Basic principles of photon detectors used in Astronomy

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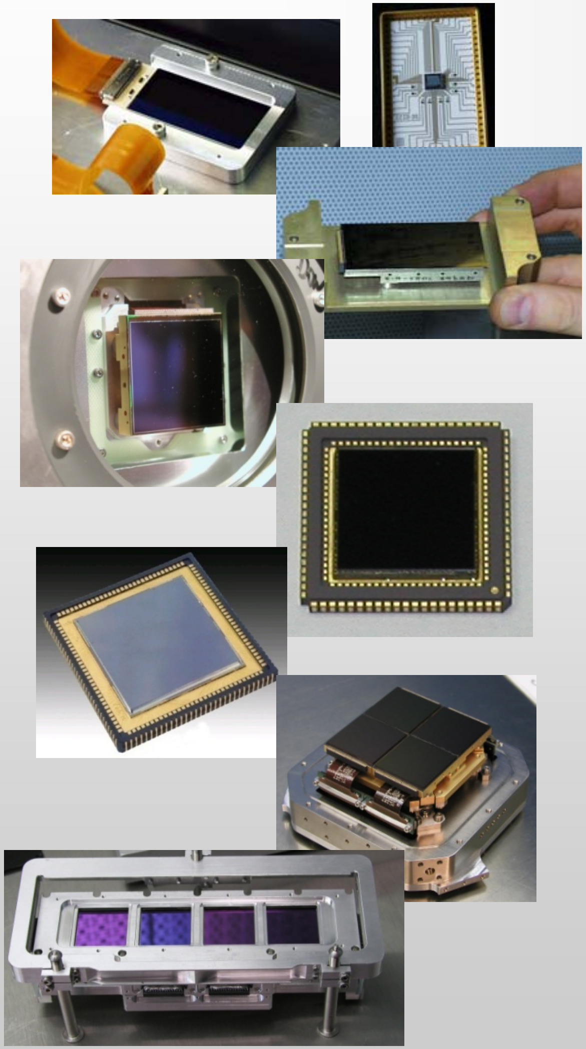
There are many ways to sense light, but ..



these notes will focus on detectors used in Astronomy with a wavelength coverage from the UV to the near infrared.

Detectors are **2-dimensional** and **detect photons or intensity** so one **cannot** measure color directly.

For wavelength longer than 20 microns the low energy photons cannot be detected directly. Those detectors measure the physical effects such as heat or a change in resistance.

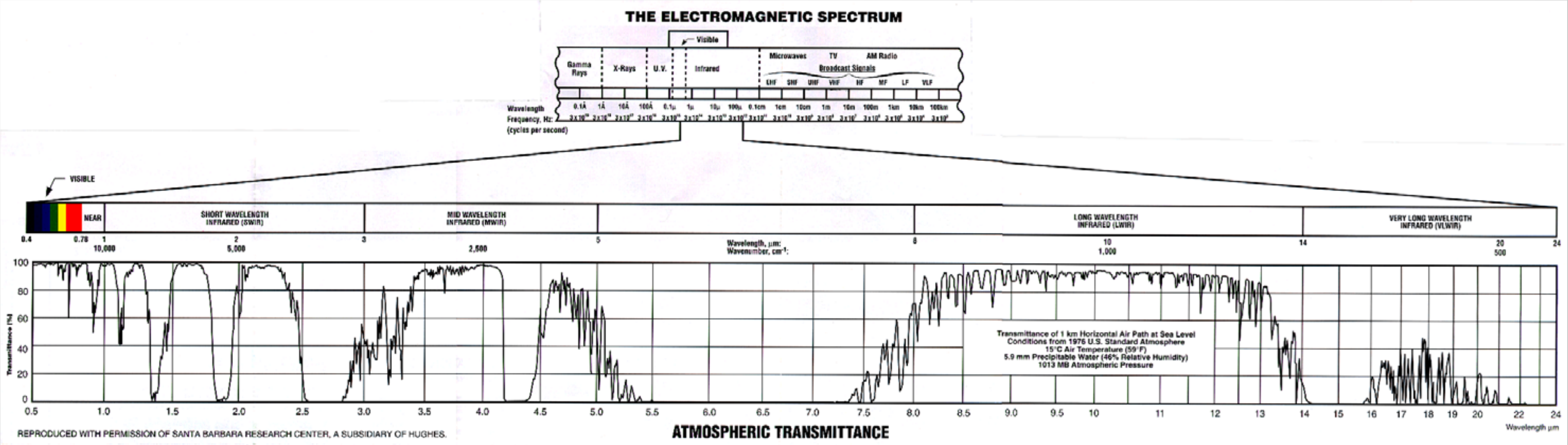
We will talk about:

1. Optical detectors are usually CCDs and CMOS devices based on silicon (SI).
2. Infrared detectors are based on IR detector material such as HgCdTe or InSb hybridized to a silicon multiplexer.

There are other technologies as APD (photon counting), wavefront sensors for Adaptive Optics and STJs (superconducting tunneling junctions, those can measure 3D).

There are many ways to sense light, but ..

not all of the light gets through the atmosphere to ground-based telescopes



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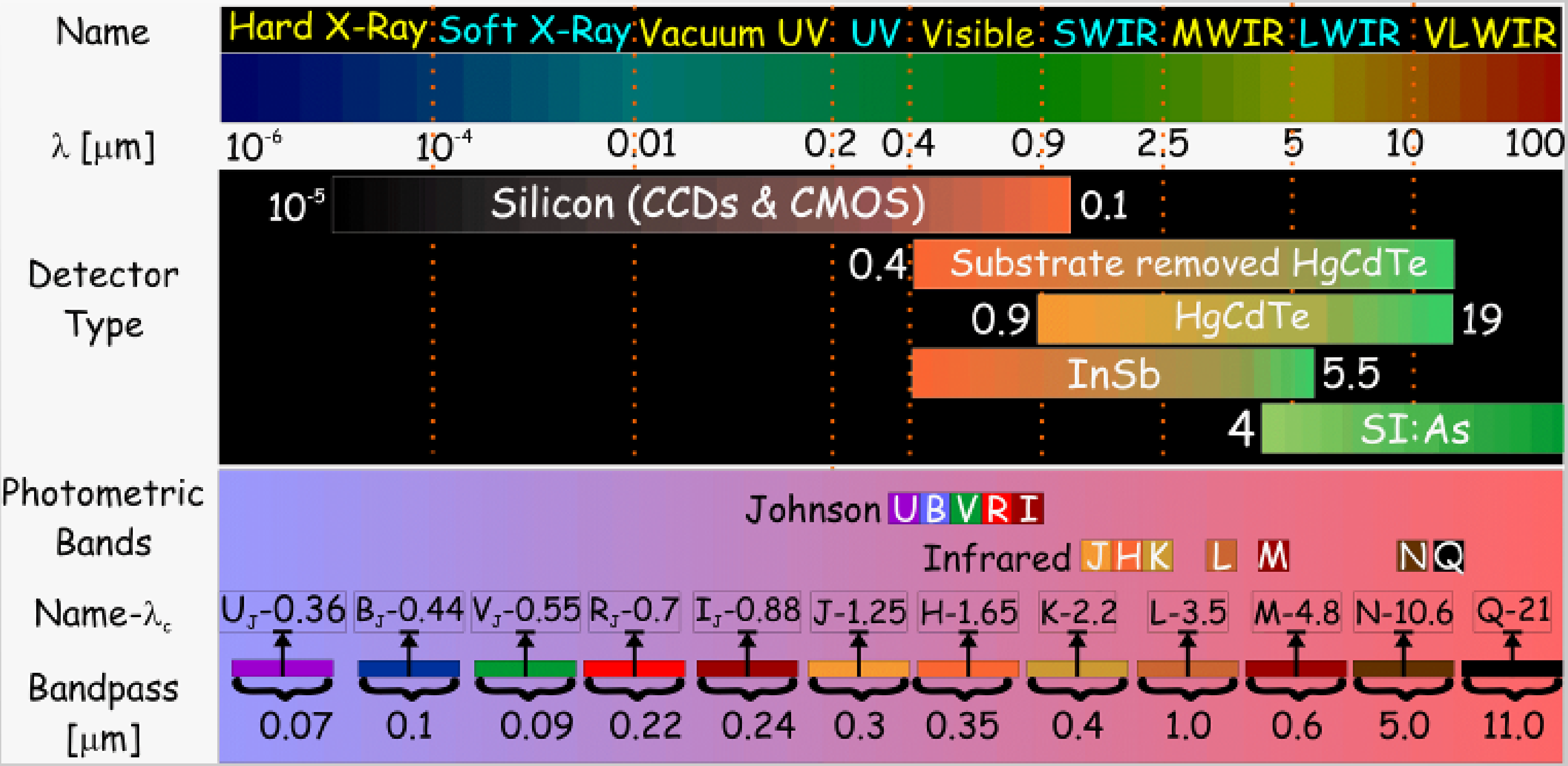
- ❑ Except for visible, some NIR and radio waves, all other EM radiation is blocked by the atmosphere
- ❑ Blocking is caused by H_2O –vapor, Ozone (O_3), oxygen (O_2) and Carbon dioxide (CO_2)
- ❑ Other observations must be made from space (i.e. Hubble, JWST, Satellites)

