Direct charge sensing for light dark matter detection

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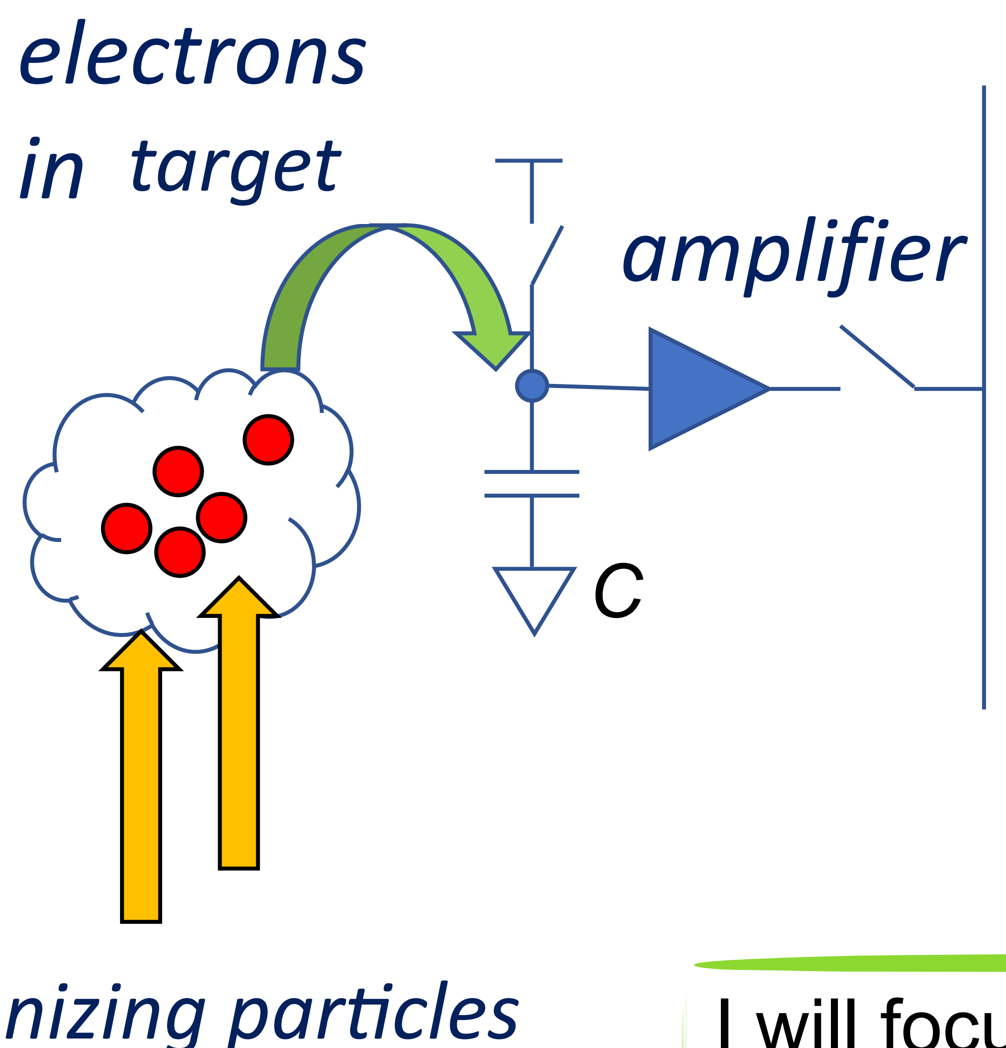
Outline

- Direct charge measurement.
- General scheme.
- Noise sources.
- Correlated double sampling (CDS).
- Multiple uncorrelated measurements.
- Skipper CCD.
- RNDR DEPFET.
- Dark current.
- Requirements for 1 kg and beyond.

Charge measurement

**Direct* charge measurement. I will not consider secondary detection mechanisms like electroluminescence or Luke phonons.



$$\Delta V = \Delta Q/C$$

For ***C*** **~ 10 fF**: **ΔV/ΔQ ~ 16 μV/e⁻**

Signal that you can measure

Small capacitance can be achieved with ***physically*** **small** components, e.g., $C \propto A/d$ ~ *linear scaling* for a parallel plate capacitor.

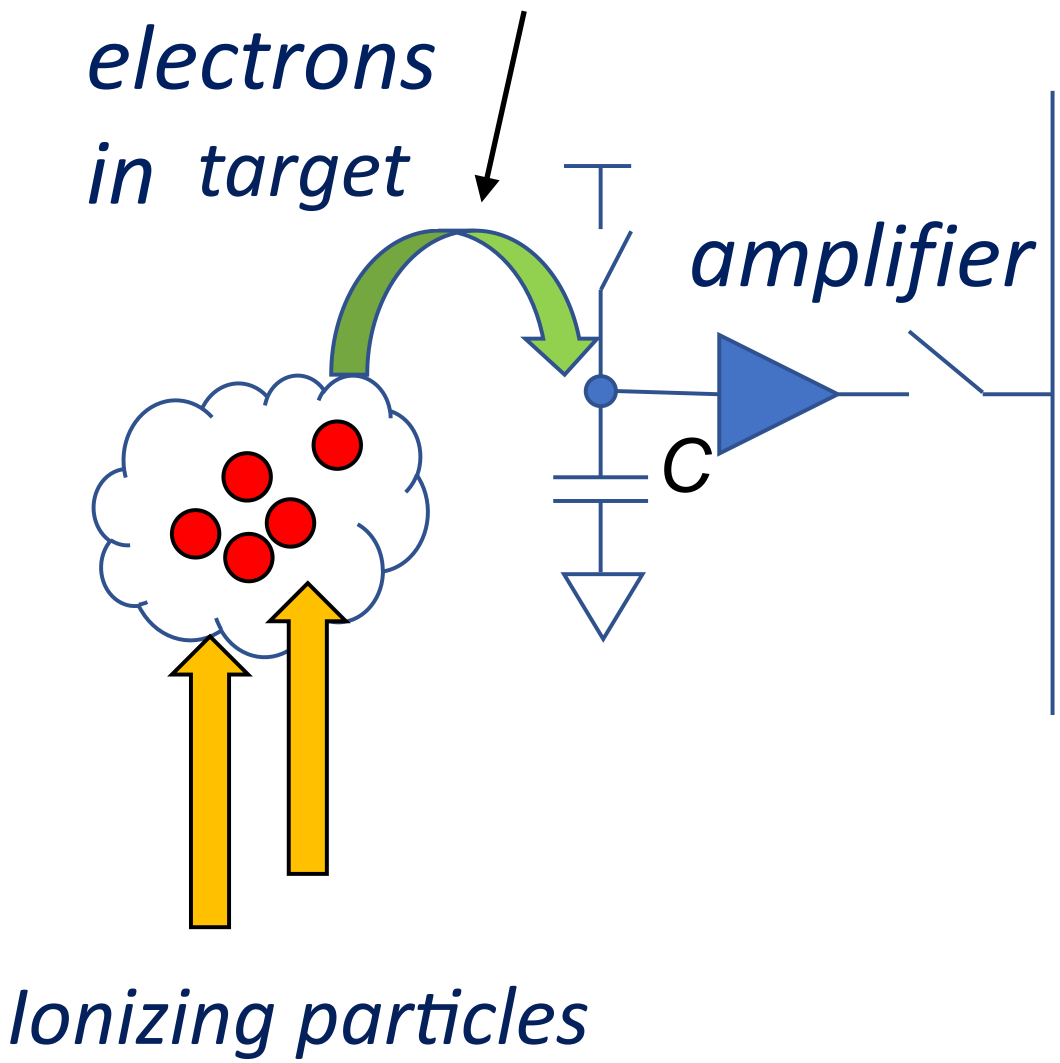
I will focus on low-capacitance *pixelated* devices from integrated-circuit (IC) microfabrication.

Charge measurement

**Other possibilities for direct charge measurement I will not consider.*

Amplify the signal here by avalanche multiplication, e.g., EMCCD and SPAD.

$$\Delta V = \Delta Q / C$$



For **C ~ 10 fF**: **ΔV/ΔQ ~ 16 μV/e$^-$**

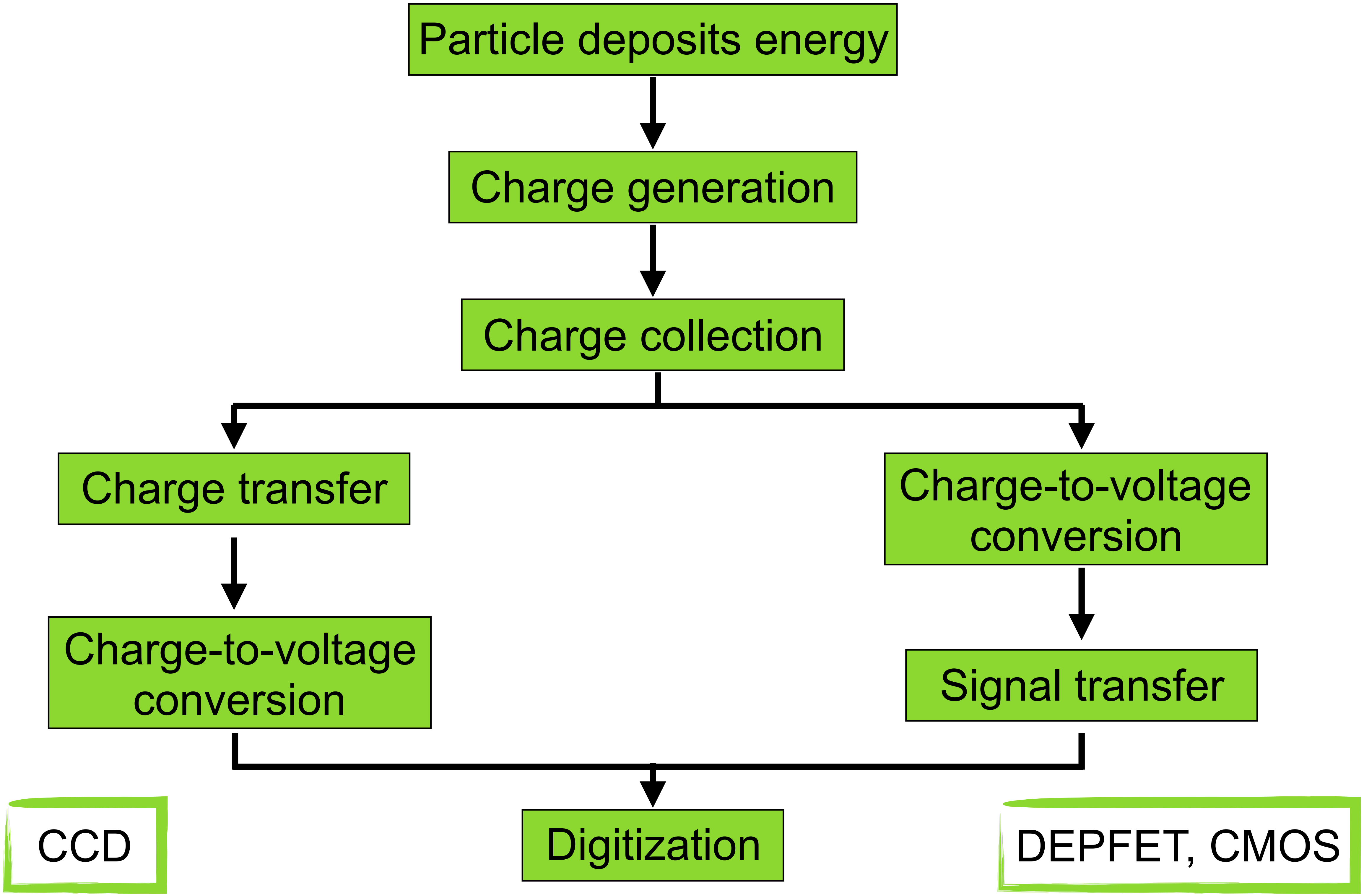
Signal that you can measure

Small capacitance can be achieved with ~~*physically* small components~~ clever geometric arrangements:

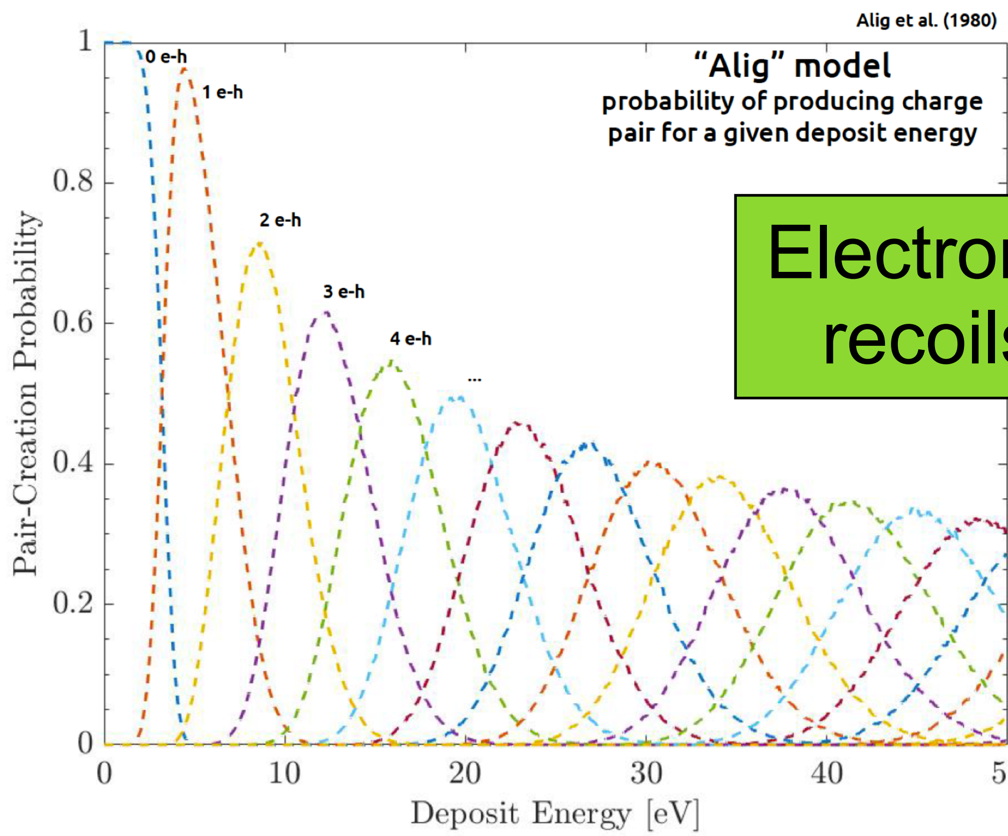
P-type point-contact Germanium detectors, e.g., CoGeNT.

