CMOS Image Sensors for Science and Space

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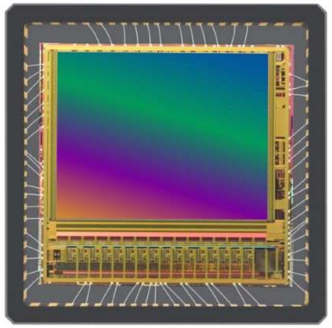
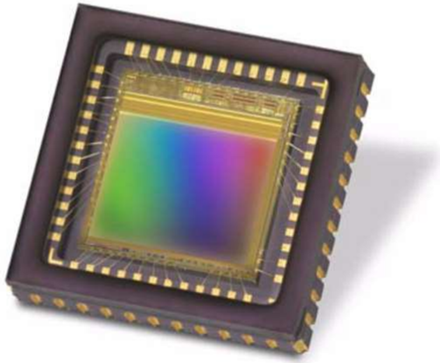
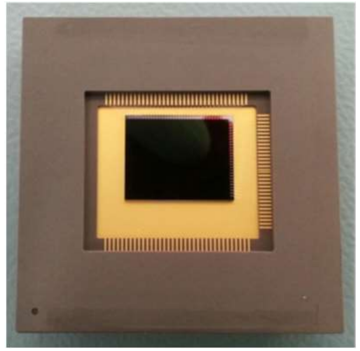
  - Challenges
  - TDI imaging, CCD-in-CMOS
  - Radiation hardness
- Future trends



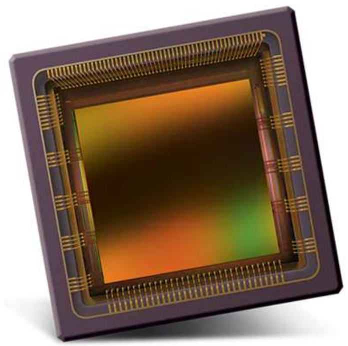
ONSemi PYTHON5000
(5.3 Mpixel, 4.8 µm)



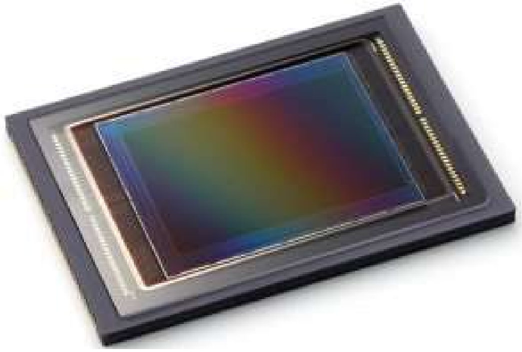
Te2v EV76C560 Sapphire
(1.3 Mpixel, 5.3 µm)



Te2v CIS115
(3 Mpixel, 7 µm)



ams OSRAM CMV4000
(4 Mpixel, 5.5 µm)



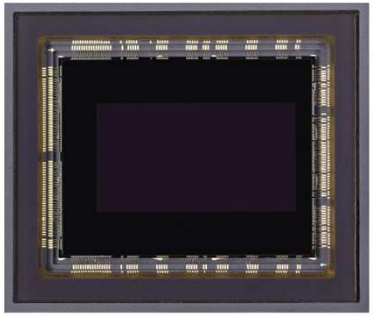
SONY IMX211
(100 Mpixel, 4.6 µm)

Omnivision OV24A10
(24 Mpixel, 0.9 µm)

Key features and important achievements

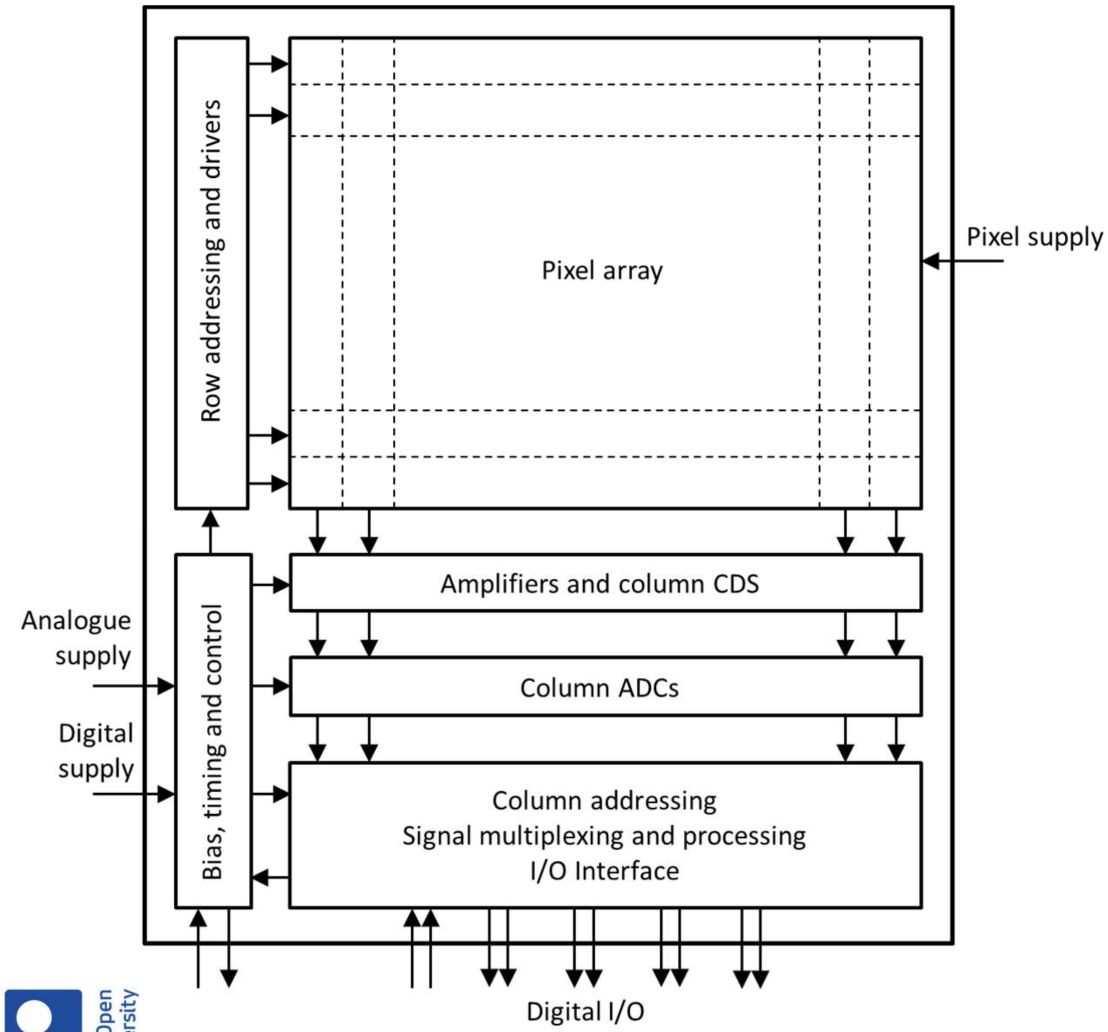
- Huge variety of CMOS image sensors for different markets:
  - Consumer
  - Industrial
  - Scientific (sCMOS started around 2010)
  - Space
- More than 100 companies worldwide
- Continued innovation:
  - 3D integration
  - Backside illumination, QE > 90% in the visible
  - Pixel pitch = 0.56 µm (2022)
  - Devices with > 200 Mpixels
  - Readout noise < 0.3 e- RMS
  - Dynamic range > 120 dB
  - Dark current of only a few electrons per second at room temperature

BAE Systems sCMOS
HWK4123 (9.3 Mpix, 4.6 µm, 0.5 e-)



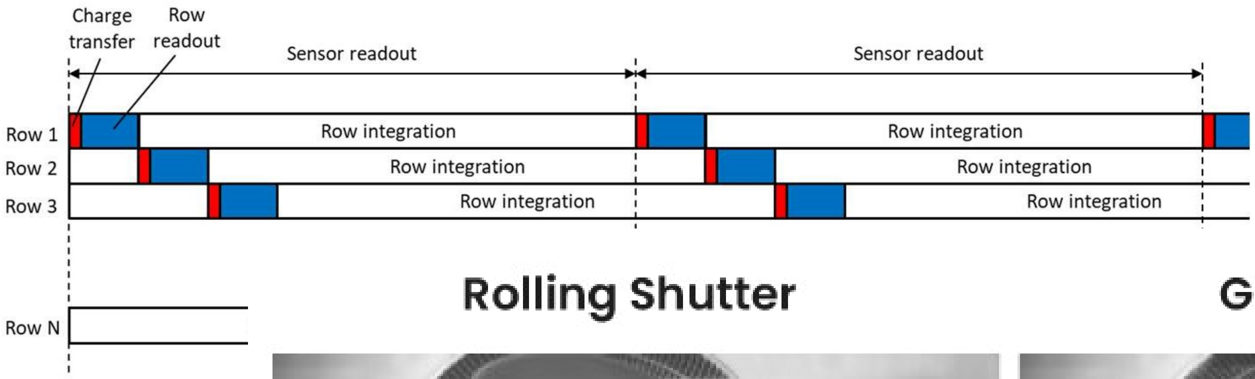
GSENSE400BSI
(4.1 Mpix, 11 µm, 1.2 e-)

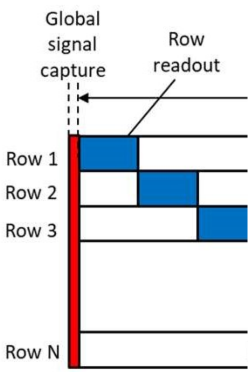
Architecture



- Highly integrated
  - Most require (multiple) power supplies and a clock
- Massive parallel readout – high speed
  - Whole row(s) readout
  - CDS and ADC per column as standard
- Control via SPI or I^2C interface – configuration, gain, etc.
- High speed data interfaces: LVDS, CML, MIPI …
- High flexibility in readout - multiple ROI, arbitrary row access, image flip and mirror
- Power dissipation
  - Low power (in general) – only the addressed row dissipates power
  - Few watts in large sensors
- "Old" 180 nm and 65 nm processes widely in use, but consumer imagers go down to 22 nm

Readout modes: rolling and global shutter





- **Integration = a row is not being read**
- **Equal light sensitivity during integration and row readout**

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light for the same
t at the same time
in moving scenes
rmance

tured simultaneously

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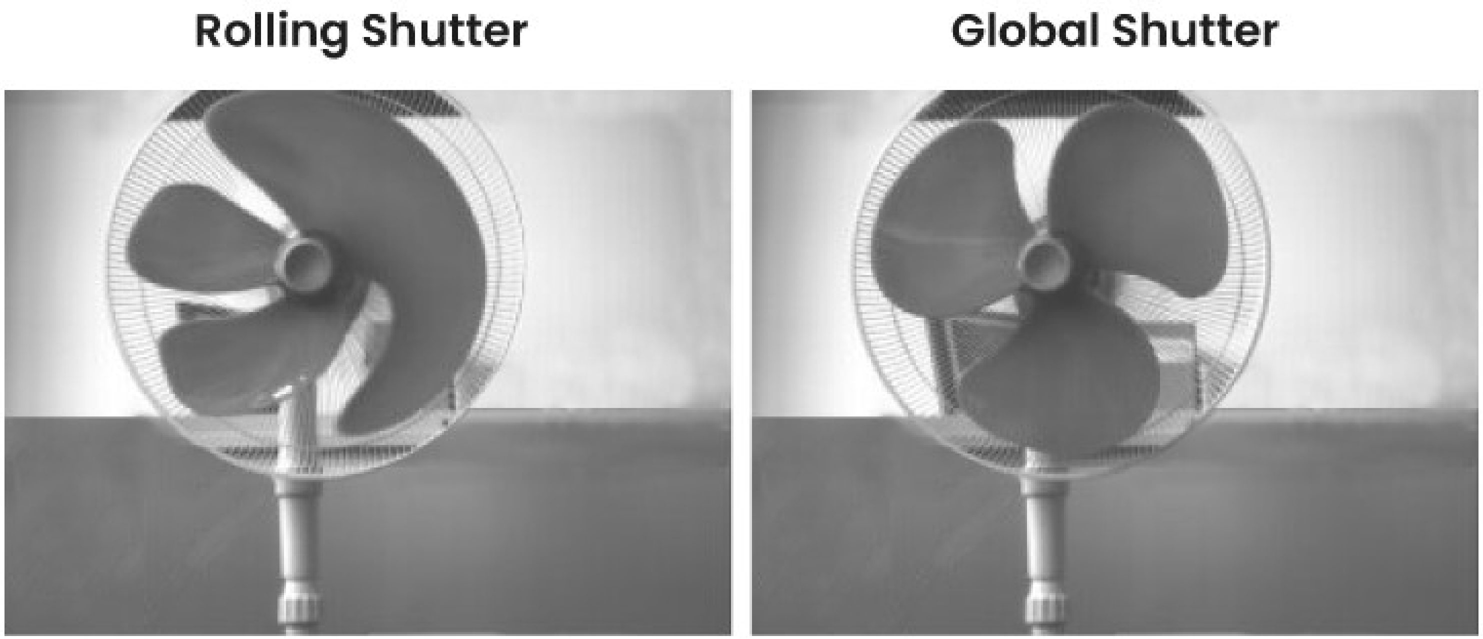
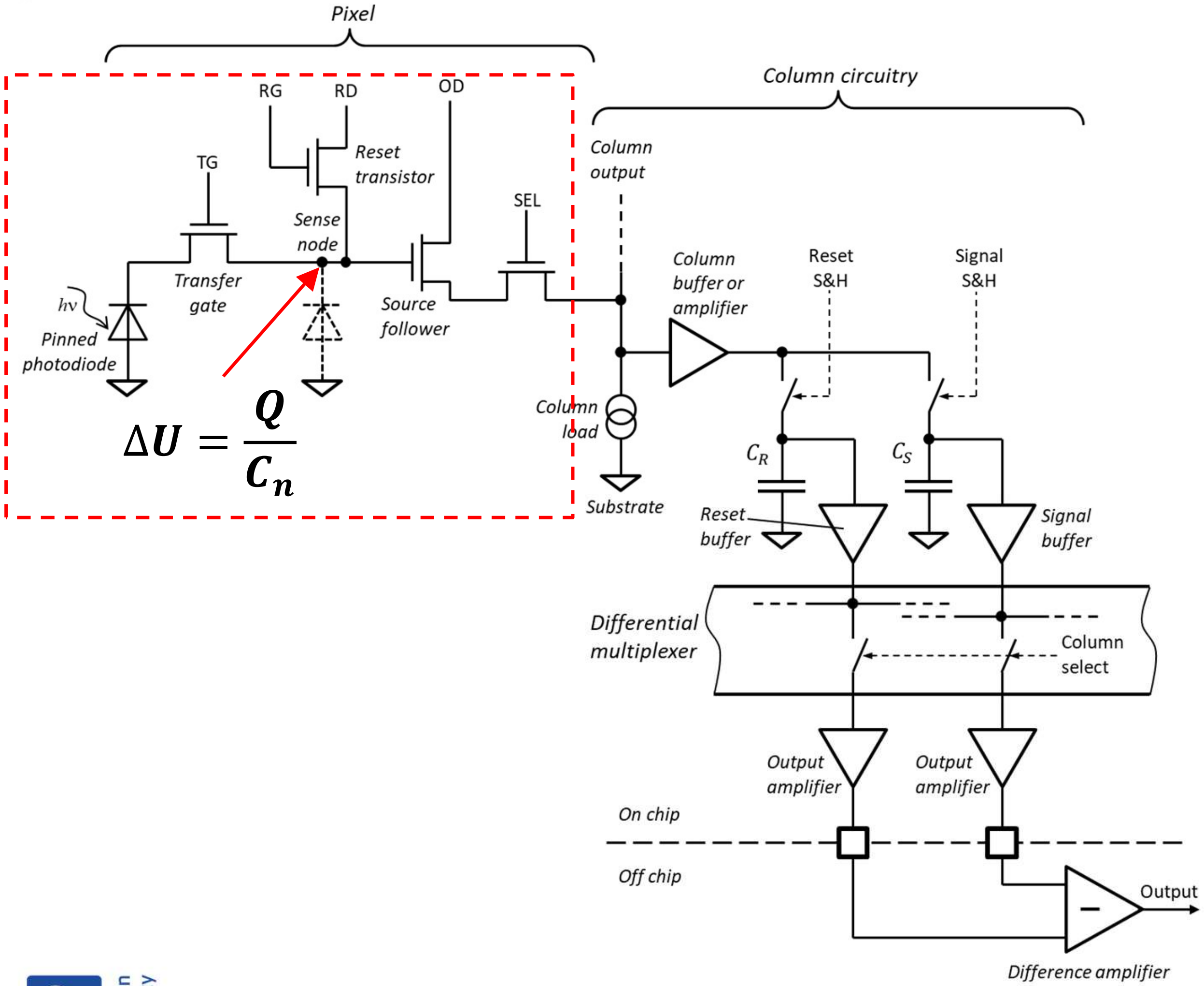
nplex

