Advanced Instrumentation Lectures: Short topic – silicon imaging detectors (CCDs etc)

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Outline

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- Fundamental difference between imaging detectors & detectors mainly used in particle physics
- **General concepts in Imaging detectors**
  - QE
  - PSF/MTF
  - X-ray measurement & Fano factor
  - Photon Transfer Curve
- **CCDs**
  - Basic idea
  - Construction
  - Buried Channel
  - Noise Sources & radiation hardness
  - Use of CCDs in particle physics (& “skipper” readout)
  - “Modern” CCDs: thick, full depletion devices
  - Modern CCD effects – fringing, tearing, tree rings, Brighter-Fatter effect
  - Esoteric CCDs – delta doping, Ge CCDs, p-channel CCDs, EM-CCD
- **CMOS-APS**
  - Basic Idea
  - Basic pixel architectures -3T, 4T, 5T & pinned photodiode
  - APS effects – cross talk & lag
  - Use of “APS-like” detectors in particle physics
- **DEPFETs**
  - Basic Idea & applications

Motivation

I am about to tell you ways in which imaging and integrating sensors are quite different to the silicon sensors we use in the vast majority of HEP applications.

So, **apart from** the few particle physics experiments which do need these types of sensors, **why should you care?**

1) In the broader semiconductor industry, imaging detectors are way more common – should go without saying. Mobile phones, photography cameras, etc etc, all work on imaging detectors (CMOS APS).

2) Astro / bio / materials / industrial instrumentation work is interesting and challenging too! - much of astro instrumentation works on imaging detectors. If you end up working in instrumentation, one day you may want to have a job in astro or e.g. bio-imaging instrumentation (I did this the other direction!)

3) Imaging detectors in particular CCDs are where "it all started" for silicon pixel trackers, **including in HEP** - right (M.Turala, 2005)

4) There are some current (and future??) HEP experiments which do use these detectors

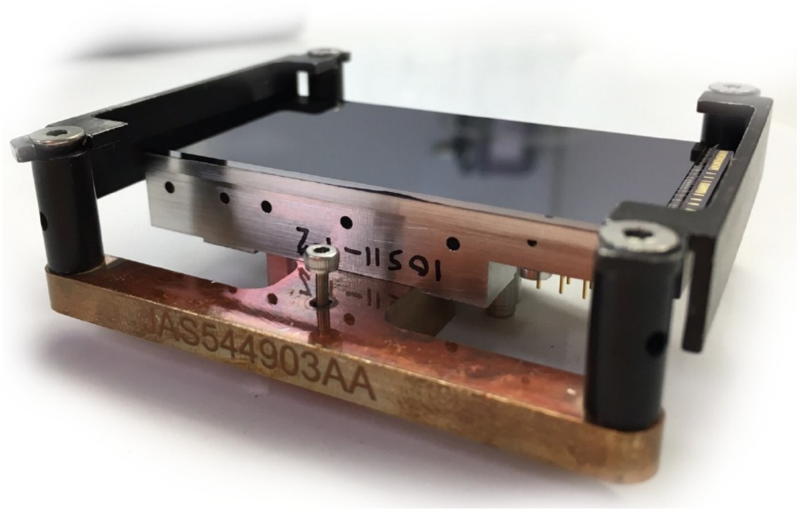
outs was pursued. In 1982, the Rutherford Laboratory group published results, showing that standard Charged Coupled Devices (CCD) could be used for recording of minimum ionizing particles [20]. The signal obtained from a very

Imaging / Integrating Detectors

- Most solid state particle physics detectors give a **current pulse** output in response to a particle being absorbed. We amplify and shape the pulse and obtain timing and height information.
- **By contrast**, an integrating detector is designed for charge to be stored and accumulated (integrated!) in a **collecting potential well**, and later **read out**.
- Each element / pixel gives us a signal which is the total charge arriving since the last readout.
- **“Disadvantages”:**
  - no timing information retained at level below the “frame” (or “line” in some cases) rate.
  - Can no longer distinguish between individual particle hits (pile-up)
- **“Advantages”:**
  - **Much higher effective signal to noise ratio** (so long as the “total count” of arrived particles was what you cared about!)

NB most of the time we’re using imaging detectors to detect low energy (i.e. visible, near-UV & near-IR) photons.

But they are also well suited to detecting soft X-ray photons, and can of course “see” massive particles too.



Origin of signal (c.f. Ramo theorem)

Signal is not due to charge "collection"

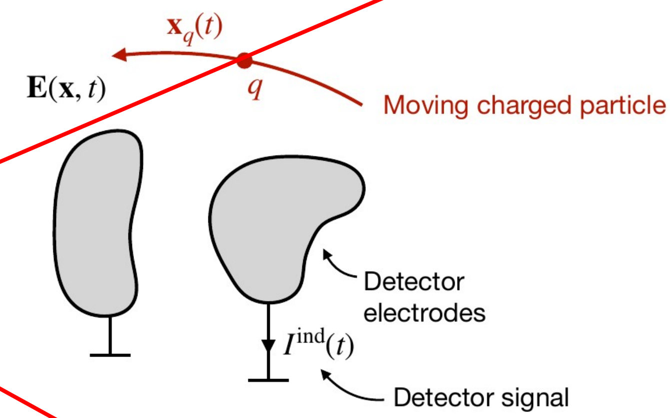
Charges can be far away from the electrodes and still induce a signal (radio telescopes!)

Electrical signals in detectors are <u>exclusively</u> due to induction by moving charged particles

Signals in silicon detectors may be computed with the Ramo-Shockley theorem *(itself a special case of a more general fact)*

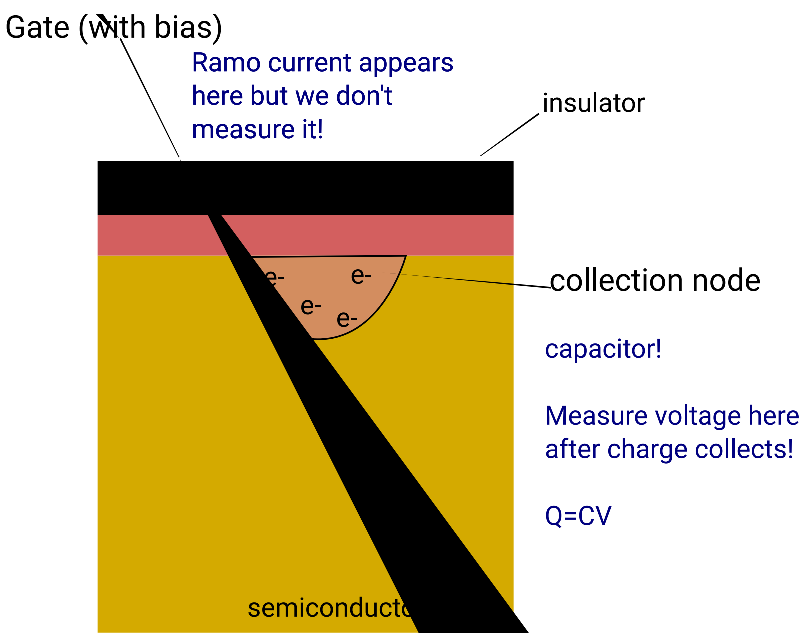
$$I^{\text{ind}}(t) = -\frac{q}{V_w}\mathbf{E}_n(\mathbf{x}_q(t); V_w)\cdot\dot{\mathbf{x}}_q(t)$$

Weighting field of electrode — Particle trajectory



CORRECT...

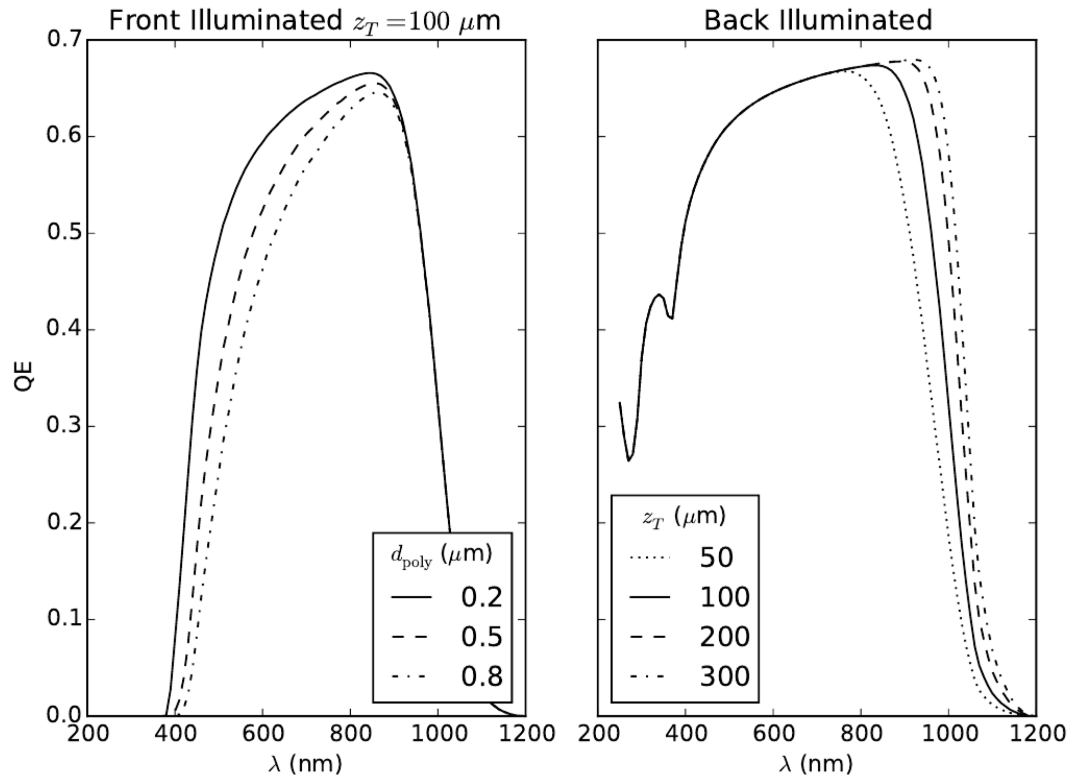
BUT NOT TODAY!



- In Philipp's excellent talk in this series he told you that "signal is not due to charge collection" and "signal is exclusively due to induction by moving charges"
- Of course he's right… but in (almost all) imaging detectors we **actually do collect charge** and read it out via the change in voltage of a capacitive node
- A Ramo current appears at the electrodes but we **almost never** care about it

Quantum Efficiency (QE)

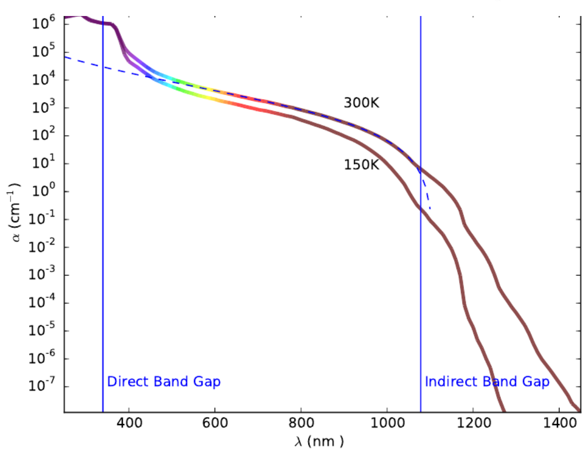
QE is the ratio of the number of photons that impinge on the detector to the number that contribute to the readout signal (NOT including noise floor considerations).

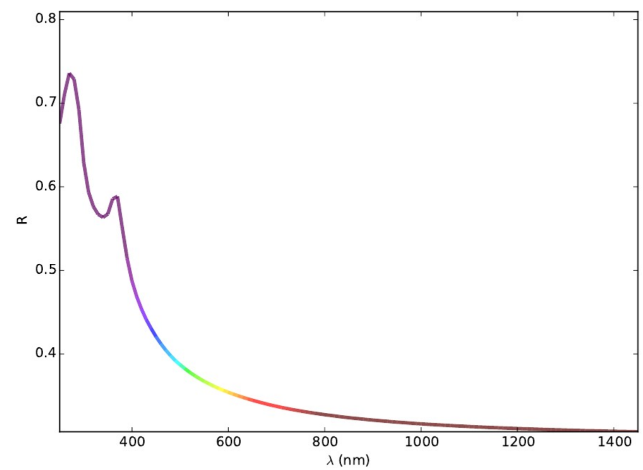


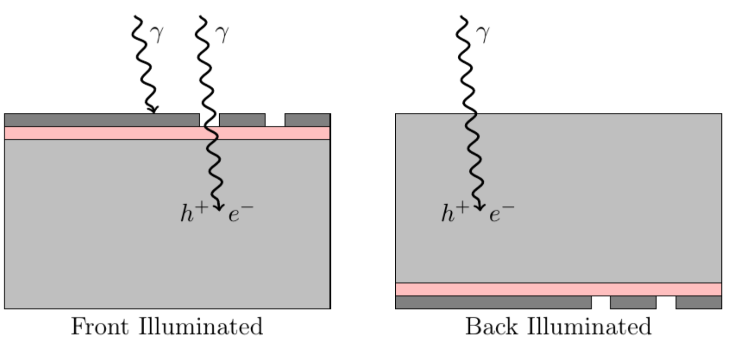
Theoretical QE calculated just from reflectivity a absorption of silicon. In reality, better can be achieved with the use of AR coatings. QE in rec improved by thicker (depleted) device. QE in blı improved by "back illumination"

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

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





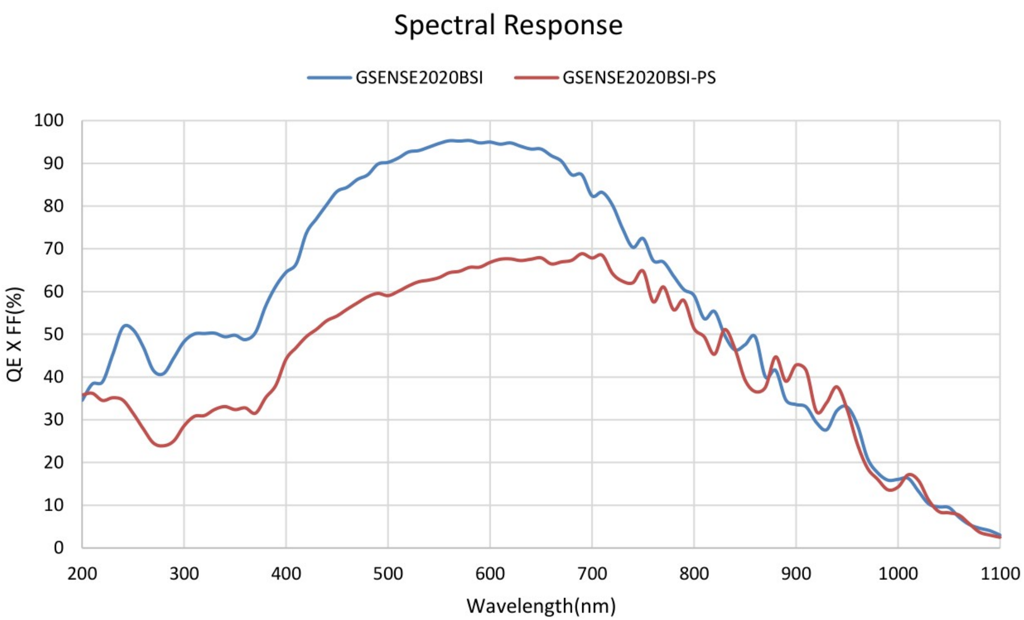


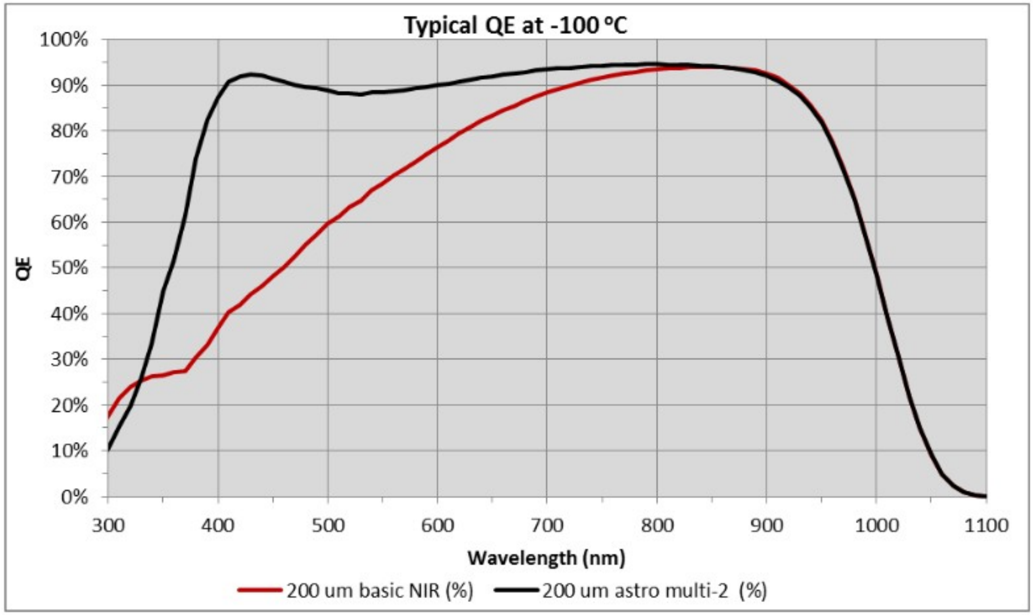
QE2

Left: a truly “boutique” level AR coating as used for astronomical instrumentation gives detector a very blue colour (longer wavelengths absorbed very efficiently and reflectivity attenuated)

There are some technical complications (i.e. iQE vs dQE) comparing different types of device that need not bother us today. In principle, CCD remains the king of high-QE -especially in the red, since can be made thicker than APS, and in the blue with absurd proprietary AR coatings **(below right, courtesy Te2v)**, But modern “sCMOS” (**below left, courtesy gsense)** is getting pretty close.

Red QE also gets worse with low temperature (opposite to dark current!), so choosing operating temperature can be a big challenge.

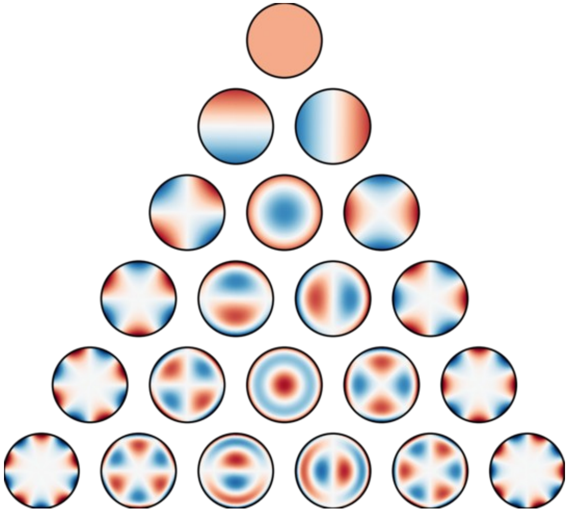




PSF / MTF

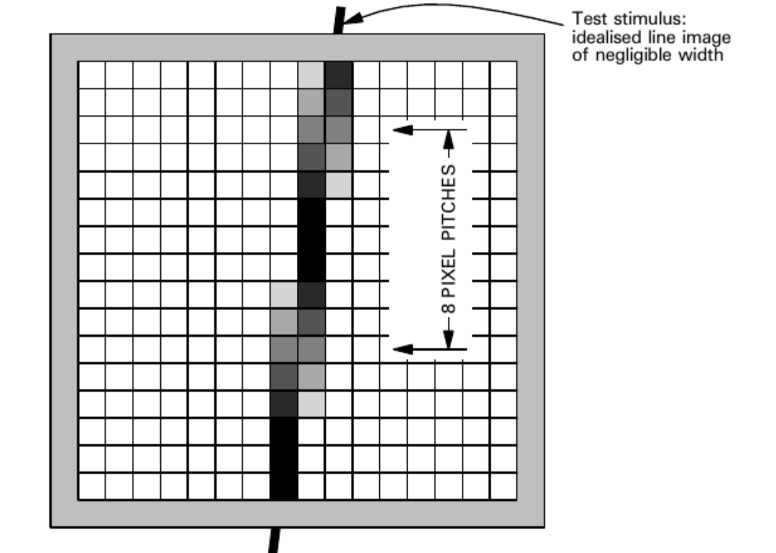
PSF (point spread function) is the response of the system to a point source.
For example, a diffraction limited rotationally symmetric optical system has the PSF of an Airy disk. In practice, ground based, wide field, imaging optical telescopes **never** have a PSF close to an Airy disk.

Contributions to the PSF from the optical system (which includes the atmosphere) and motion jitter of the instrument during observation can be well modelled using a linear combination of the **Zernike Polynomials + a continuous profile (e.g. Voigt profile), provided there are no diffraction effects present. PSF depends on wavelength, time etc etc as well.**
MTF (Modulation Transfer Function) is the magnitude of the Fourier Transform of the PSF, describing resolution space rather than direct space.



