Uncooled Long Wave Infrared Sensors/Cameras

Sander Gierkink
Teledyne Dalsa

Eindhoven, the Netherlands

26 September 2024

Outline

- Long Wave Infrared (“LWIR”) basics
- Vanadium Oxide (V_xO_y) MEMS bolometer pixel
- Wafer bonding for vacuum pixel packaging
- CMOS Read Out IC (“ROIC”) design

Long Wave Infrared (LWIR) Basics

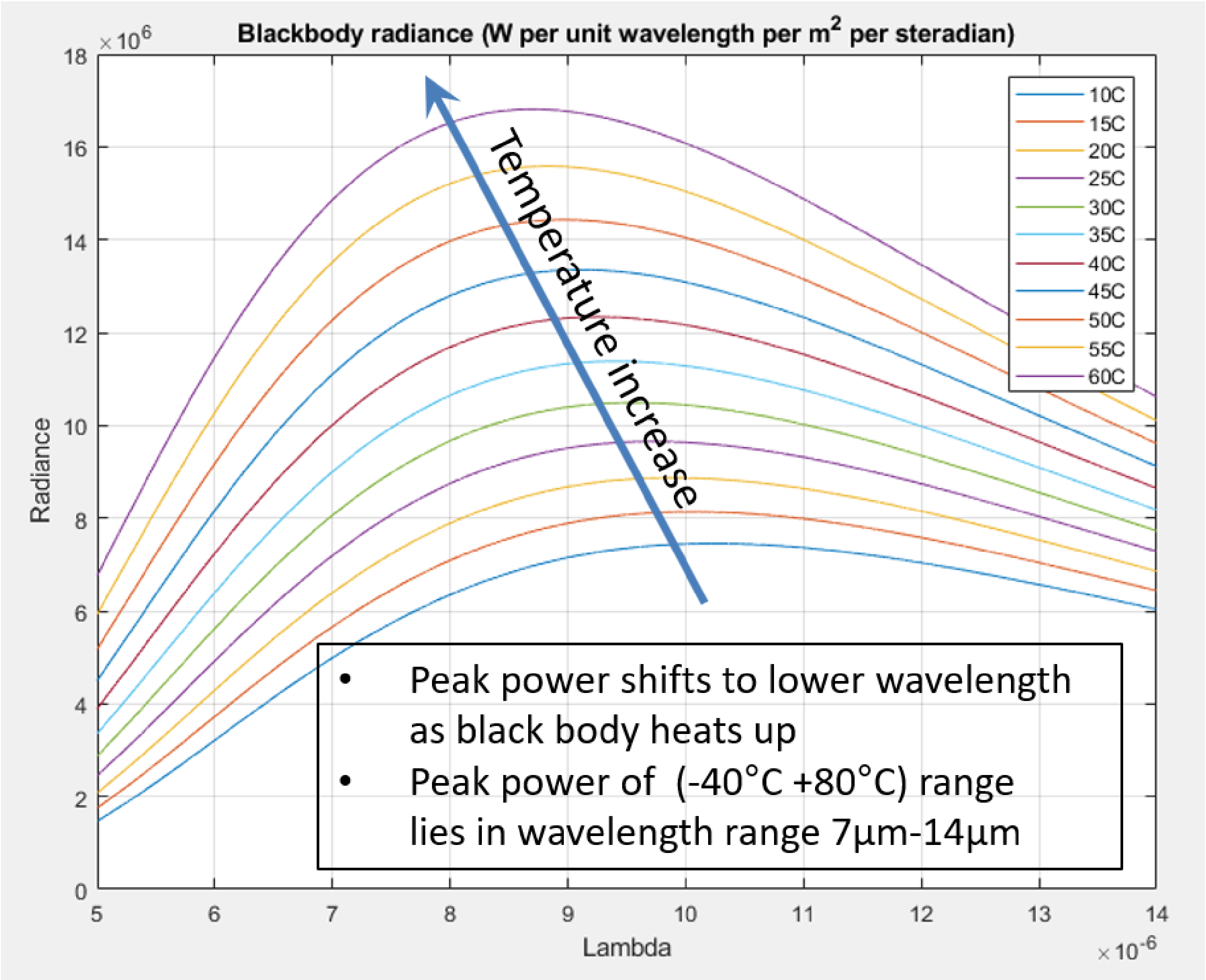
Planck’s law of Blackbody radiation

Black Body: opaque, non-reflective object

A black-body’s self-radiated power at a given wavelength depends only on its temperature T

Yes blackbody **No blackbody**

Ideal blackbody radiance B(λ,T) versus wavelength λ



https://en.wikipedia.org/wiki/Black-body_radiation

Why not use Silicon Solid-State pixels for Long Wave Infrared (LWIR) detection?

Energy of LWIR photons is too small to generate free electrons
with classic Si bandgap

→ requires "exotic" materials like for example **Mercury Cadmium Telluride (MCT)**

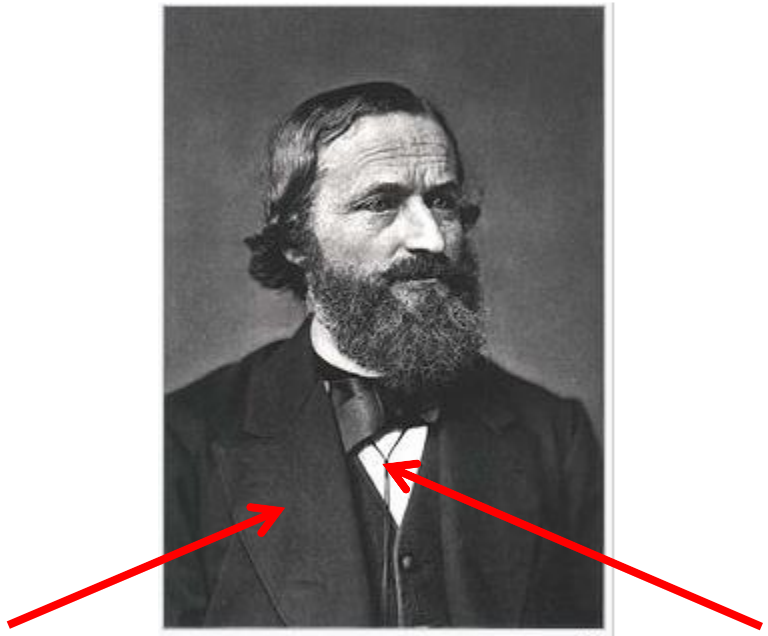
MCT has a chemically tunable bandgap

https://en.wikipedia.org/wiki/Mercury_cadmium_telluride

Kirchhoff's law of Thermal Radiation

Relationship

Absorptivity ↔ Emissivity ↔ Reflectivity



Gustav Kirchhoff (1824–1887)