Concentric conductive spheres, e.g., NEWS.

General scheme



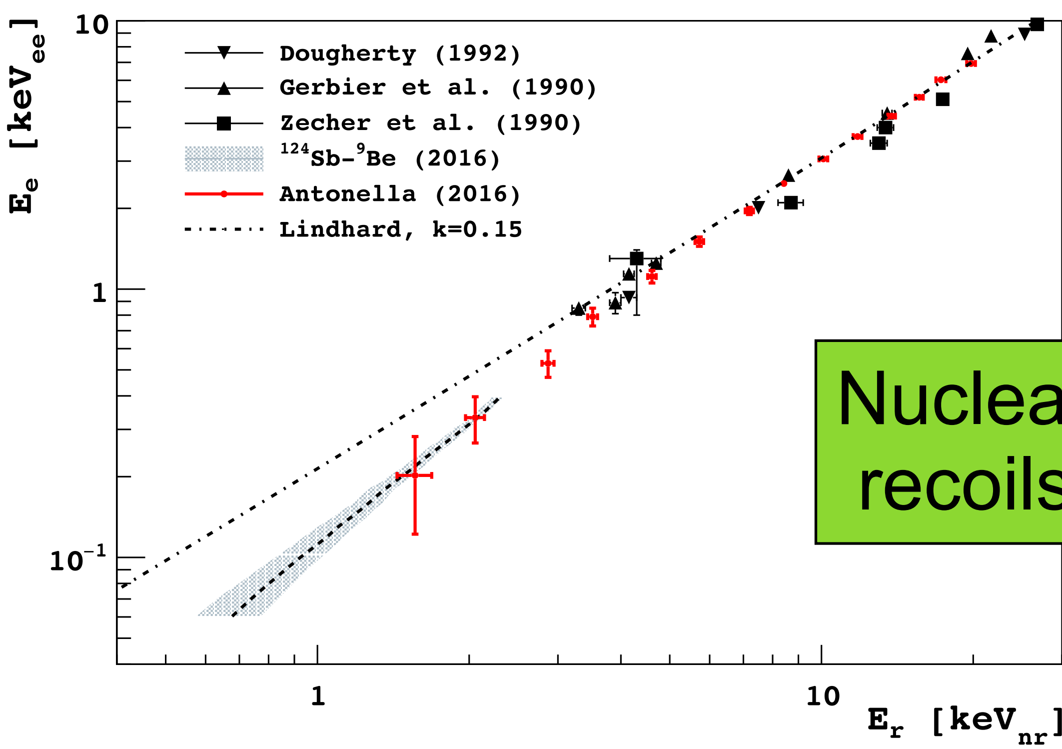
Charge generation + collection



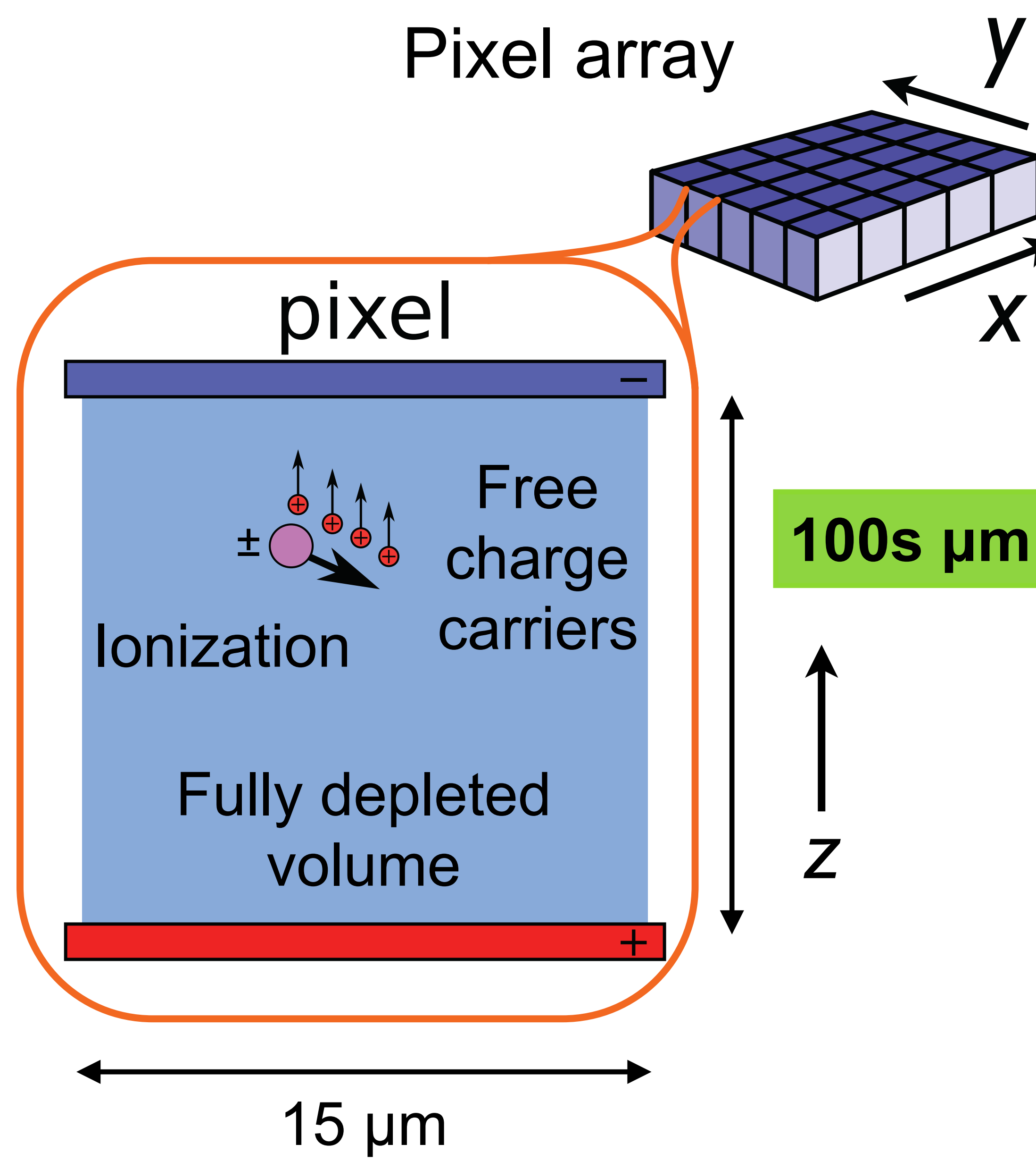
Electronic recoils

Mean:

$$\frac{E}{3.8\ \mathrm{eV}}$$

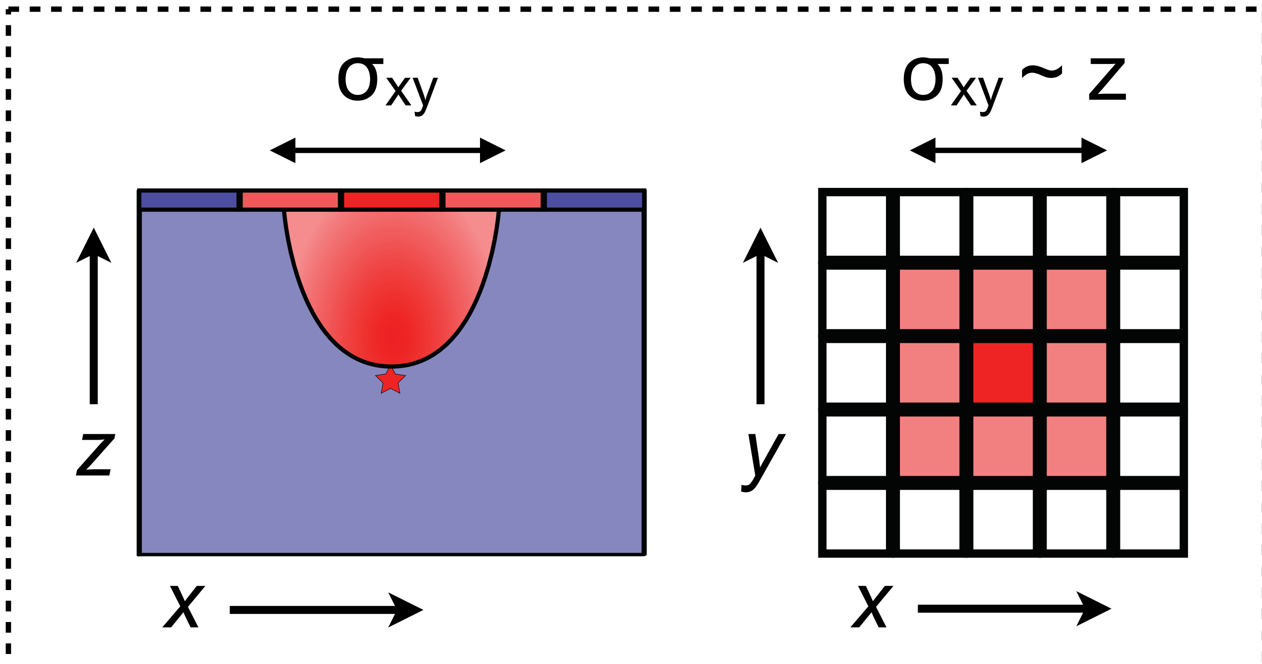


Nuclear recoils

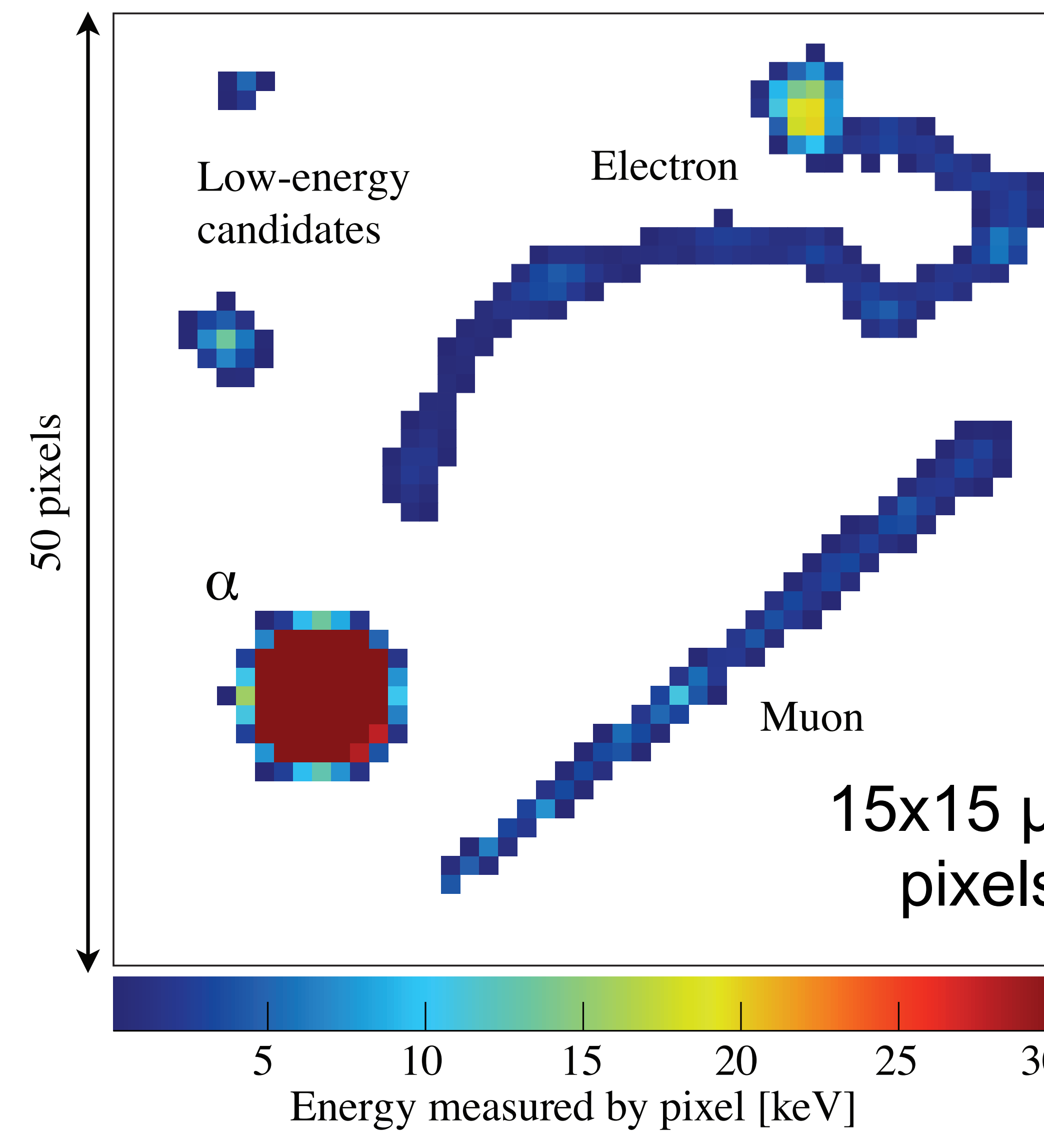


Pixelated sensors

Few µm dead layers on the surface, otherwise fully active



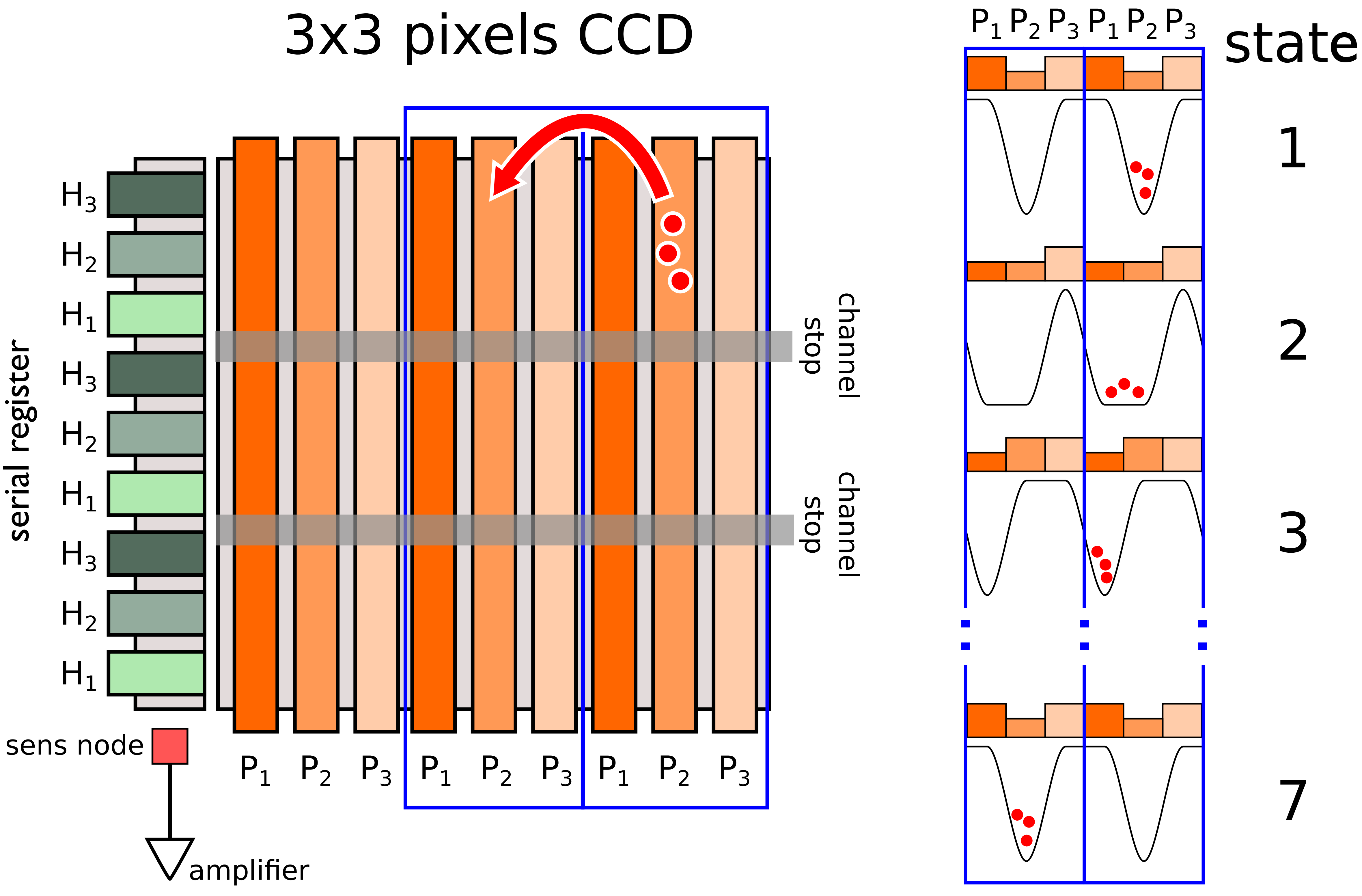
Distribution of charge on the pixel array allow to discriminate against surface backgrounds



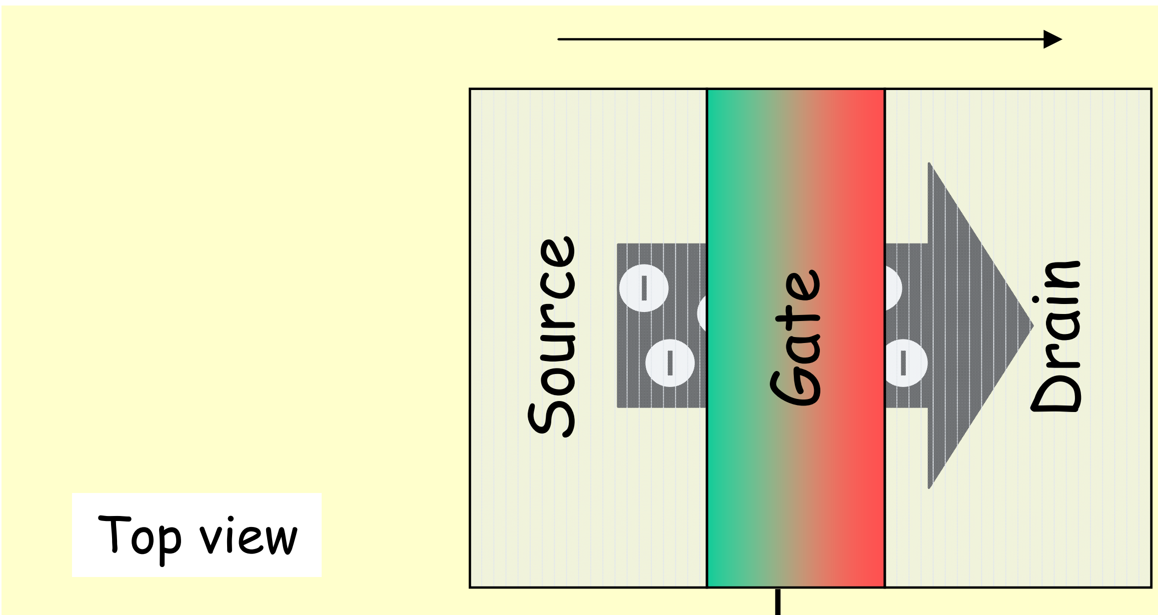
15x15 µm² pixels

Run in integration mode: not triggered

Charge transfer



Output MOSFET

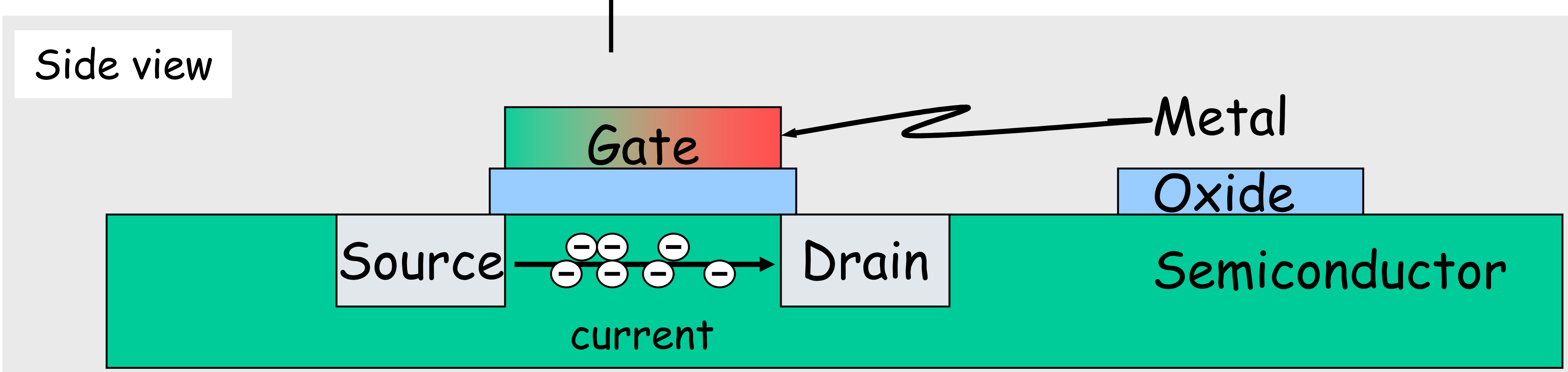


Change in potential at the Gate (by adding charge to the sense node) controls the flow of charge from the source to the drain, i.e.,

Current is proportional to charge on the sense node.

Fluctuations in the current are a source of noise but **main uncertainty is the initial state of the gate potential,** which can only be "zeroed" to **±100 *e*⁻.**