The detector itself has several PSF contributions, among which:
Sampling PSF (c.f. Nyquist theorem & pixel size)
Thermal diffusion of charge as it travels to collection sites (~Gaussian but not exactly)
Statistical variation in collection depths modulates the diffusion (very small effect in LSST except at very red wavelengths!)
It is very hard to directly measure properly, because: **aliasing, noise**, **vibrations,** etc
MTF is the standard way to define “resolution” of an imaging detector. Could spend a whole lecture talking about how it’s defined and how to measure it etc

Measuring Detector PSF /MTF



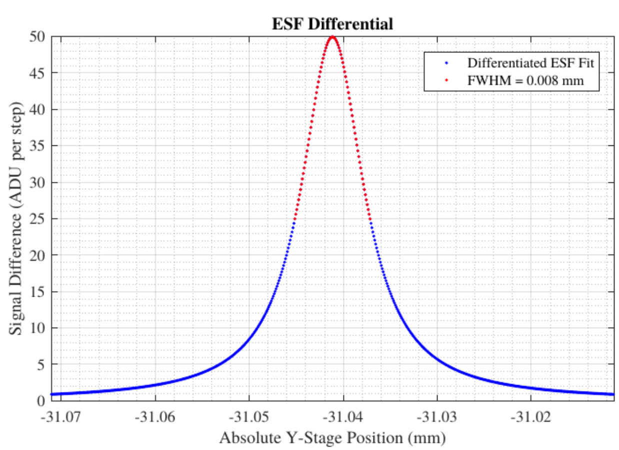
Notes

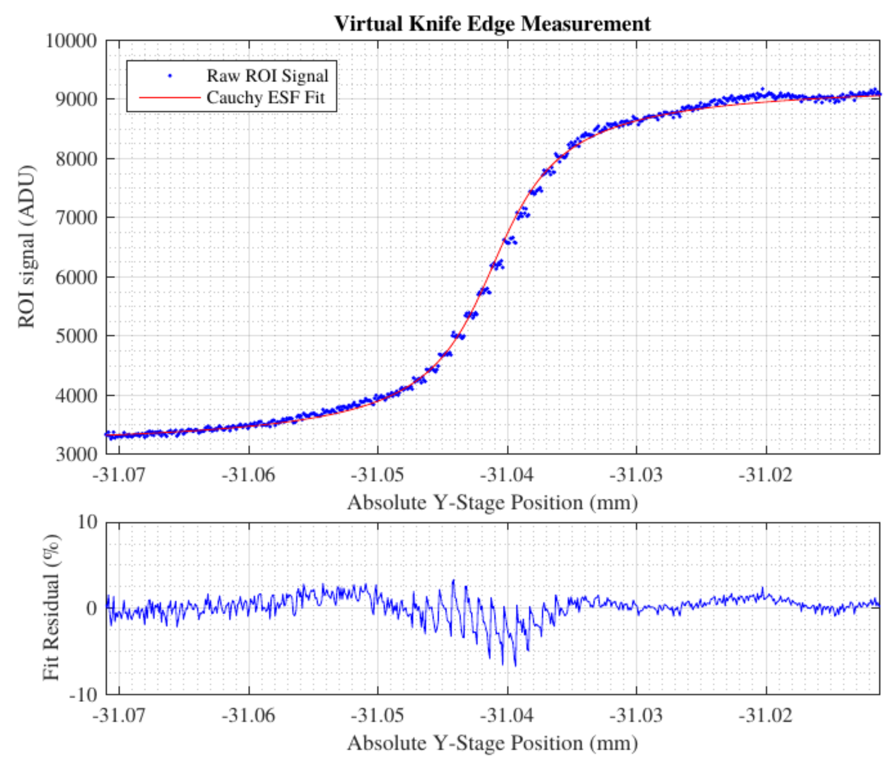
[1] In this example a 16 x 16 pixel region is designated on the sensor, e.g. enclosed by a one pixel width border suitably highlighted on the image display. The test image is focused as shown with a slope of 1 in 8 with respect to the pixel columns or rows.

[2] An almost ideal sensor will yield a response as illustrated above. The shaded pixels indicate partial responses because the line energy is shared between adjacent pixels.

Left: the “vernier” method,
Standard for astronomy for decades.
Image courtesy of e2v

Below: the “virtual knife edge” method – state of the art for accurate direct MTF measurement
Images courtesy of Ed Allanwood





X-rays & massive particles

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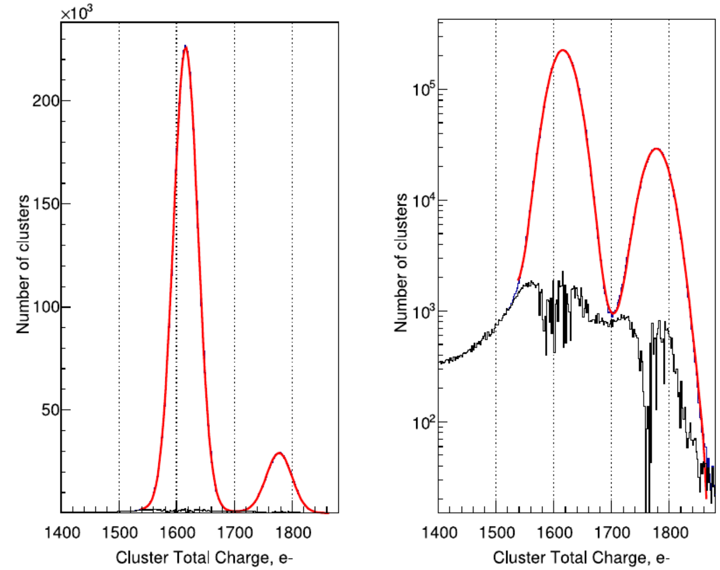
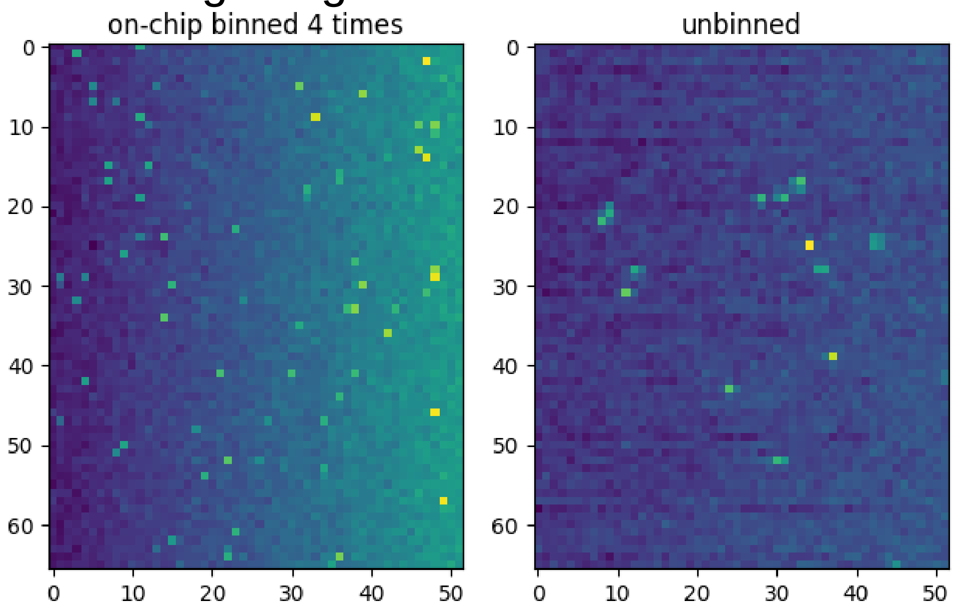
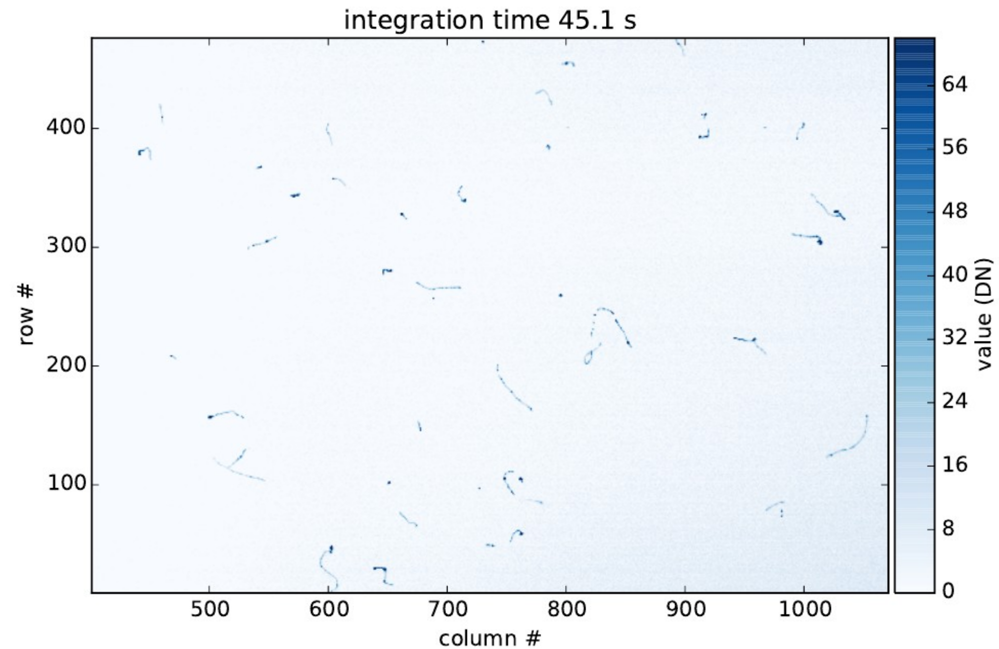
Since an X-ray will deposit many electrons, you can see these pretty well in imaging detectors.

(right) – most accurate to date measurement of silicon Fano factor F using clusters in e2v CCD-250 (Kotov et al 2018)
(below left) – Fe-55 “events” in a CCD
(below right) – “cosmic ray” events in a CCD integrating for 45 seconds







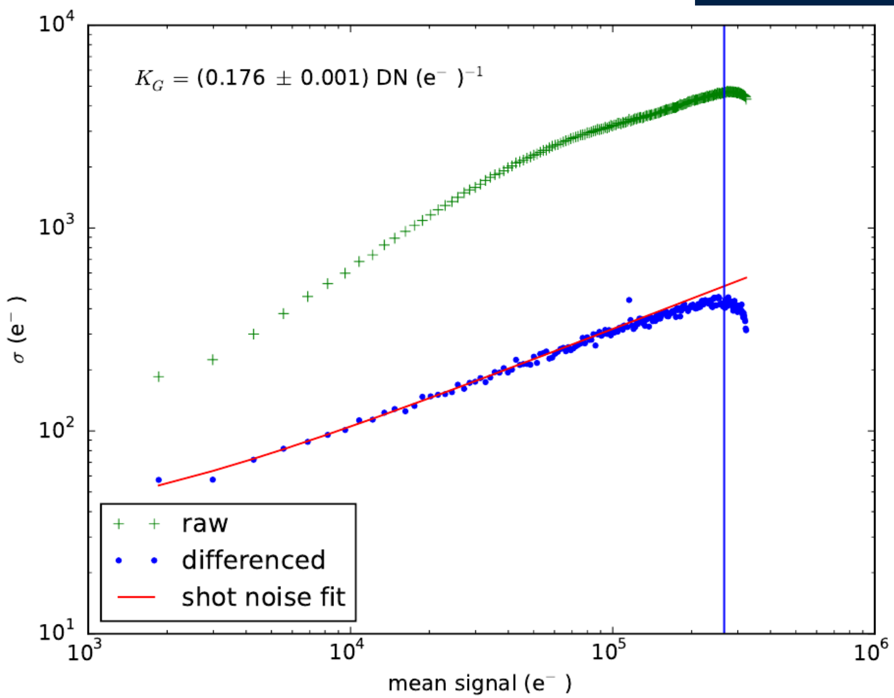
Photon Transfer Curve

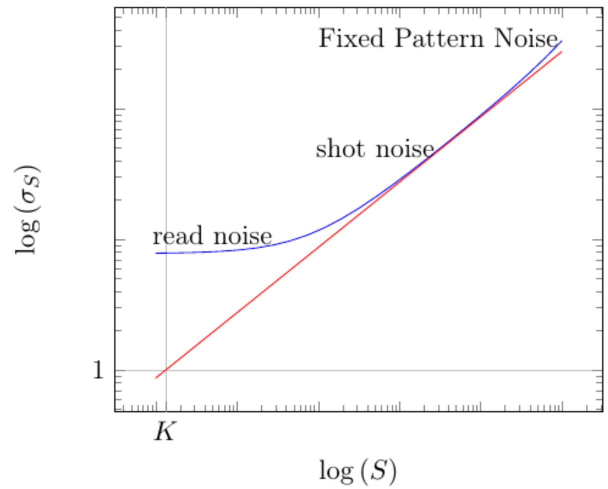
Note in the previous slide I said that Ivan Kotov ***measured*** F using X-rays. How did he do that? In many HEP applications, we use either x-rays or MIPs to **calibrate** the gain.

In an integrating detector, we have another (much more accurate and sensitive) calibration method: **the photon transfer curve**.

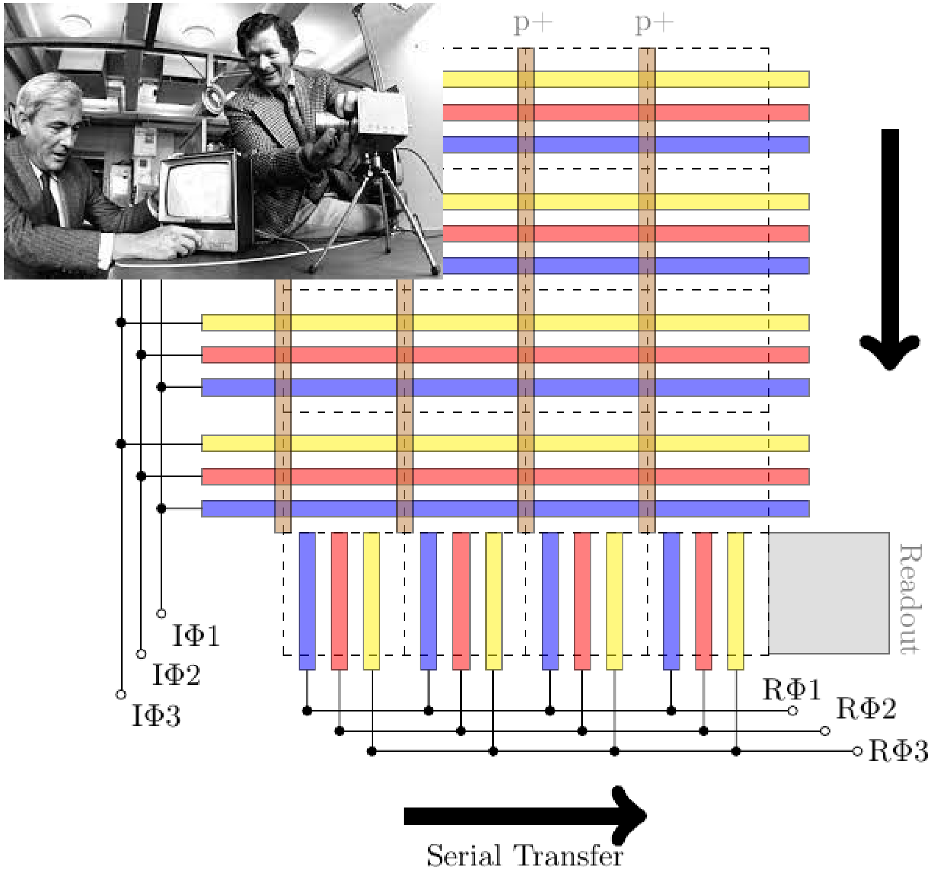
Since we know that (incoherent illumination) photons arrive with shot noise statistics (i.e. mean = variance), a graph of mean number of counts vs standard deviation of counts will **directly give the camera gain, linearity and full well capacity.** Because the detector itself physically does the time integration of the samples, no off board processing or calibration of downstream electronic losses for this procedure to be accurate!

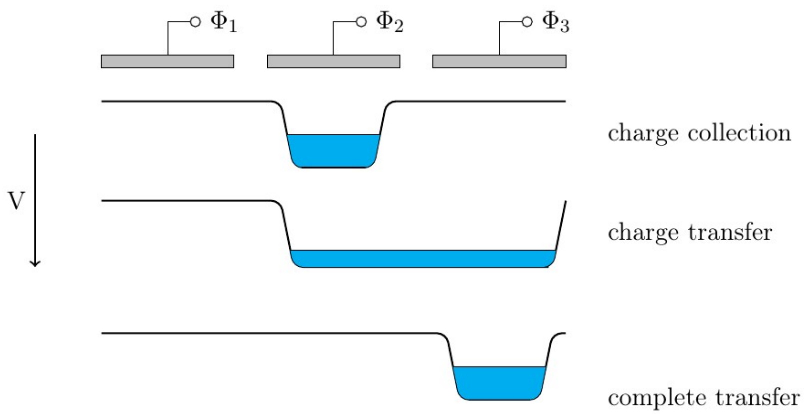
Lots of details and things that can be extracted from this technique, not enough time to go into today!





CCD Basics #1 – transfer





- Stored charge is transferred through the array by clocking a series of neighbouring MOS capacitors
- Gates must have some overlap (which is why "true" CCDs are so rare now- **not compatible with standard CMOS process**
- Allows many pixels to share one amplifier & output, maximal linearity and low noise
- Allows 100% sensitive area fill factor of pixels – there are no transistors (**nor any active circuitry!!)** in the pixels themselves!
- Transfer process is **extremely efficient** and well optimised, in a science grade sensor >99.999% of charges successfully transferred

- Nobel prize awared to Boyle & Smith in 2009 for inventing this technology

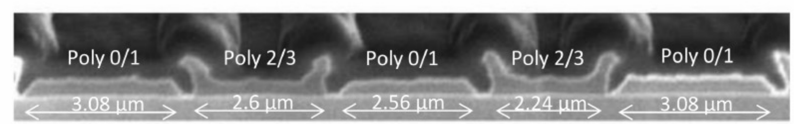
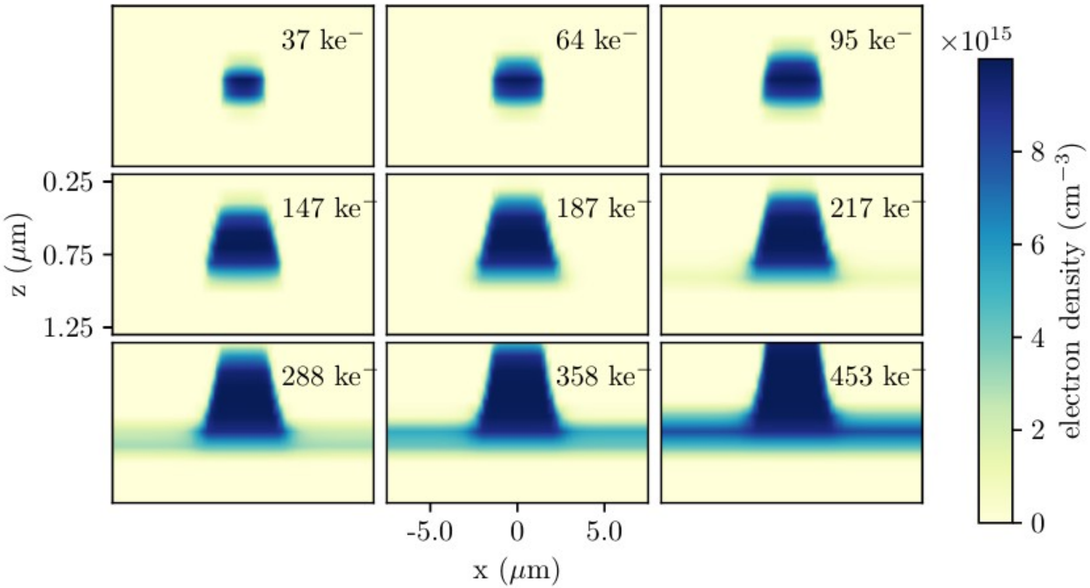
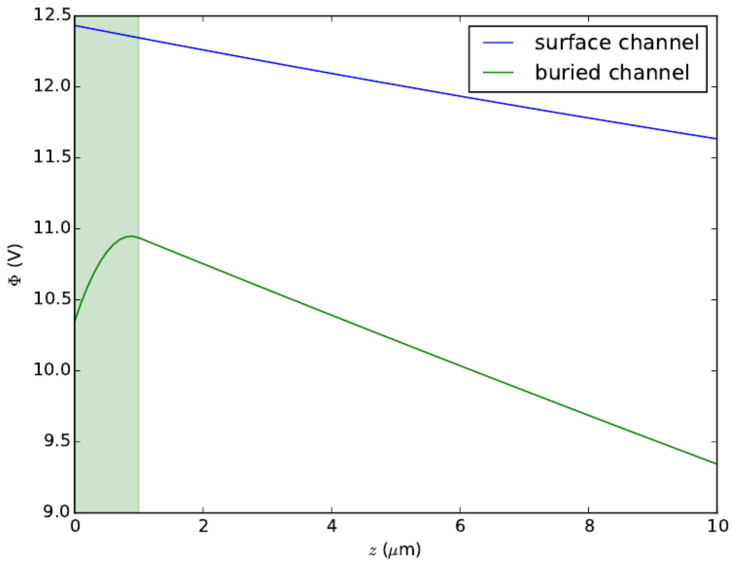


FIGURE 7.15: FIBSEM cross section courtesy of Andrew Clarke, revealing the electrode widths of an unused CCD273 wafer.