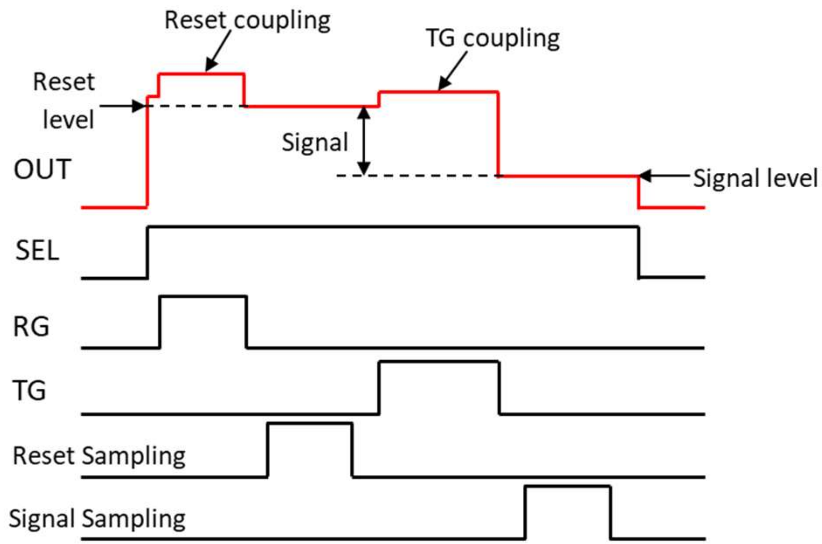


https://www.dpreview.com/forums/thread/4714730

Readout (1)

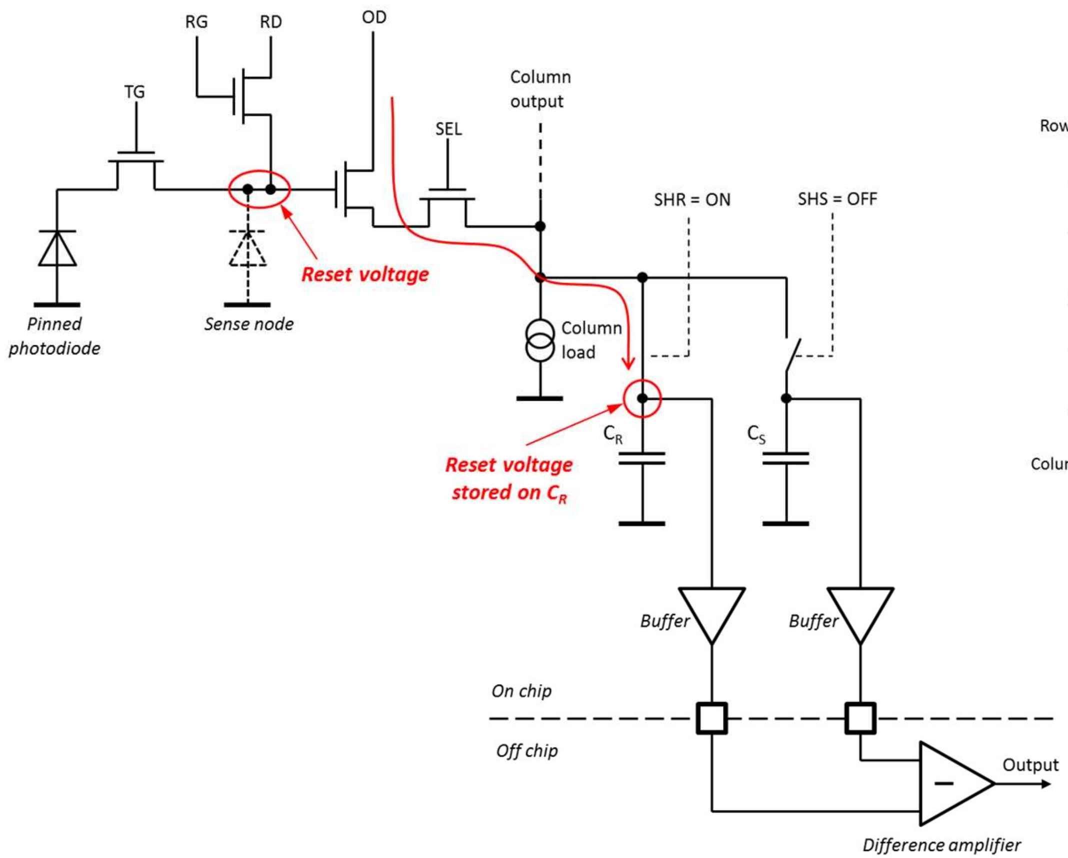


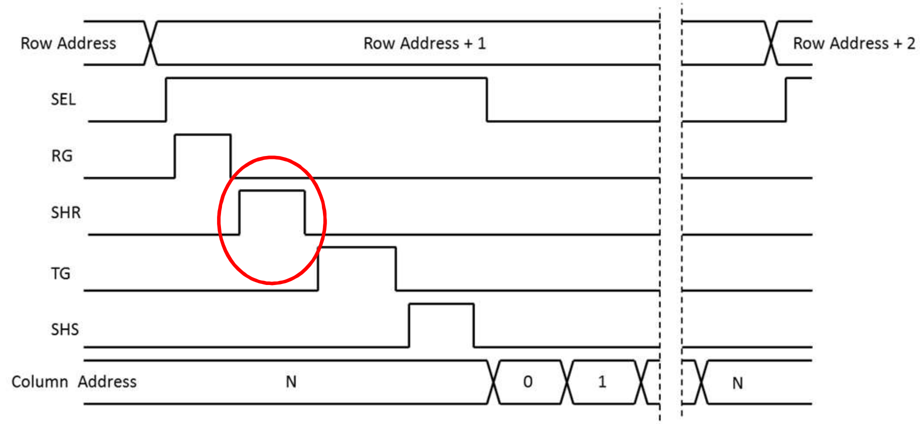
Pixel
Column circuitry
RG
RD
OD
TG
Reset transistor
Sense node
SEL
Column output
Transfer gate
Source follower
hν
Pinned photodiode
$\Delta U = \frac{Q}{C_n}$
Column buffer or amplifier
Reset S&H
Signal S&H
Column load
Substrate
C_R
C_S
Reset buffer
Signal buffer
Differential multiplexer
Column select
Output amplifier
Output amplifier
On chip
Off chip
Output
Difference amplifier



Reset coupling
TG coupling
Reset level
Signal
OUT
Signal level
SEL
RG
TG
Reset Sampling
Signal Sampling

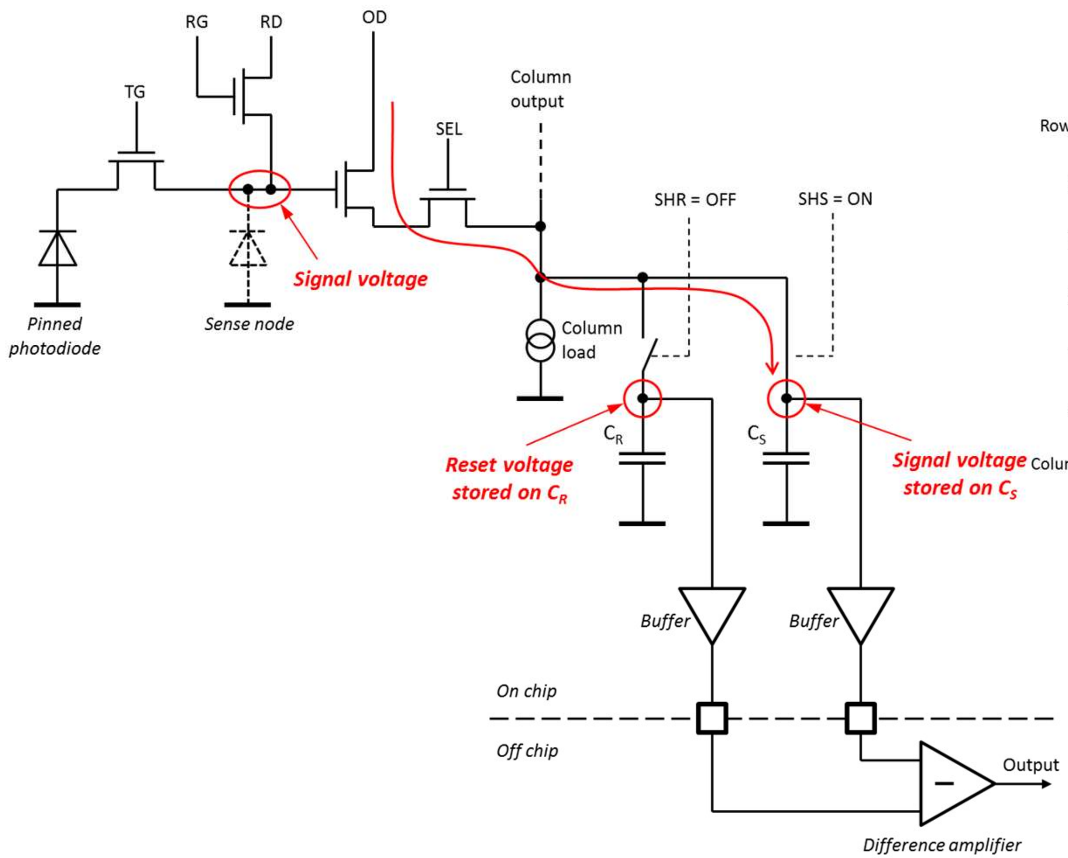
Readout (2)