Takeaway for us dummies:

1. Emissivity = absorptivity → a black body is both a good absorber and good emitter of thermal radiation
2. reflectivity = 1 – absorptivity → a reflective (“shiny”) material is a poor absorber, and also a poor emitter

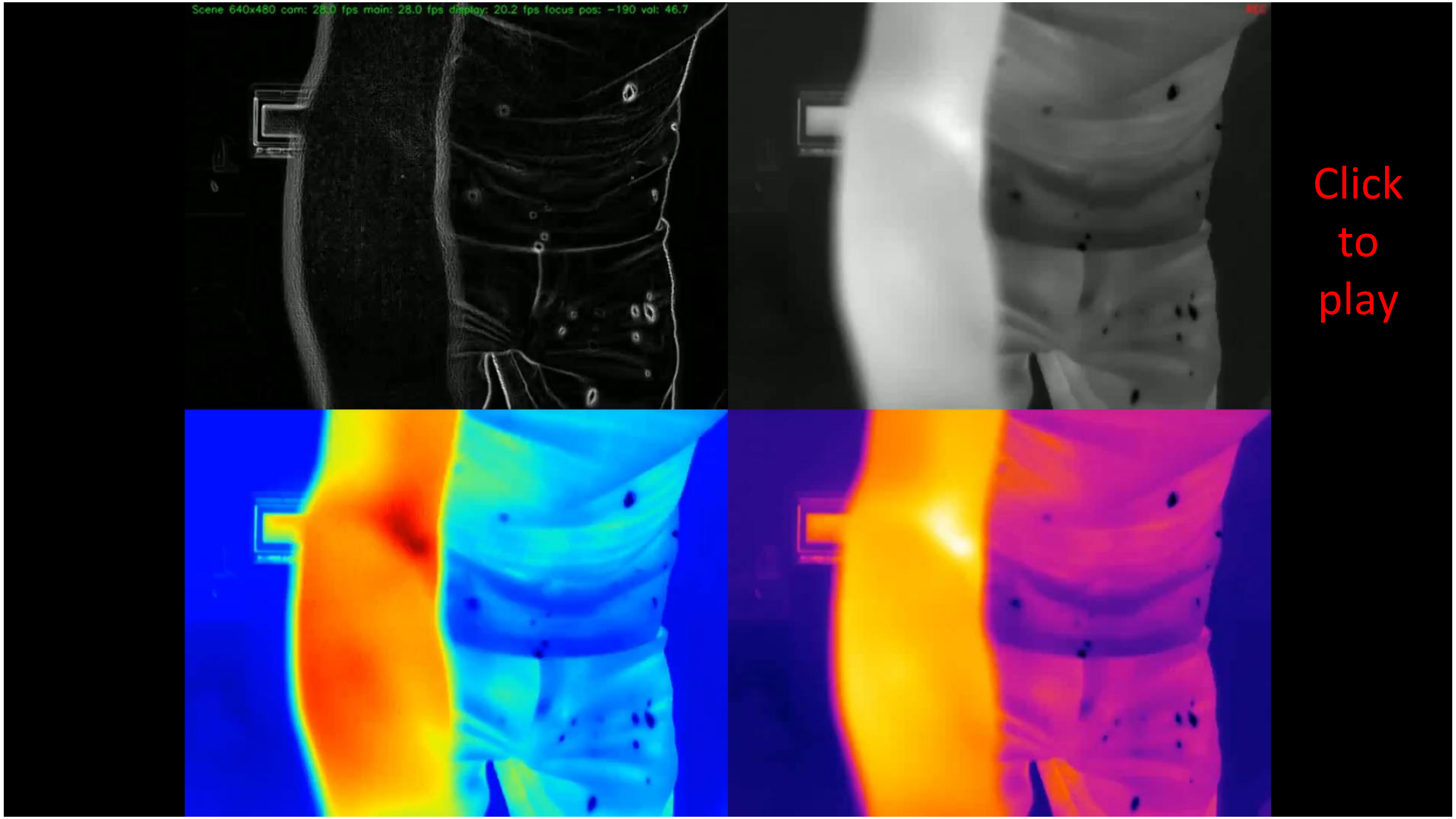
https://en.wikipedia.org/wiki/Kirchhoff%27s_law_of_thermal_radiation
https://en.wikipedia.org/wiki/Gustav_Kirchhoff

Comparison of emissivity

Experiment:
partially paint a shiny metal object black,
heat it up,
and image it.

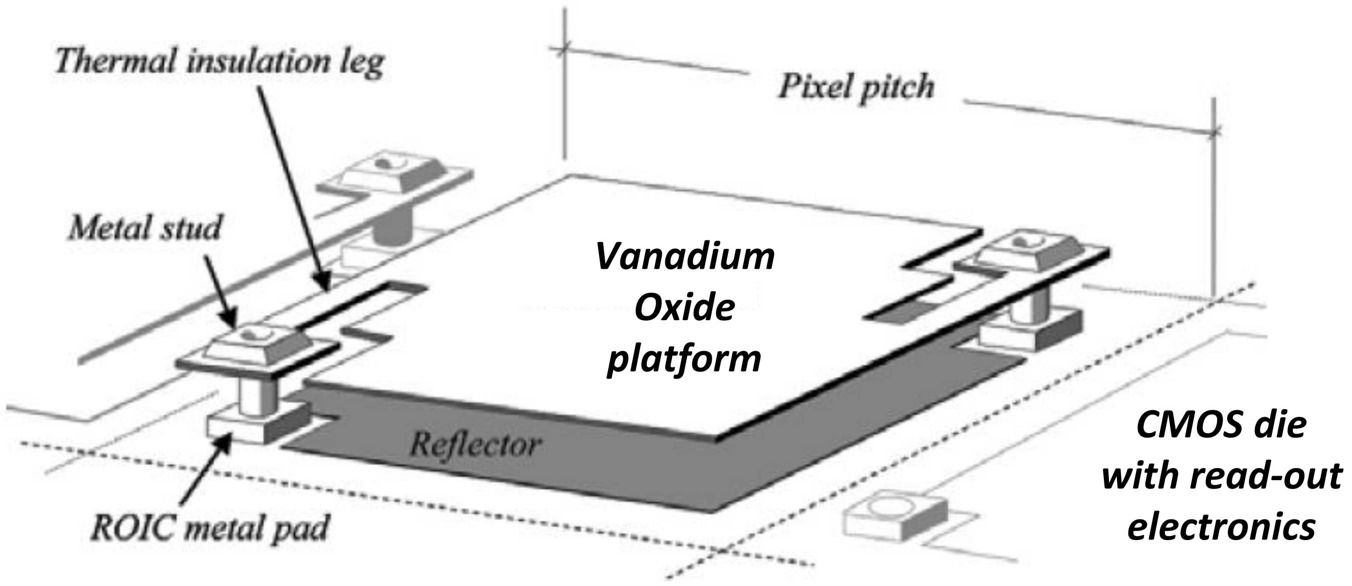
Takeaway:
A true radiometric* LWIR camera requires the object's emissivity to be known.