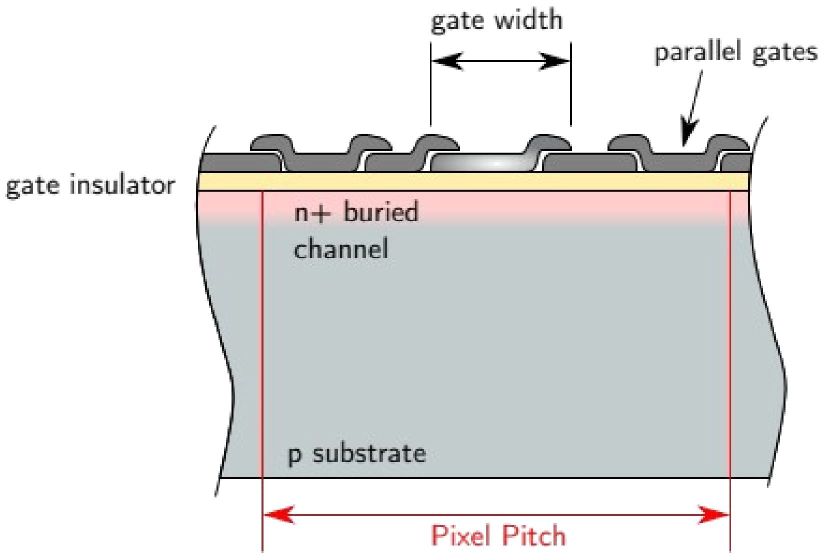
Charge Collection & Storage



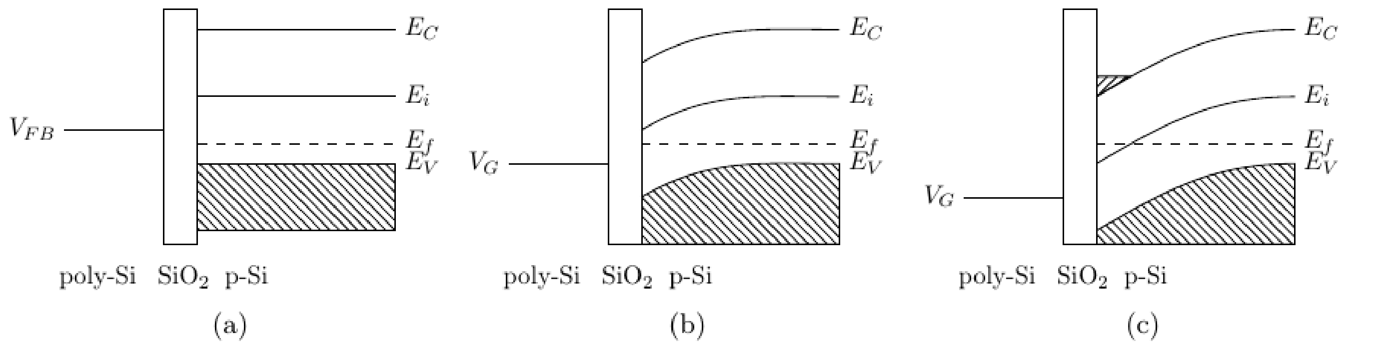


Photons absorbed in the volume, and then collected by strong drift field until they reach the storage "well".
The well has a finite capacity, beyond which charge will "bleed" up and down the columns

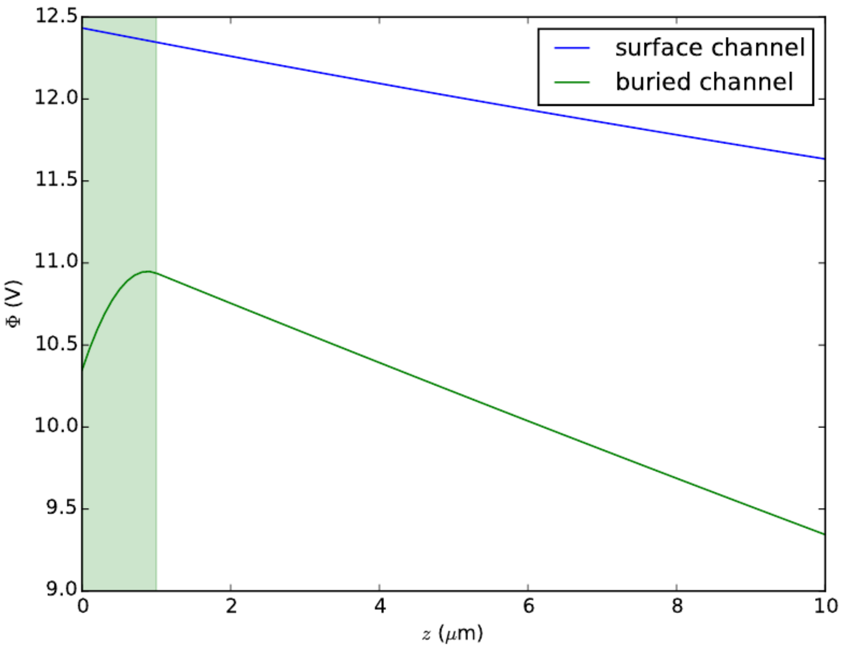
All modern CCDs use a buried channel implant (shown for n-channel on the right), which keeps the electron storage away from the insulator interface. Storage capacity reduced, but dark current **massively** reduced. Similar trick (see later) used in "pinned" photodiode in CMOS-APS.



Aside: Physics



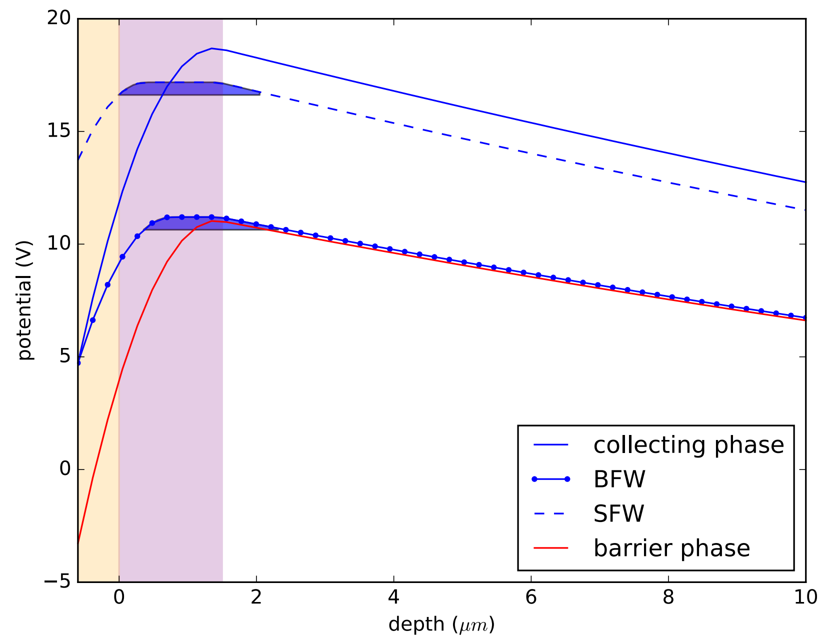
A CCD is only useful when it is f<u>**ar**</u> **from thermal equilibrium.**

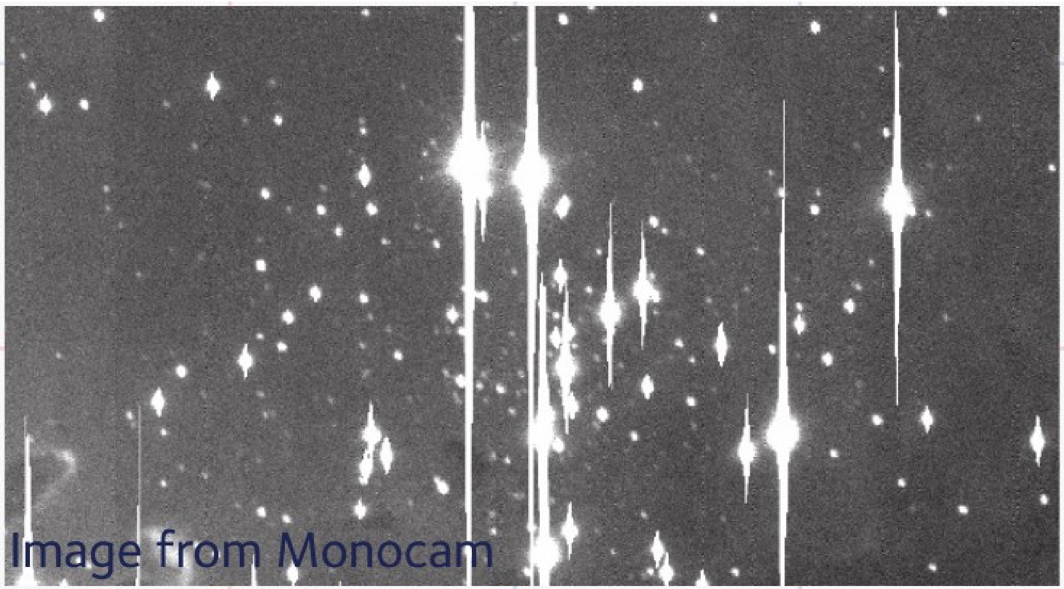


- When a voltage is applied to the CCD gate, the equilibrium state would be for electrons to fill the well
- Since no source of electrons nearby, it takes a long time (e.g. hours) to reach this state from thermal generation
- A buried channel (n) implant is introduced to move the potential well away from the surface, improving transfer efficiency, dark current, noise
- **BUT**: must empty buried channel of majority carriers, & drastically reduce full well capacity

CCD Full Well & Bleed Trails

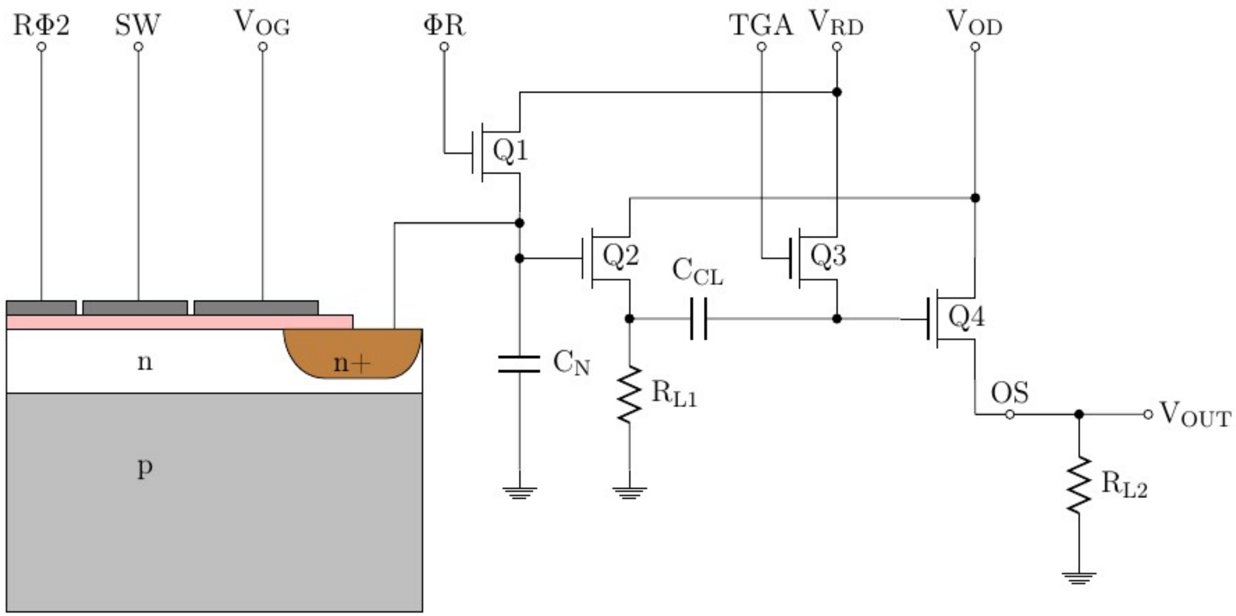
- Normally consider full well to be reached when charge overwhelms potential well capacity and “blooms”
- In some operating conditions (i.e. high gate voltage), charge can contact the surface before this happens
- Normally considered unacceptable for scientific CCD operation
- We carefully optimise gate voltages to make sure this doesn’t happen



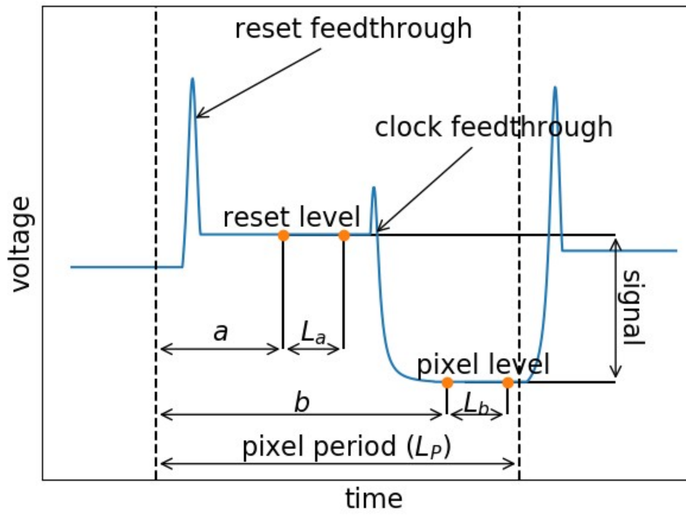


- Perhaps surprisingly, the exact device physics behind the shape of “bleed trails” is also not fully understood yet!
- Bottom line: the CCD is a truly analog device, and you have to get a **lot** of voltage and timing parameters right to get the best out of one (unlike modern particle physics detectors with fewer levers to play with!)

CCD basics #2 - readout



"video"

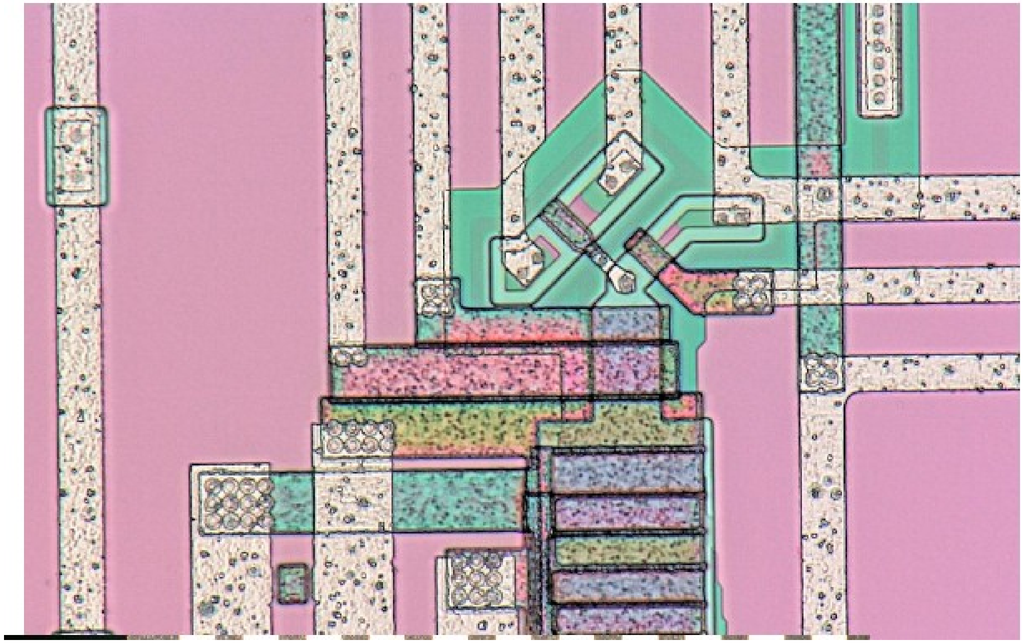


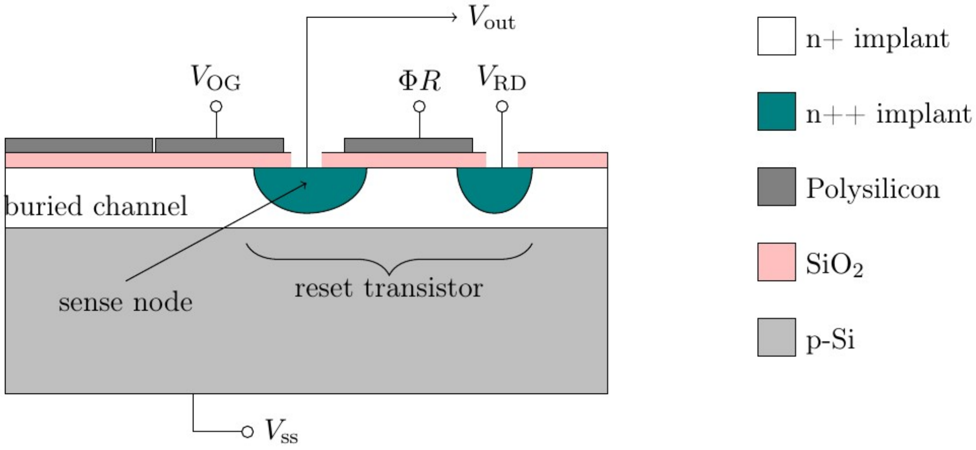
The typical CCD readout circuit is simply a node capacitance with a source follower. There is also a (usually MOSFET) transistor to reset the node to "empty".

Charge is "dropped" into the node via the output gate from the serial phases

Above left diagram is a 2-stage circuit, as used in e2v CCD250 in LSST camera, which has onboard a 2nd stage follower to drive the cable / ADC load, with its own reset (stages are AC coupled because they run at about 30V DC!)
Above right shows time sequence of a single pixel readout, as seen from V_out.

Readout in practice



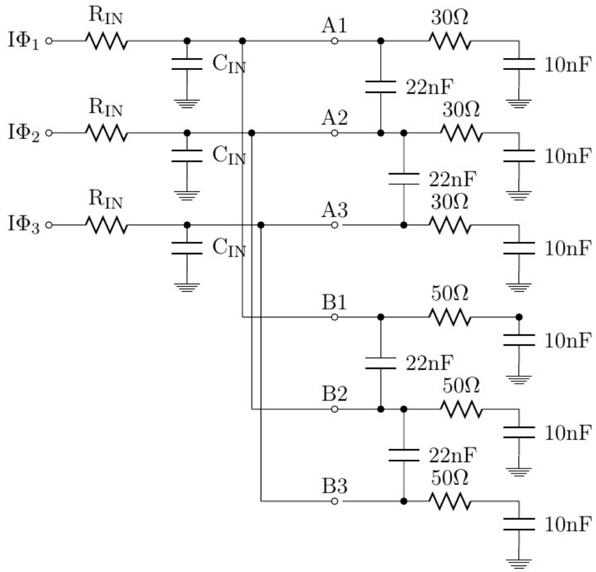


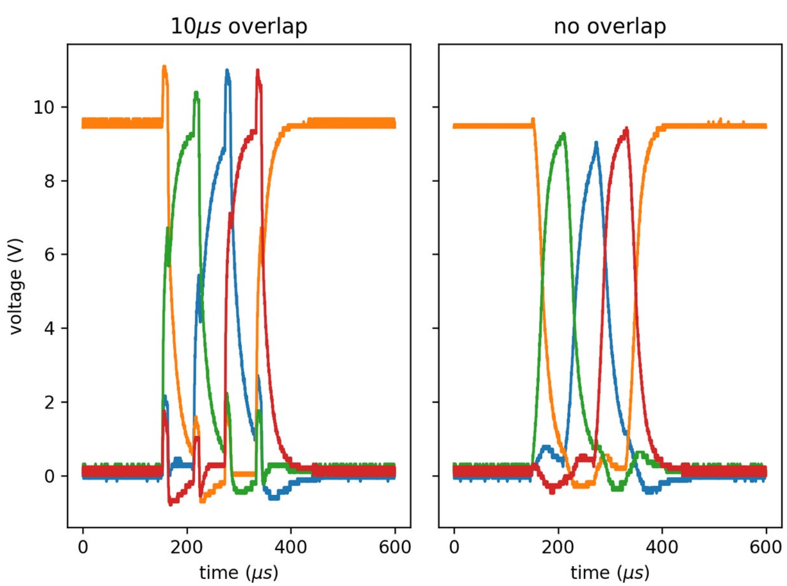
Above left: micrograph of a 2-stage CCD output circuit (made on 1um!! technology, in about 2014!!!!).