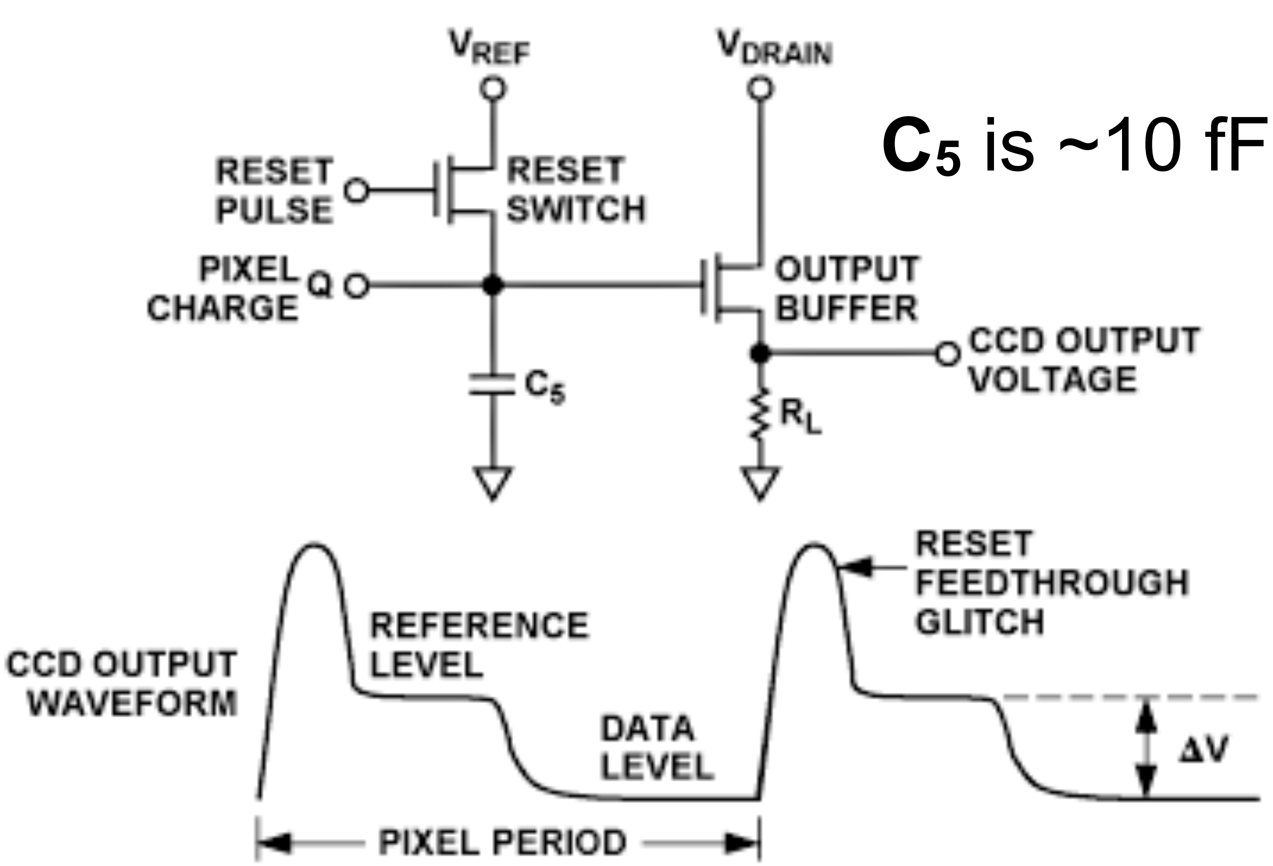
Gate connected to the sense node



CDS readout

Reset MOSFET

Output MOSFET

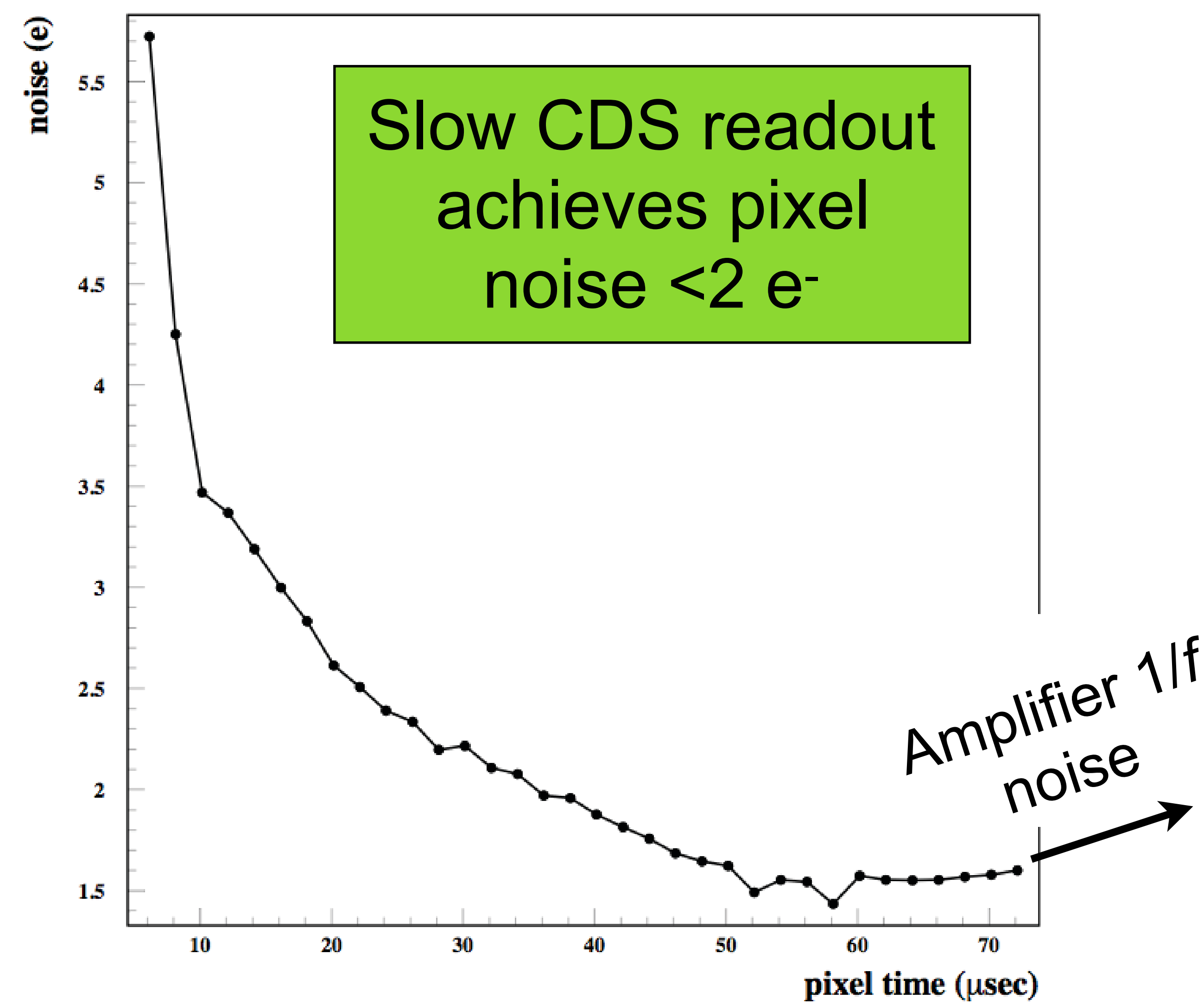


C_5 is ~10 fF

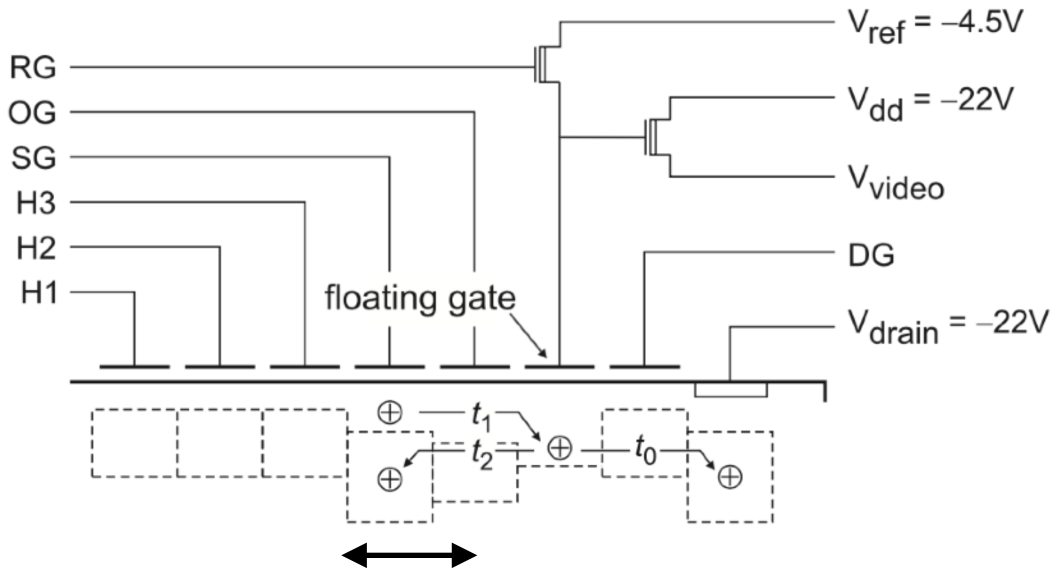
ΔV is ~15 μV per e^-

CDS: “Correlated double sampling”

Removes reset noise by making a differential measurement



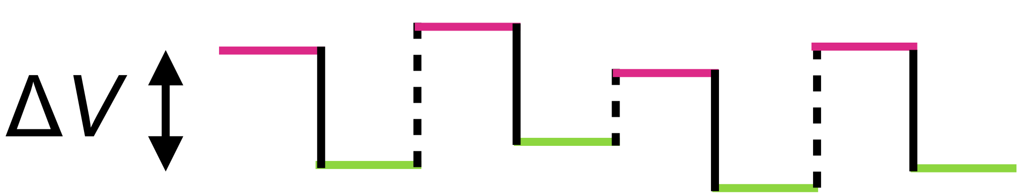
Skipper CCD



move charge back and forth

Measure ΔV N times

Reference

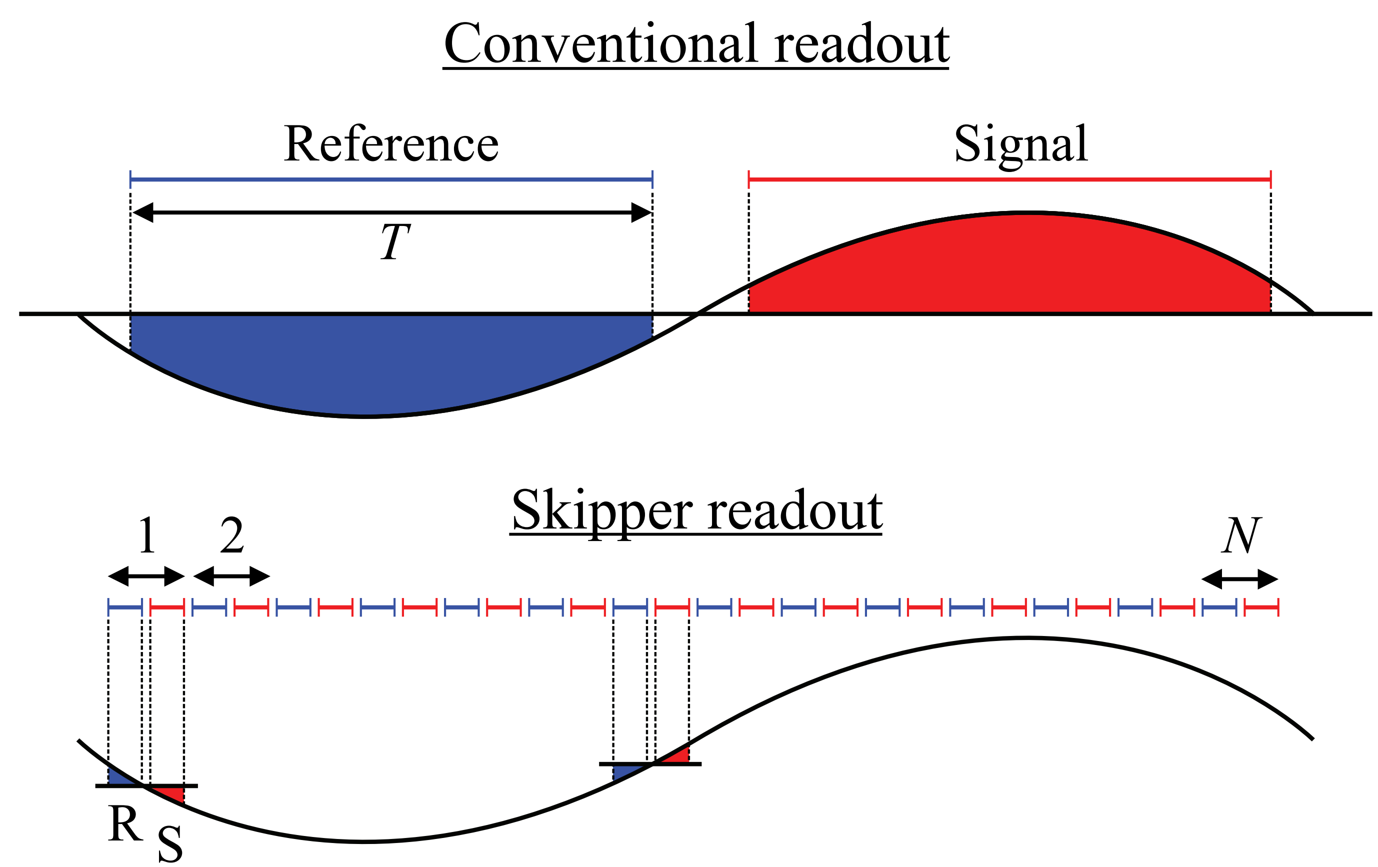


Signal

Technology proposed in the 1990s

“Skipper” readout: Perform N uncorrelated measurements of the same pixel.