*) calibrated camera with absolute temperature reading



Vanadium Oxide (V_xO_y) Bolometer Pixel

MEMS Bolometer Pixel

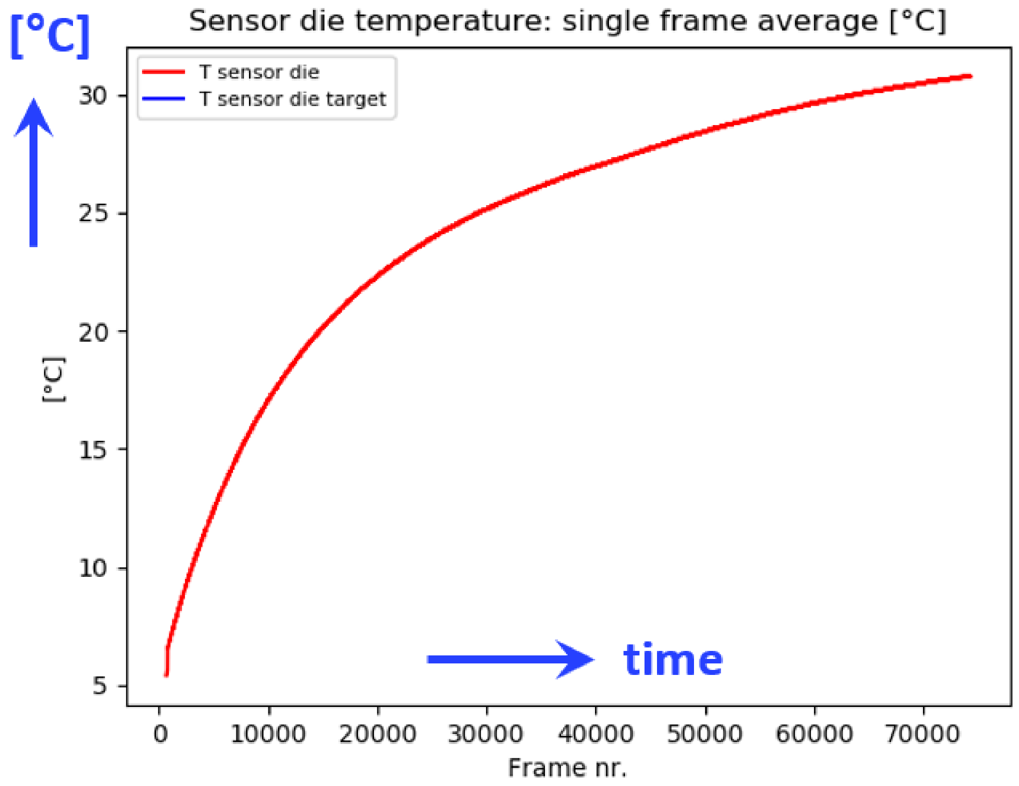


- MEMS pixel built on top of CMOS wafer (20+ masks)
- Infrared heats up Vanadium Oxide → resistance change → converted to digital code in CMOS
- Pixel has long, thin legs for high thermal isolation→ improves thermal sensitivity
- Pixels are operated in vacuum to prevent energy loss towards air
- Vacuum: created by using wafer level packaging under vacuum
- Metal reflector below pixel at λ/4 to improve absorption (“Fabry-Perrot”)

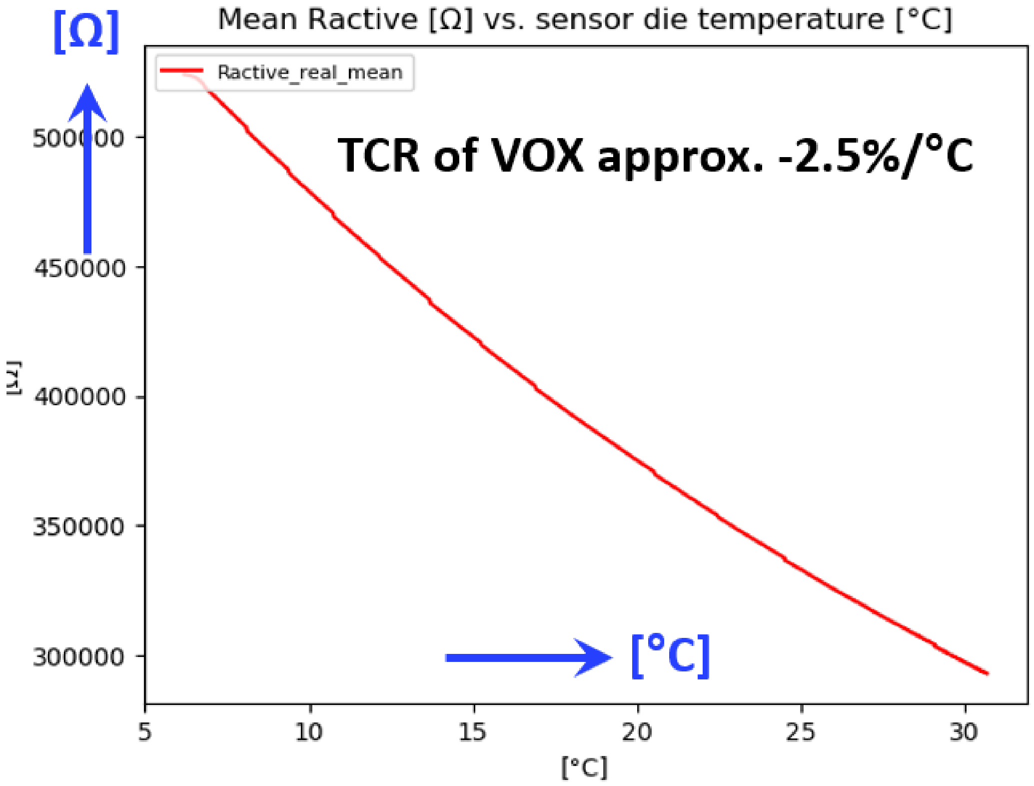
Vanadium Oxide resistance versus temperature

measured during power-up of camera

Sensor die temperature vs. time



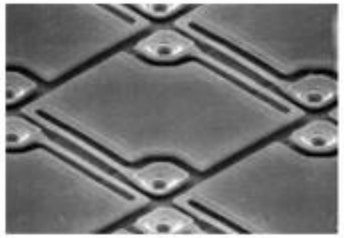
Mean pixel resistance vs. sensor die temperature