Above right: diagram of the sense node and reset node implants

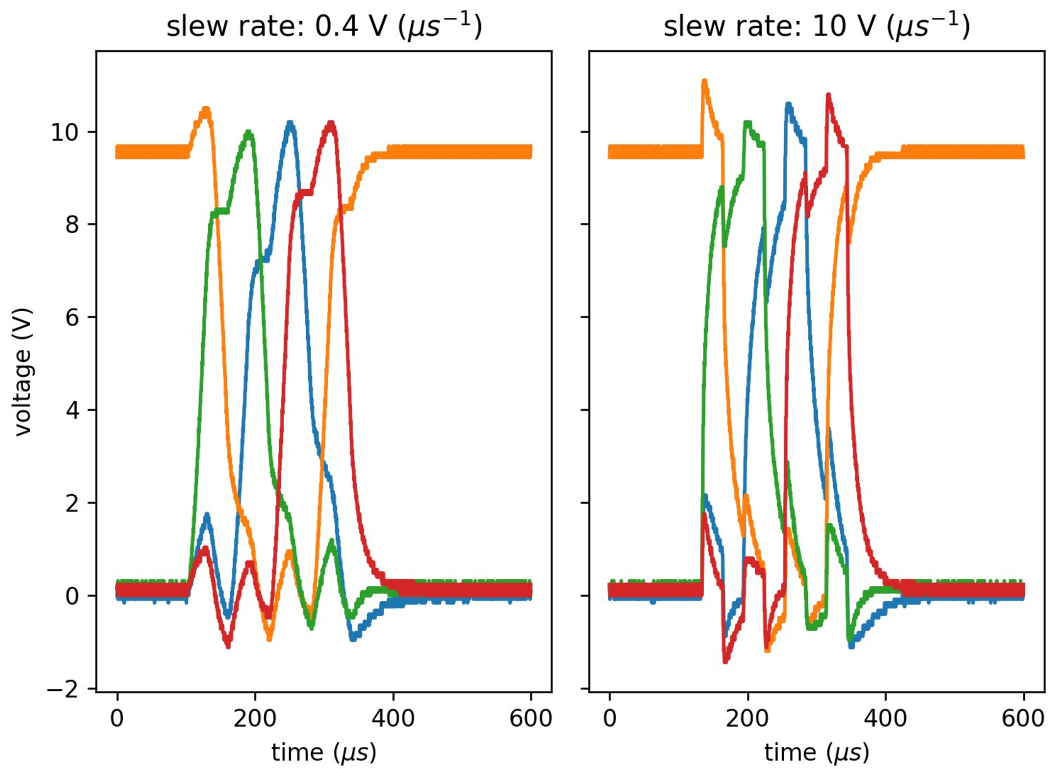
Right: what CCD readout looks like on a scope. Top trace is the pixel output, bottom traces are sequences of reset clock and two overlapping serial clocks

Aside: Clock Optimisation





- Simplified but quite accurate model of CCD gate interactions can be produced in SPICE, but these are actually real measurements from the “outside”. You of course can’t probe the point you want to because it’s inside the chip!
- Right is the result of changing (only) the slew rate of clocks – which might affect transfer efficiency, full well, and noise
- In practice, clock feed-through is nowadays the dominant excess noise source in CCD readout optimisation (somewhat surprisingly)



Clock Optimisation #2

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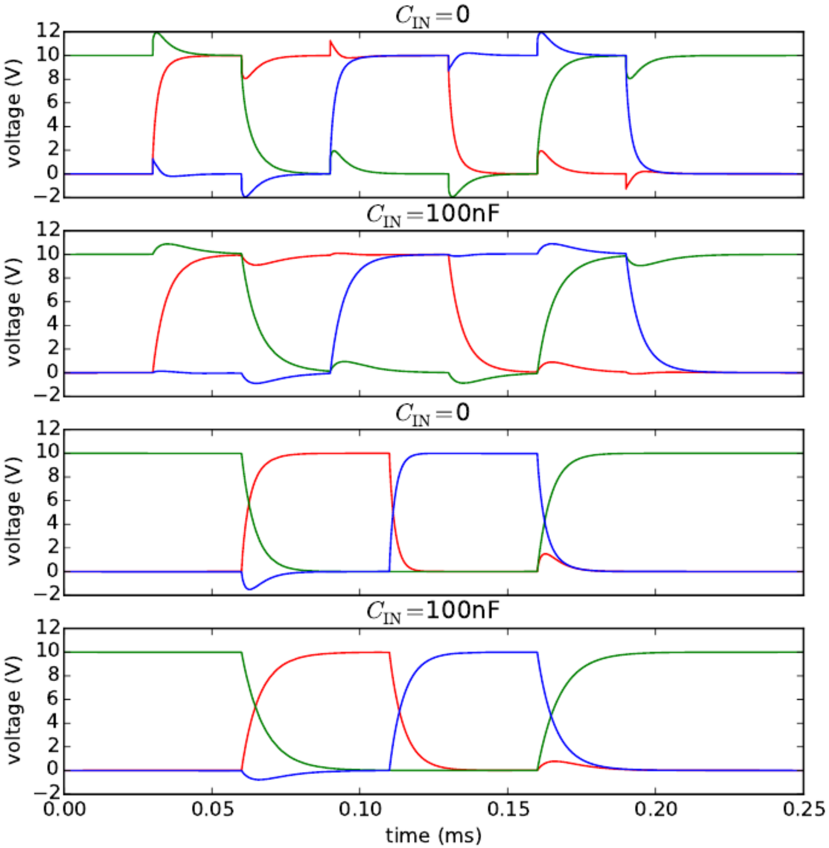

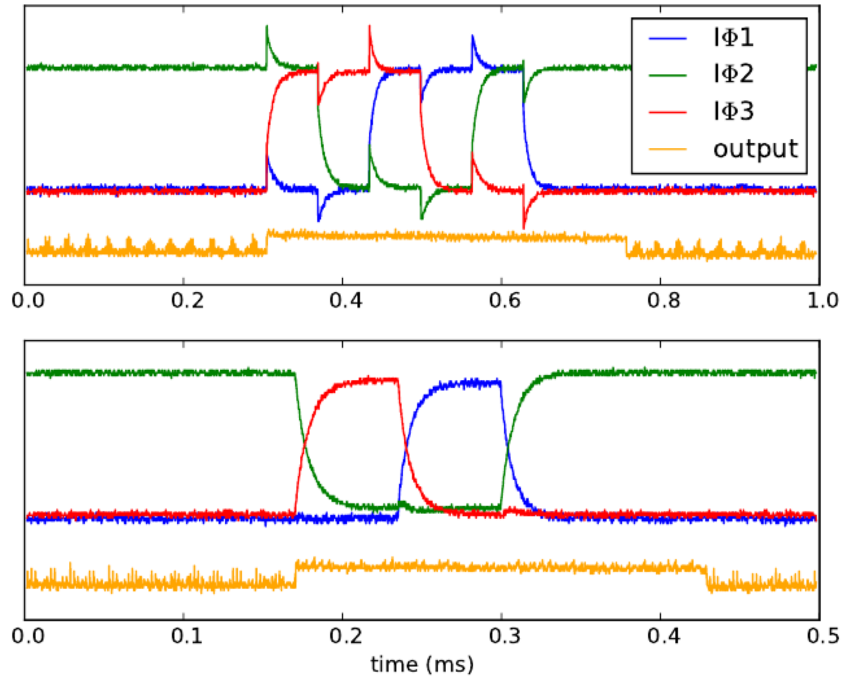

- There are many free parameters in clock optimisation (duration, slew rate, overlap, high level, low level)
- In the past (e.g. Hubble, GAIA), often optimised by whether traces look “pretty” or not
- In my view: this isn’t a good idea – whether it looks pretty on the outside doesn’t tell you directly about the physics on the inside!
- **Above left** – SPICE simulation of parallel clocks on an e2v-CCD261, **above right** – measurements under similar conditions

Eliminating Reset Noise

- Finite bandwidth of the reset transistor causes reset level to fluctuate between pixels.
- If not removed by processing, this reset noise would be the largest component of noise present in CCD readout.
- For T=178 K (LSST nominal) and C=15fF (typical high responsivity CCD), equivalent of roughly 40 e-.
- NB readout noise spec of LSST CCD operating @550kHz pixel rate is ~4e-.

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

$$|N(f)|^2 = K\left(1 + \frac{\alpha}{f}\right)$$

Read noise frequency spectrum for a CCD readout (excluding reset noise) looks like what you expect - broadband white noise & a 1/f flicker component. It's just like any other transistor

SOLUTION (in basic terms):

Measure both the signal and reset levels for each pixel, and subtract one from the other. This procedure almost perfectly eliminates the reset noise.

It is called "correlated double sampling" or CDS

Analog CDS (Dual Slope Integrator)

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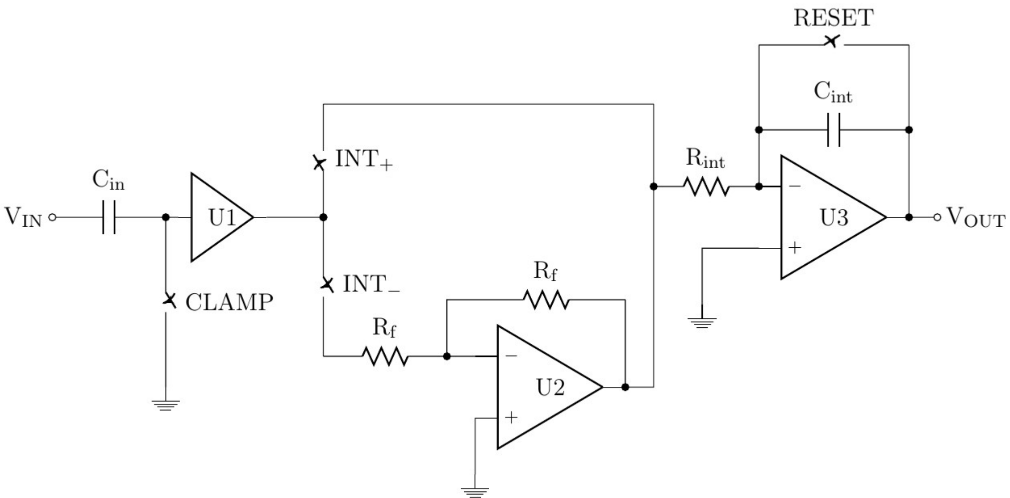
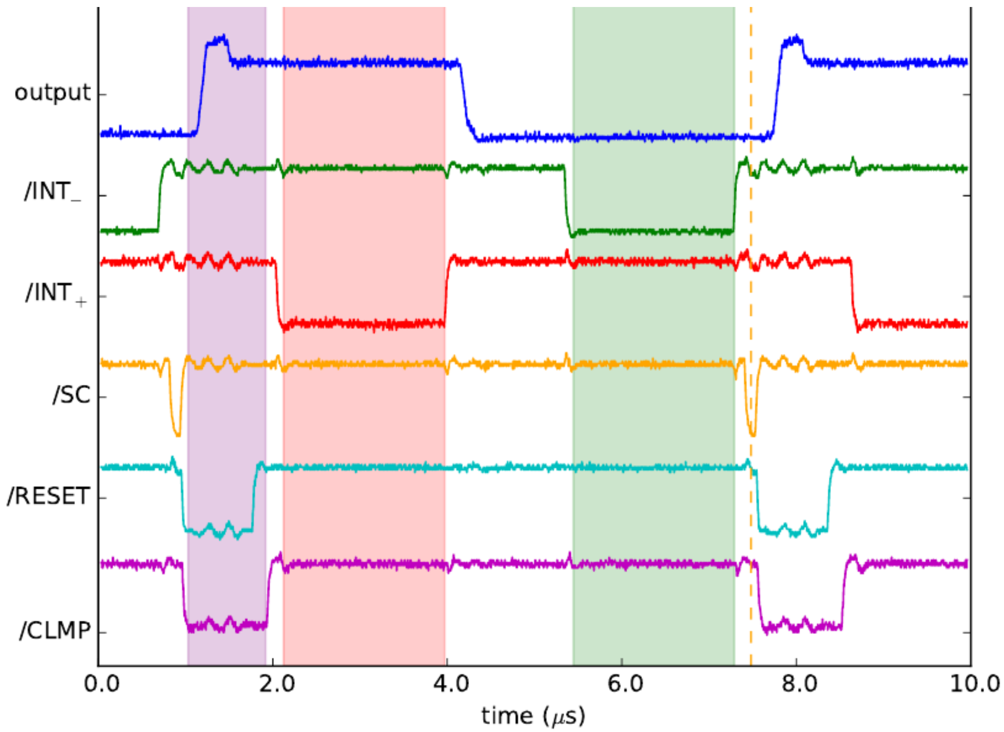
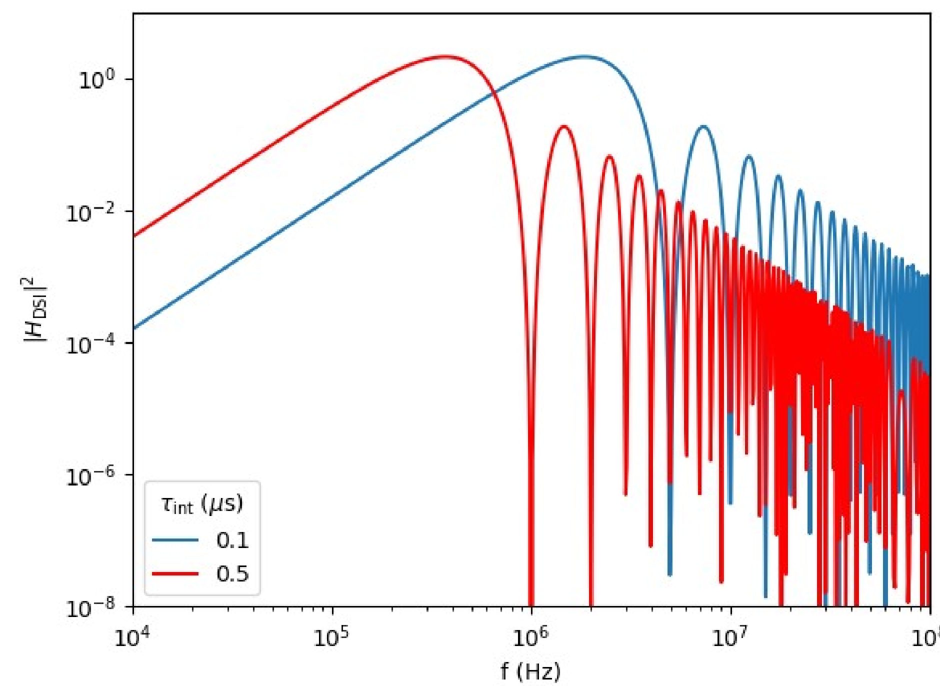


$$|H_{\mathrm{DSI}}(f)|^2 = \frac{4\sin^4(\pi f \tau_{\mathrm{int}})}{(\pi f \tau_{\mathrm{int}})^2}$$

- Integrate down for the reset, then up for the signal. The resultant is the pixel value.
- It turns out, this is a **matched filter** when only **white noise** is present. See proof in e.g. Stefanov (2015)





Analog CDS in reality...

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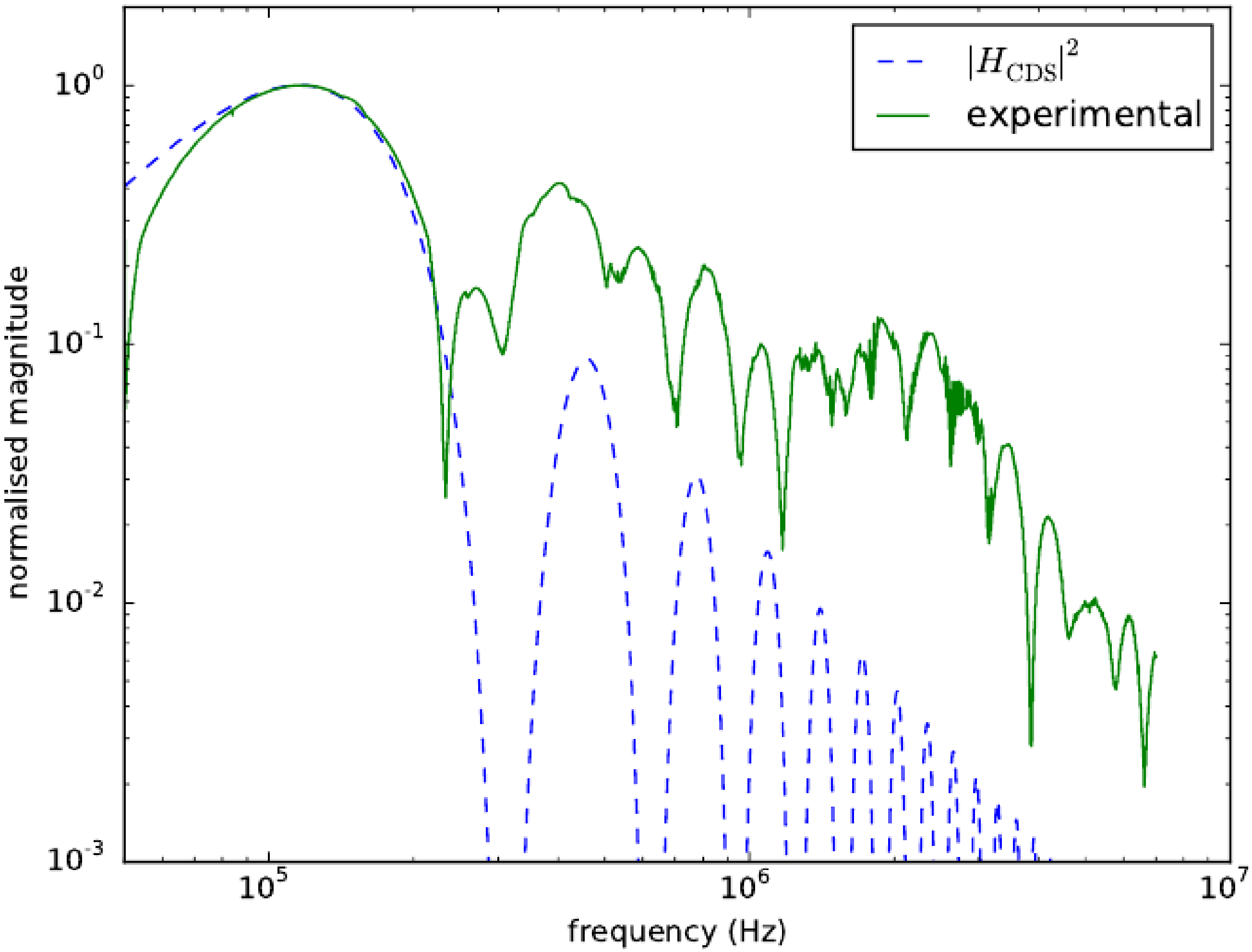
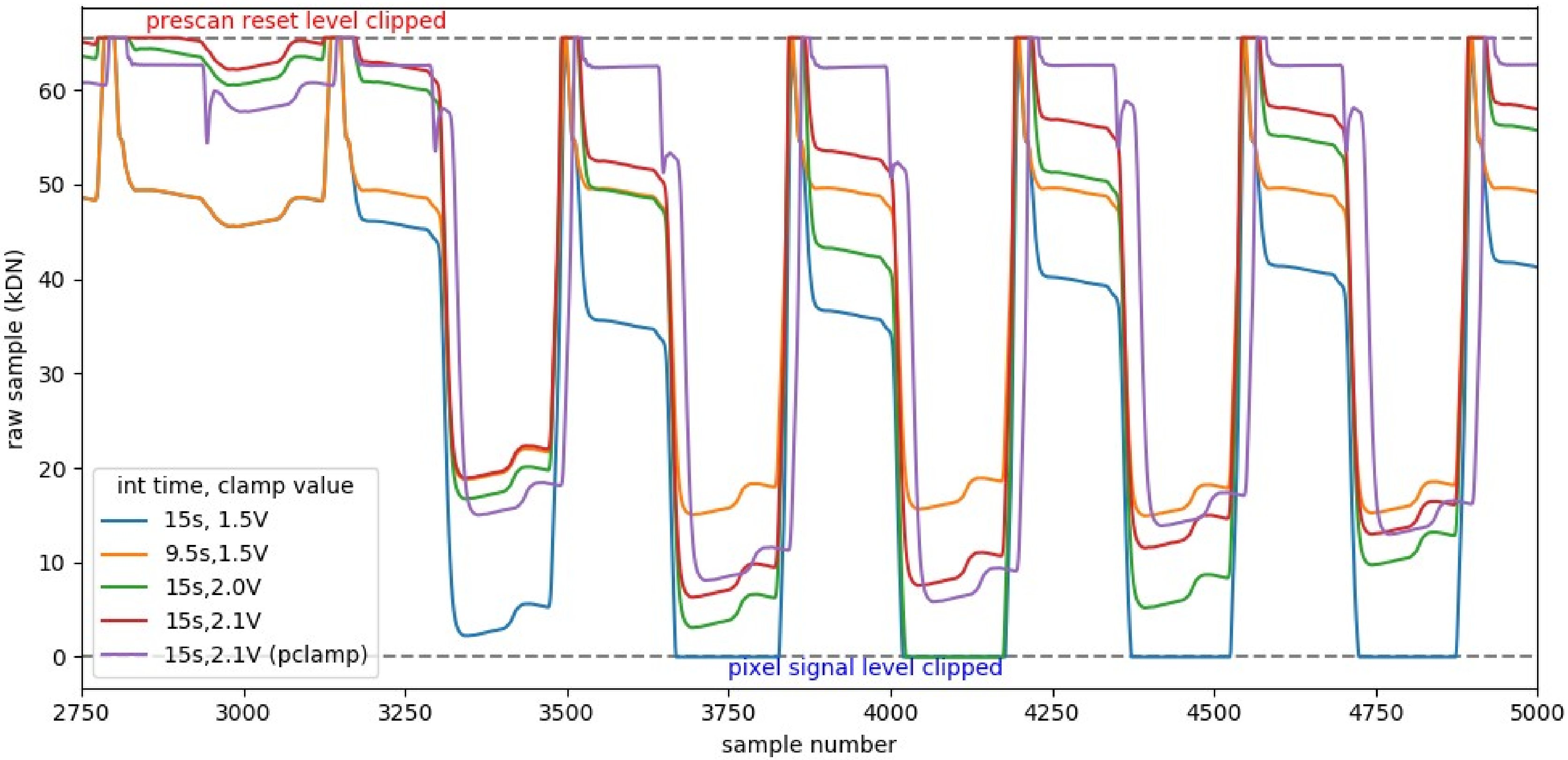


Measured on an e2v CCD261 during my phD thesis days using a new technique I first developed (though it is pretty obvious how to do it)

Digital CDS



$$X = \frac{1}{L_a}\sum_{i=a}^{a+L_a} \hat{x}_i - \frac{1}{L_b}\sum_{i=b}^{b+L_b} \hat{x}_i$$

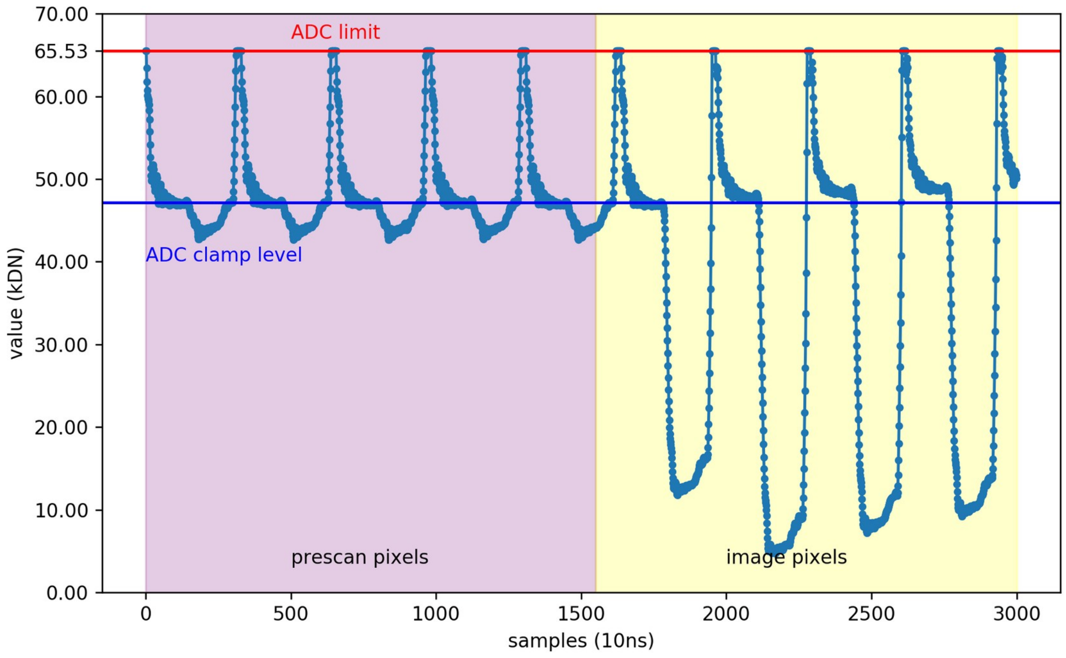
Digital CDS approximates the analog CDS by oversampling. It has its own problems (in particular ADC clipping!), but is (surprisingly) generally less temperamental than analog CDS.