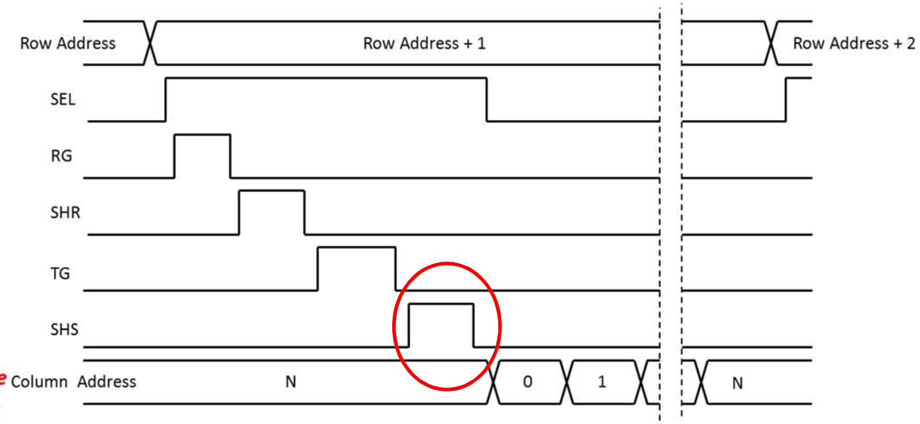




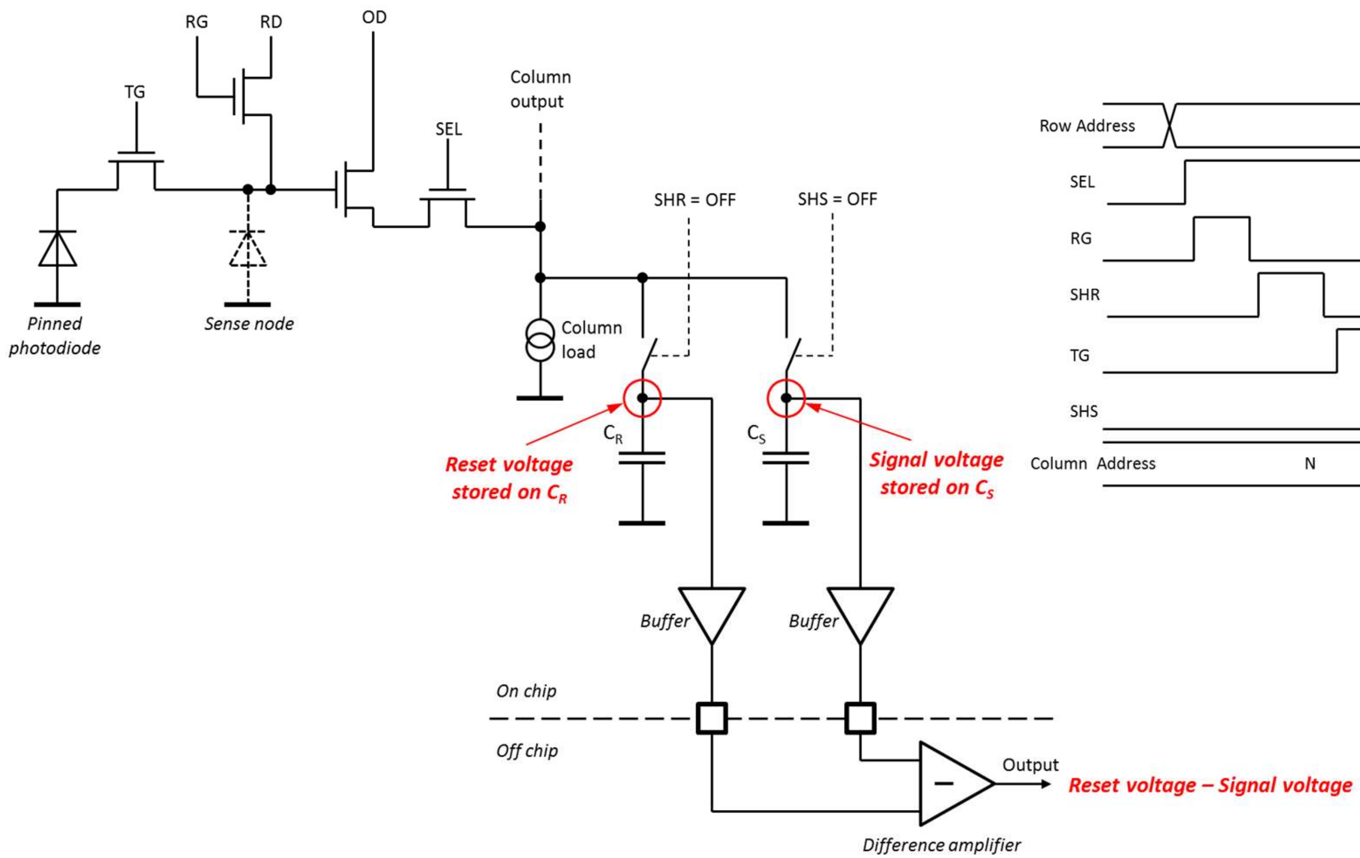
- **The outputs from the whole row are captured in one go**
- **Thousands of transistors are operating simultaneously**

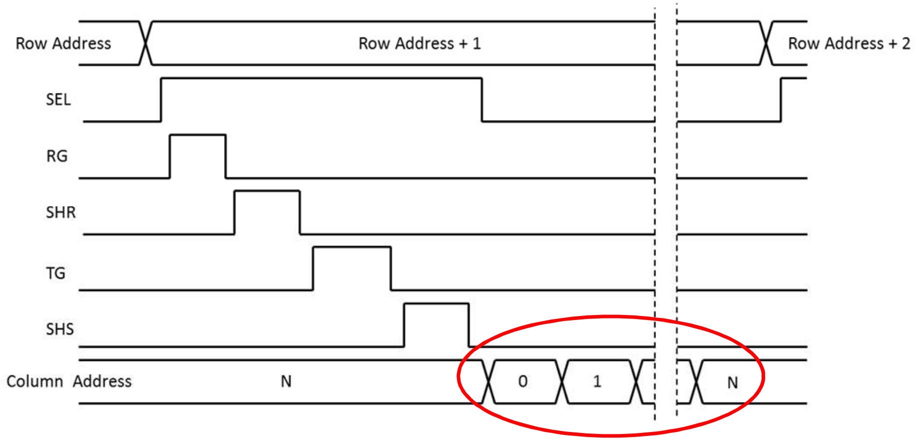
Readout (3)


RG
RD
OD
TG
Column output
SEL
SHR = OFF
SHS = ON
Signal voltage
Pinned photodiode
Sense node
Column load
C_R
C_S
Reset voltage stored on C_R
Signal voltage stored on C_S
Buffer
Buffer
On chip
Off chip
Output
Difference amplifier

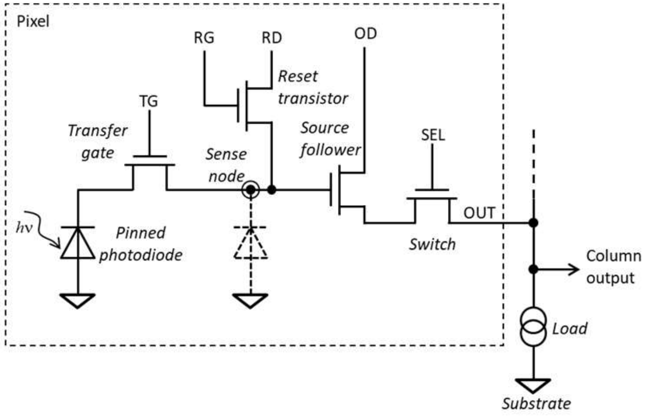

Row Address
Row Address + 1
Row Address + 2
SEL
RG
SHR
TG
SHS
Column Address
N
0
1
N

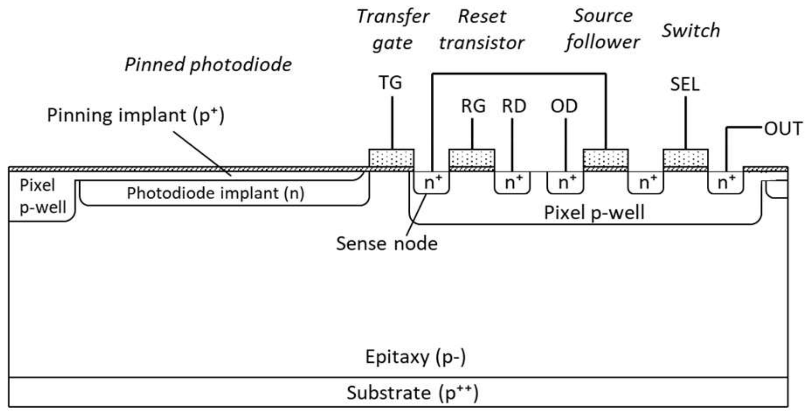
Readout (4)

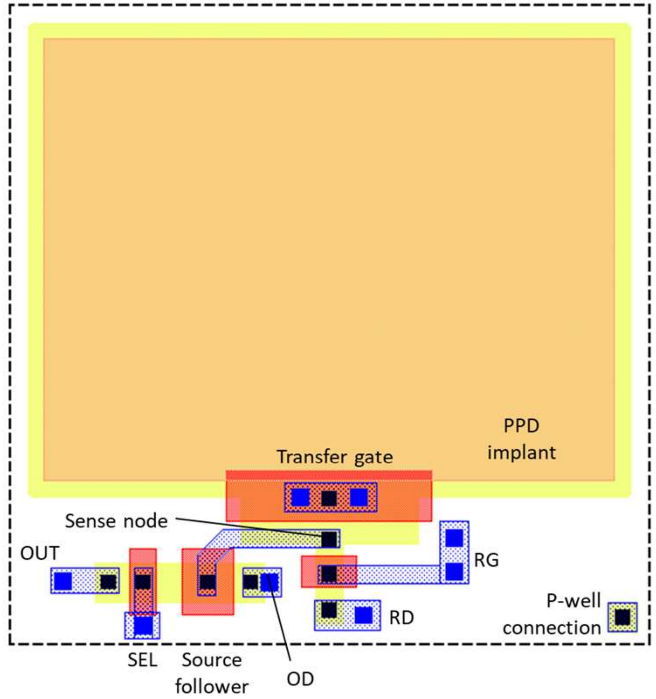

RG
RD
OD
TG
Column output
SEL
SHR = OFF
SHS = OFF
Pinned photodiode
Sense node
Column load
C_R
C_S
Reset voltage stored on C_R
Signal voltage stored on C_S
Buffer
Buffer
On chip
Off chip
Output
Reset voltage – Signal voltage
Difference amplifier


Row Address
Row Address + 1
Row Address + 2
SEL
RG
SHR
TG
SHS
Column Address
N
0
1
N

PPD (4T) pixel structure



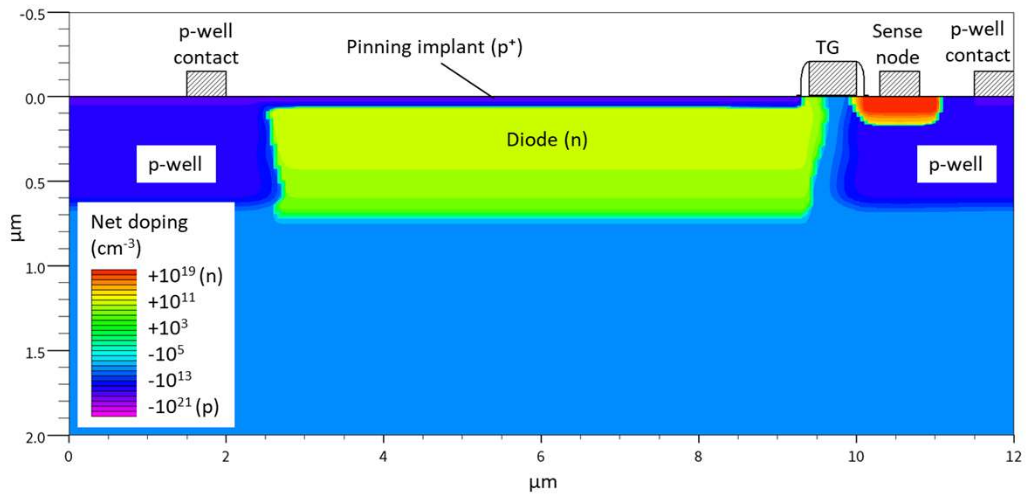


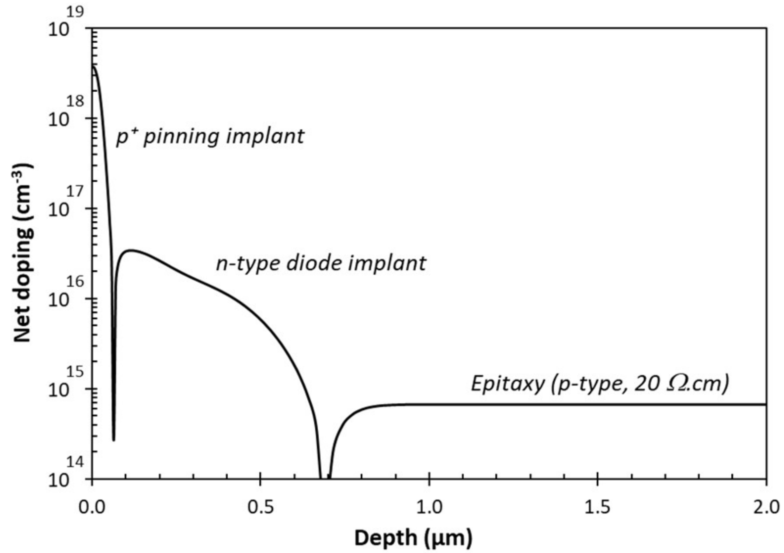


Why using the pinned photodiode?

- **Dark current below 1 pA/cm² at 20 °C**
  - **6.25 e⁻/s in 10 µm pixel, 0.0625 e⁻/s in 1 µm pixel**
- **High conversion gain in excess of >100 µV/e⁻**
  - **Charge-to-voltage conversion on a small sense node**
- **Low (even sub-electron) noise**
  - **"True" correlated double sampling done in the column readout**

