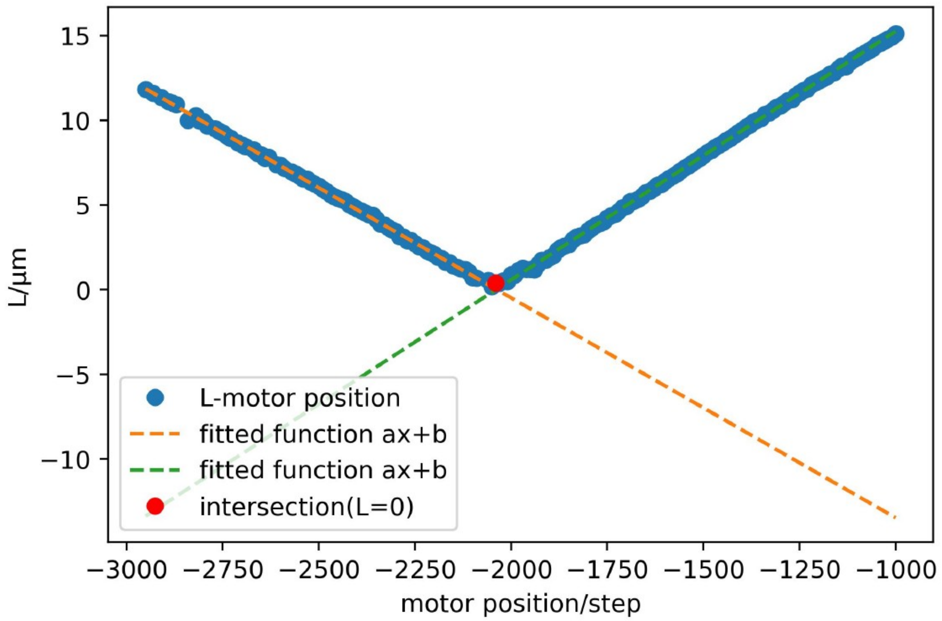






Scanning Mirror Position





With the mirror surfaces, we’ve been able to align the two arms to a (compensated) differential length now < 2um at centre.

We think there is still a tilt error, as evidenced by the differing slopes either Side of 0, and more evidence later