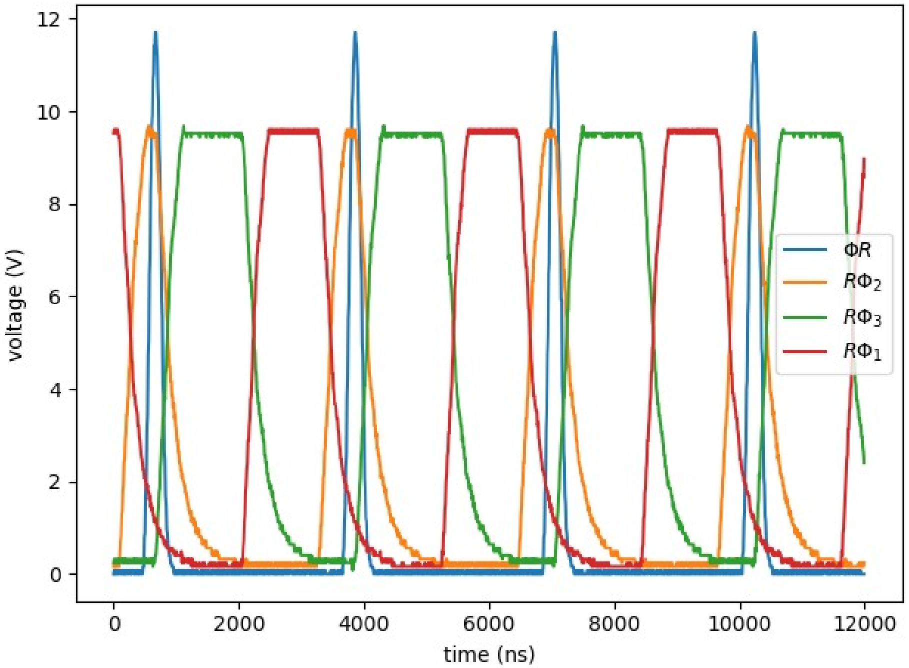
It can be used to **also** optimally remove 1/f (using a non-causal filter).

Readout Optimisation

Serial and reset clocks have much less interesting behaviour (right)

The trick here is to try and squeeze as much speed out of the sequence as possible, without impacting CTI or noise.





In OPMD we have a very high speed state of the art digital readout which oversamples the CCD clocks hugely (each channel runs at **100MHZ!!!**). This is fine for 16 channels of one sensor, but for ~3000 video channels in LSST camera would be impractical due to power & cooling requirements.

Radiation Hardness

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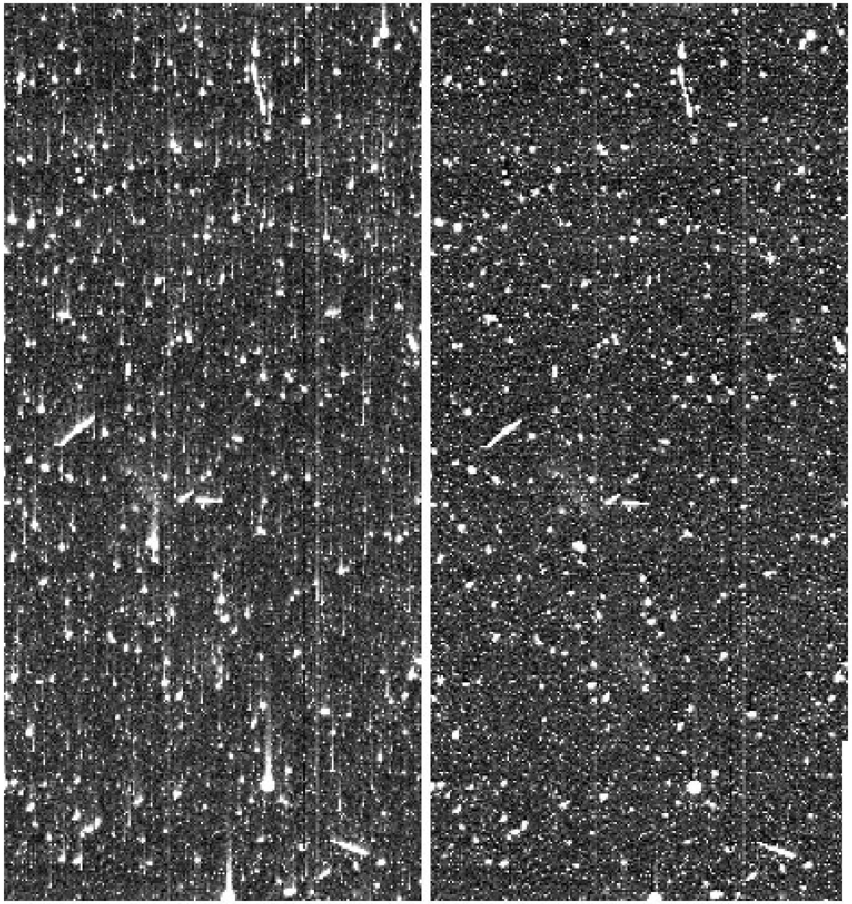
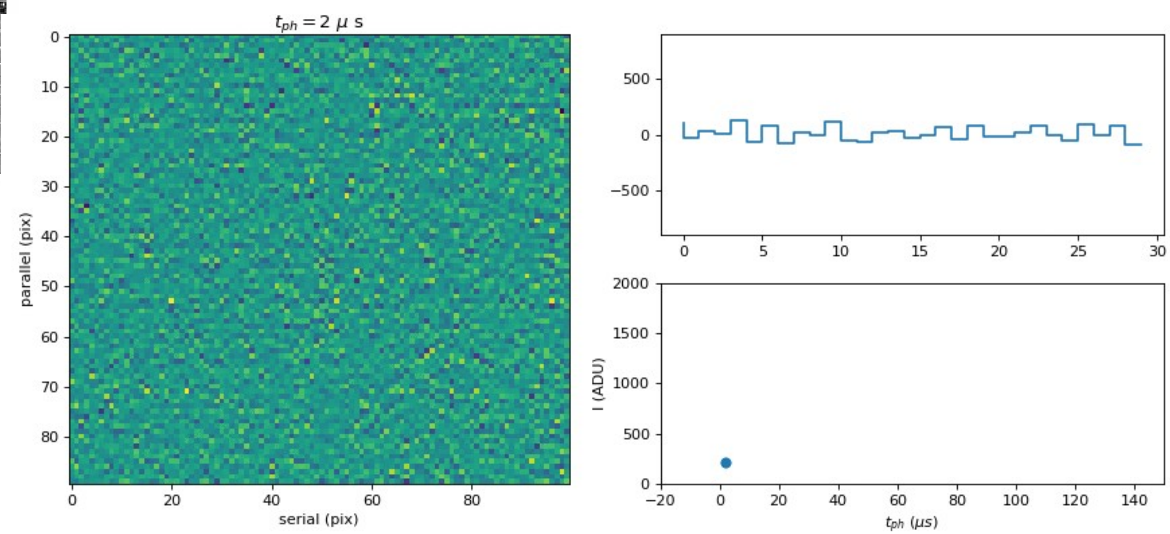


In brief – they aren’t. Particularly susceptible to displacement damage which causes increased CTI(**left)** after a tiny (in particle physics terms) amount of radiation (mission lifetime dose of Euclid is something like ~10^10 protons cm^-2.

Large amount of work goes into characterising (and correcting) the CTI effects on space based instruments.

NB image below is animated, won’t show up in PDF version!



This has led to techniques such as **trap pumping** (right), a whole other talk to explain but allows characterisation of **individual l**attice defects to an unprecidented level of accuracy

CCDs in particle physics - SLD

A VERTEX DETECTOR FOR SLD **1989**

C.J.S. DAMERELL, R.L. ENGLISH, A.R. GILLMAN, A.L. LINTERN, D. PHILLIPS, RONG G., C. SUTTON and F.J. WICKENS

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England

G. AGNEW, P. CLARKE, S. HEDGES and S.J. WATTS

Physics Department, Brunel University, Uxbridge, Middlesex, England

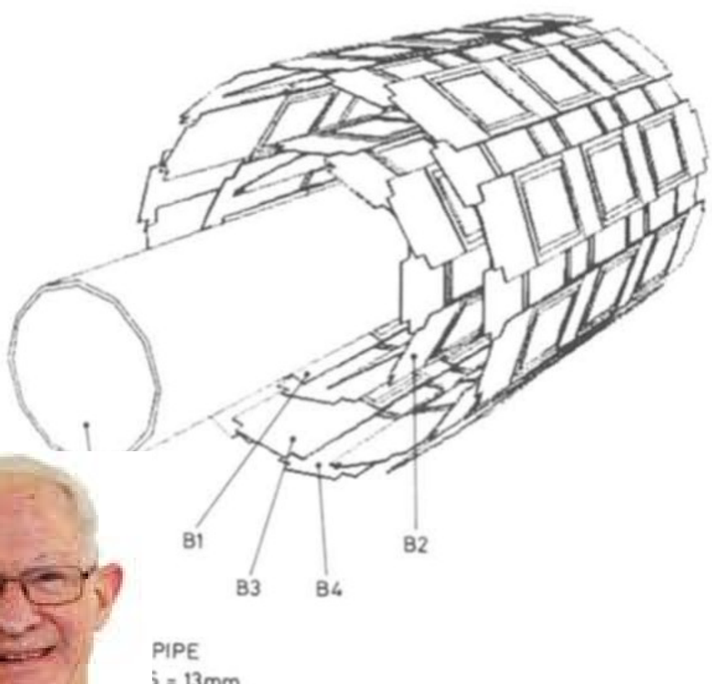


Fig. 3. The SLD vertex detector.

A major development by our group has been the implementation of low noise fast CCD readout. While we do not achieve the noise levels of astronomers (we have ~ 30 e noise where they can achieve ~ 10 e), we are able to read out about 100 times faster (50 ms instead of several seconds).

In view of this process, a min-I particle traversing a CCD produces a response (total charge in cluster) of about $80\ e/\mu m \times 20\ \mu m = 1600$ e. The precision for tracking is $\sigma_x \sim \sigma_y \sim 5\ \mu m$, and the 2-track resolution is around 40 μm. These results were established some years ago [4] in a CERN test beam.

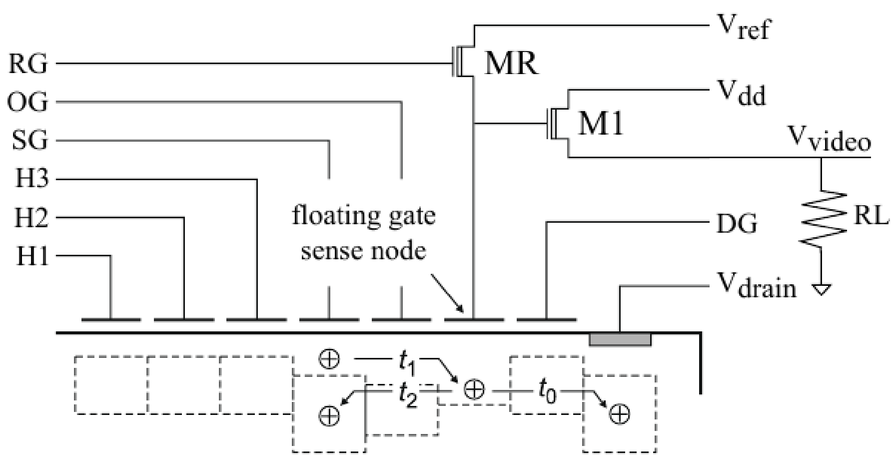
Indeed, CCDs are proving themselves much more resilient with respect to high rate operation than had been first thought. The areas where they are completely excluded for HEP use are those in which the high background necessarily persists during readout, i.e. *circular* colliding beam machines. In such cases, successors to the basic CCD will be needed, in which readout times of $\leq 1\ \mu s$ are achieved by some form of random access sensing of the pixel contents, as opposed to the

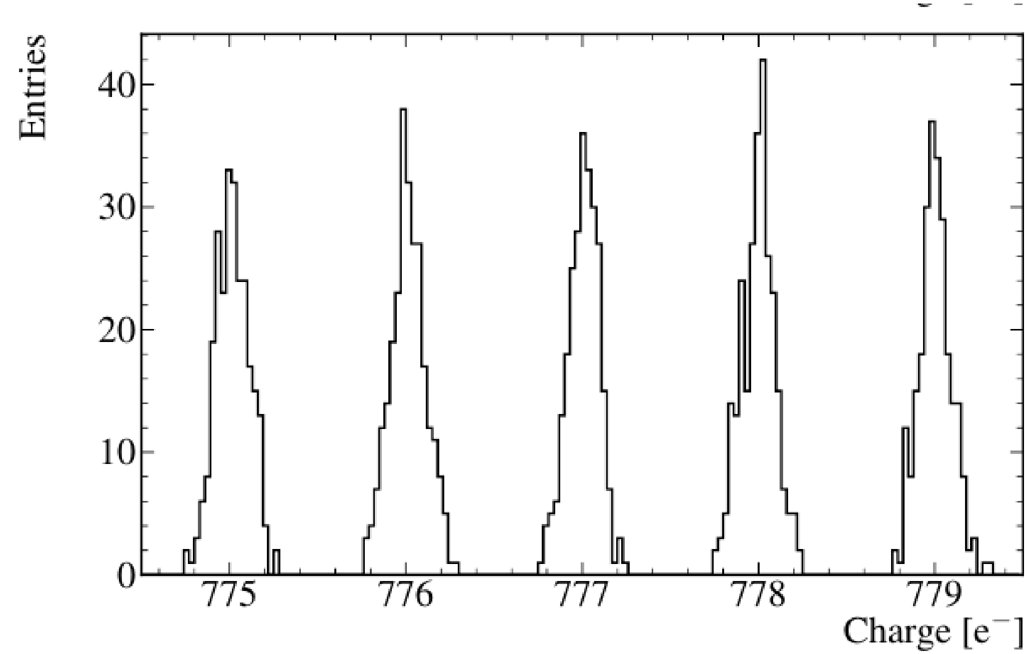
CCDs in particle physics - SENSEI

UNIVERSITY OF OXFORD

Single-electron and single-photon sensitivity with a silicon Skipper CCD

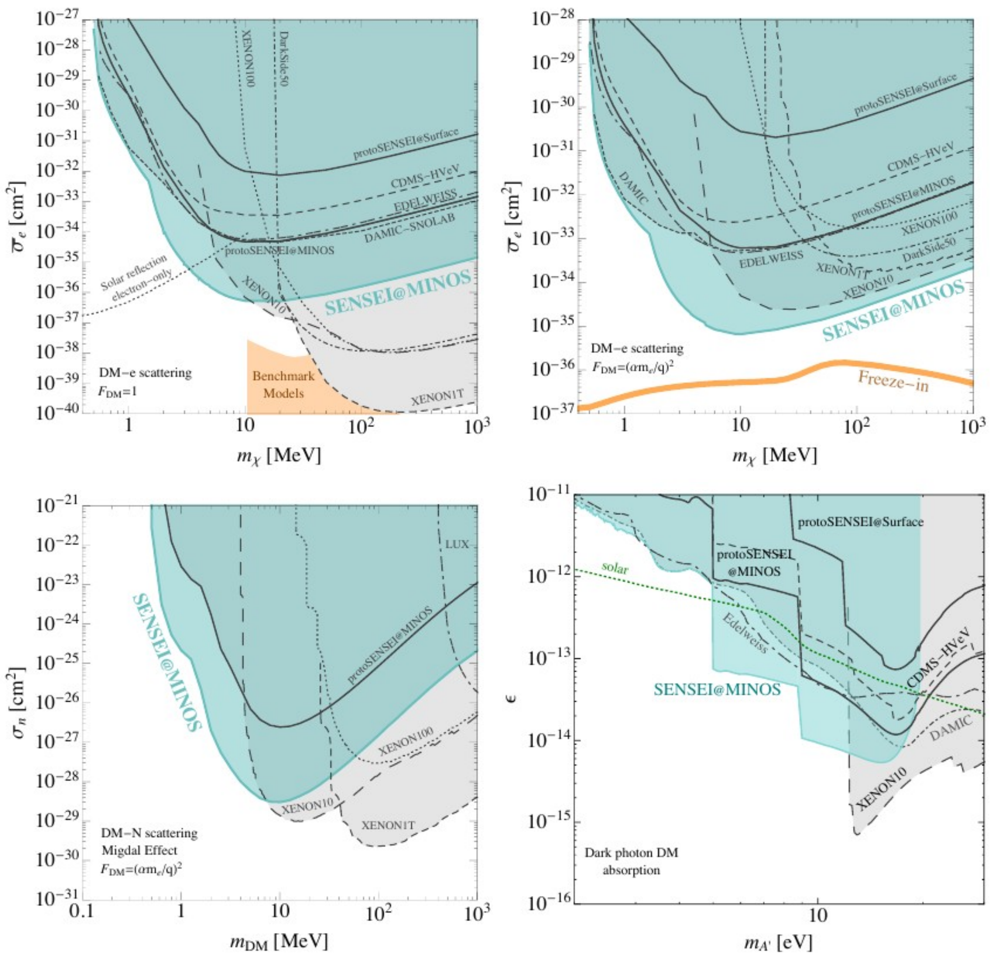
Javier Tiffenberg,[1,*] Miguel Sofo-Haro,[2,1] Alex Drlica-Wagner,[1] Rouven Essig,[3]
Yann Guardincerri,[1,†] Steve Holland,[4] Tomer Volansky,[5] and Tien-Tien Yu[6]





- If you slow down the readout of a CCD, noise goes down. Slow down enough, and the limit on readout noise is 1/f noise.
- “skipper” CCD with **non-destructive** readout. Sample the same pixel many times in the output amplifier, with a frequency designed to **eliminate 1/f noise**
- Can obtain (arbitrarily?) low readout noise by doing more and more samples. SENSEI instrument (above) has demonstrated 0.068e- (!!!!!!) noise per pixel
- **IMPORTANT DETAIL**: it takes 3 hours to read out an image from this CCD ;-)

SENSEI #2



SENSEI run in the MINOS shaft @ Fermilab, constraining light dark matter cross section (low enough noise to see recoils from **electrons** in the CCD, not just nuclei.