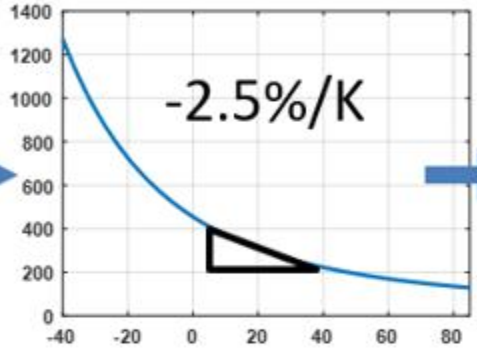


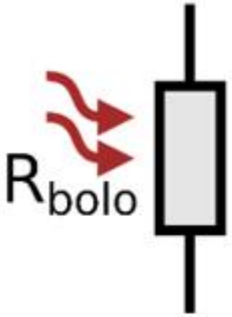
→ Vanadium Oxide has a large relative resistance change of approx. -2.5% per degree Celsius!

Vanadium Oxide resistance change due to a change in scene temperature

Scene → Lens → Microbolometer → TCR → Resistance







$\Delta T_{scene} = 50$ mK
(NETD)

Factor 100x less!

$\Delta T_{VOx} = 0.5$ mK
(depends on pixel size
and pixel thermal properties)

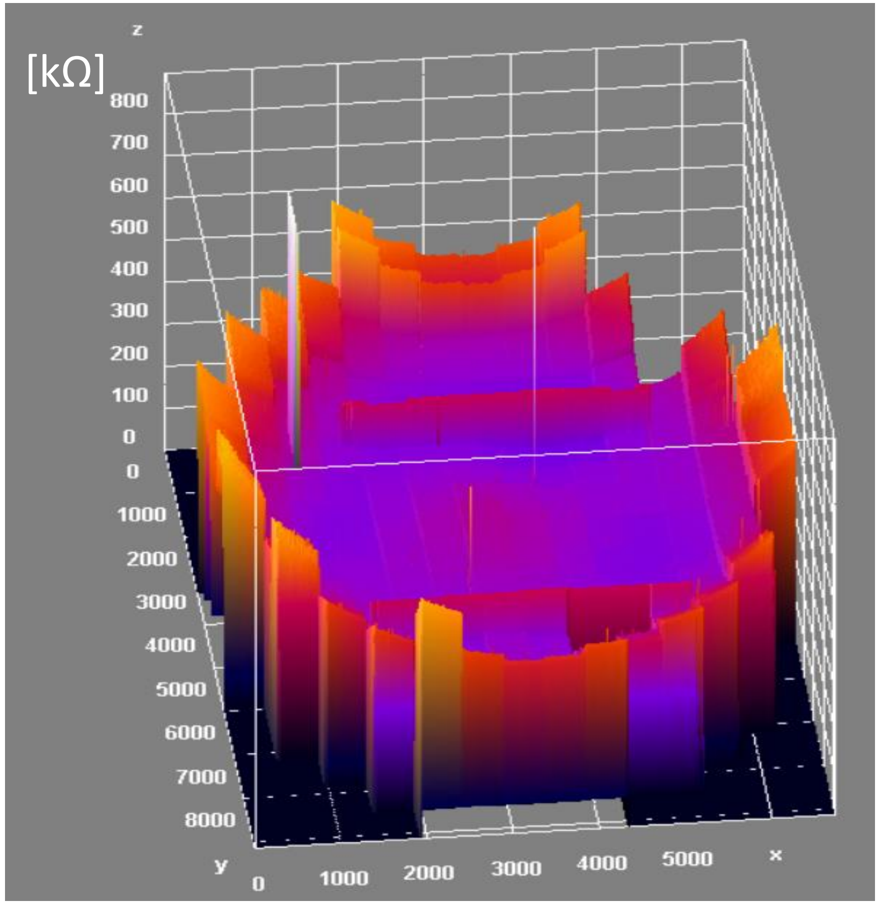
$$\frac{\Delta R_{bolo}}{R_{bolo}} = 0.001\%$$
(10ppm)

NETD: Noise **E**quivalent **T**emperature **D**ifference
The minimum detectable delta scene temperature

NETD = 50 mK → $$\frac{\Delta R_{bolo}}{R_{bolo}} = 10 \text{ ppm}$$

Challenge: Vanadium Oxide resistance spread across a full wafer

Pixel resistance [kΩ] across all dies of a complete wafer
(extreme example..)