Effect on low frequency noise

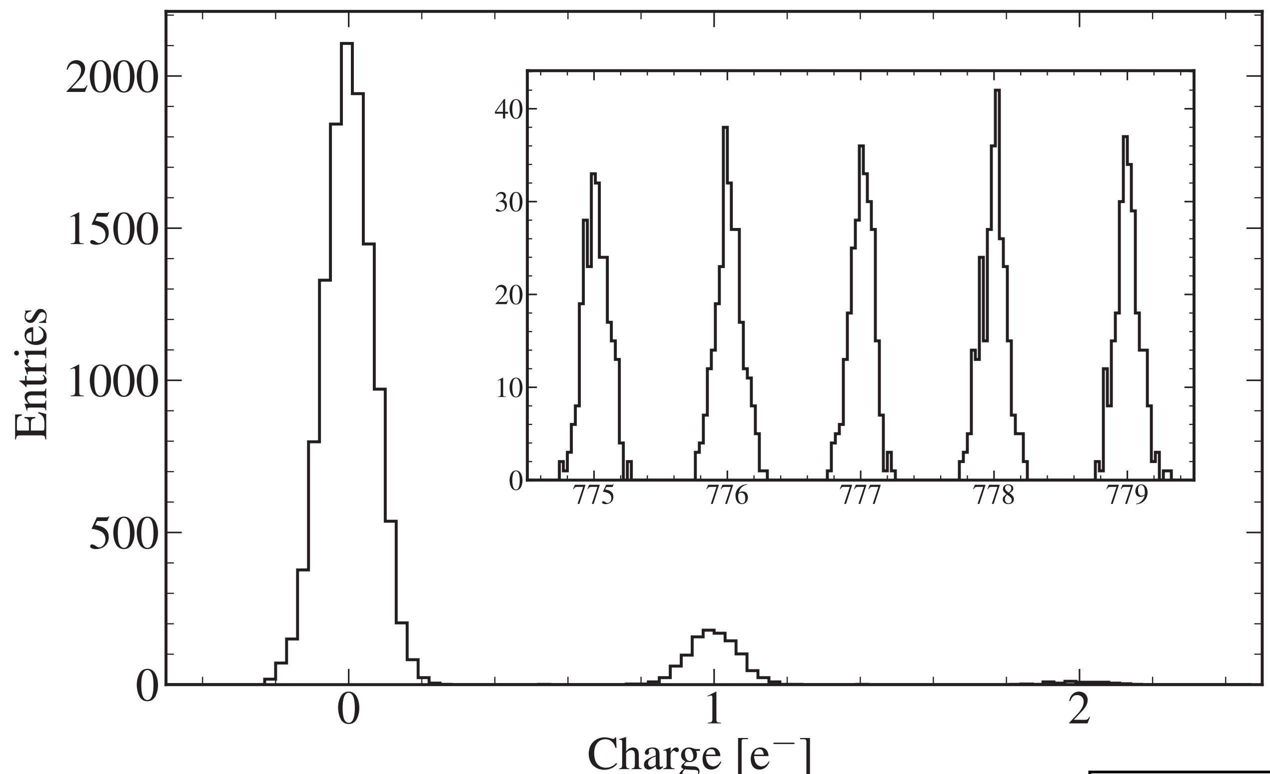


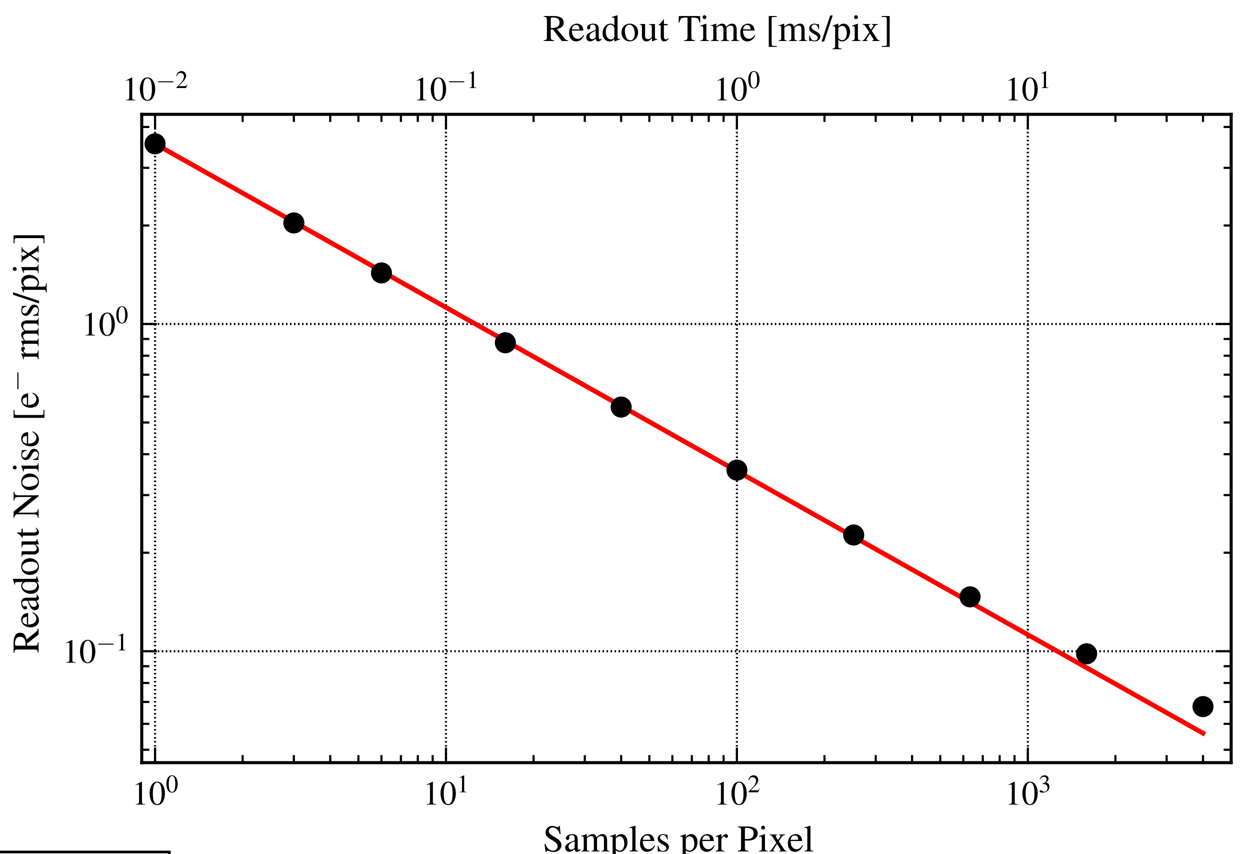
SENSEI

LDRD at Fermilab: Skipper CCDs (**LBNL design**) successfully tested with sub e⁻ noise. X-ray spectroscopy demonstrated.

Technology will allow 2 e⁻ (few eV) threshold.

Observed ~$1/\sqrt{N}$

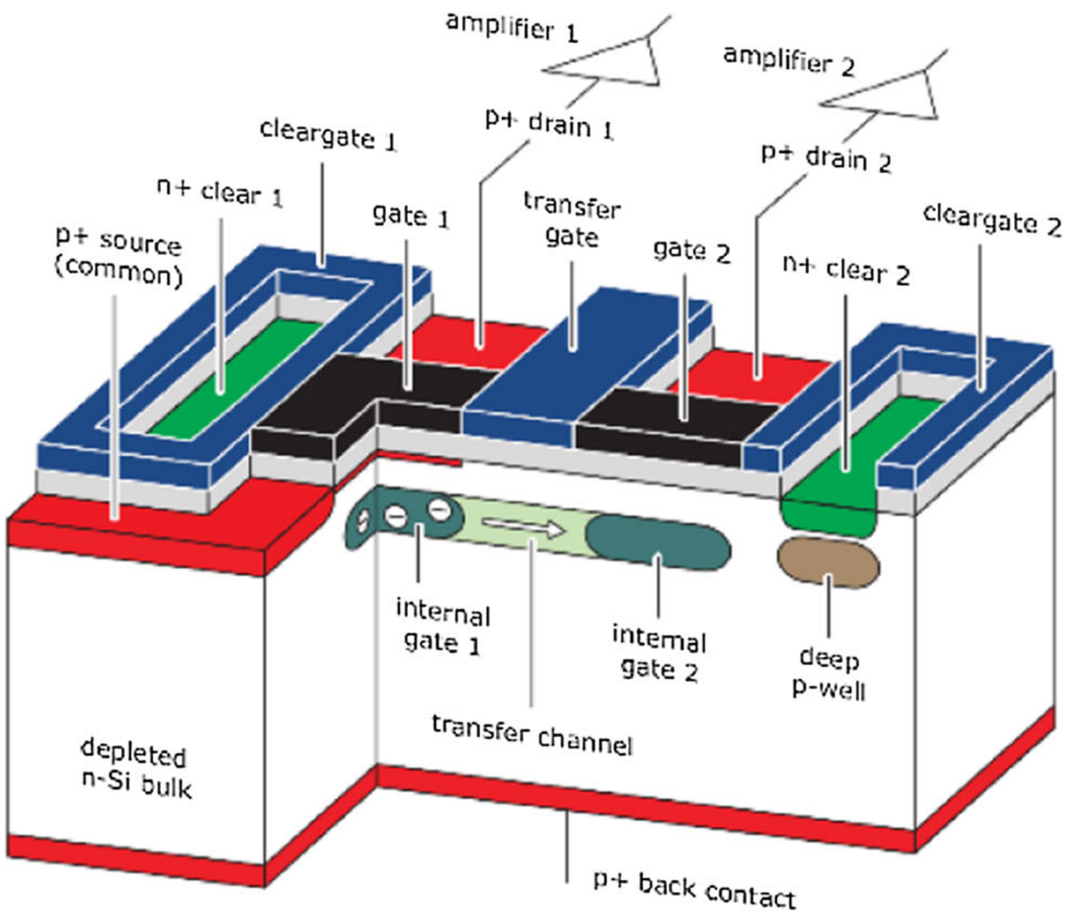


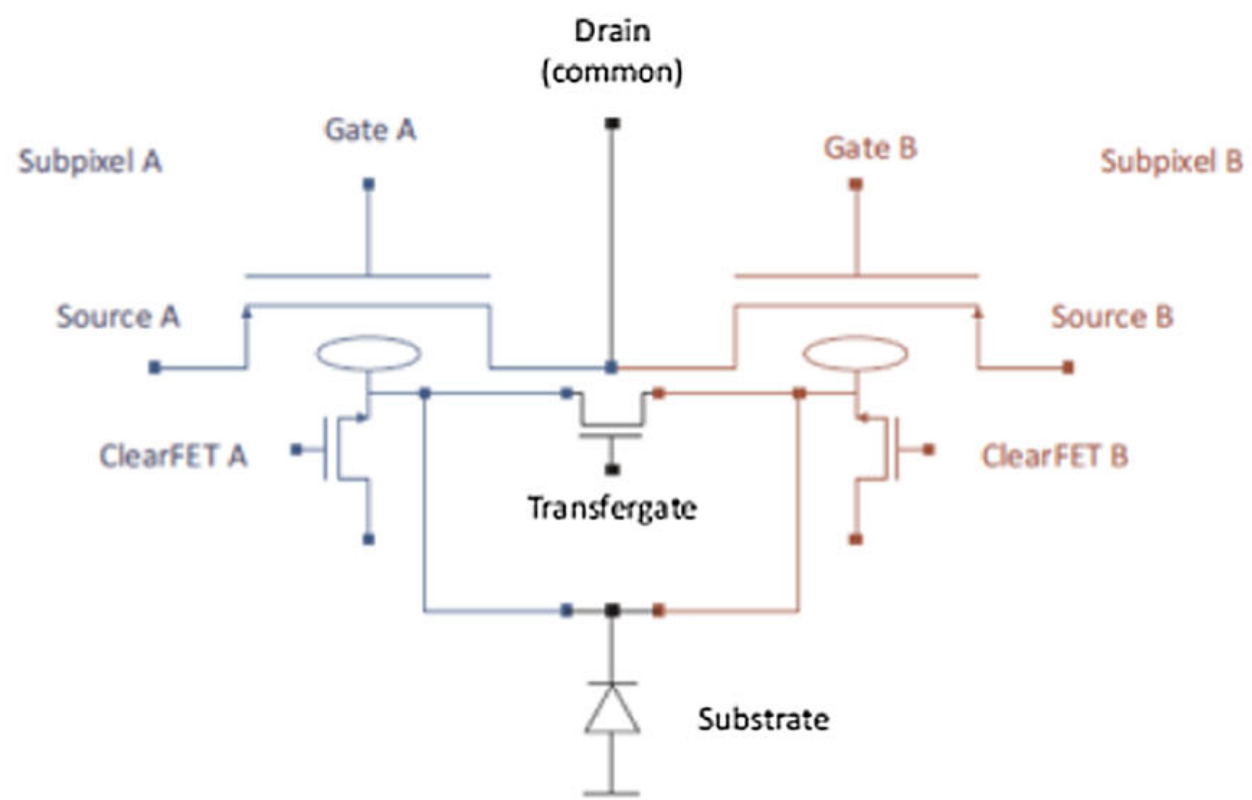


PRL119 131802 (2017)