Sir Isaac Newton
identified the
problem 300
years ago

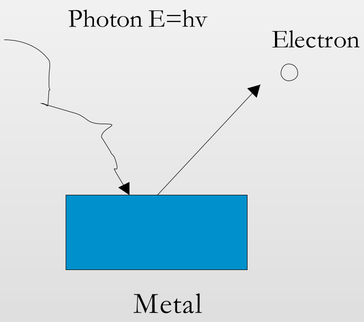
"For the Air through which we look upon the Stars, is in a perpetual Tremor".... "But these Stars do not twinkle when viewed through Telescopes which have large apertures"... "The only Remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds." (Isaac Newton, 1730)

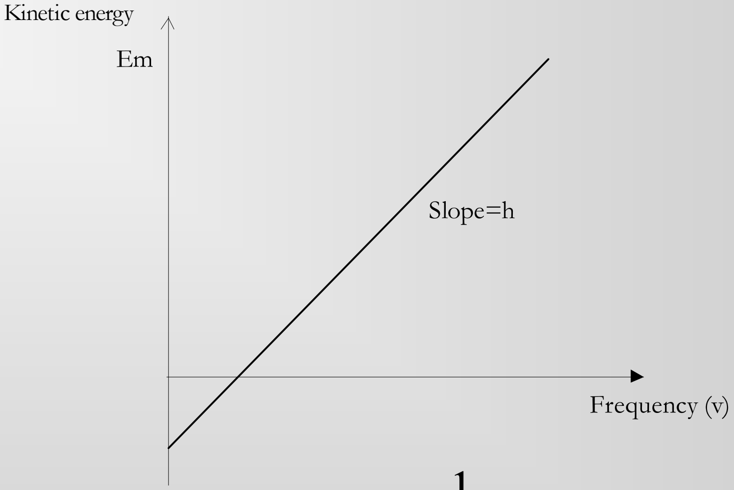
Detectors used in Astronomy are usually made out of semiconductor materials



The basic mechanism behind the CCD and IR detectors is the principle of the photoelectric effect.

- ☐ Plank said that radiation from a heated sample is emitted in discrete energy levels, called "quanta".
- ☐ The Energy is hv, where h is the Plank constant and v the frequency.
- ☐ Soon after Plank, Einstein interpreted an experiment which proofed the discrete nature of light.





By measuring the energy of the escaping electron a plot can be made of maximum kinetic energy as a function of frequency of the photons. E_{kin} of the electron is independent of the light intensity.

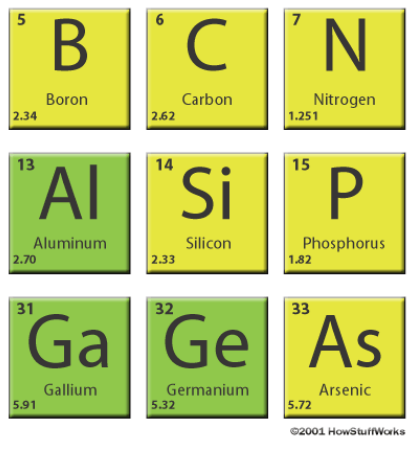
Lets assume that a UV photon of one wavelength hit the surface of a metal plate in vacuum.