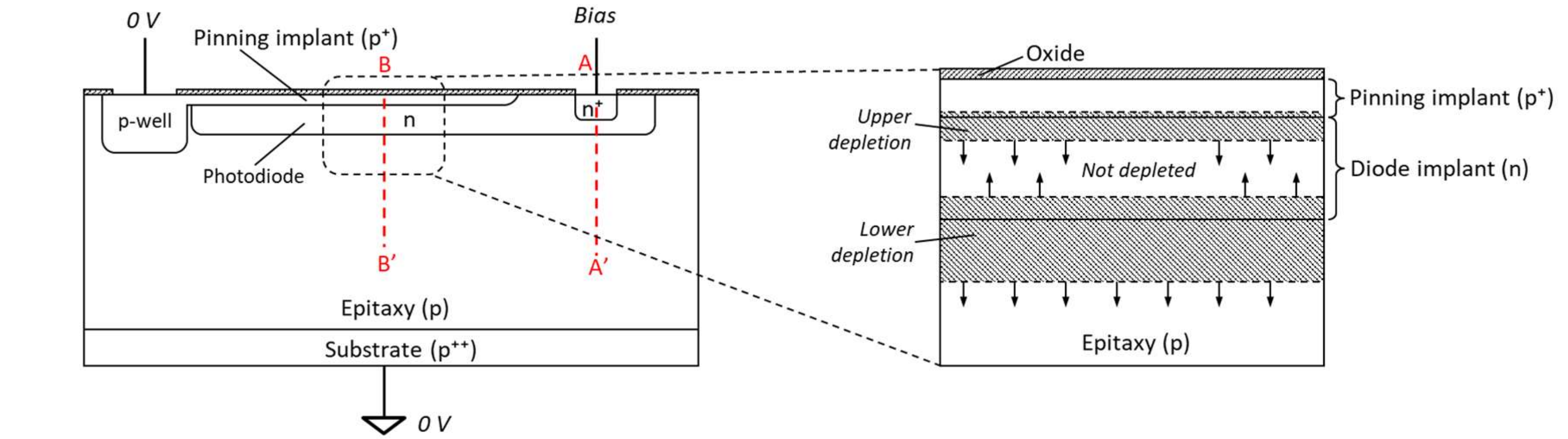
PPD structure

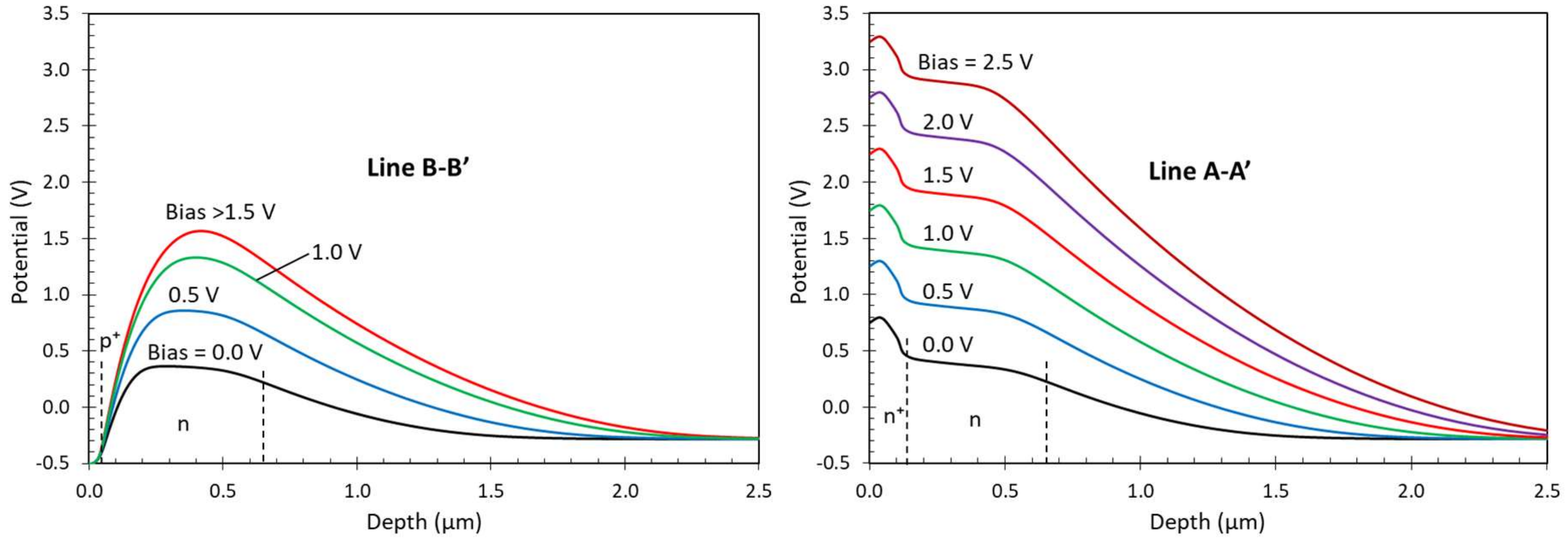




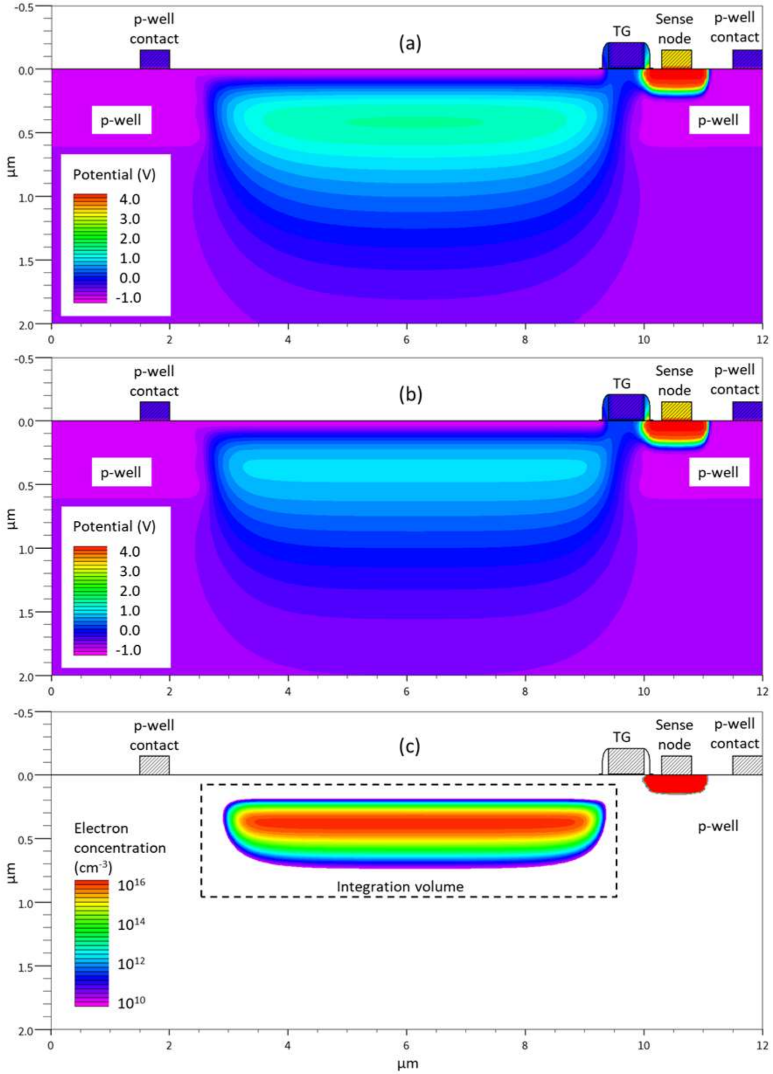
- N-type PPD (diode) implant covered by a shallow p^+ implant
  - The p-well is at substrate potential and connects to the pinning implant
  - The top of the PPD is fixed ("pinned") to substrate potential
- There is no direct electrical connection to the PPD

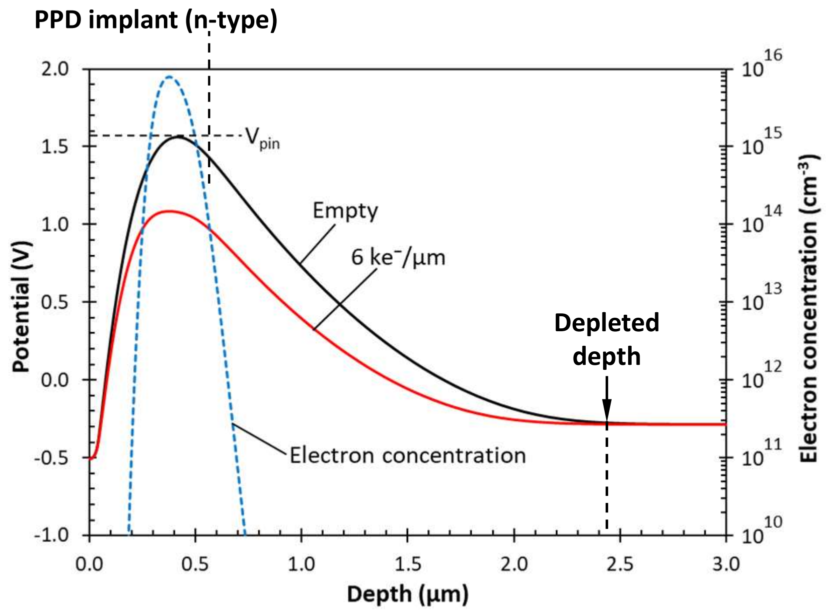
PPD operation – pinning and potential peak





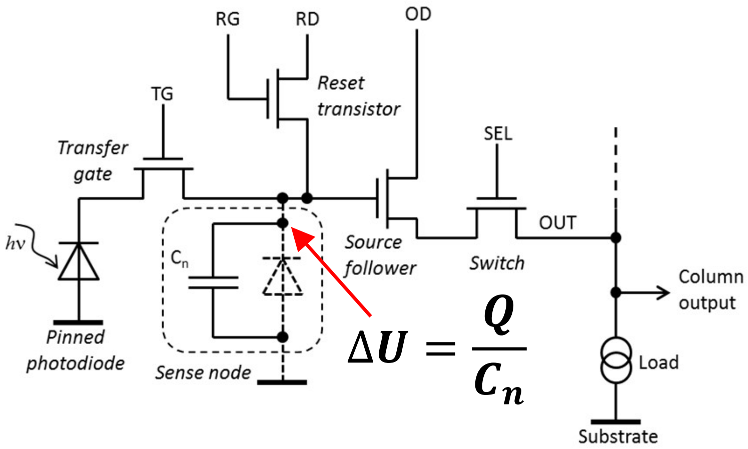
PPD operation



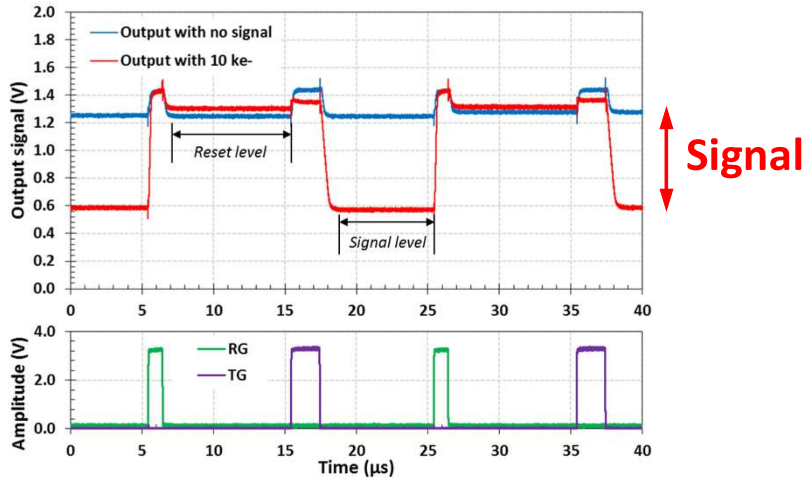


- Thin sheet of electrons "floating" in silicon, not touching anything
- Confined around the potential maximum by the pinning implant, the p-wells and the off-state transfer gate

4T pixel operation – an example

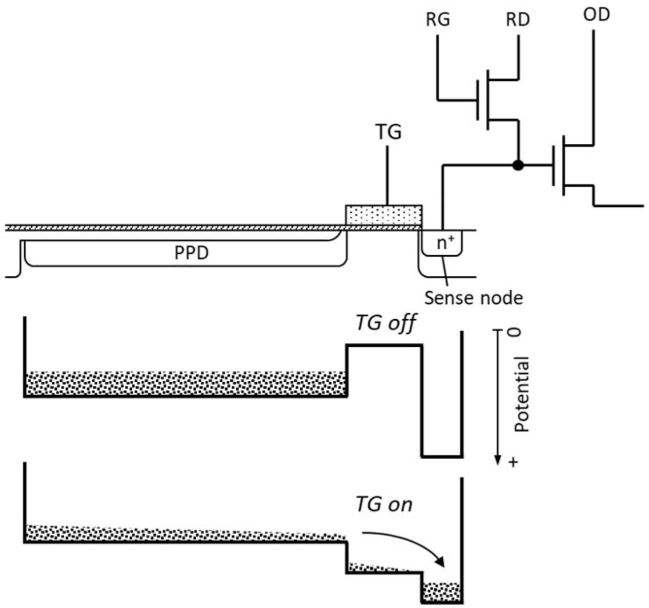


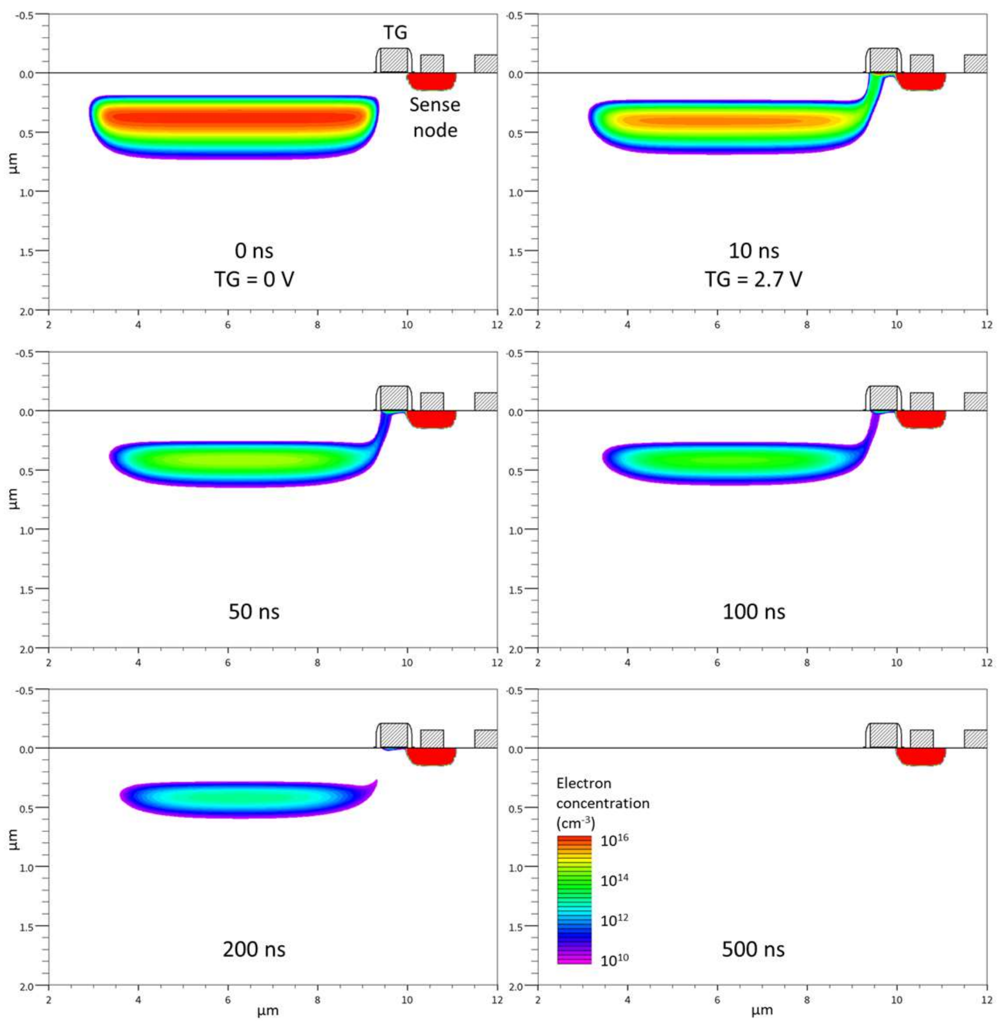
$$\Delta U = \frac{Q}{C_n}$$



- **After allowing sufficient time for reset, the reset transistor is turned off**
  - **The output level settles to the "reset level", almost the same for every pixel**
- **Charge transfer follows after TG is pulsed high**
  - **The output reaches the "signal level"**
- **The signal is the difference between the two levels**
  - **Due to the clocks coupling to the output, there will be "signal" even without transferring any charge**