Rose Bowl Stadium, Pasedena, CA

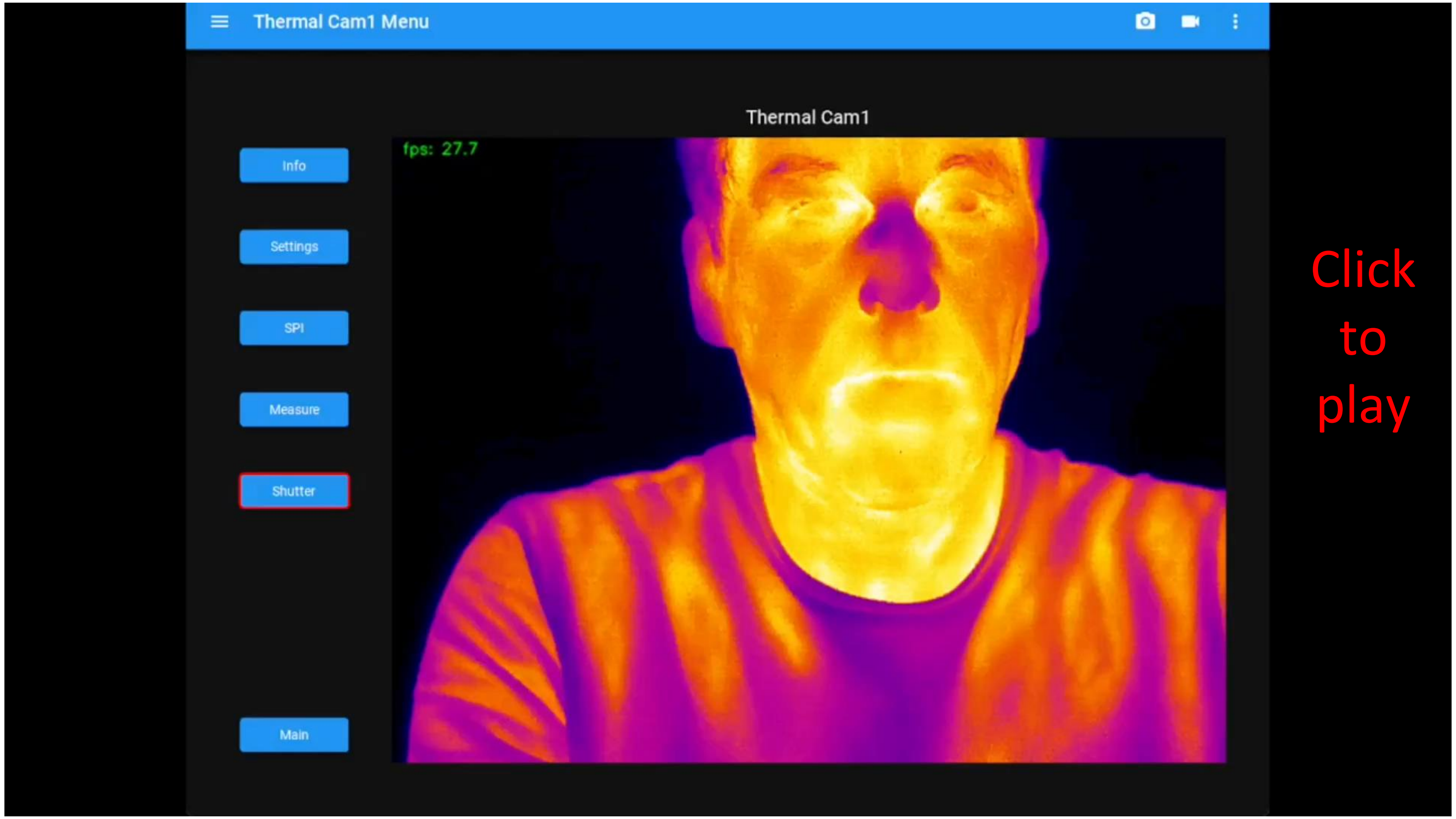
Challenge:
resistance-spread is not allowed to clip the ADCs in the CMOS Read Out IC

Challenge: memory effect in Vanadium Oxide Resistance

Caused by (semi?) permanent change in Vanadium Oxide chemical composition

$$V_{x1}O_{y1} \rightarrow V_{x2}O_{y2} \quad x1 \neq x2 \;\; y1 \neq y2$$

Burn-in caused by a cigarette

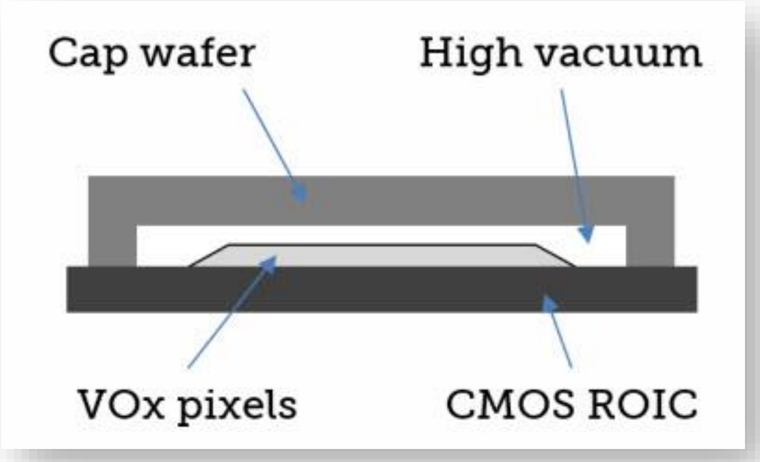


Click to play

Vacuum Wafer Level Packaging ("WLP")

The CMOS Read Out IC wafer is bonded under vacuum with a 2nd "lid" wafer:

- Lid wafer has cavities at each pixel array location
- Pixel array cavities are hermetically sealed during wafer bonding to guarantee vacuum over life-time
- Lid wafer has MEMS engineered anti-reflective window above each pixel array

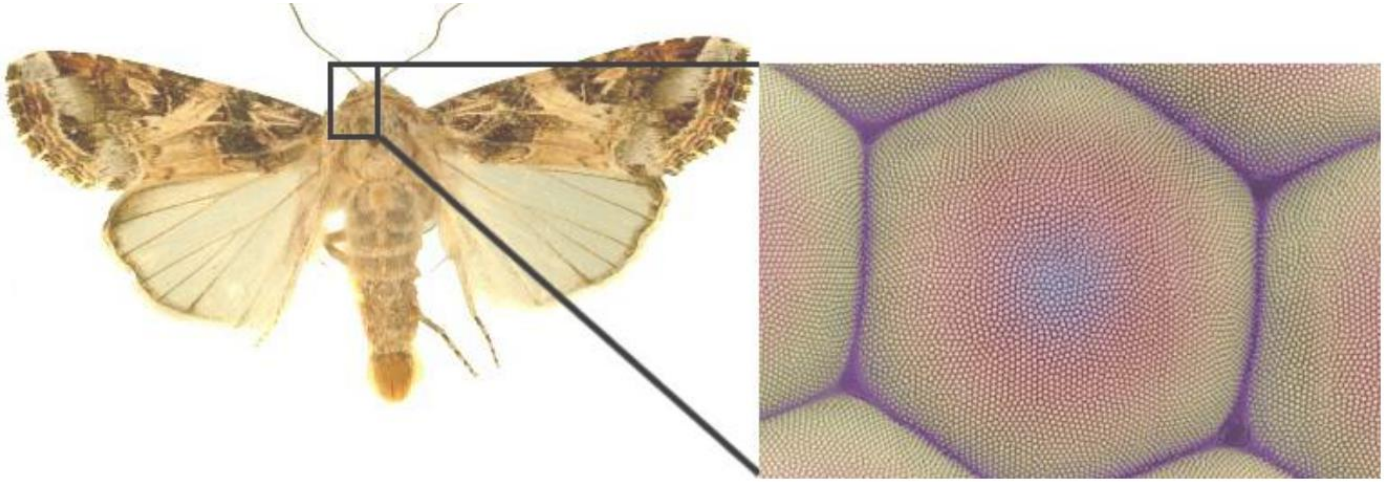


MEMS engineered anti-reflective window in lid wafer

Inspired by Moth-Eye

Goal:
- minimum reflectance
- maximum transmission

Optimize:
- shape of pillars
- size and spacing of pillars
- Wavelength cut-off (see next slide)



Moth eyes are highly antireflective due to their surface nanostructure.