RNDR DEPFET

Repetitive Non-Destructive Readout DEpleted P-channel Field Effect Transistor



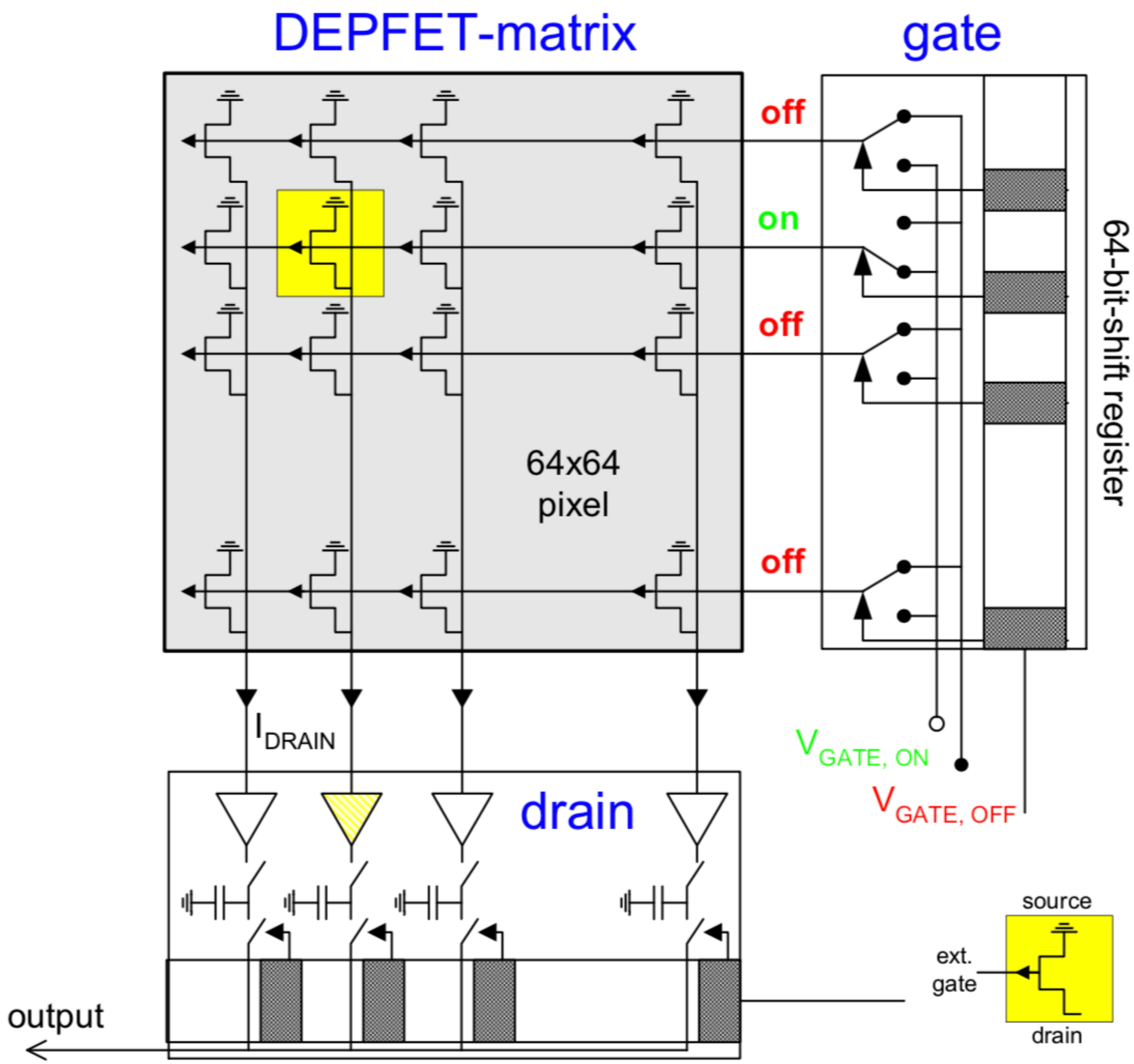


75 x 75 μm² superpixel
Also 36 x 36 μm²

Readout on pixel

Eur. Phys. J. C (2017) 77:905

Signal transfer

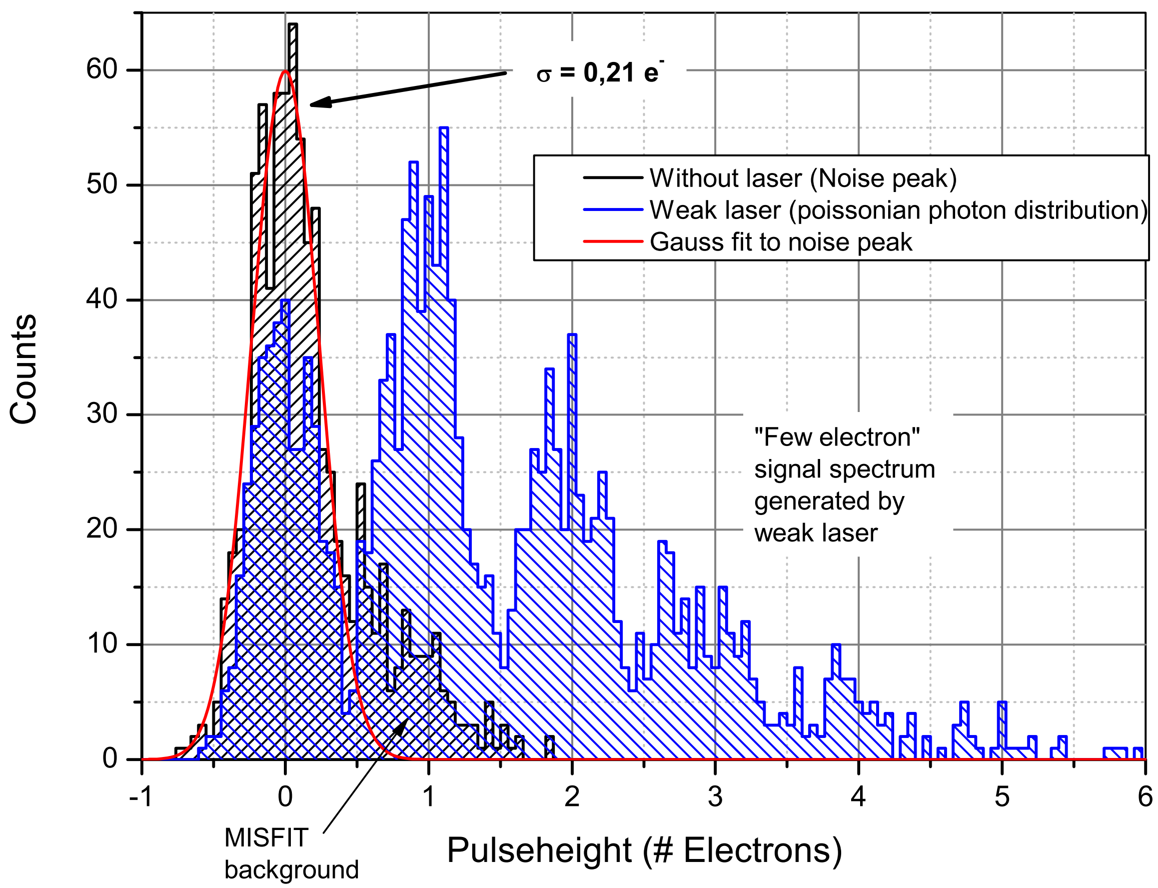


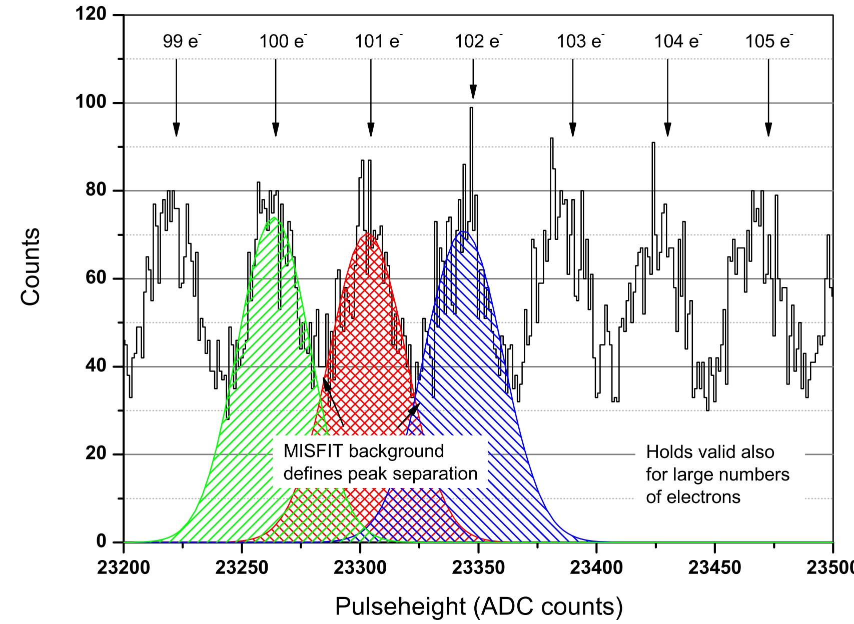
Many DEPFET pixels can be put in a matrix and shift registers can be used to select which row is live to read.

Inactive pixels remain “exposing” and collecting charge from ionizing particles.

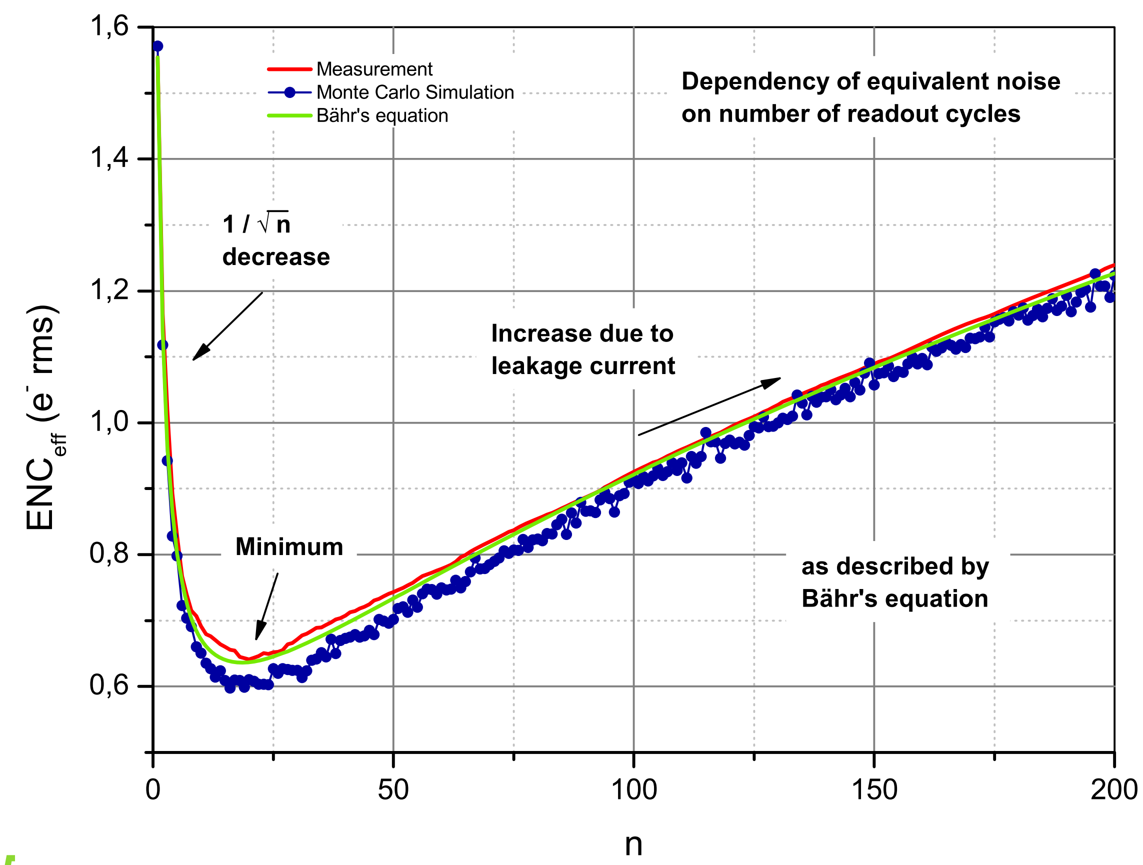
A CMOS active pixel sensor would operate in a similar way