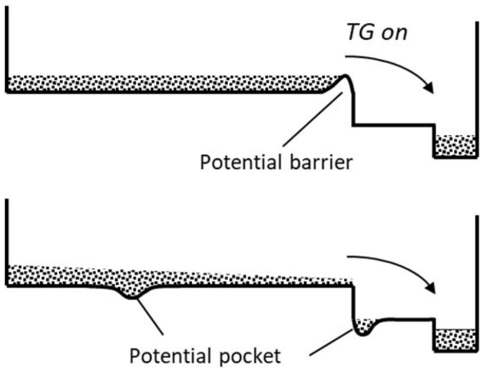
PPD – charge transfer

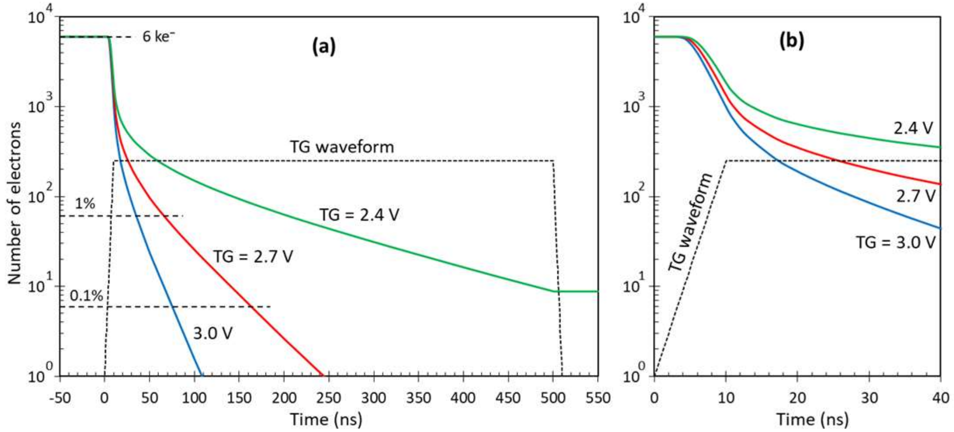




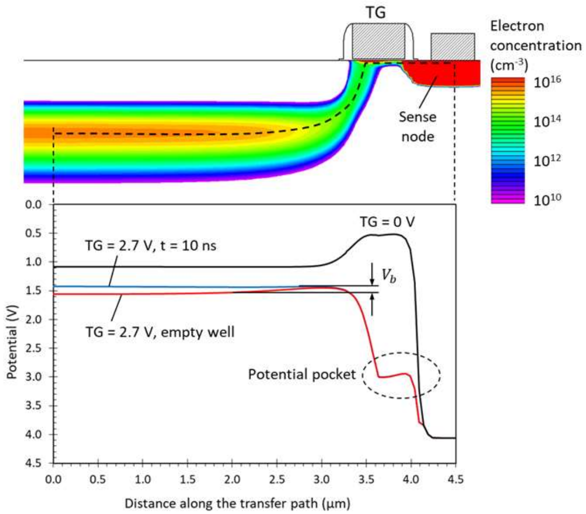
- **One of the strongest features of the PPD**
  - **Allows "true" CDS, low noise and high conversion gain**
- **At the same time – its weakest feature**
  - **Prone to inefficient transfer – image lag**
  - **Radiation damage weakness**

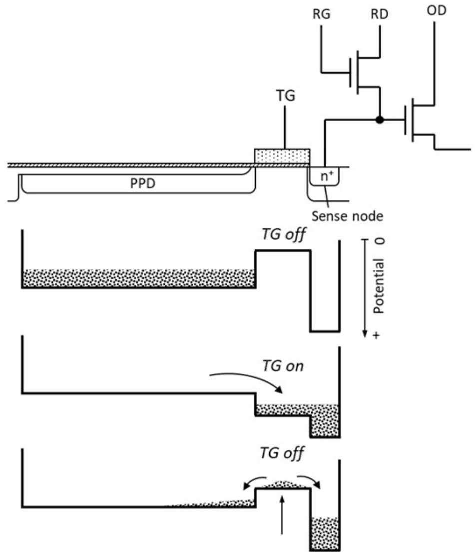
PPD – image lag



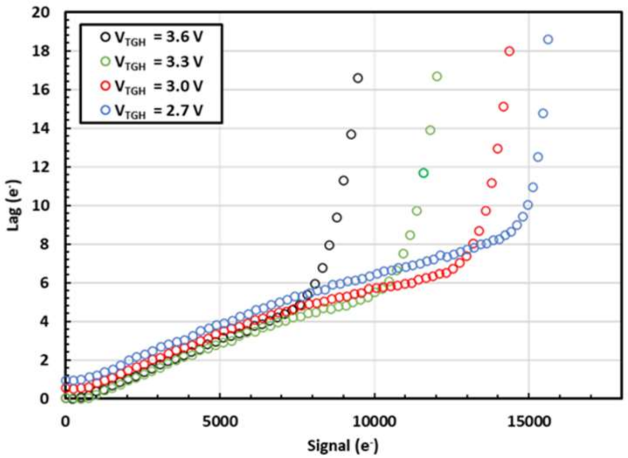


Simulated lag dependence on the TG voltage



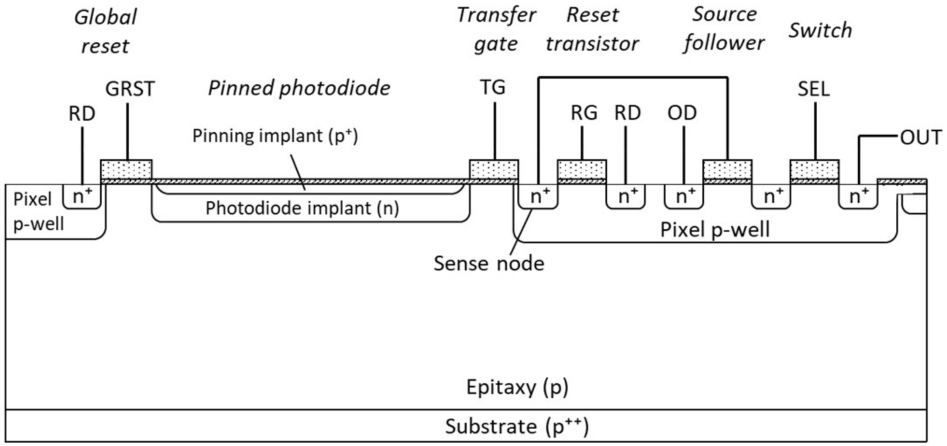


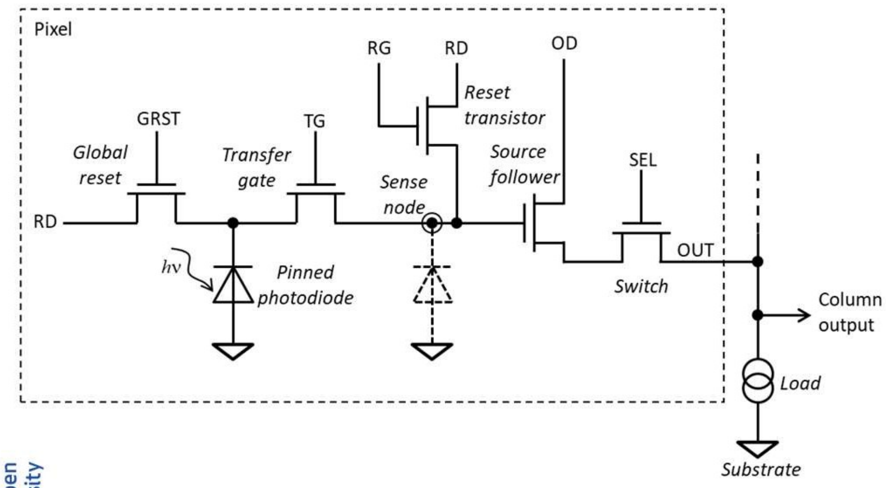
Charge spill-back at large signals



J. Ivory et al, Proc. SPIE 114540F (2020)

PPD-based complex pixels – 5T



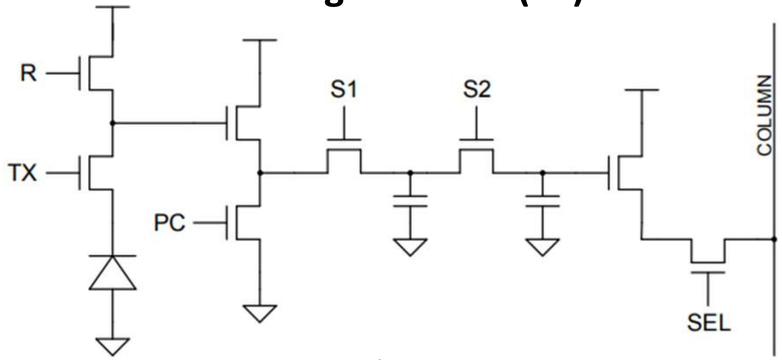


- **Global reset (5T)**
  - **A PPD can have more than one transfer gates**
- **Often used for global shutter readout without CDS**
  - **Device-wide charge transfer and reset**
  - **The reset level is measured after the global capture of the signal level**
  - **No (or poor) CDS, noise performance suffers**

C_n (fF)	CVF (μV/e⁻)	Reset noise (e⁻ RMS)
1	160	12.6
2	80	17.8
5	32	28.1
10	16	39.7
20	8	56.2

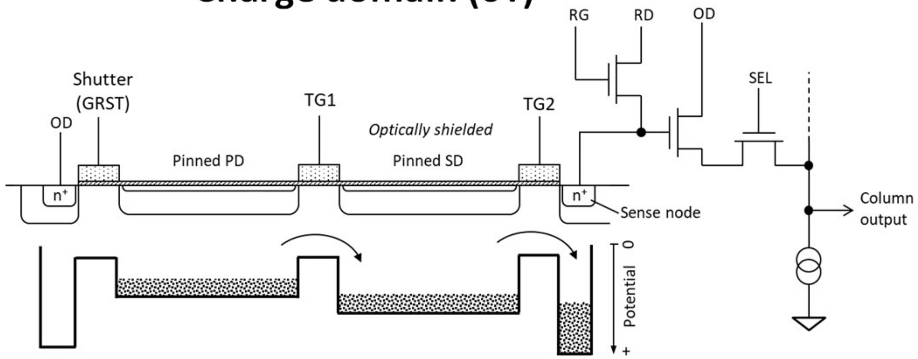
Global shutter imagers with in-pixel storage and CDS

Voltage domain (8T)



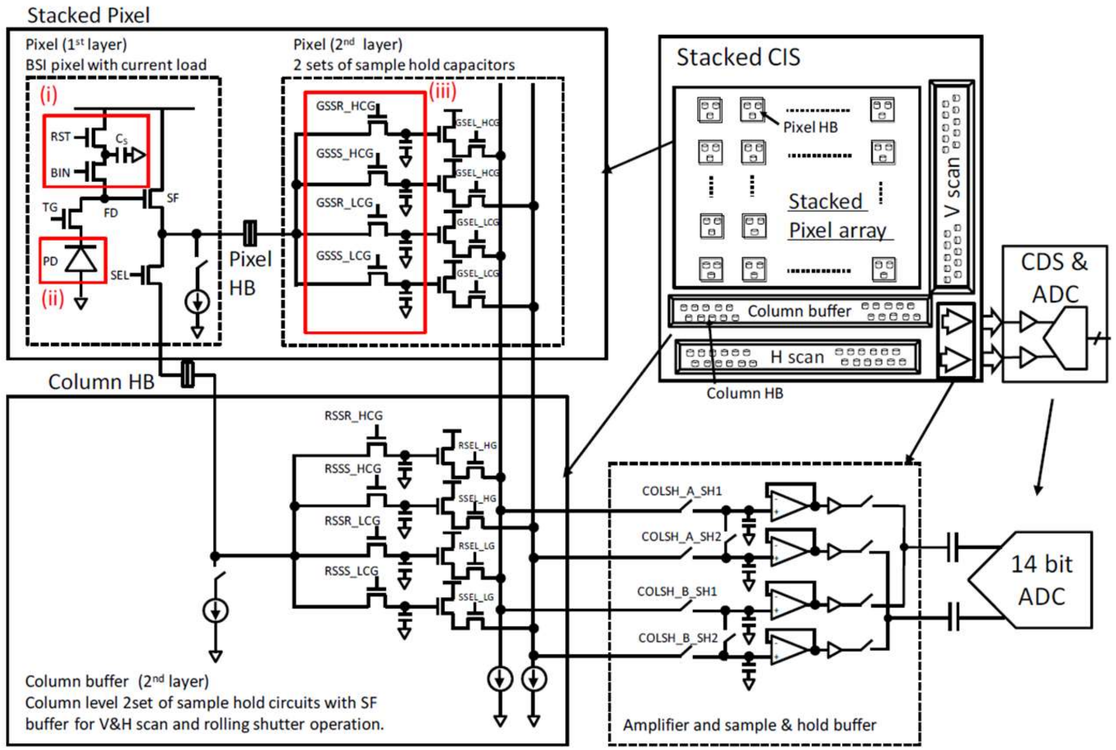
Meynants et al, IISW2017, R61

Charge domain (6T)



S. Velichko et al., IEEE Trans. Electron Dev., vol. 63, pp. 106-112 (2016)

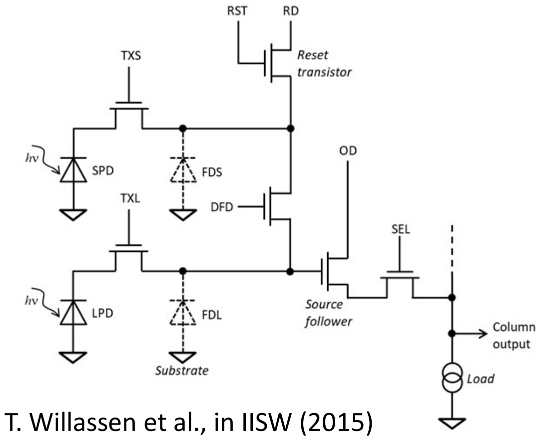
Voltage domain (3D stacked sensor)