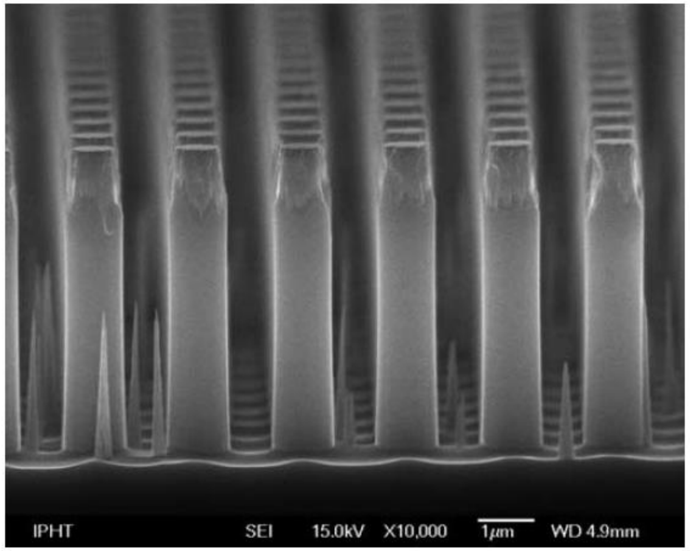


Fig. 4. Binary structures with an aspect ratio of 1:5.8 generated with an ECR-process

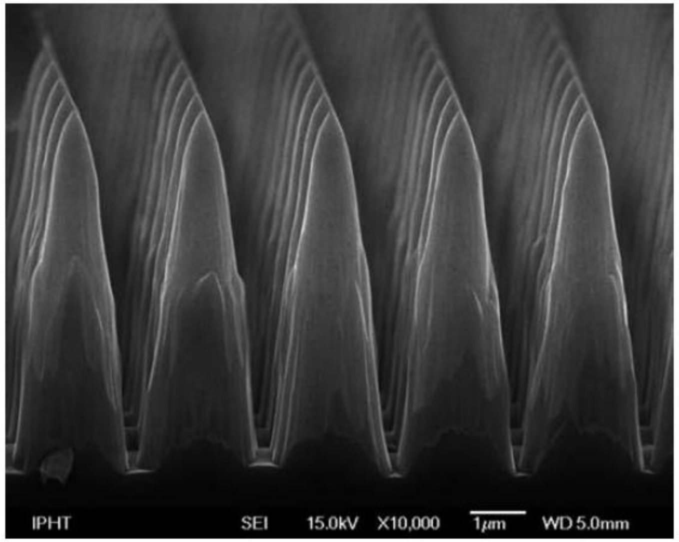
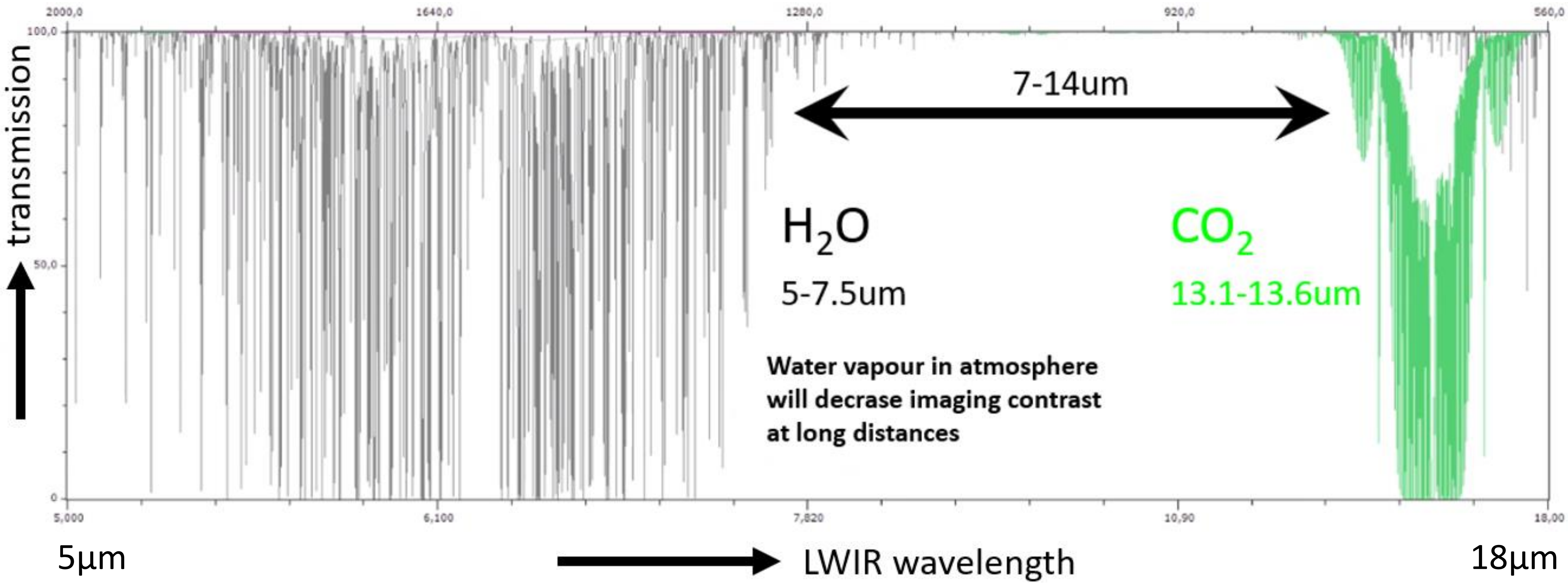


Fig. 3. Pyramidal silicon structures after a SF_6/O_2 process

https://phys.org/news/2015-07-artificial-moth-eyes-silicon-solar.html
https://www.researchgate.net/publication/225638988_High_temperature_resistant_antireflective_moth-eye_structures_for_infrared_radiation_sensors