The electrons in the metal absorb the energy of the photons and some receive enough to be ejected into the vacuum.

$$E_{kin} = \frac{1}{2} m v^2 = h\nu - q\phi$$

where E_{kin} is the maximum Energy of the ejected electron,
q is the electron charge and
Φ (volts) is the characteristics of the metal used.
q Φ is the minimum required energy for the electron to escape from the specific metal (workfunction)

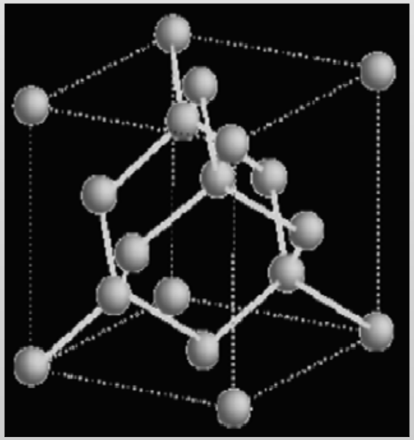
What are Semiconductors ?



- Elemental semiconductors are column IV elements (e.g., Si, Ge)
- Outermost shell contains 4 electrons
- The four electrons form perfect covalent bonds with four neighboring atoms creating a crystal **lattice**

- Electrons are trapped in the crystal lattice
  - by electric field of protons
- Light energy can free an electron from the grip of the protons, allowing the electron to roam about the crystal
  - creates an “electron-hole” pair.
- The photo charge can be collected and amplified, so that light is detected
- The light energy required to free an electron depends on the material.

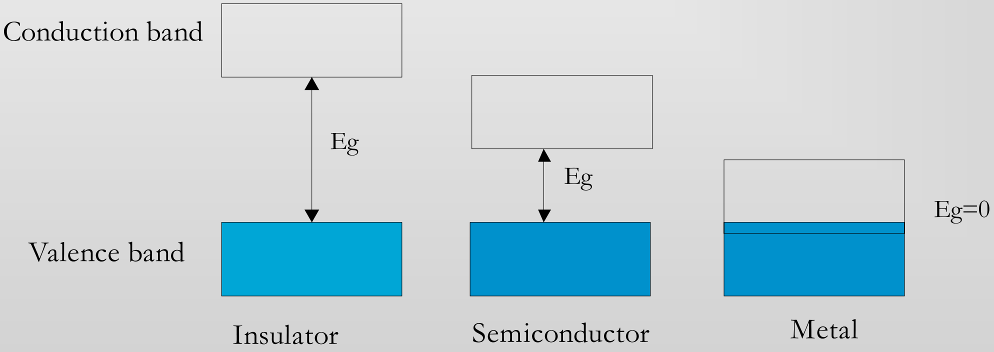
Si - IV semiconductor
HgCdTe - II-VI semiconductor
InGaAs & InSb - III-V semiconductors



Silicon Crystal Structure

Absorption of photons in a semiconductor - Valance & Conduction Bands

- ❑ In a crystal lattice, the allowed bands of electrons can be described by valence and conduction bands (this is similar to quantum orbits of electrons in Hydrogen).
- ❑ valence band = "ground states" that are normally completely filled
- ❑ conduction band = "excited states" that are normally completely unfilled, electron in the conduction band can move if there is electric field
- ❑ no electrons between valence and conduction bands



Eg is the bandgap energy between the valence and the conduction band.

Eg(Insulator) >> Eg(Semiconductor)>> Eg(Metal)

How do we move electrons from valence band to conduction band in semiconductors?

There are **two** methods to move electrons from the valance band to the conduction band:

- ☐ **By thermal excitation of electrons in the valance band (intrinsic)**

$$n_e = N \exp\left[-\frac{E_g}{2kT}\right]$$

n_e → Number of electrons promoted across the gap *(= no. of holes in the valence band)*

N → Number of electrons available at the top of the valance band for excitation

This is the origin of dark current and why we have to cool detectors

$$T_{\max} = \frac{200K}{\lambda_{cutoff}}$$

- ☐ **Photoelectric effect by photons absorbed by the semiconductor**

Photon energy (hv) > band gap energy (Eg) => photo-electron can jump into conduction band