DEPFET Results





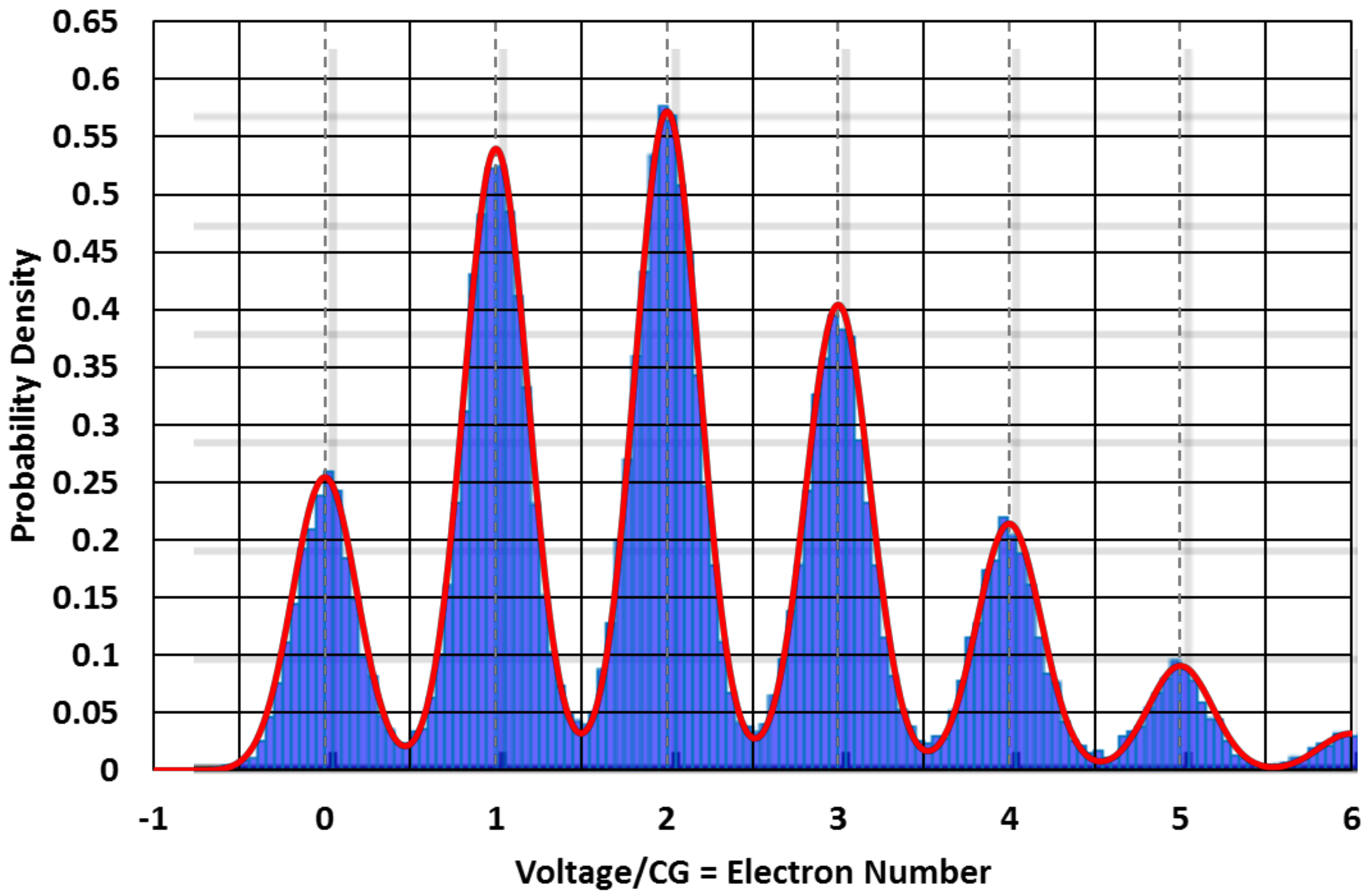
Excellent dynamic range (also skipper CCD)

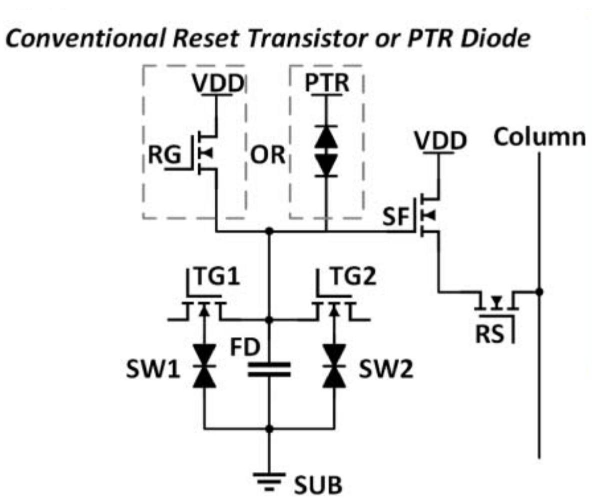


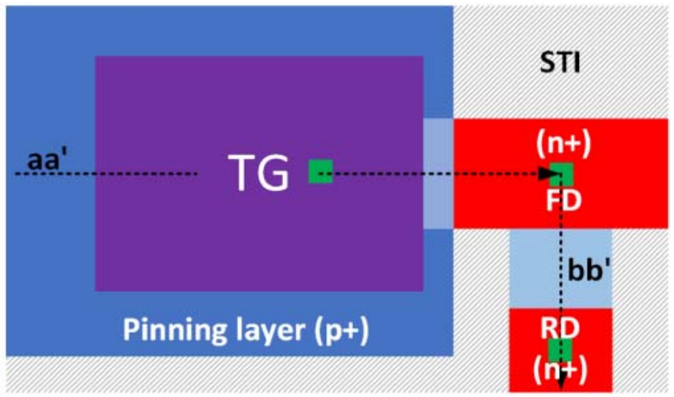
Charge collected by pixel during readout sequence

Eur. Phys. J. C (2017) 77:905

CMOS results







Optica 4, 1474-1481 (2017)

Recent results demonstrate excellent performance for CMOS sensors.

As a matter of fact, single photon counting in CMOS demonstrated at Max Plank a decade ago…

Challenge is building a thick fully depleted sensor with low leakage current.

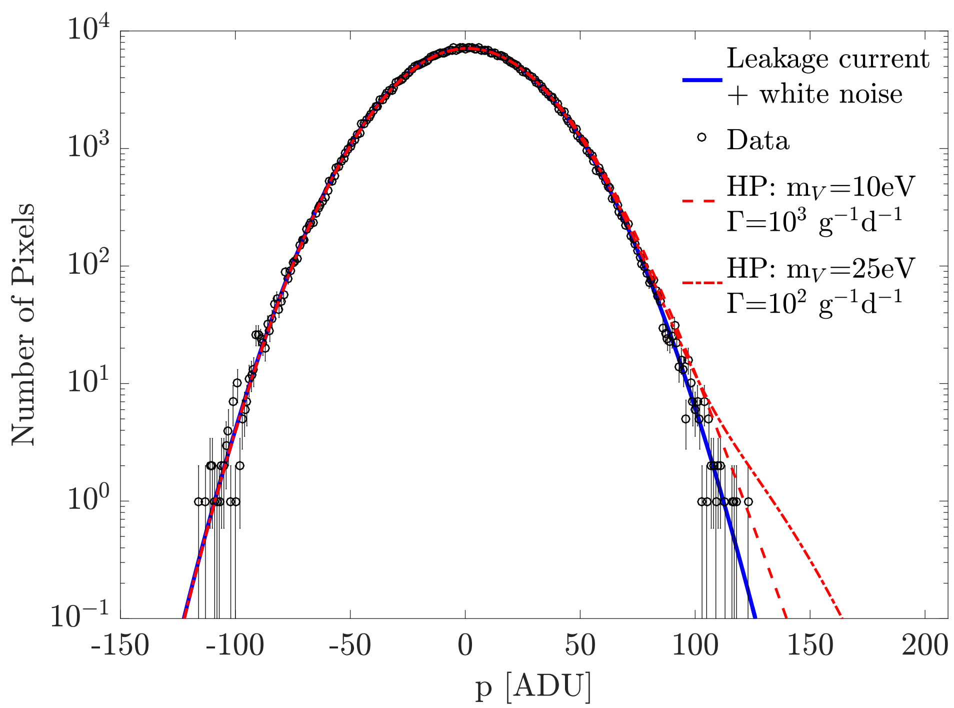
For dark matter

…it takes more than single electron counting!

- Devices must be thick and fully depleted for significant exposure.
- Ionizing backgrounds from natural radioactivity must be low: 1 d.r.u. for zero events with 2–10 e^- in a 0.1 kg-year exposure.
- Ionizing backgrounds from photons must be low.
- Device dark current must be low.

Leakage current!

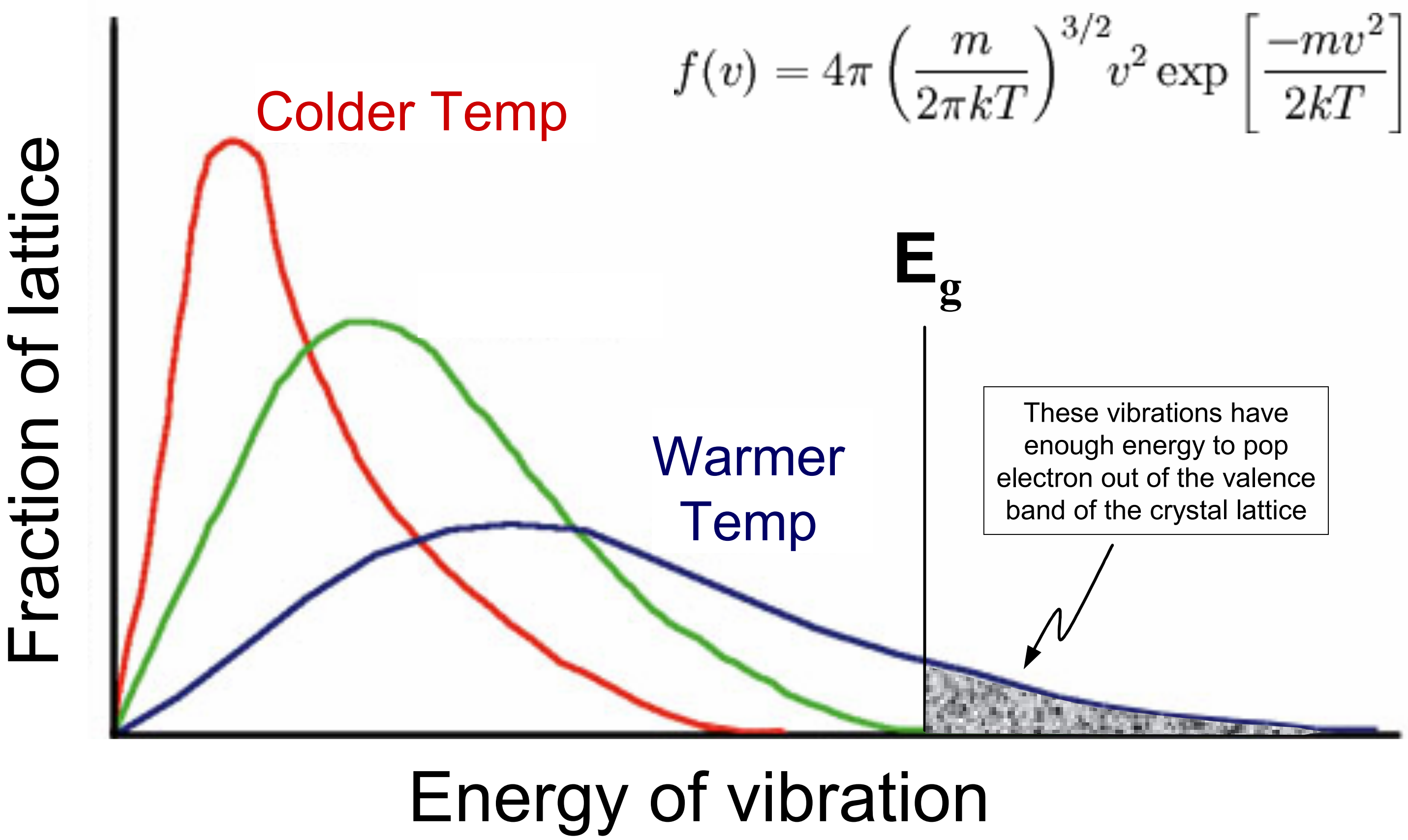
DAMIC has the lowest measured LC by orders of magnitude!



Number of background events in a 1 kg-year exposure:

I_l / mm^{-2} d^{-1}	$Q \geq 1$	$Q \geq 2$	$Q \geq 3$
2	3×10^8	8600	0.1
0.04	7×10^6	3.4	10^{-6}
4×10^{-3}	7×10^5	0.034	10^{-9}

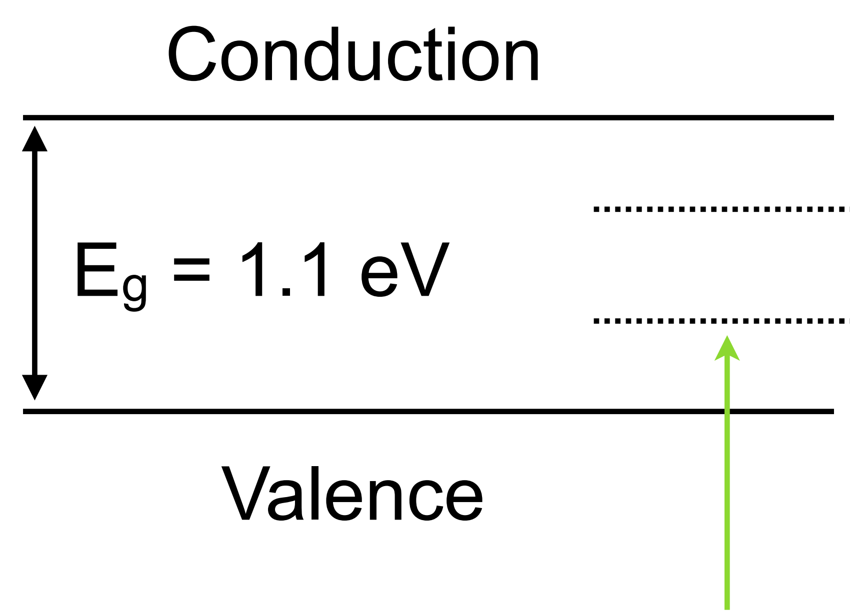
Dark current



Can cool down the device but not past the point of “freeze out” (~77 K) where free charge recombines with the donor atom!