Simulation of atmospheric transmission

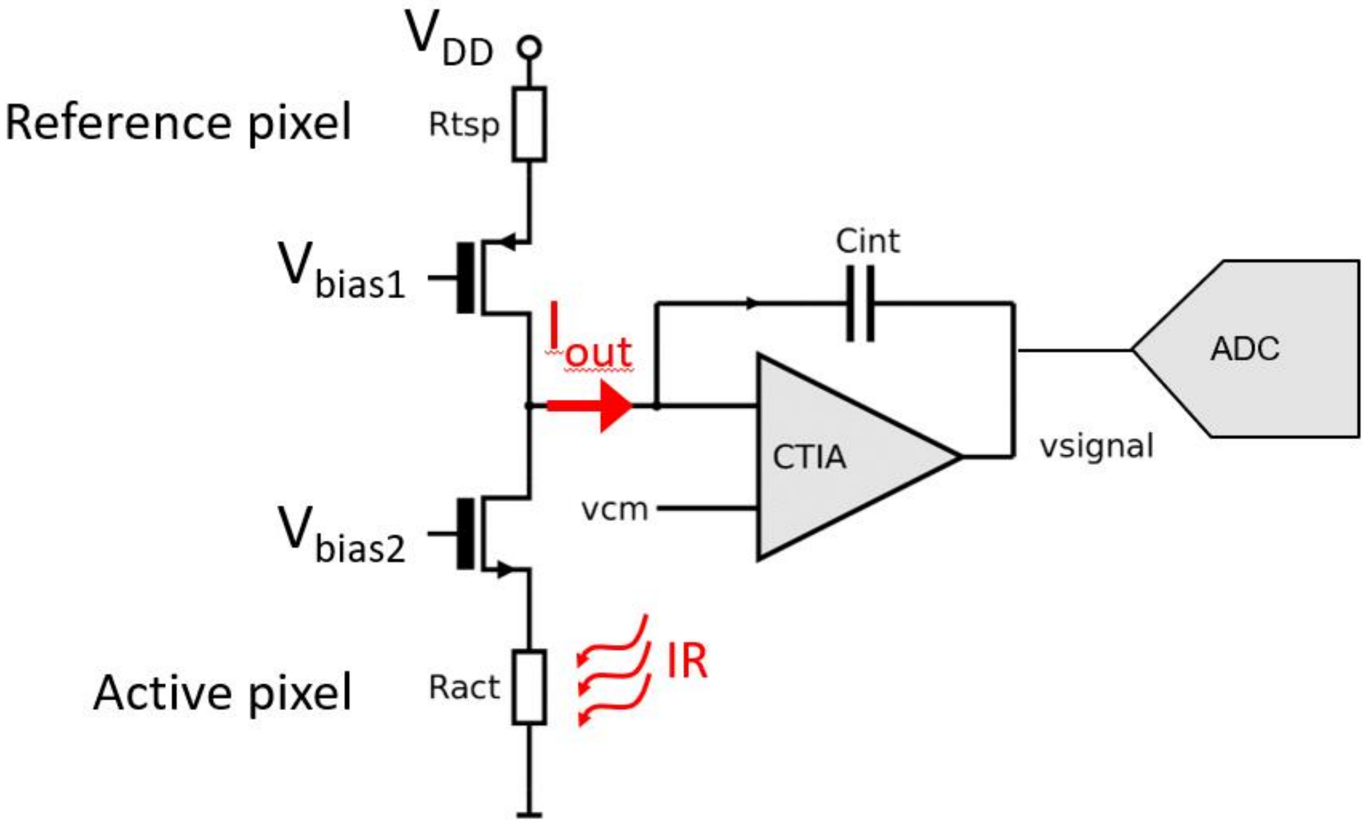
US standard 1976 with path length: 1m
(since then: more methane and CO_2 in the air…)



→ Apply sharp lens/lid cutoff at 7µm and 14µm
to make temperature reading insensitive to atmospheric conditions