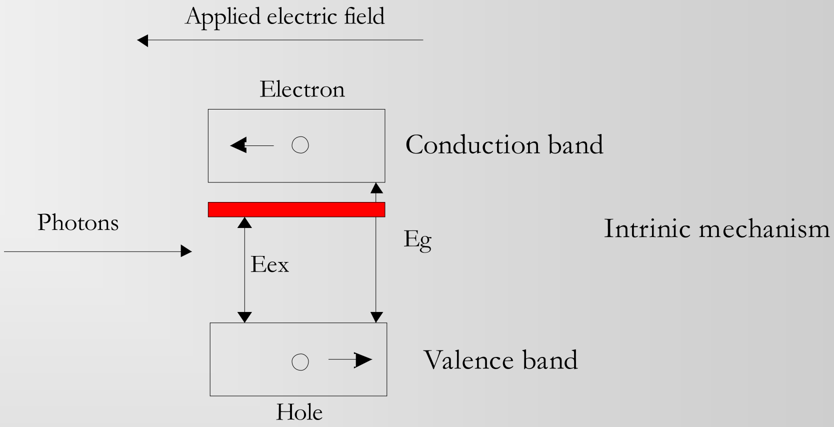
This is basically why semiconductors are used for astronomical observations.

The longest wavelength a detector is sensitive is the cutoff wavelength λ_{cutoff}.

$$\lambda_{cutoff}(um) = \frac{hc}{E_{bandgap}} = \frac{1.24}{E_{bandgap(eV)}}$$

- A detector in a semiconductor is now made by implanting ions of another material.
- This forms a p-n junction or diode which is biased to produce an electric field.
- An electron-hole pair is separated by the E-field and the electrons are accumulated on the diode.
- Then you can measure the voltage across the diode which is proportional to the number of electrons.

Photovoltaic effect



Bandgaps for various detector materials:

Material	Symbol	$E_{bandgap}$	λ_{cutoff}
Silicon	SI	1.12	1.1
HgCdTe	HgCdTe	1.0-0.09	1.24-14
Indium Antimonide	InSb	0.23	5.5
Arsenic doped Silicon	Si:As	0.05	25

More energy levels in the bandgap are done by doping at low concentrations, typically < 10^{-8} like AS doped SI. This is called extrinsic. For long wavelength detectors like Si:As.

Tunable Bandgap - A great property of Mer-Cad-Tel

$Hg_{1-x}Cd_xTe$

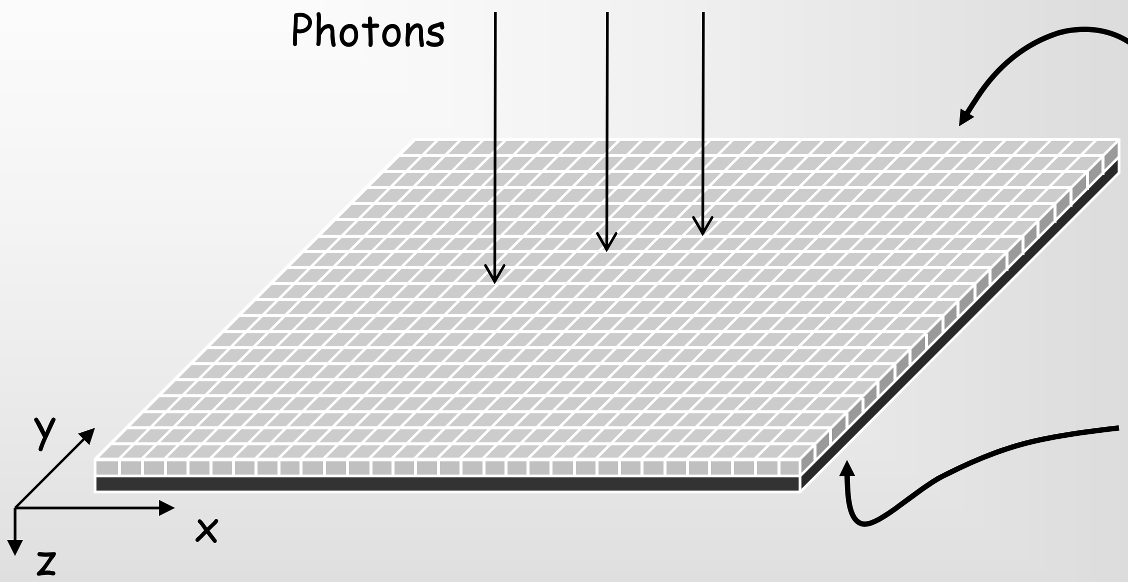
Modify ratio of Mercury and Cadmium
to “tune” the bandgap energy