K. Miyauchi et al., Sensors (2020), 20, 486

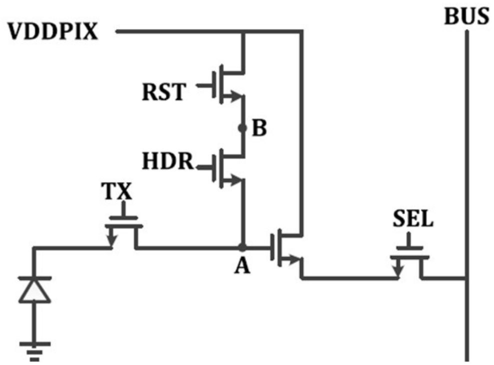
High dynamic range (HDR) methods

Dual photodiode



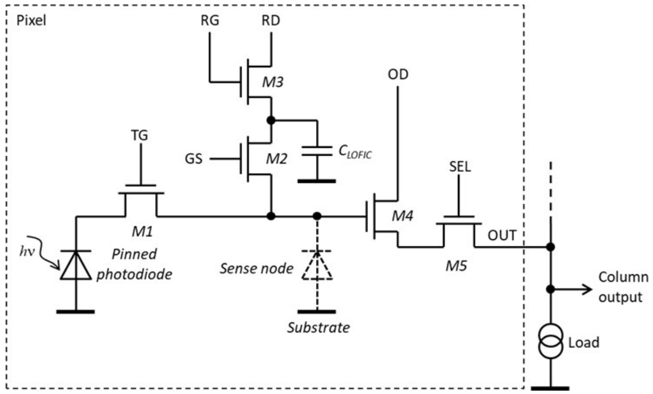
T. Willassen et al., in IISW (2015)

Multiple conversion gain

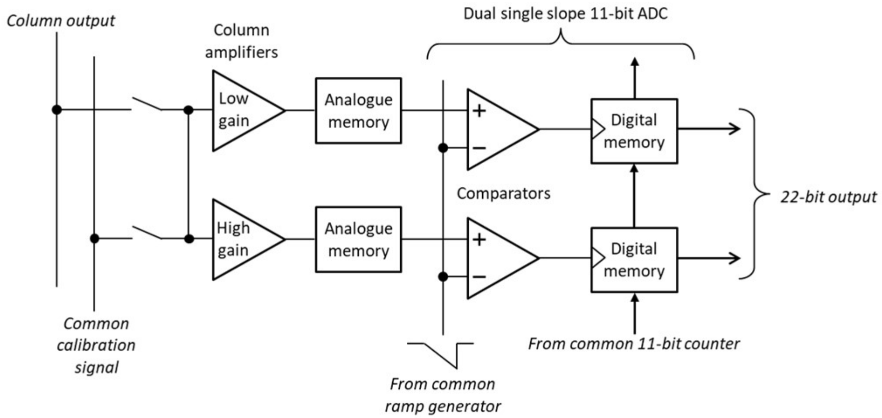


C. Ma et al. *IEEE Trans. Electron Dev.* vol. 64 (2017)

Overflow signal storage



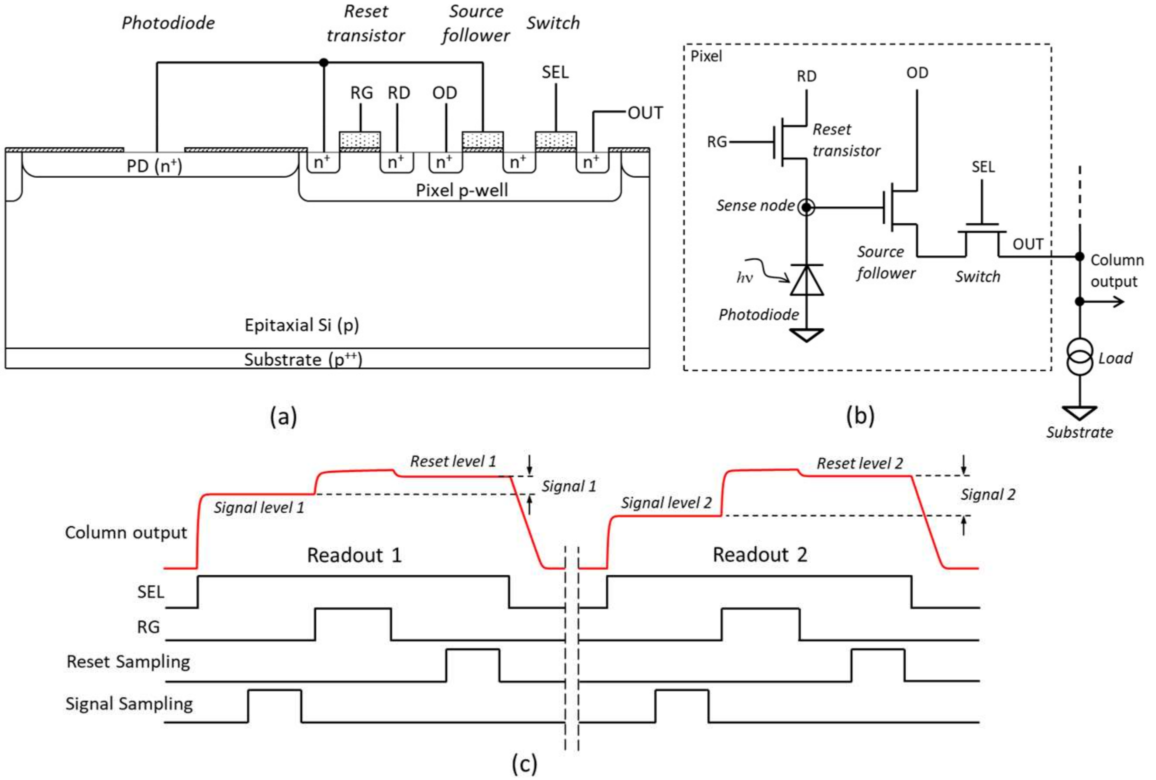
N. Akahane et al., *IEEE Journal of Solid-State Circuits,* vol. 41, (2006)



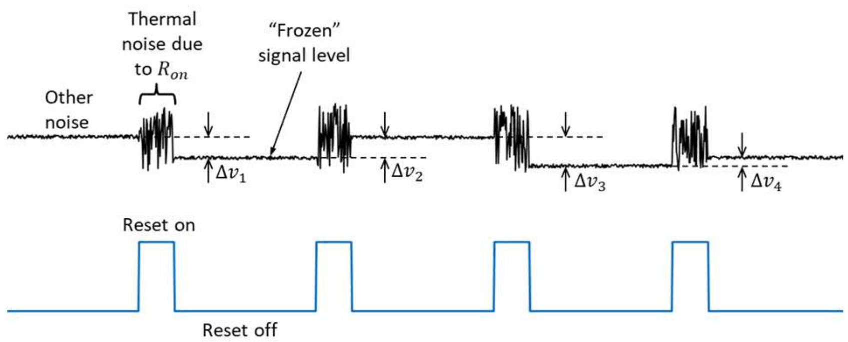
P. Vu et al., in IISW (2011)

- **Many image sensors use HDR techniques**
- **Dual column gain and ADCs – uses normal 4T pixel**
- **Dual photodiode**
- **Multiple conversion gain**
- **Overflow signal storage - lateral overflow integration capacitor (LOFIC)**

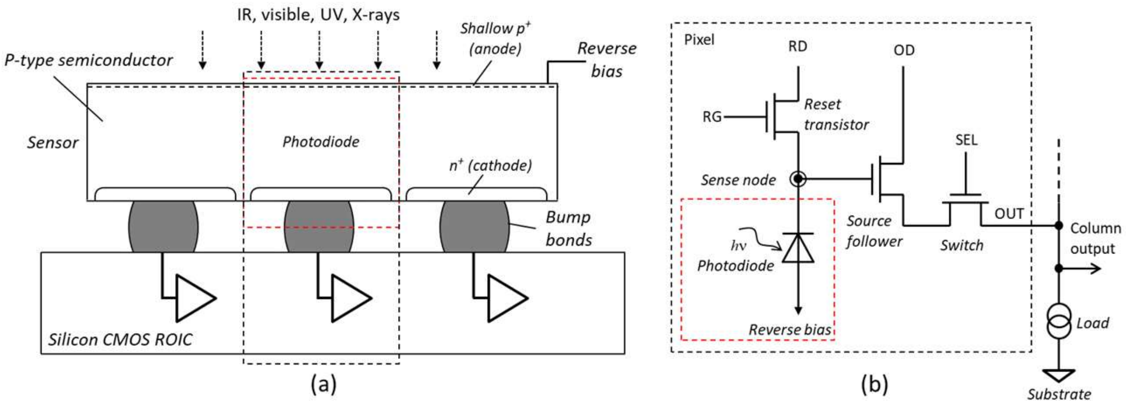
Other pixel architectures – 3T

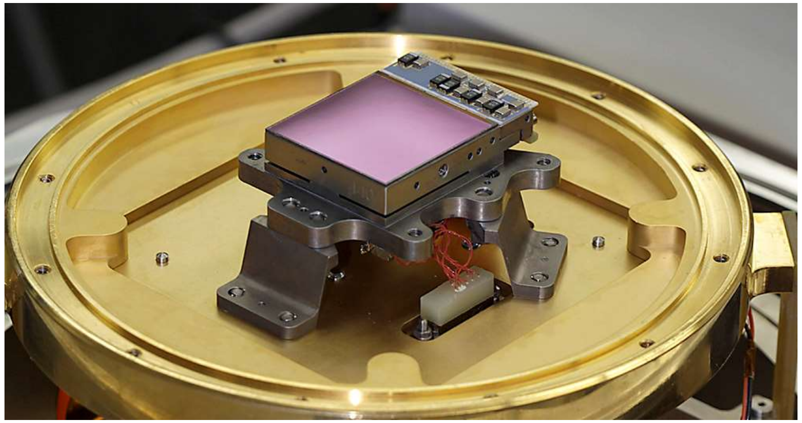


- The first pixel architecture, developed in the 1960s
- Forms the basis of all modern pixels
- Still used in very large pixels and high-speed imaging
- Charge collection and conversion to voltage done at the photodiode
- Suffers from reset noise (no CDS without separate image storage)
- Strong fixed pattern noise
  - Each source follower has its own threshold



Hybrid sensors





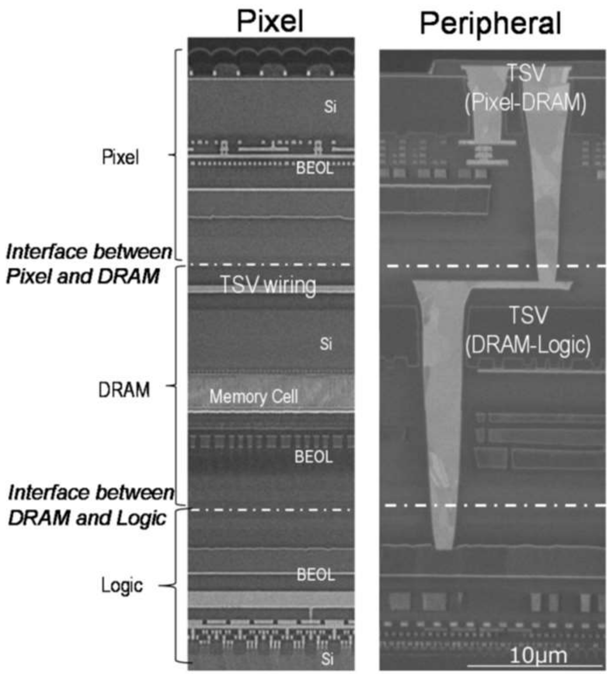
Credit: University of Arizona/NASA

- **Used mostly for infrared imaging**
  - **Also X-rays, visible and UV with a choice of sensor semiconductor**
  - **Higher noise and lower conversion gain than monolithic sensors**
- **Prime example – H2RG series of HgCdTe sensors, NIRCam in JWST**
- **3T pixel architecture is very common**
- **Transimpedance amplifier per pixel also used**

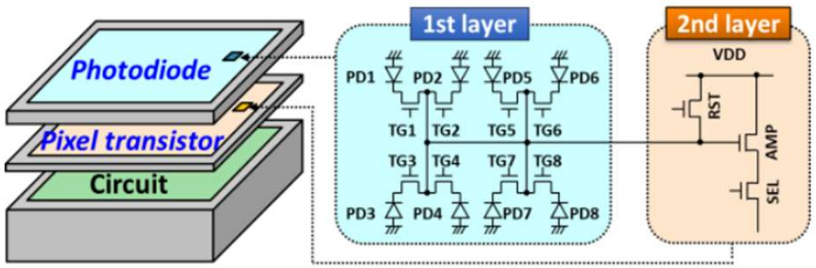
Credit: NASA, ESA, CSA, Jupiter ERS Team; image processing by Judy Schmidt.