Over several months:

~758 1e- events
5 2e- events
0 3+e- events

SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD

The SENSEI Collaboration:

Thick, Full Depletion CCDs

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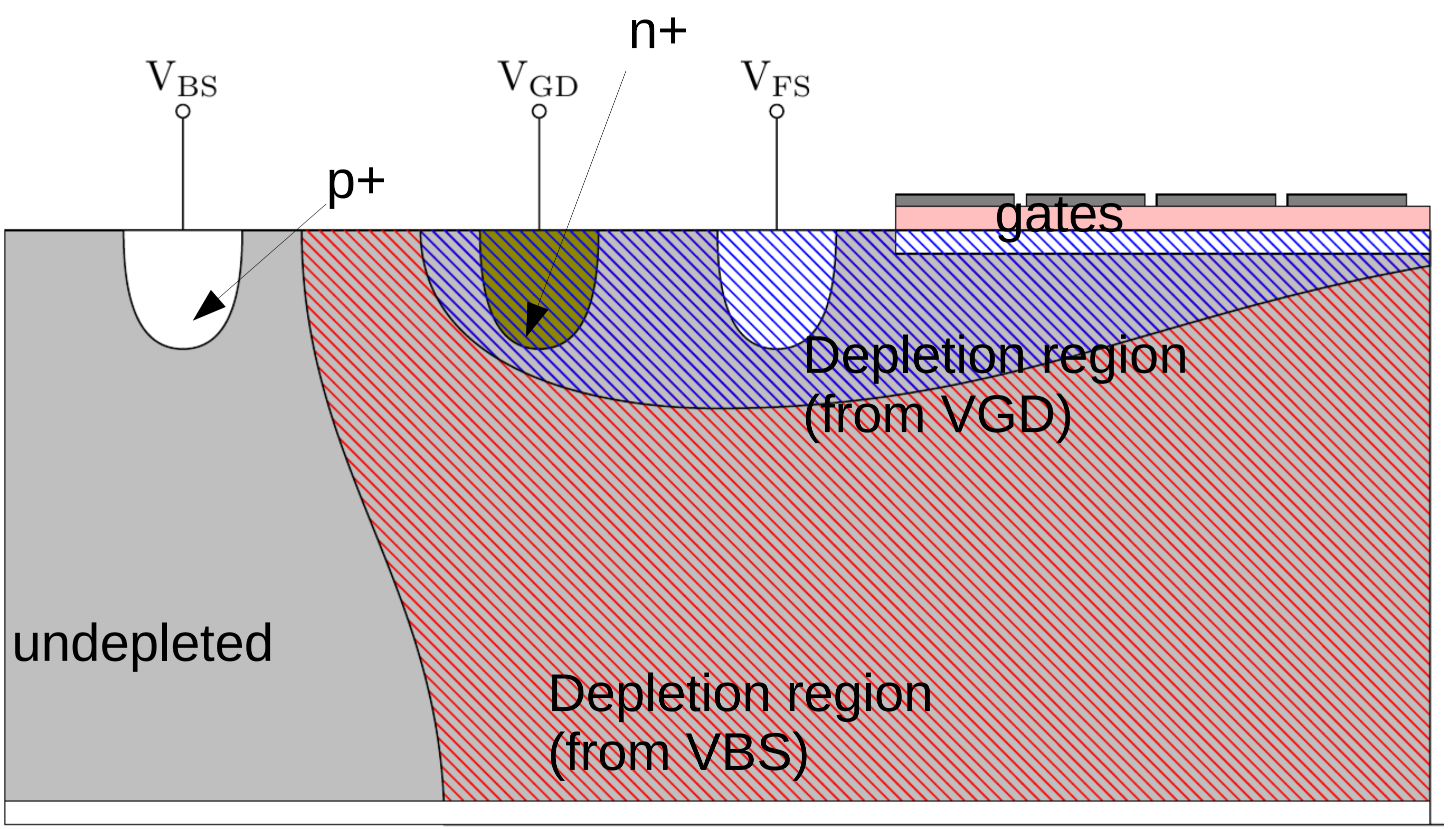


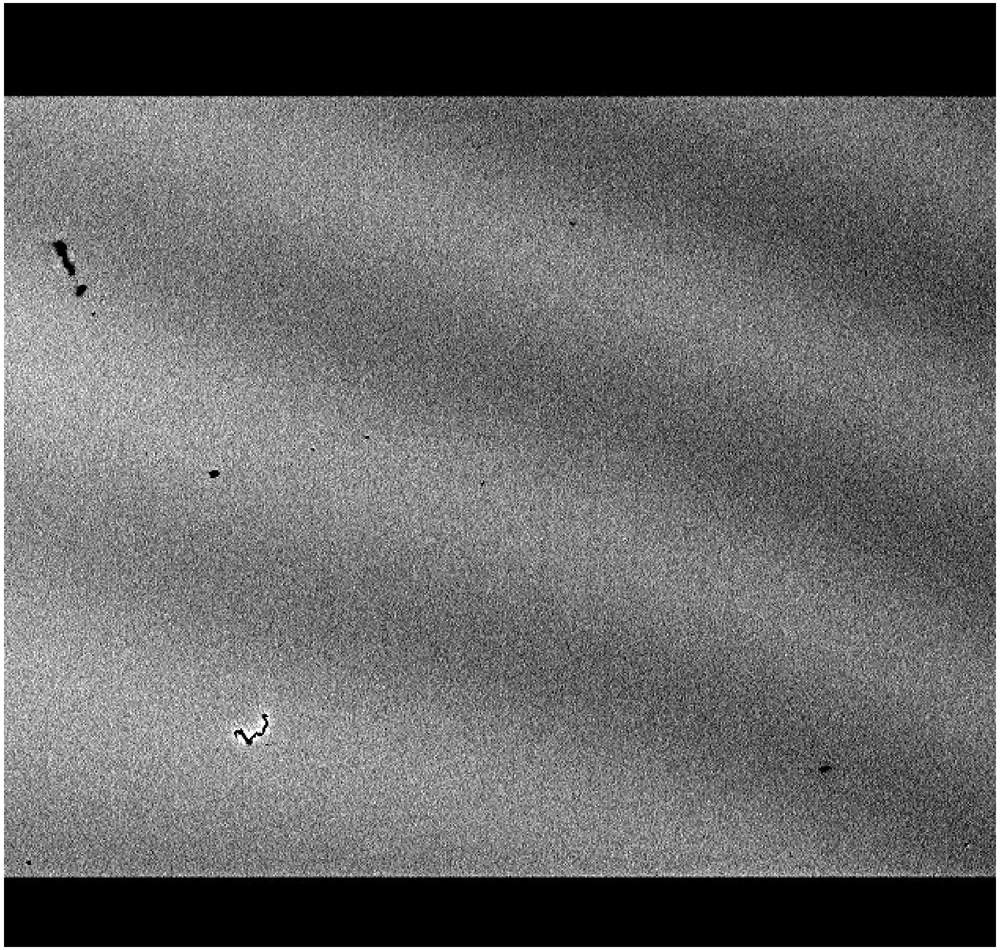
- **Problem: we want MAXIMUM QE (especially in IR).**
- **SOLUTION: make CCD thicker!**
- **NEW PROBLEM:**
- A thick detector implies a long drift time for electron collection. This, in turn, implies a large diffusion

$$r_{\mathrm{diff}} = z_T\sqrt{\frac{2k_BT}{q_eV_{\mathrm{coll}}}}$$

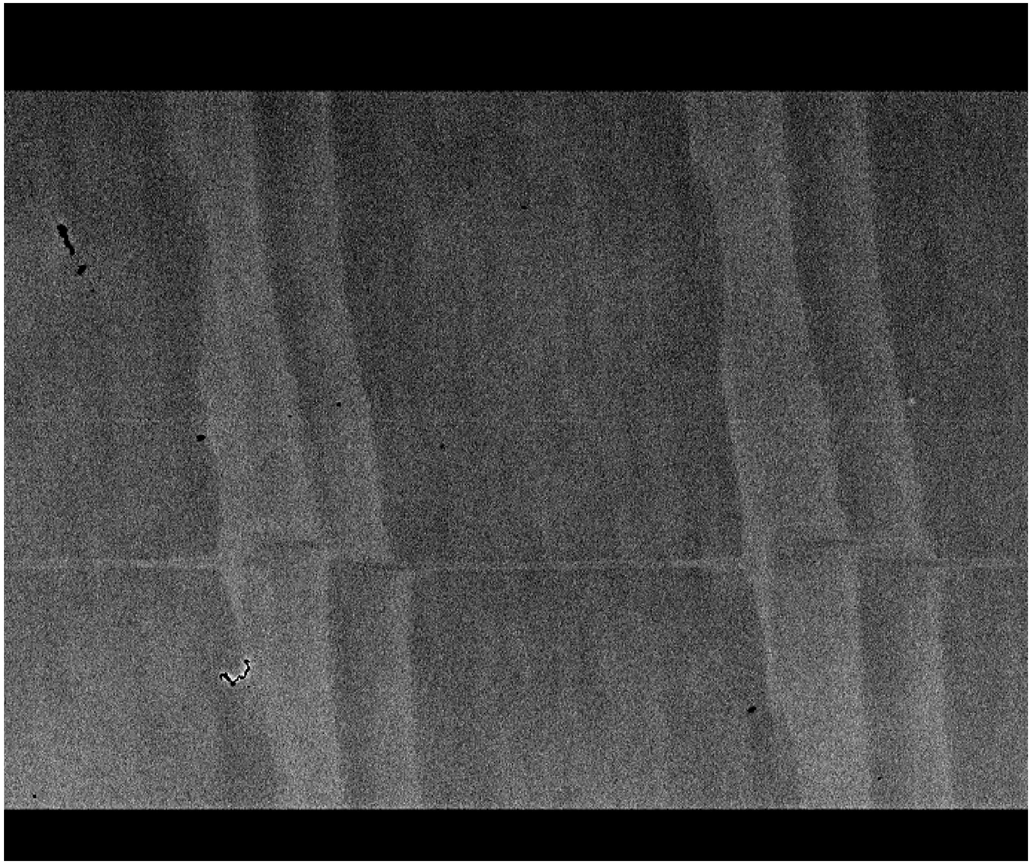
- **SOLUTION:** to reduce the collection time of charges (and thus the diffusi is applied to the back side of the chip
- **NEW PROBLEM:** this high field will cause leakage currents, at best increased dark current, at worst, heating and destruction of the chip
- **NEW SOLUTION**: (just like in particle physics!) guard ring around the edge of the chip, pinch off the front depletion region from the back side depletion region!
- **This is becoming common in modern CCDs for ground based astronomy, e.g. LSST camera, ZTF, DES etc**

Fringing

Detectors look different at different wavelengths! At short wavelengths, we see Various manufacturing pattens due to AR coating variations and resistivity variations.
At long wavelengths, we see fringing patterns due to Etalon-style interference within the detector volume



Fringing pattern @960nm



Stitching pattern @450nm

Tree Rings

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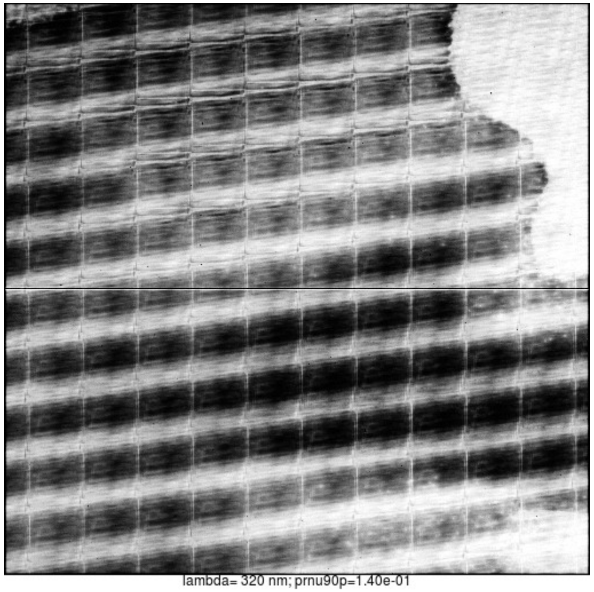
These circular patterns are perhaps intersting from a fabrication perspective.

We believe these "tree rings" result from spatial variations in resistivity on the float-zone silicon waver.

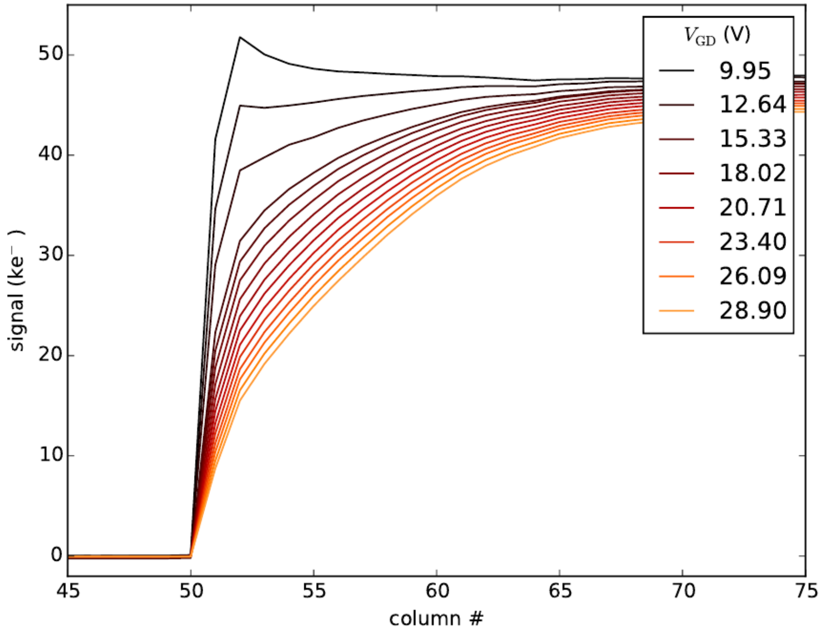
In fact, studies have been done by BNL on sensors which are known to come from the same wafer, you can even match the patterns up between different sensors.

Left: tree rings in an e2v CCD250 sensor

Right: animation of illuminating
An ITL sensor at different
Wavelengths.
(image courtesy of C. Lage)

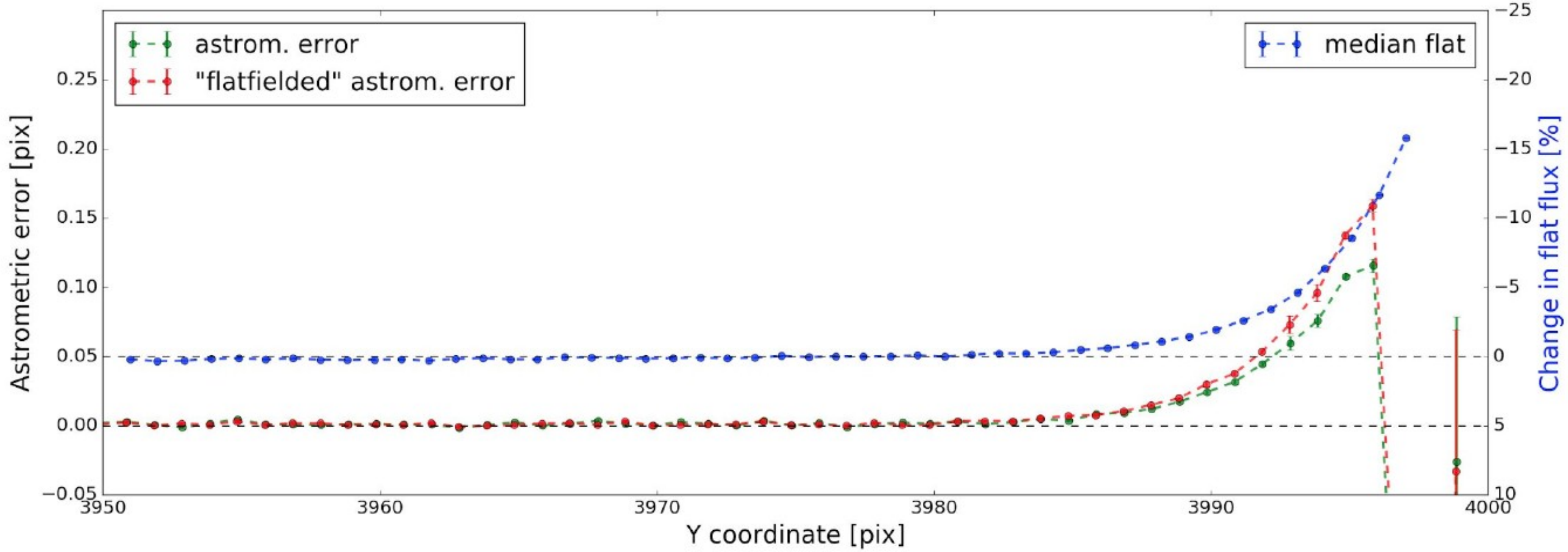


Astrometric Error



The guard drain / “scupper” field at the edge of the sensor “drags” incident charge around, which causes a shift in position of measured sources. This can be seen in both flat field measurements (left, Weatherill 2016) and in spot projection measurements (below, due to Bradshaw et al 2019).

Many voltage parameters affect the degree of astrometric shift, and for some parameters it can be eliminated entirely. Unfortunately those particular conditions aren’t ideal for many other reasons



Brighter – Fatter Effect

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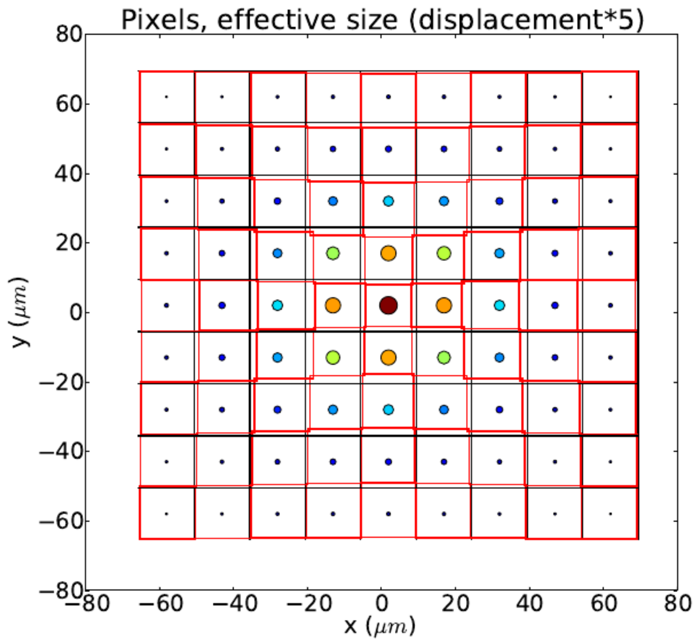
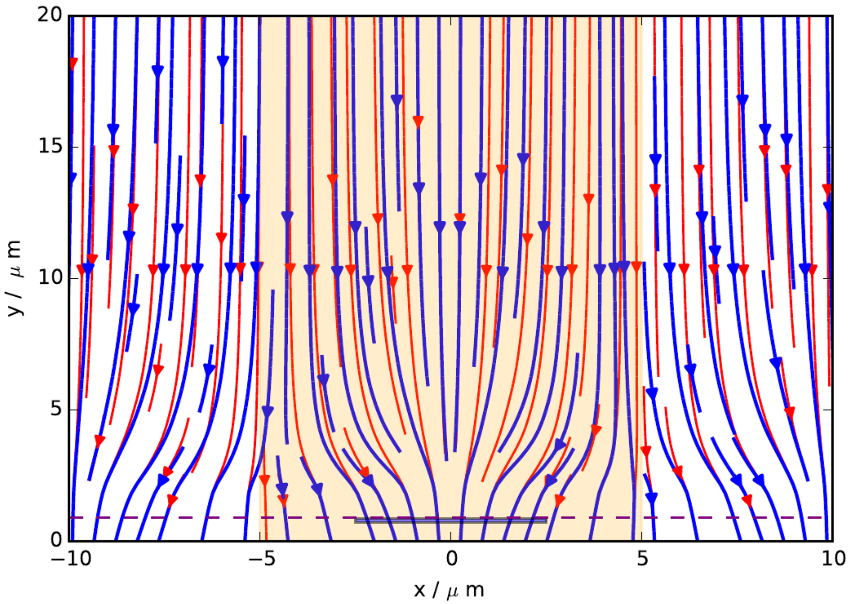
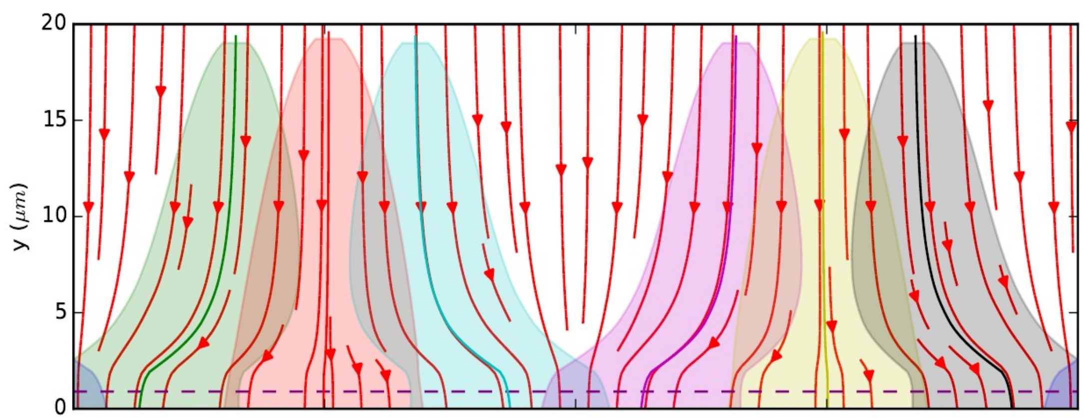


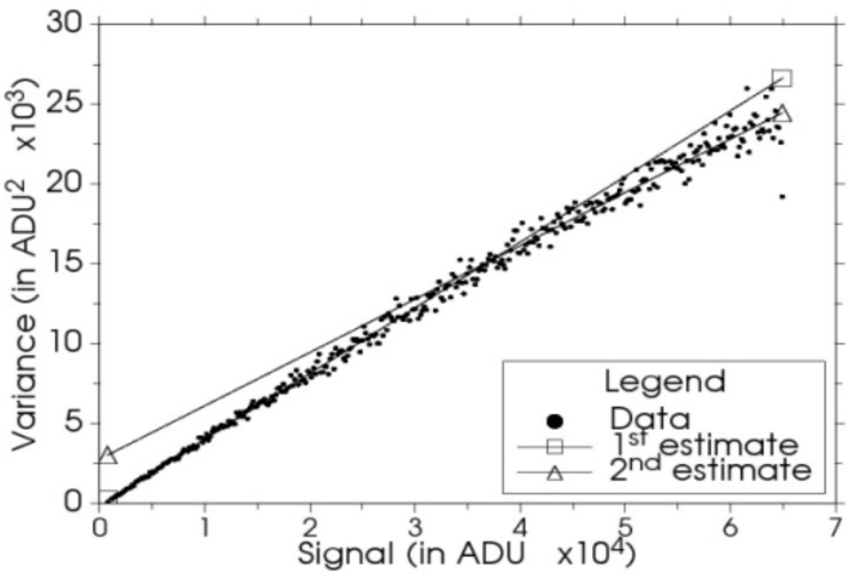
- As charge accumulates in potential wells during integration, it causes the electric field structure of the pixel to change slightly, influencing the collection of further charge.
- This introduces correlations between nearby values in a flat field, and an increase in ellipticity of point sources (possibly serious for weak lensing measurement)
- Analogous to space charge effects in other types of detectors
- There is a secondary (minor) brighter-fatter effect: electrons with **longer** trajectories, travel a further distance hence time to collection and experience a slight **excess diffusion**. This is around ~2% of the total BFE effect.