CMOS Read Out IC (“ROIC”) design

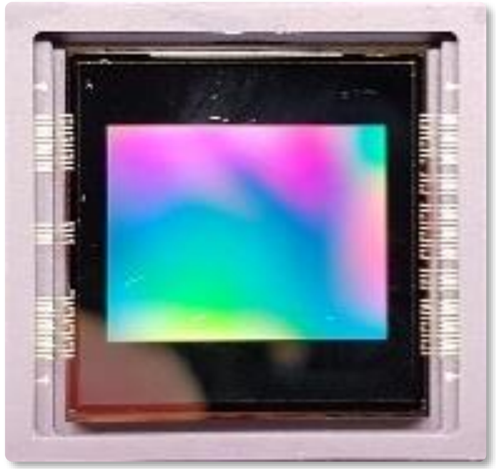
Typical ROIC front-end

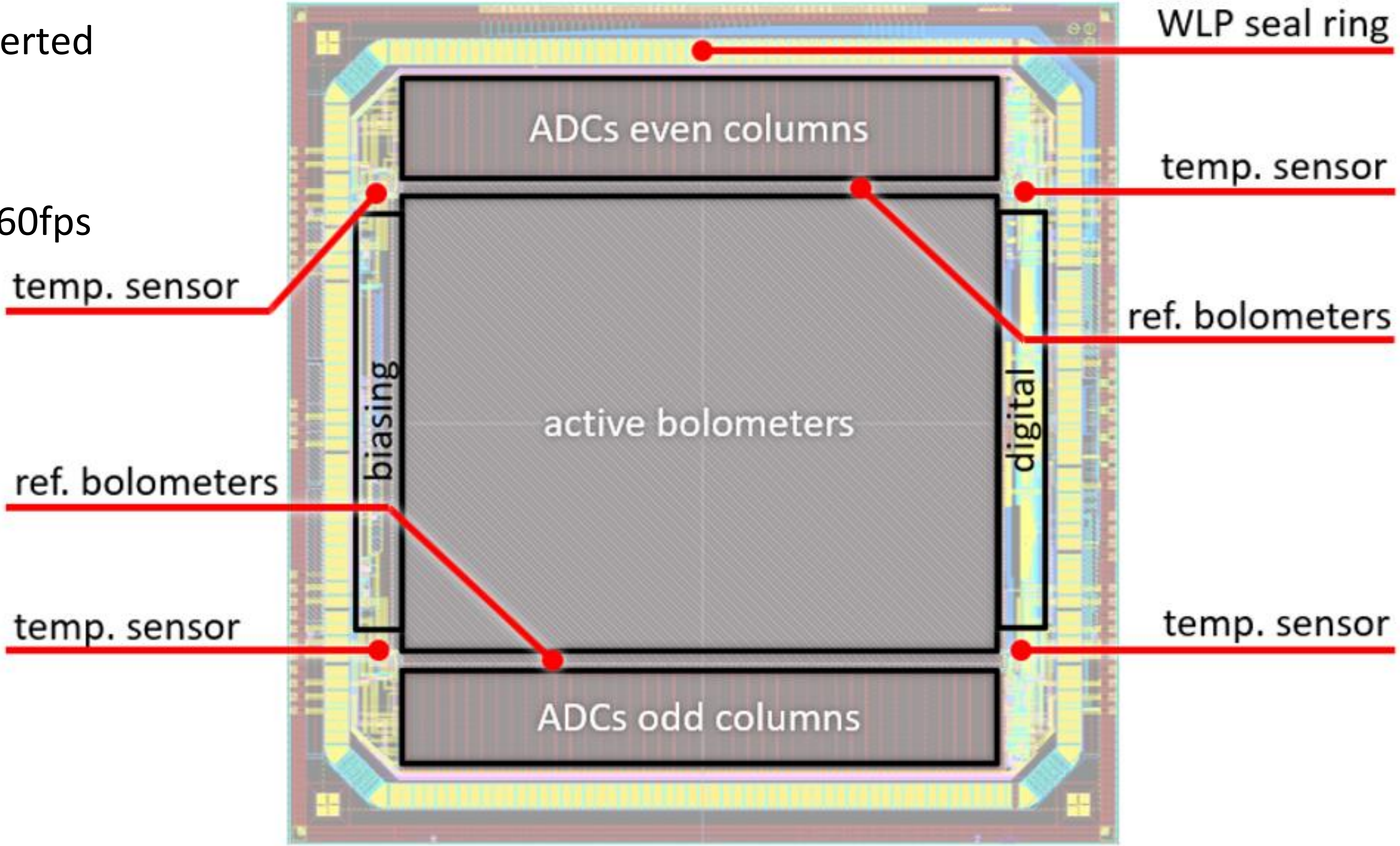


- Active pixel reacts to incoming LWIR→ resistance change
- Reference pixel is shielded or thermally shorted to substrate → does not react to incoming LWIR
- Intrinsic vanadium resistance of active and reference pixel are matched (ideally..)
- Challenge: intrinsic pixel mismatch “eats up” large portion of ADC dynamic range

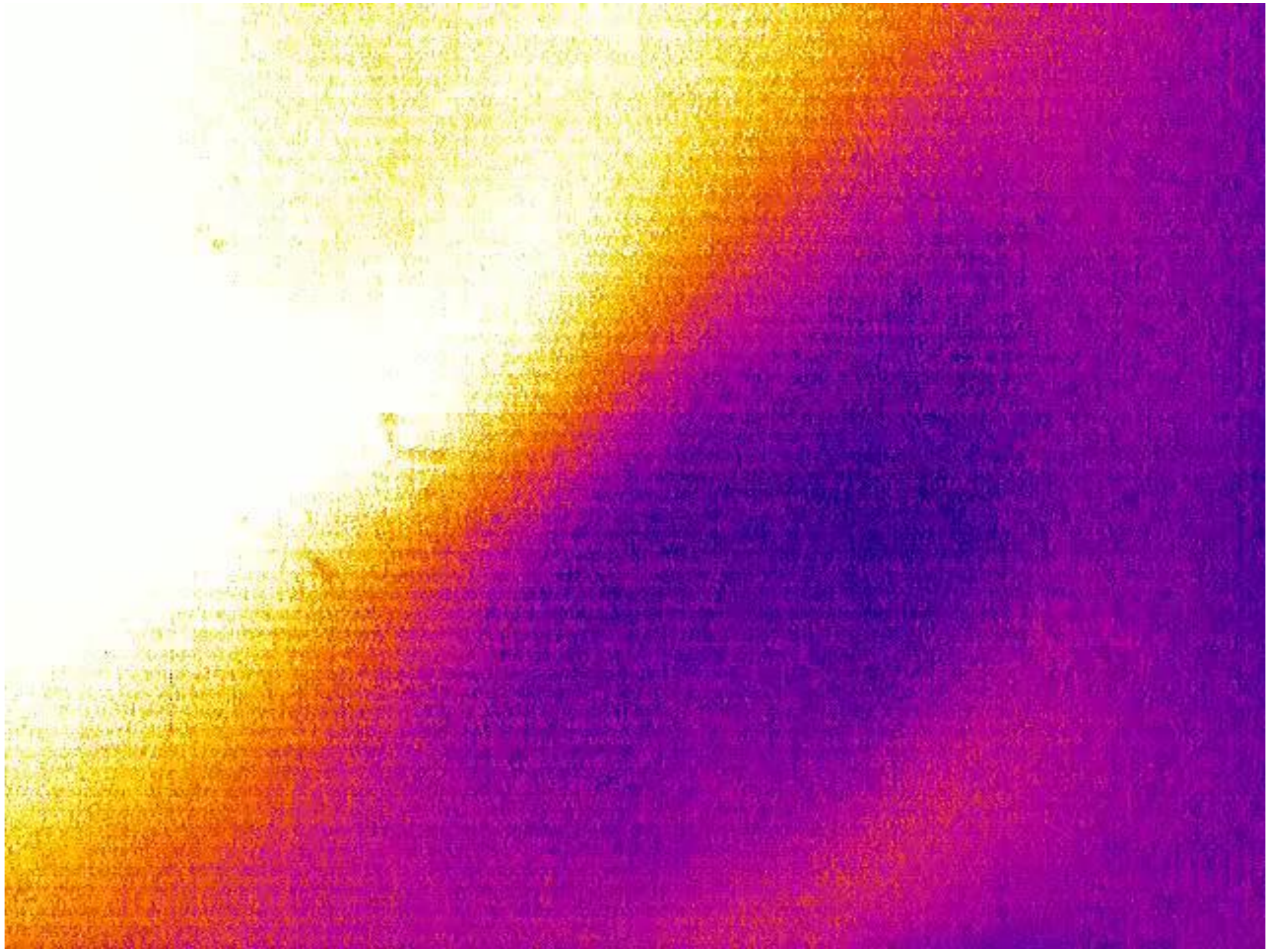
Layout of VGA ROIC
640 x 480 pixels

- One ADC per pixel column
- Pixels are biased and converted row by row
- Serial digital output
- Typical frame rates 30fps-60fps





High dynamic range: image a burning cigarette without ADC range switching



Click
to
play


Scene 640x480 cam: 23.4 fps main: 23.8 fps display: 23.4 fps
REC
TELEDYNE
DALSA
BG INTERP

Workshop 2024

ePicture This

An initiative by PENTA/XECS label projects MANTIS, IMAGINATION and ELEVATION supported by AENEAS

THANK YOU

Penta Xecs EURIPIDES² European Smart Electronic Systems Aeneas