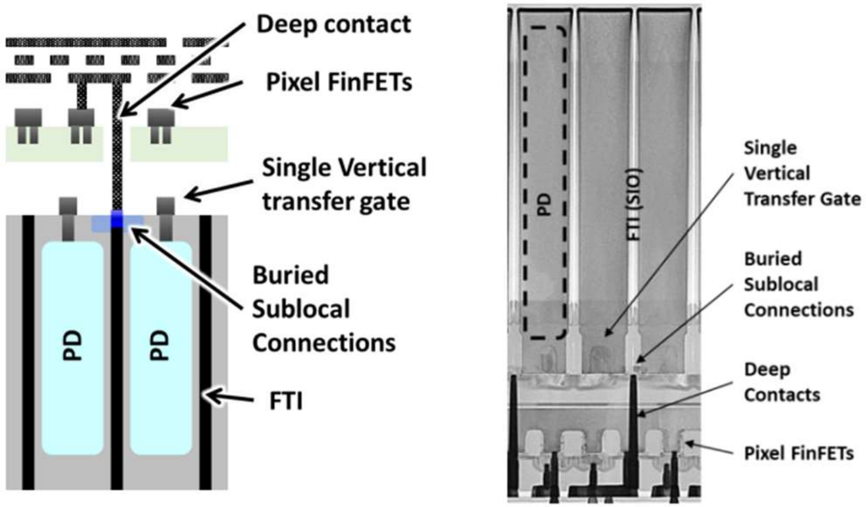
Recent sensor developments – 3D integration

- **3D integration by Sony:**
  - **In 2019: imager, DRAM, logic tiers**
  - **In 2023: PPD, source followers, digital tiers on 0.6 µm pixel pitch**



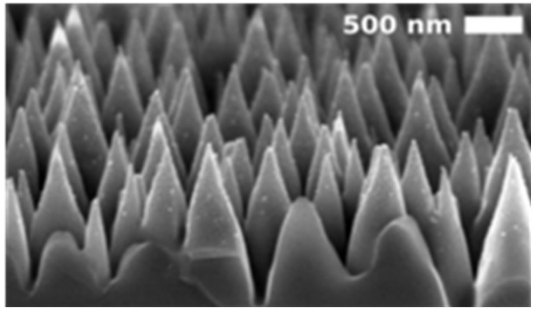
Y. Kagawa and H. Iwamoto, in *International 3D Systems Integration Conference (2019)*

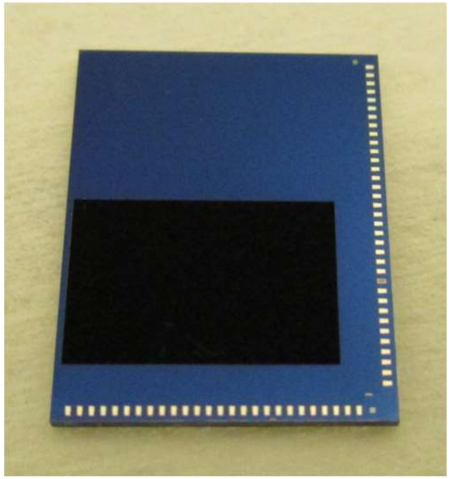




M. Sugimoto et al., in *IISW (2023), R1.2*

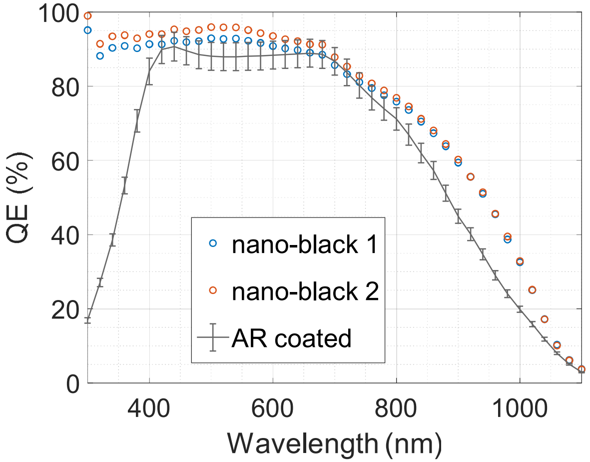
Recent sensor developments – NIR sensitivity in silicon





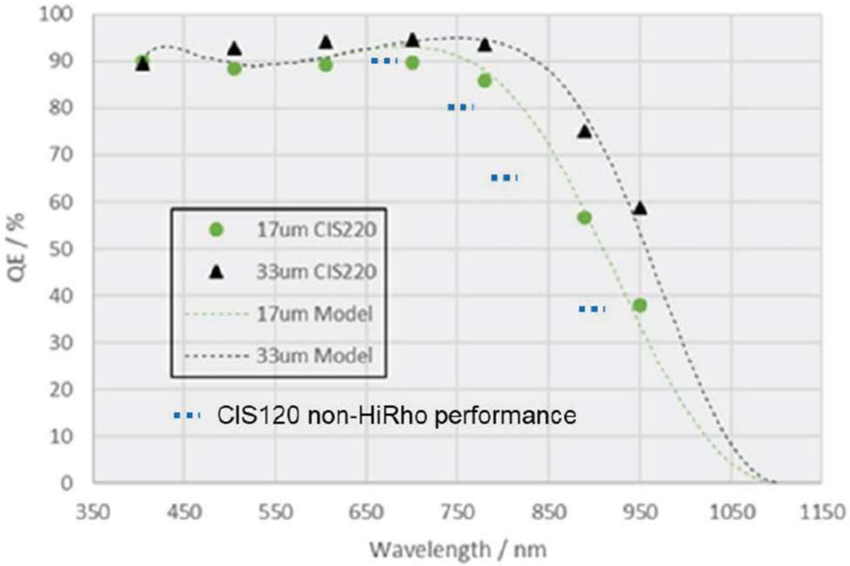
Prest et al., IISW2023 R3.5 (2023)

Black silicon



- **Methods to increase the photon path used by many manufacturers**
- **NIR-enhanced sensors**
- **Some claim sensitivity up to 1200 nm!?**

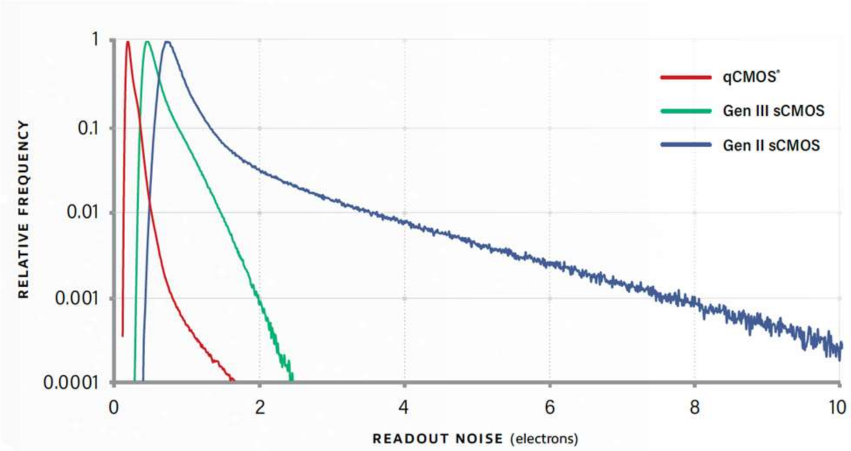
Thick, fully depleted, reverse-biased PPD CMOS sensor



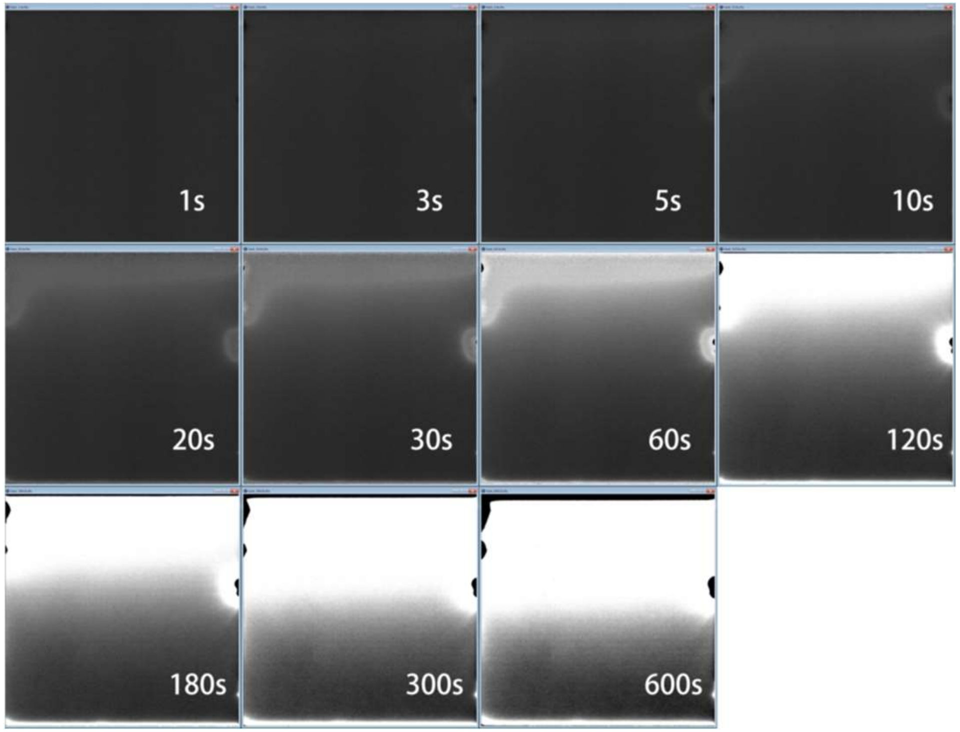
Pratlong et al., Proc. SPIE 1277712 (2023)

Challenges

- Image glow
- Random telegraph signals and noise
- Image lag for large pixels
- Hot pixels
- Non-linearity at the gain switching point
- Gain distribution
- Signal-dependant baseline shift

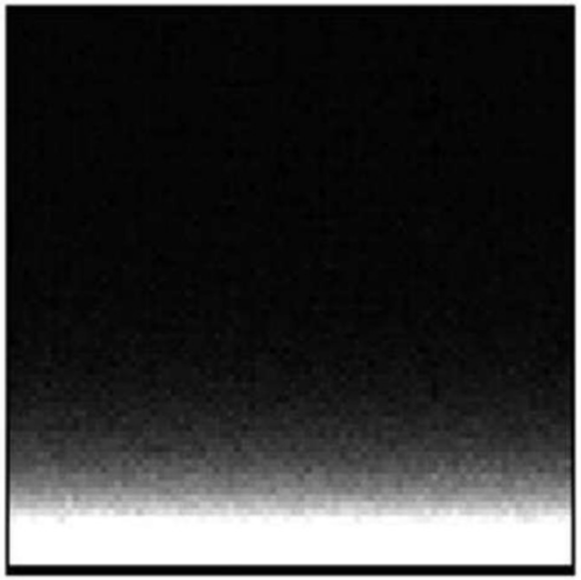


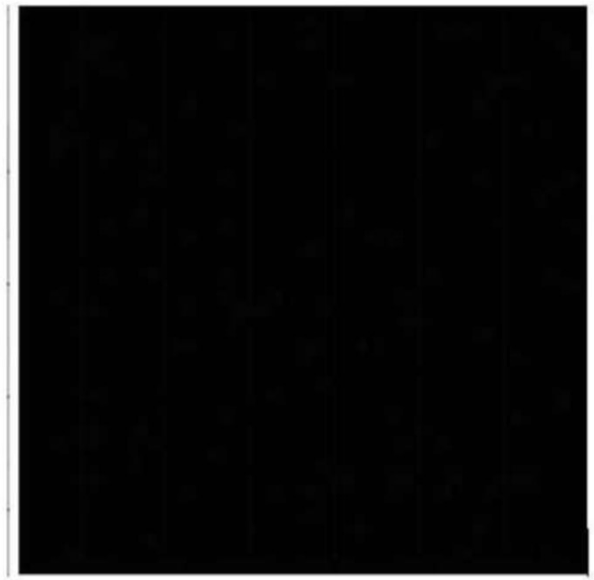
qCMOS, Hamamatsu Photonics (2023)

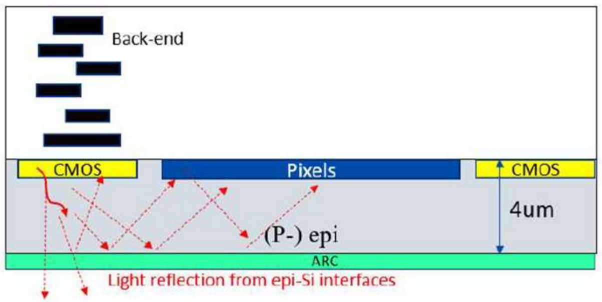


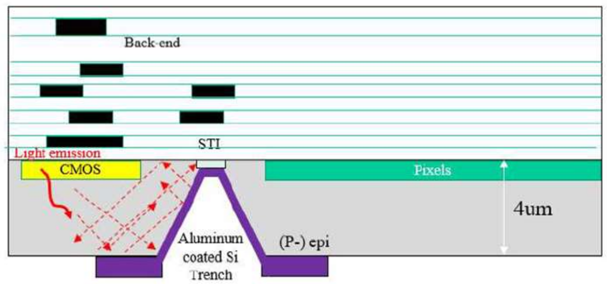
Peng Qiu et. al, 2021 Res. Astron. Astrophys. 21 268

Image glow







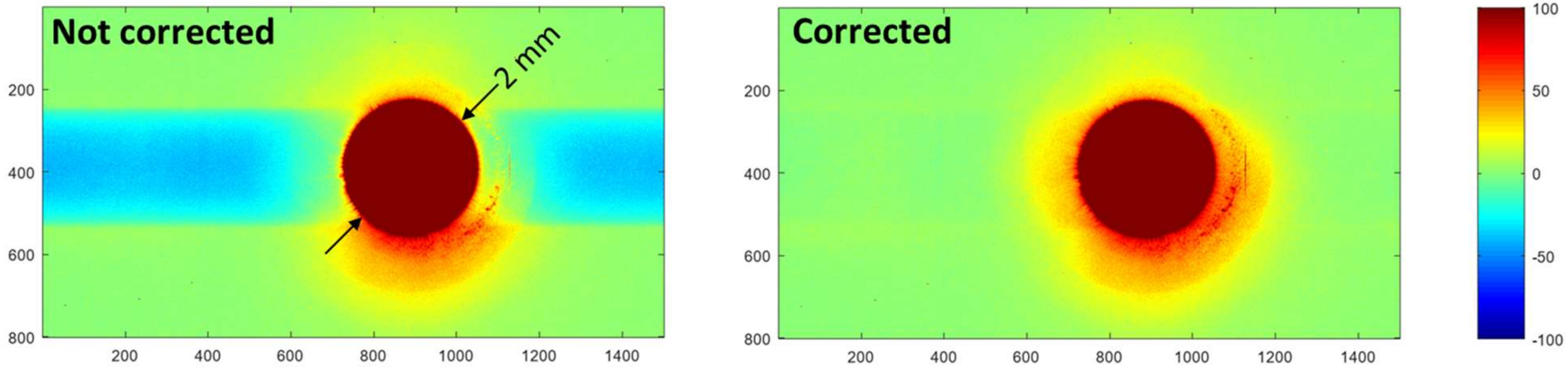


- **“Optical trench” developed by TowerJazz**
- **Image glow is eliminated**
- **Dark current = 0.02 e⁻/s at -50 °C**
- **9.5 µm pixel**