Upper left: nice visualisation of pixel boundaries from BFE simulation courtesy of Antilogus et al (2014)



Brighter – Fatter Effect



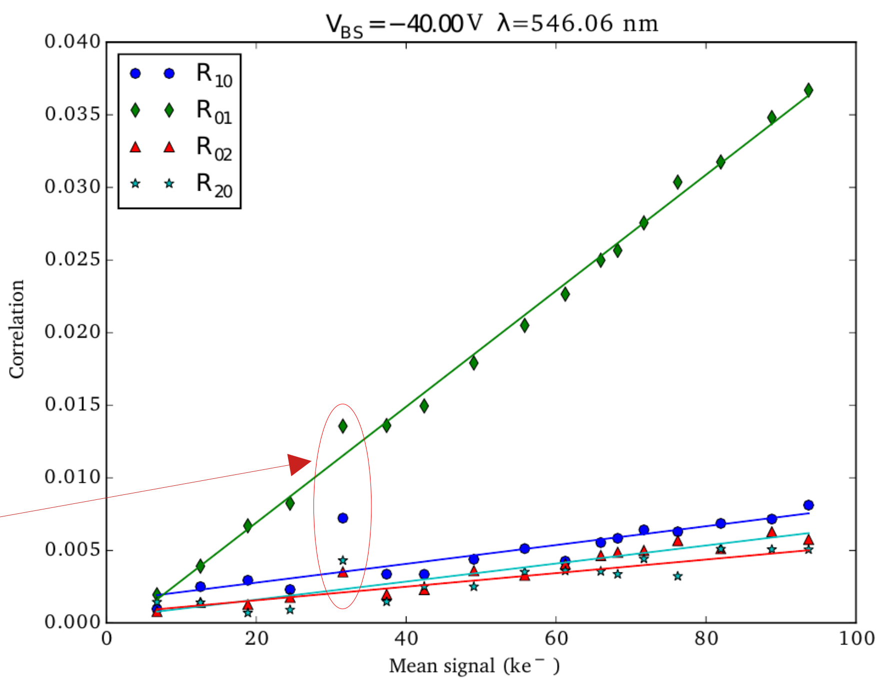
First observed (in 2006, left) by Mark Downing of ESO as an unexplained non-linearity in mean-variance data

- The process re-distributes charge, and hence reduces variance **below Poisson shot noise**
- Many models were thought of in the early years, some more sensible than others (e.g. Downing etc 2008, Allanwood etc 2011, Stefanov etc 2012, Weatherill etc 2014)

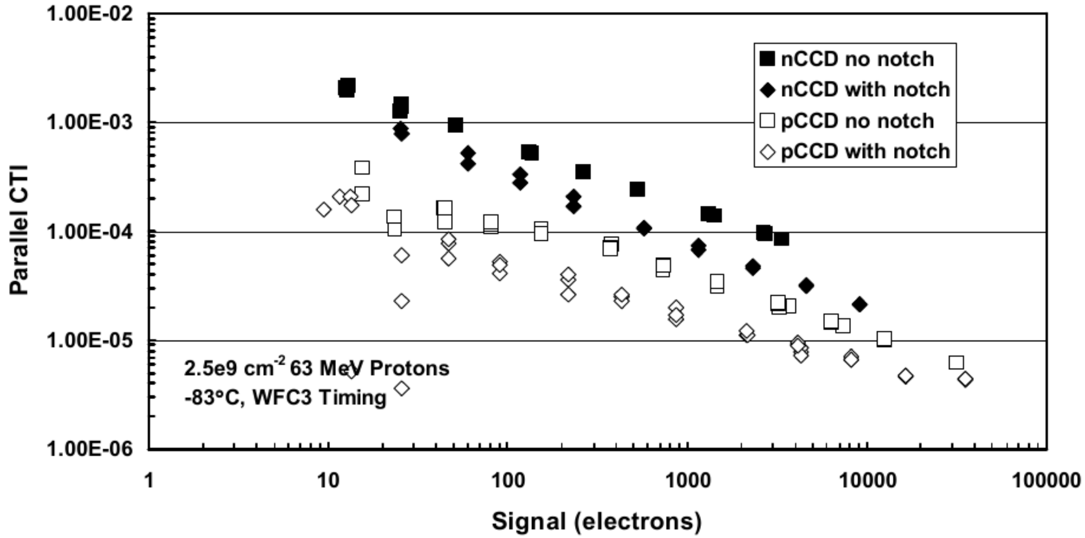
The current explanation (due to Astier, Antilogous, Lage, Rasmussen, especially Guyonnet 2015, and many others) has a lot of evidence and simulations behind it at this point!

Should mention: The plot on the right is from my thesis. It is interesting for 2 reasons:

- My phd external examiner (Craig Mackay, inventor of “lucky imaging”) claimed he’d probably seen this effect in the 80s and ignored it
- that anomalous data point is a hint towards an even more esoteric effect called the “Downing Dip” that was only properly noticed ~5 years later



P-channel CCDs



Build CCD on p-type substrate (n-type buried channel), it now collects holes rather than electrons.

Some disadvantages (because hole mobility is lower)

Aside: A “notch” / SBC is a confinement structure designed to reduce charge cloud volume and increase radiation hardness

BUT: trap species in p-doped silicon different than n-doped.

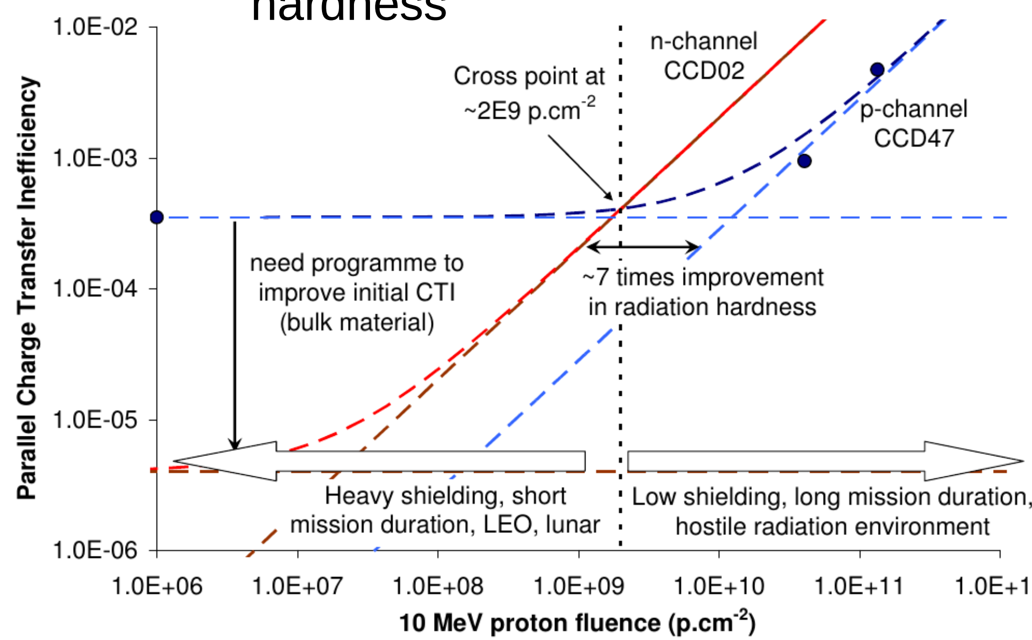
Turns out the p-channel version is quite a lot more radiation hard! Could extend the life of space missions.

ESA is quite interested in this at the moment!

Figures from:

(Gow, Murray et al 2009)

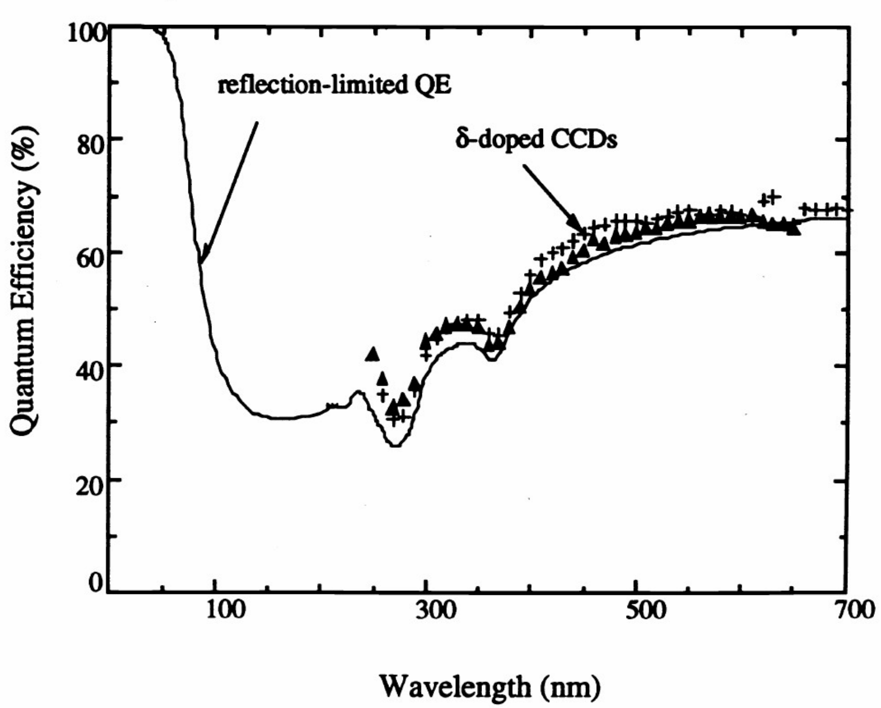
(Marshall et al, NASA Goddard)



“Delta-doped” CCDs / Ge CCDs

Delta Doping:

Grow a very thin, extra epitaxial layer on the back of the CCD with very high doping. Passivates the surface and increases UV responsivity and QE stability. Developed @ JPL
(below: Nikzad et al, SPIE 1994)



CCDs on Germanium:

Germanium has a band gap of ~0.7 eV (compared so Silicon’s ~1.1 eV). So a CCD build on Germanium can see much further into the infra-red

A native oxide of germanium exists, though it’s chemically quite difficult to use.

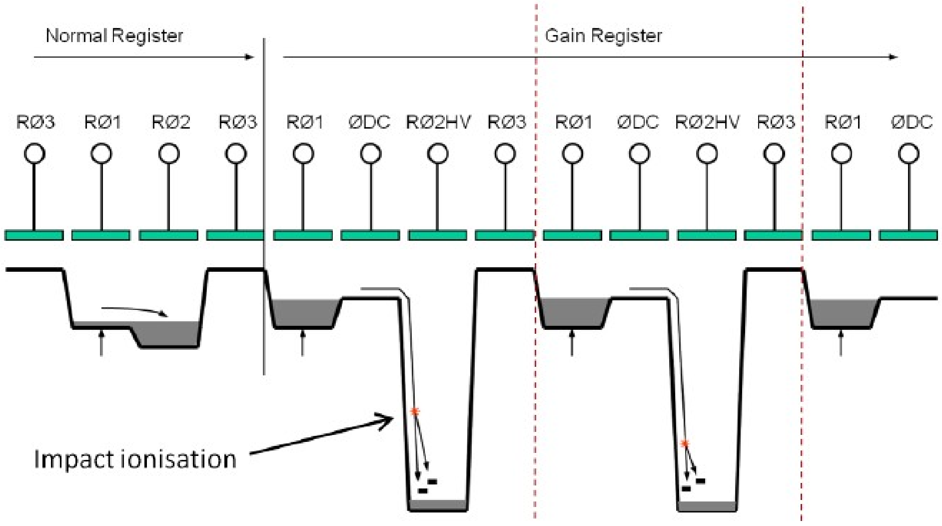
Lots of development work out of MIT Lincoln Labs has fairly recently produced reliable Ge-CCDs

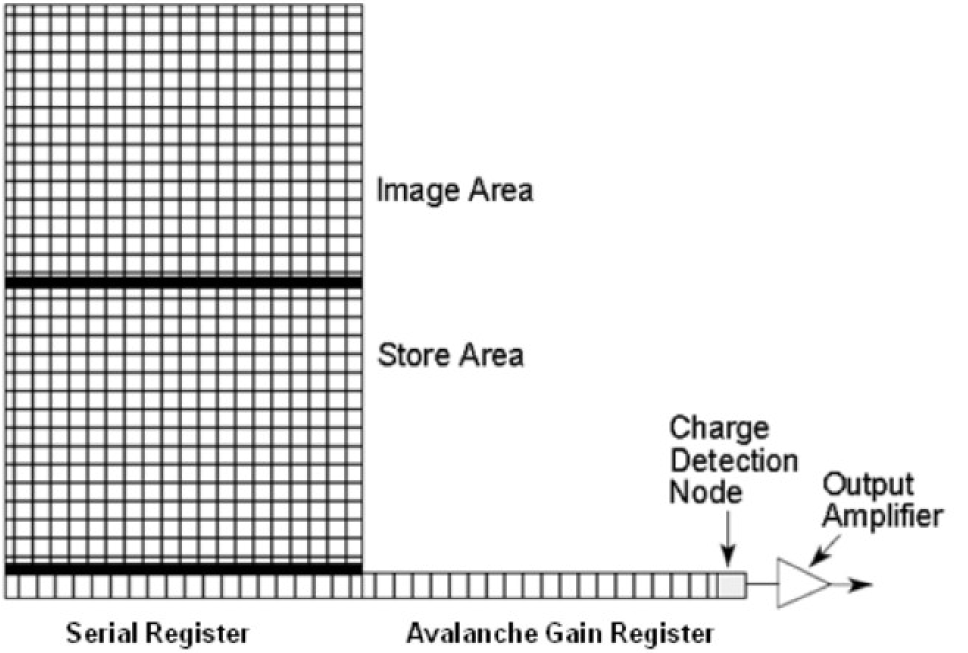
EM-CCDs

Similar concept to **LGAD**s - add a high voltage extra register on the end of the CCD readout, high enough field to produce **impact ionization** and multiply the signal charge before readout.

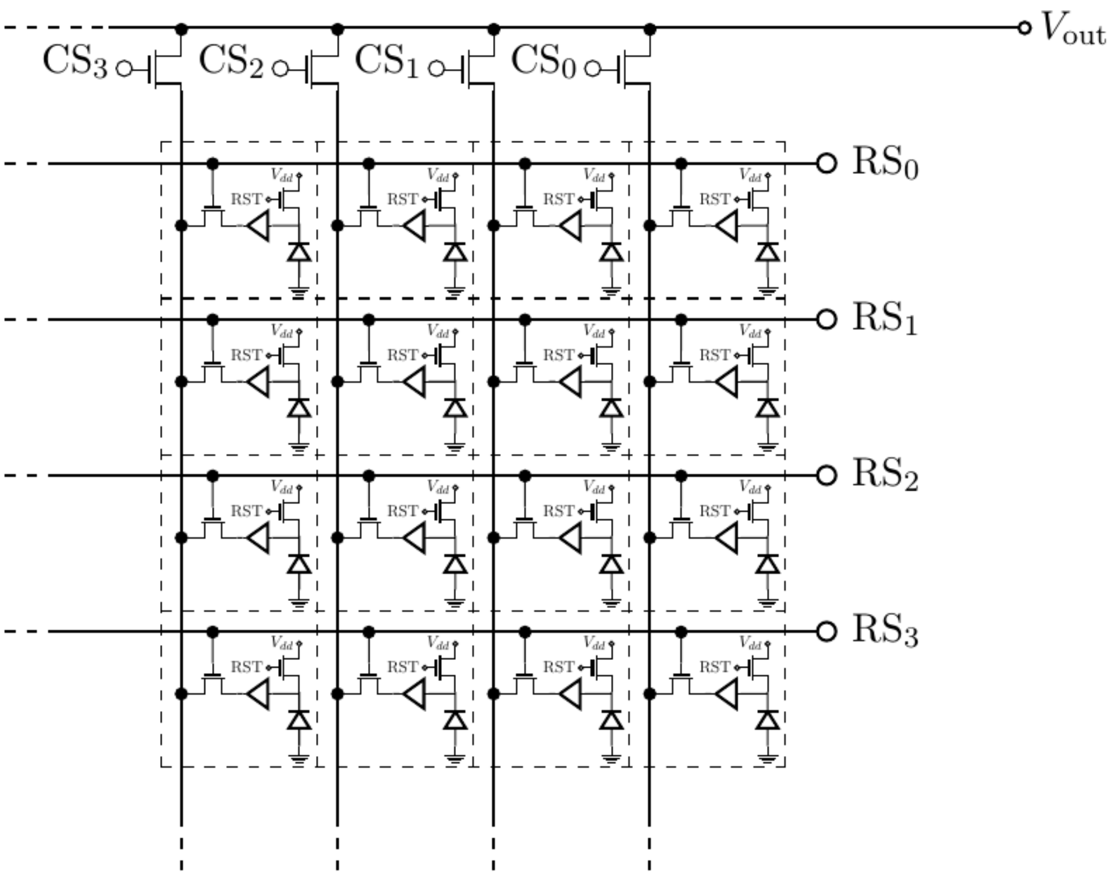
Allows for either: faster readout speed for same noise, or lower effective readout noise for same readout speed. NB unlike LGADs we're not doing this for extra timing information.

Now a fairly mature technology, TRL raising to fly them in space by NASA is ongoing. Images below from (Evagora et al, 2012)





CMOS-APS - concept



One of the key limitations of CCDs (as mentioned by Chris Damerell earlier!) is the lack of ability to do random access readout of any kind, and the inflexibility in readout in general (other than noiseless binning)

One solution is to have a switched matrix of pixels, with an amplifier transistor in each pixel, and not bother doing the charge transfer thing (CMOS Active Pixel Sensor "APS").

Advantages are many, so are the disadvantages – **pixels now are not 100% fill factor (astronomers care about this)!**

Calibration much harder – 1 pixel per amplifier, rather than 1 per ~millions of pixels)

Classic 3T pixel

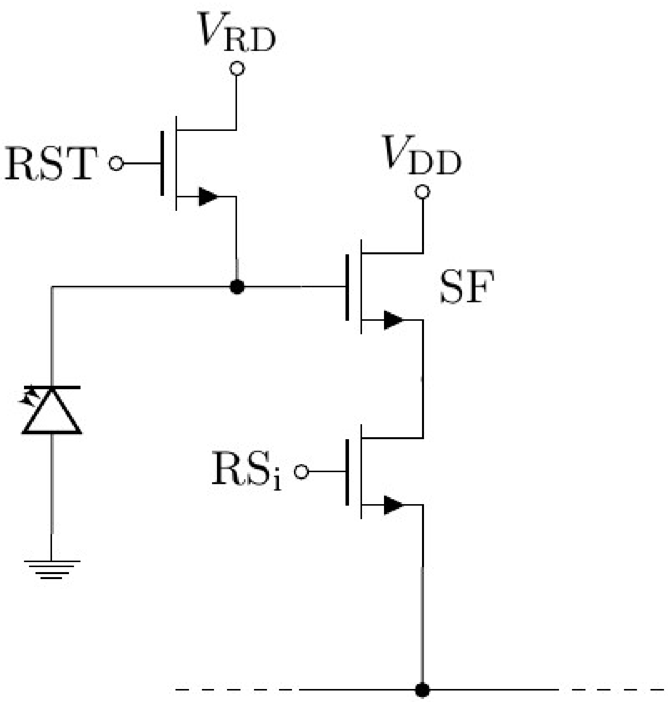
Minimum viable design – **3 transistors per pixel "3T" design.**

A reverse biased photodiode structure is connected to a reset transistor, a source follower amplifier, and a switch to address the pixel.

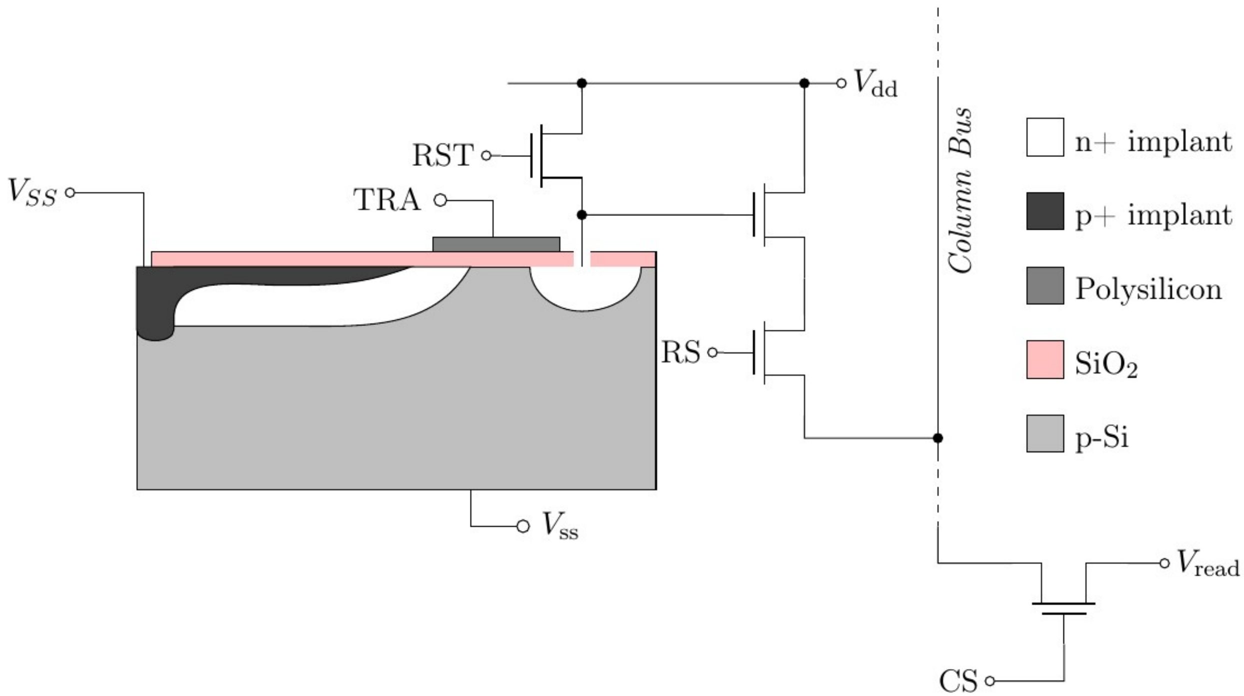
Column amplifiers and ADCs are either per array or per column, resulting in massively increased readout speed over CCDs of equivalent size.