Resistance of polysilicon increases, charge transfer suffers…

Band structure



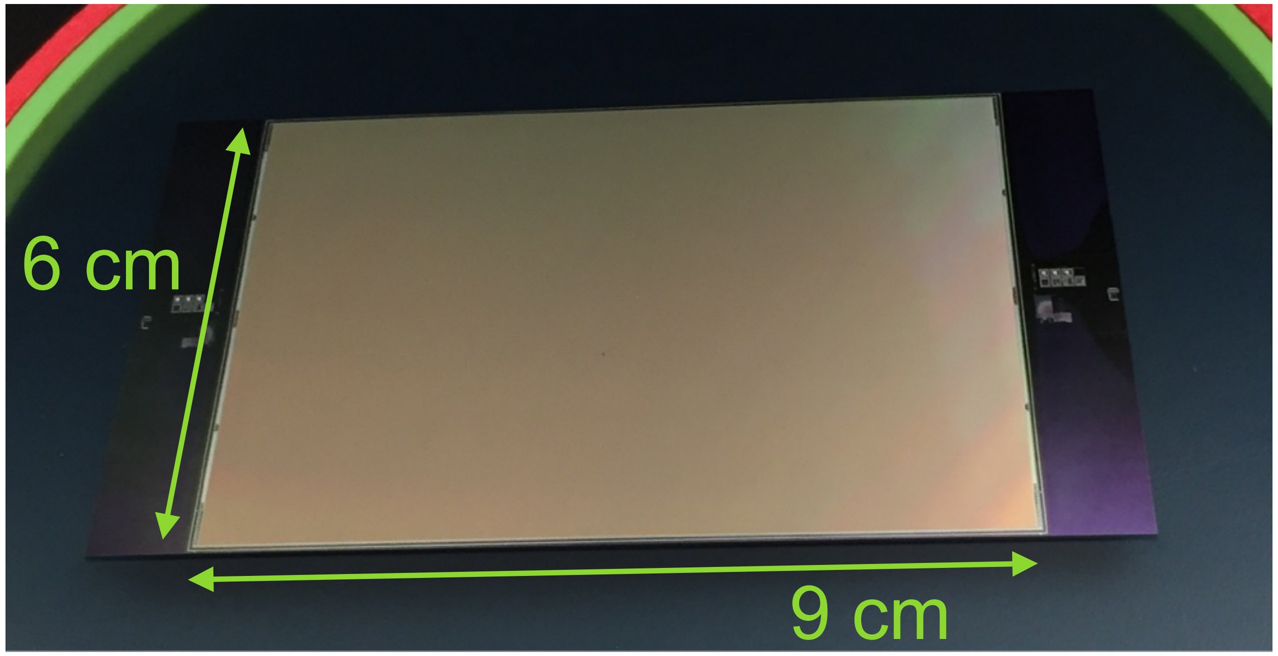
Defects in the silicon introduce levels in the between the band gap that generate dark current.

Extrinsic gettering is used by LBNL in the DAMIC CCDs to remove impurities

Upcoming developments

- Devices should get *larger* to increase dark matter search exposure. Making them ***thicker is best*** because the increase in exposure does not introduce surface backgrounds (radioactive and dark current).

24 Mpix CCD at UW: 10 g!



- Readout should get *faster* with the same readout noise performance: number of background events with 2 e^- from leakage current decreases linearly with pixel readout time.
- Dark matter search experiments in the 0.1–1 kg scale with hundreds of devices already under construction.

Conclusions

- Silicon charge sensors are the most sensitive to ionizing particles.
- They are microfabricated pixelated sensors.
- Repititive, uncorrelated measurements of the pixel charges allow for single charge resolution.
- Leakage current is now the dominant “instrumental” noise source and a significant challenge for large (100 g or more) detectors.
- Current generation of sensors are <1 g but scale up should be *fast*.

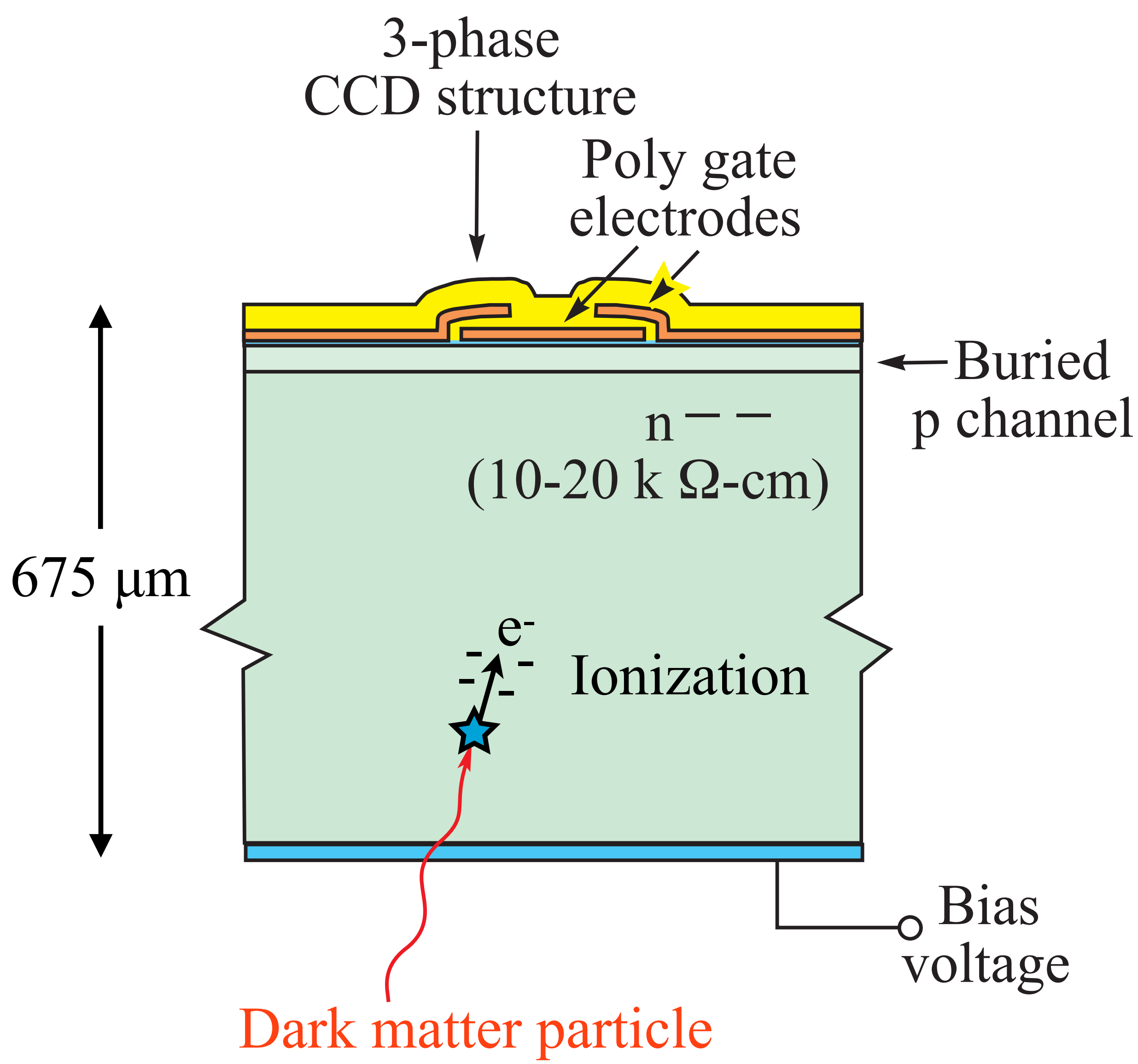
Thanks for figures and slides to:

- J. Beletic
- P. Mitra
- K. Ramanathan
- D. Starkey
- J. Tiffenberg

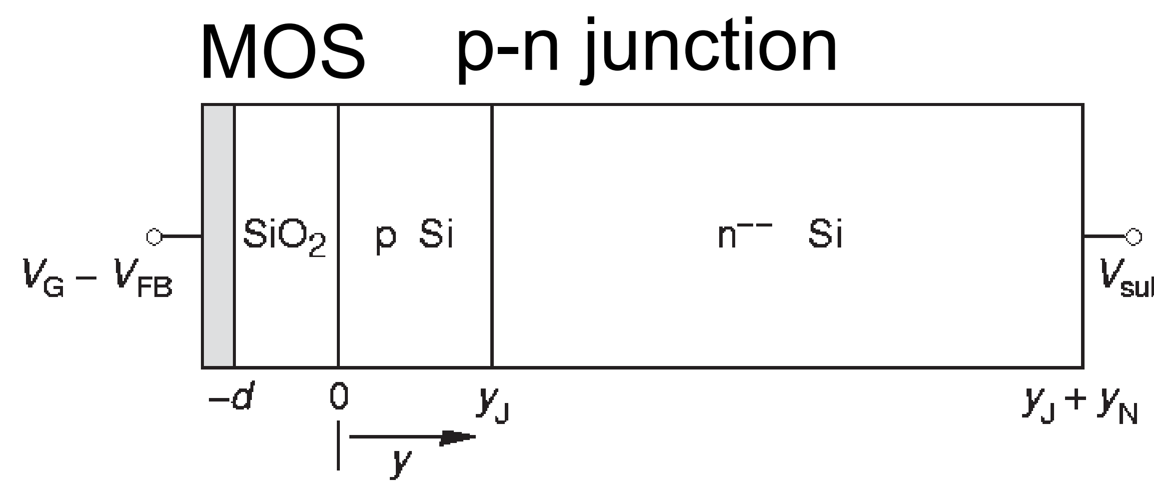
… and thank you!

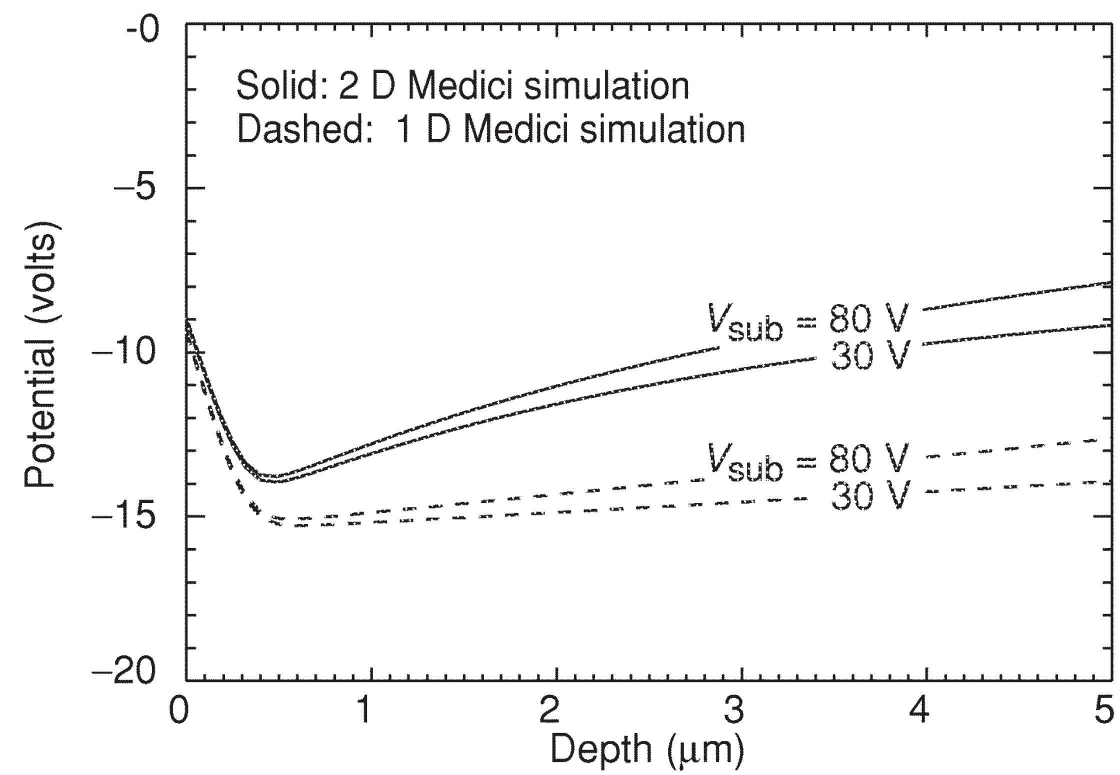
Backups

DAMIC CCD



LBNL design





Irradiated CCD