A. Birman et al., in *IISW (2023), R6.2*

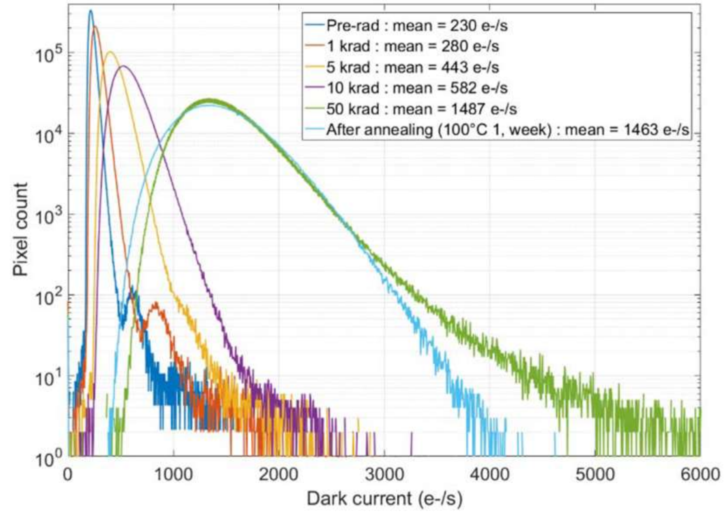
Signal-dependent baseline shift

- When projecting a large bright spot, the signal baseline in the same rows becomes negative
  - Undesirable when viewing bright objects such as planets and comets
  - The effect is ≈1% of the signal, becomes non-linear after saturation
  - Present at any illumination level and any spot size, but may be harder to see
  - Depends on the operating conditions – timing, bias currents, supply voltages
- Not part of any specification and not tested against
  - Believed to be a form of electrical crosstalk between pixels in the same row
- First order linear correction appears to work well

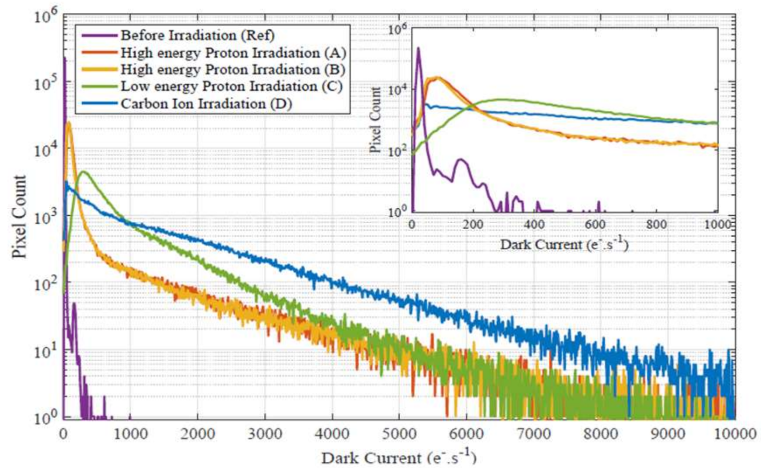


Radiation damage effects

- CMOS sensors have high radiation tolerance in general
  - Thin oxides
  - One or zero charge transfers
- Ionising radiation:
  - 4T pixels have been demonstrated to work after 500 krad
  - At high TID the pinning implant becomes ineffective, image lag deteriorates
  - Normal requirement is between 10-50 krad, >100 krad for deep space
  - Specialised 3T pixels survive 100 Mrad
- Non-ionising (bulk) damage – not much different from any other silicon sensor
  - Dark current tail, hot pixels, RTS, image lag
- Single event effects (SEE)
  - Transients, upsets, functional interrupts, latch-up
- Characterising commercial sensors could be cost-effective



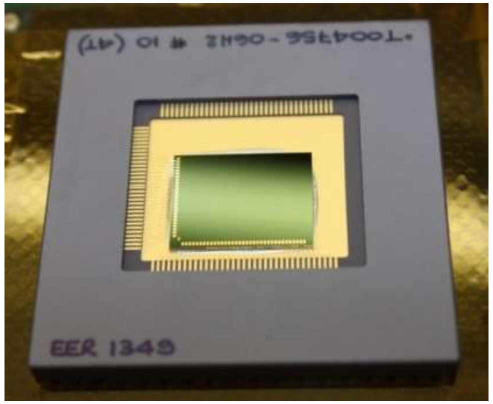
C. Virmontois et al., IEEE TNS vol. 60 (2019)



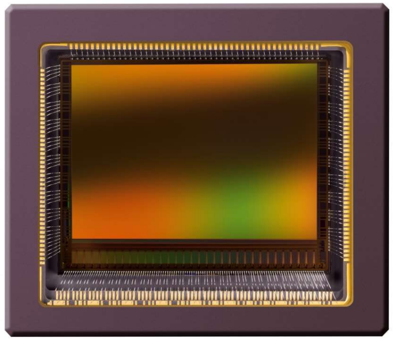
A. Le Roche et al., IEEE TNS vol. 59 (2018)

CMOS imagers in space

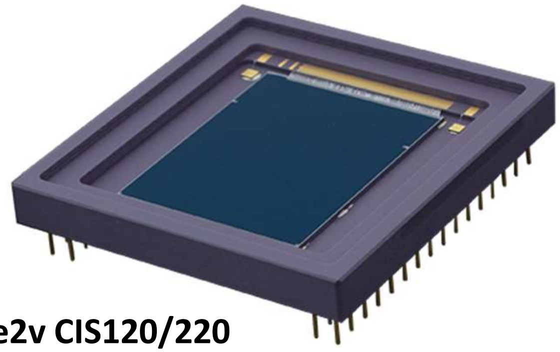
- Star trackers
  - HAS2 (3T) and HAS3 (4T)
- Science, navigation, hazard avoidance, descent
  - Many sensors on board Perseverance – e.g. CMV4000, CMV20000, PYTHON5000
  - Camera on Mars Express since 2003
- Solar Orbiter
  - Several 3T and PPD-based image sensors
- JUICE JANUS
  - En route to Jupiter, arriving 2031
- Future:
  - GSENSE1516BSI (X-rays) – The Einstein Probe
  - CIS120 and CIS220 (CO2M Copernicus)



Te2v CIS115
(3 Mpixel, 7 µm)



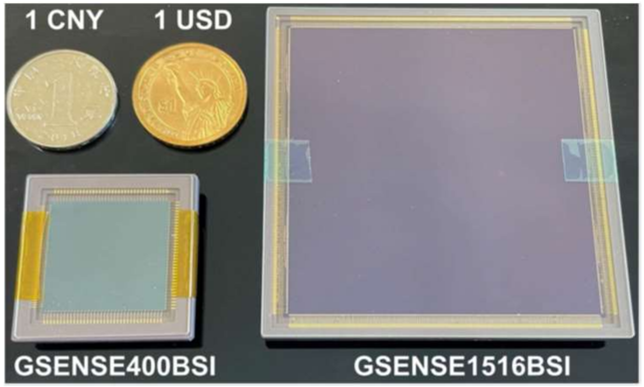
ams OSRAM CMV20000
(20 Mpixel, 6.4 µm)



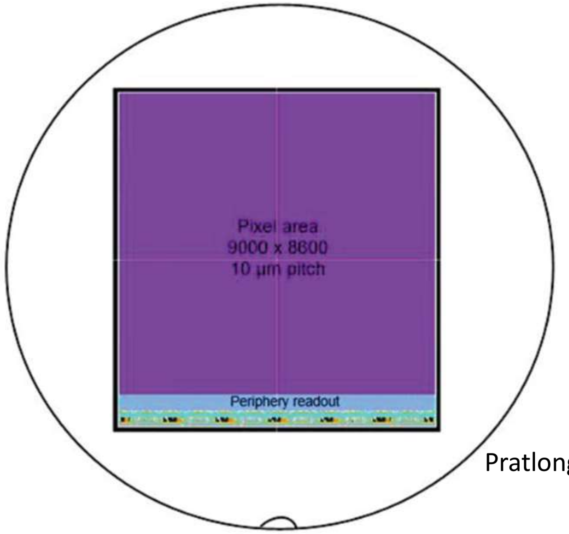
Te2v CIS120/220
(4 Mpixel, 10 µm)

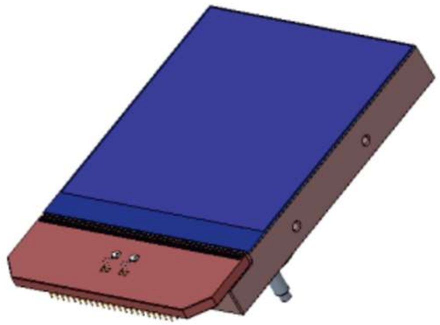
Large area imagers

- **Gpixel:**
  - **4096×4096 pixels (15 µm), 6×6 cm**
  - **5 e⁻ noise, 20 fps, 1.6 W**
  - **Einstein Probe – will be the biggest CMOS camera in space (but only for X-rays) – 1800 cm^2, 48 sensors**
- **Te2v's CIS300 series – first devices made**
  - **9000×8600 pixels (10 µm)**
  - **8 fps, 12-14 bits**
  - **Dual gain, HDR, rolling and global shutter**



Q. Wu et al., Publ. Astron. Soc. Pac. 134(1033), 035006 (2022)

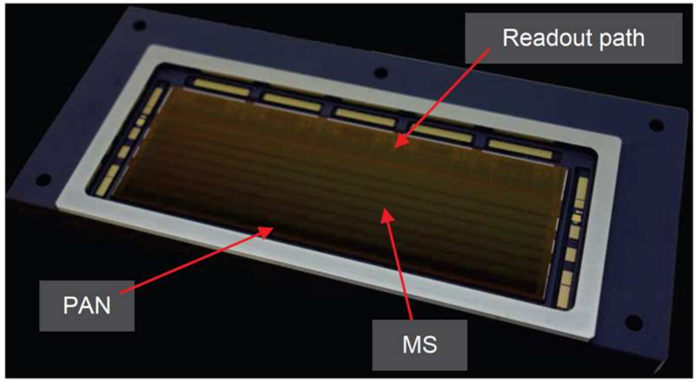




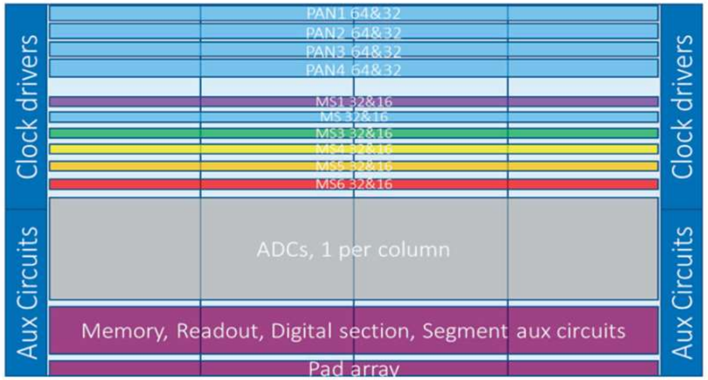
Pratlong et al., Proc. SPIE 1277712 (2023)

TDI imaging

- **Charge domain signal summing – high SNR**
  - **Earth observation from low orbits**
  - **Planetary imaging**
- **TDI in CMOS (essentially CCD-in-CMOS)**
  - **Other applications in science? CCD alternative?**
- **Example - CIS125 from Te2v**



Pratlong et al., Proc. SPIE 1277712 (2023)



The use of CMOS image sensors in science and space

- CMOS image sensors used for:
  - Fast readout rates, reduction of motion distortions (global shutter)
  - Very low noise
  - Small pixels
  - Compactness
  - Radiation hardness
  - Low power
- Many applications in high frame rate imaging
  - Solar system exploration, high-rate observations (NEO, space debris), life sciences, spectroscopy
  - Many sensors for "fast astronomy" – lucky imaging, wavefront sensing
  - Many commercial devices and cameras available
- "Proper" long integration time astronomy applications are very rare

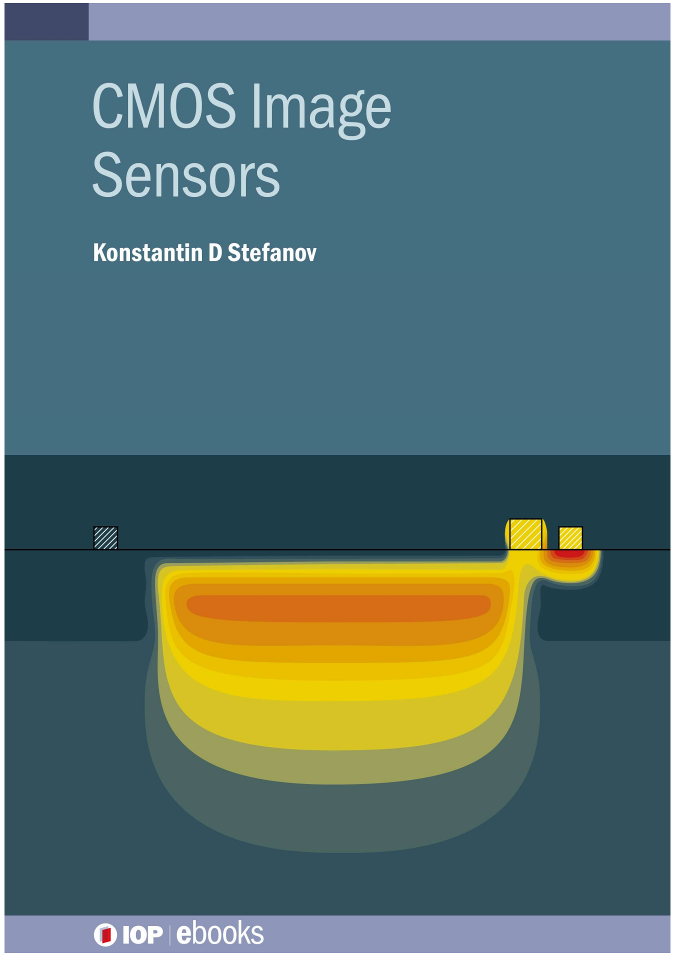
Future trends

“Predicting the future”

Prediction is very difficult, especially if it's about the future.
Niels Bohr

- **Almost all sensors will be BSI**
- **Sub-electron readout noise, leading to photon counting**
- **Multi-tier silicon, 3D integration – will allow 4-side butting, large focal plane arrays, enhanced functionality**
- **High QE, thicker silicon, “black silicon”**
- **Low noise global shutter**
- **CCD-in-CMOS beyond TDI imaging**

Further reading



- Most of the material presented here is from my book
  - Main reason for the invitation to give this talk
- Published in 2022
- Available from IOP Publishing and Amazon
- I am not getting money from any sales
- Discount code available – ask me