Disadvantage: if you want to do CDS, you have to readout the entire array twice

Also, prone to notorious "rolling shutter" effect, since still have to read out detector line by line



Pinned Photodiode & 4T readout



"Pinned" photodiode structure mimics buried channel construction of CCD (invented by E. Fossum in early 90s).
Also allows a single charge transfer from the large photodiode area to a smaller sense node, which can have lower capacitance – hence **lower noise, higher gain, no rolling shutter** (well, not quite actually but the details are too much for today). Addition of a "transfer gate" / "4th transistor??" in each pixel.
Bit of a problem with **image lag / persistence** – some charge staying in the sense node after readout (which mainly happens by diffusion)
Much progress made on reducing this in recent years!

Beyond 4T

Comparison of Global Shutter Pixels for CMOS Image Sensors

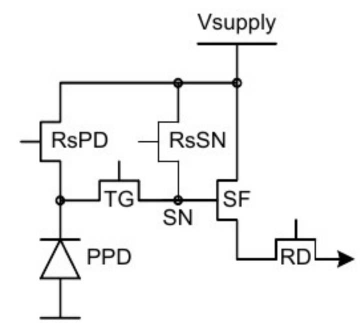
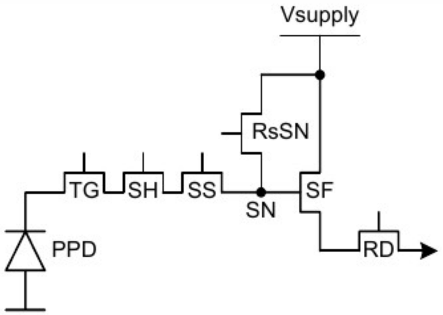
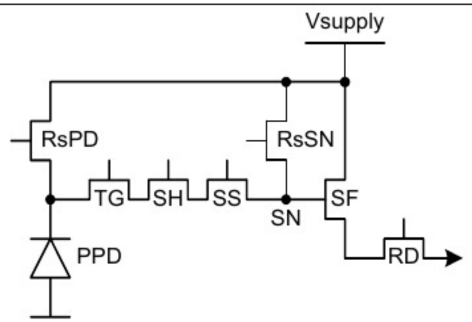
Stefan Lauxtermann, Adam Lee, John Stevens, Atul Joshi

Once you have smaller and smaller CMOS process nodes, more and more transistors can be put in each pixel without affecting fill factor too much (and microlenses on each pixel help boost QE back up as well, where appropriate).

(right) – some common "high-T" pixel designs

More pixels allows many possibilities – true global reset, integrate while read (IWR) readout for higher frame-rate

Etc etc. Even digital pixel sensors (DPS) with ADC in each pixel have been demonstrated (though at the moment **very niche** applications)

#3		5T	Integrate while read Double sampling readout Suited for high photon flux levels kTC noise limited FWC defined by PPD or SN capacity Charge transfer onto SN (based on PPD+TG technology) Estimated: ~30e- if SN has same dimensions as pixel #1
#4		6T	Integrate then read Correlated Double Sampling (CDS readout) Only suited for low photon flux levels kTC noise free FWC defined by PPD, SH or SN capacity Charge transfer onto SN Same performance as pixel #5 when RsPD kept at zero
#5		7T	Integrate While Read (IWR) Correlated Double sampling (CDS readout) Suited for high photon flux levels FWC defined by SH and SN capacity Charge transfer onto SN Measured: 10 e^-

n.5 T designs

Having multiple photodiodes per pixel can be advantagous – **e.g. for reduced image persistence, faster diffusive collection etc.**

These designs are usually termed e.g. “2.5T” designs, as on the **right** (J. Bogaerts et al, CMOSIS)

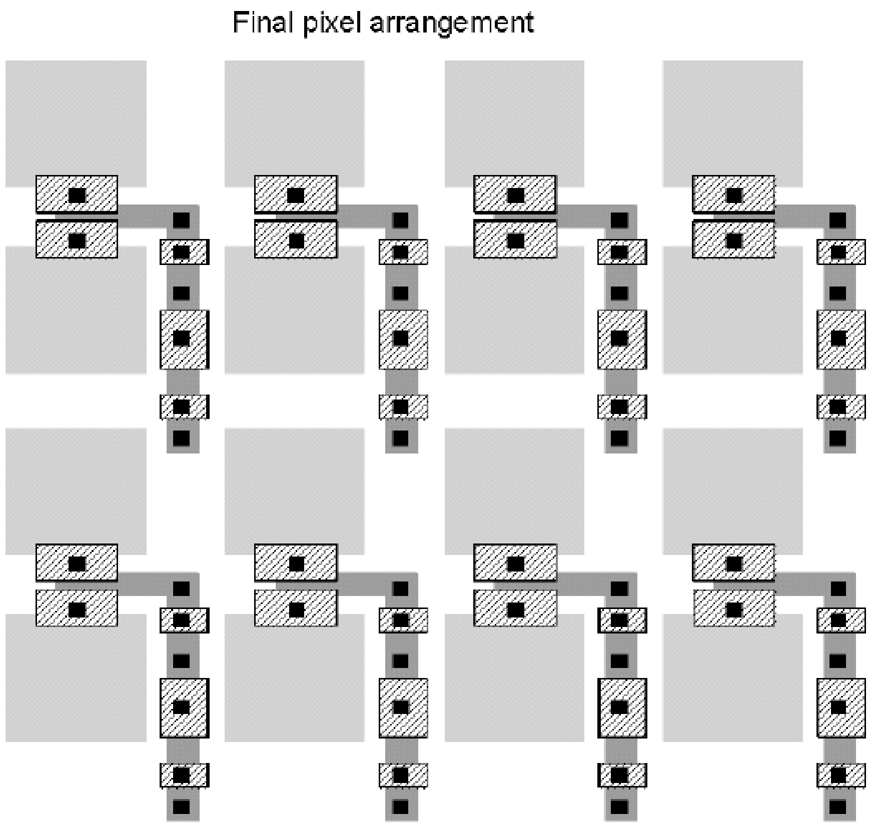
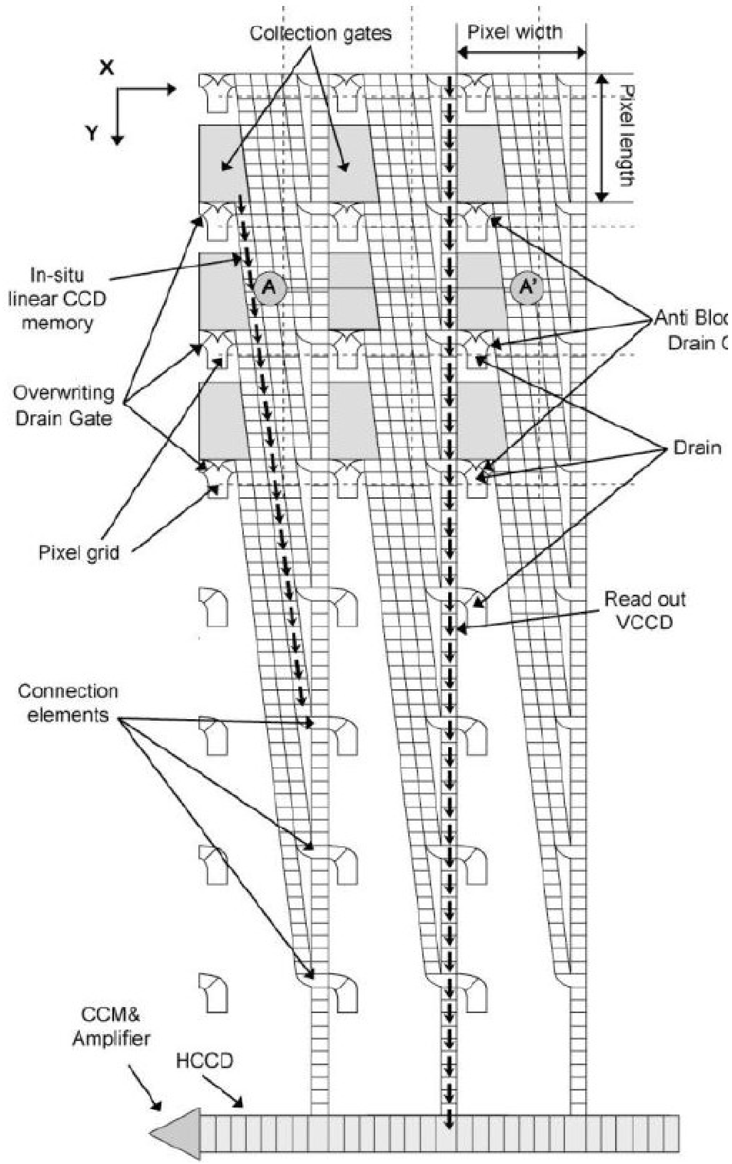


Figure 1. Conventional two-shared pixel architecture. Unit cell (top) and final pixel arrangement (bottom).

In-Situ Image Storage



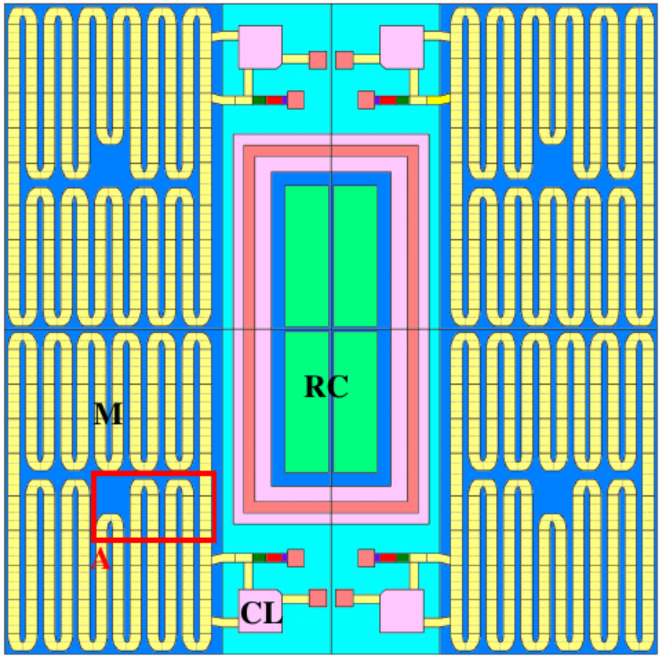


Fig. 4 Hybrid CMOS/CCD ISAS (2x2 pixels):
M: Memory CCD; CL: Collection gate;
RC: CMOS readout circuit

Can combine ideas from CCD & CMOS technologies to implement “storage” in a CMOS pixel (**above, Etoh et al).**

This allows for very high burst-mode imaging (the above sensor can hit 16 Mframes per second)

APS problems – lag & crosstalk

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Image Lag:

Already mentioned, anything with a PPD and transfer gates relies to some degree on diffusion for collection (lateral field pretty small!).

So, some charge left behind in the collection area. Which can appear in subsequent images (in designs without global reset).

Even in designs with global reset, you have still **lost that charge!**

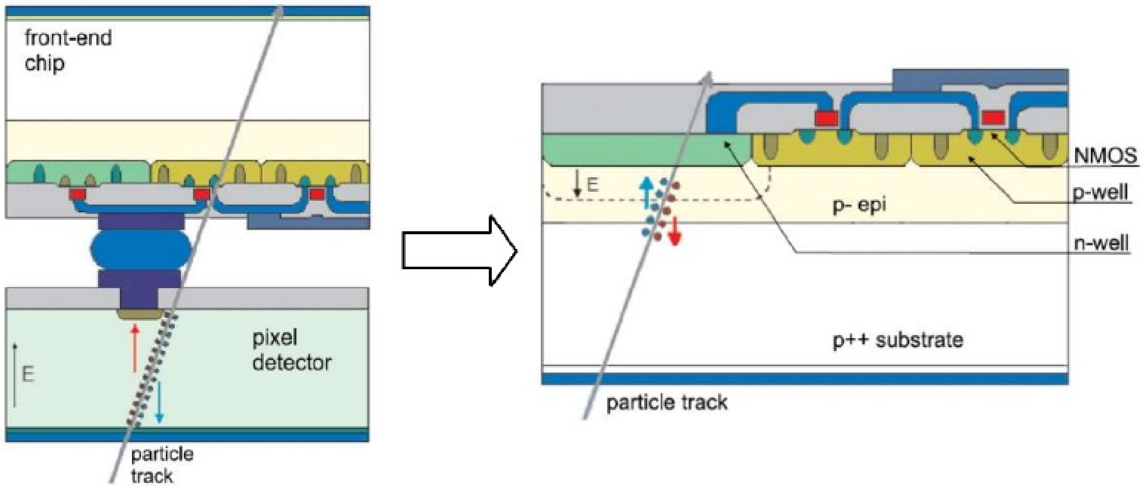
Crosstalk:

Capacitive coupling between neighbouring pixels can result in image correlations.

NB this is different to BFE in CCD sensors because it is at the readout electronics level, i.e. doesn't depend on pixel size or field distribution

It also isn't really simply a worseining of the PSF, because it's signal dependent (like BFE) and not shift invariant

“APS” in particle physics - MALTA

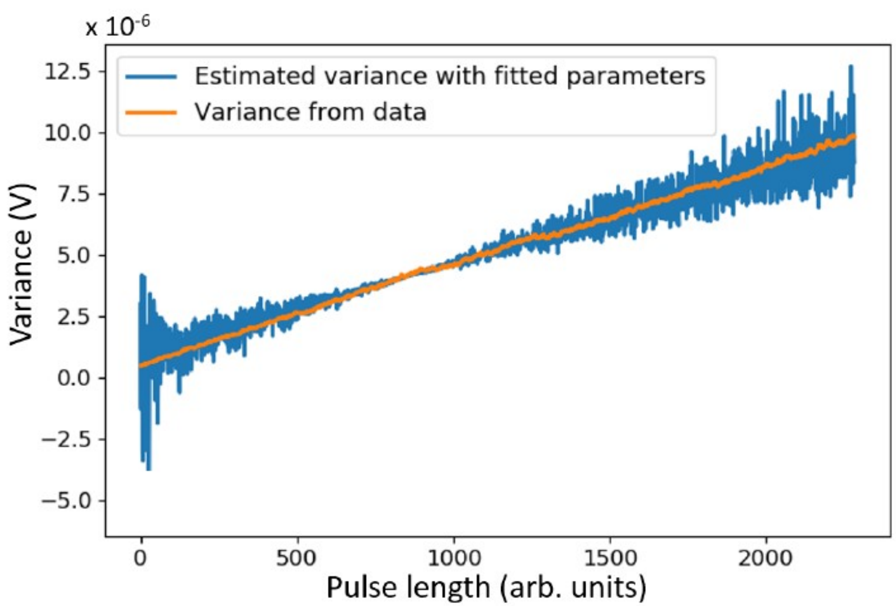


Monolithic pixels are all the rage in HEP nowadays! **(left- Riedler 2018)**
Of course, from the imaging detectors perspective, monolithic is “normal” and hybrid is the new, exciting thing (e.g. HgCdTe IR detectors are hybrids!)

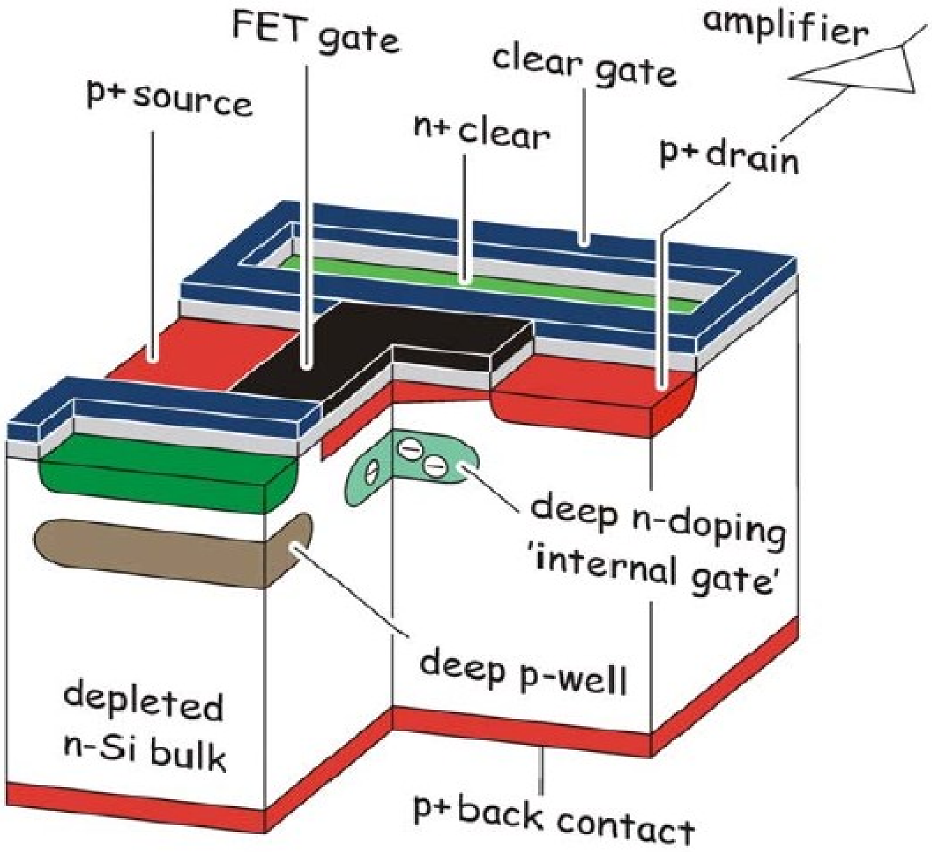
$$\sigma_V^2(P) = \sigma_{readout}^2 + P\left[\frac{\langle V(P)\rangle'}{\eta}\right]^2 + \sigma_{electrons}^2\left[\frac{\langle V(P)\rangle'}{\eta}\right]^2 \qquad (3.12)$$

For some of these chips (e.g. the MALTA demonstrators), you can use techniques derived from astro imaging (e.g. the “pain-hancock” advanced mean-variance method) to do calibrations, because it is (as a side effect of being monolithic!) actually an integrating detector!

(right – Metodiev, 2021)



DEPFETS - concept



Depleted P-channel FET

(left – Kemmer & Lutz, 1987)

A Depleted P-channel FET ("DEPFET"), works kind of like a modern back-biased CCD. Charge integrates under the gate of the FET.

Because it's p-channel, charge gets collected while the gate is in the "off" state. It's read out a bit like a 3T CMOS APS.

Huge depletion volumes are possible without the issues you have to deal with from modern thick CCDs with back biasing. Each FET effectiively has its own isolated well.

DEPFETS – astro & HEP

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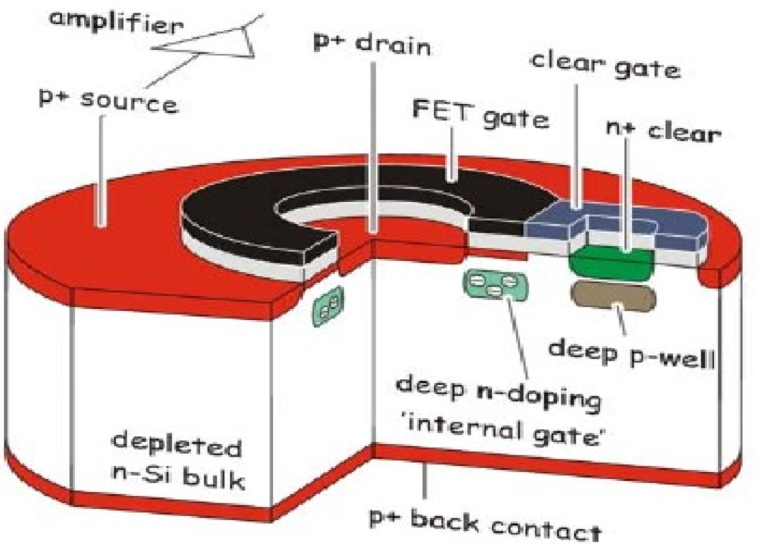
Images **right** from presentation by Andricek, SLAC 2006.

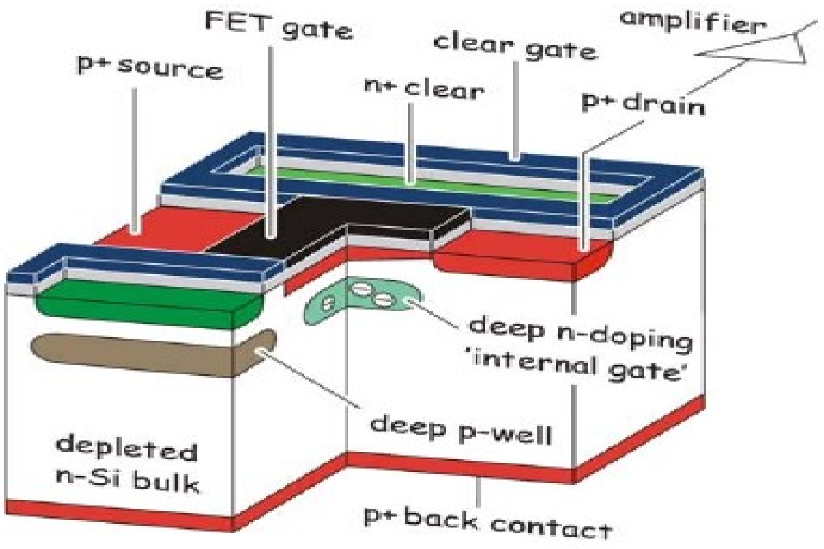
DEPFET "pixels" can be designed suitable for e.g. X-ray astronomy (large depletion volume & pixel area, slowish readout allowing low noise ~4e-

ESA's future ATHENA X-ray space observatory WFI instrument is baselined to use a DEPFET sensor.

Or

HEP tracking – proposal for ILC vertex detector, smaller pixels ~25um, with ~100e- noise and faster readout (~20ns).





Thanks!

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Questions, comments etc greatfully received:

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This lecture is brand new for the first AITL series, all feedback is VERY USEFUL!