x	E_g (eV)	λ_c (μm)
0.196	.09	14
0.21	.12	10
0.295	.25	5
0.395	.41	3
0.55	.73	1.7
0.7	1.0	1.24

Semiconductor summary

- ☐ Detectors used in Astronomy are made out of semiconductors
- ☐ The Photo-electric effects is the basic principle
- ☐ To avoid thermal excitation detectors need to be cooled
- ☐ The photons can generate photo-electrons in conduction band of semiconductors
- ☐ The material of semiconductors determines band gap energy which determines the wavelength of photons and the cutoff wavelength of the detector material
- ☐ The photo-electrons needed to be transferred, be amplified, and eventually be digitized.

Detector architecture (CCD and CMOS)



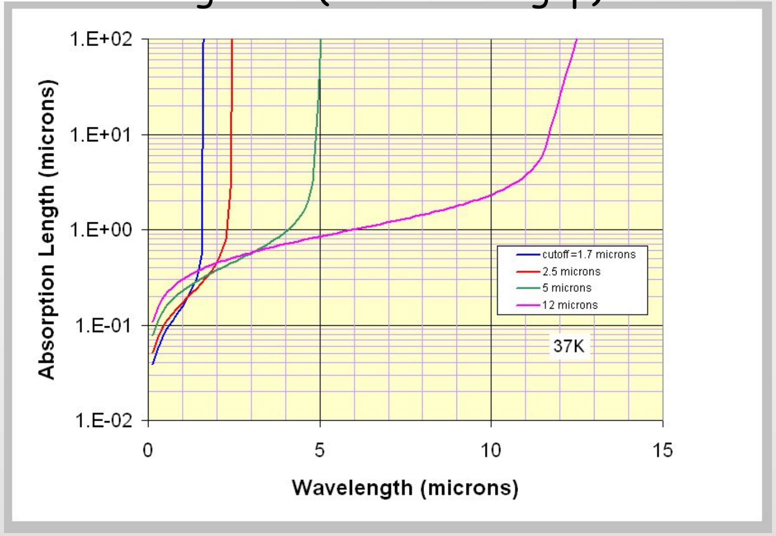
Light sensitive material is electrically partitioned into a 2-D array of pixels (each pixel is a 3-D volume) Photons > Electrons

Solid state electronics that amplify and read out the charge

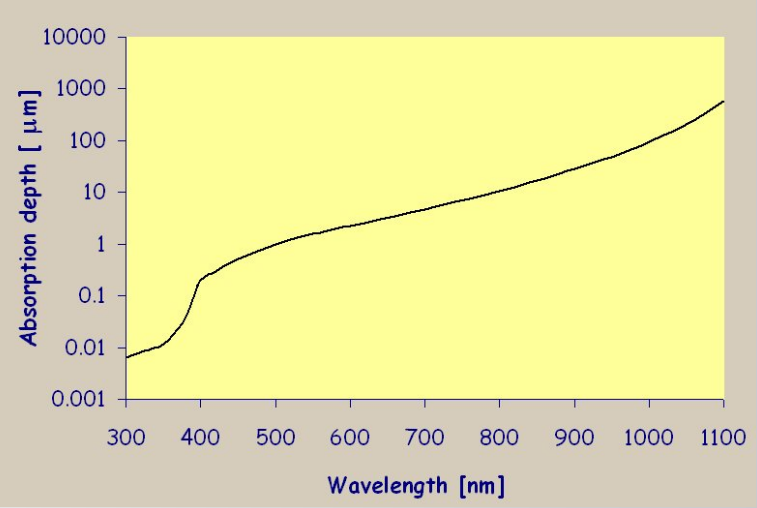
- Intensity image is generated by collecting photo charge generated in 3-D volume into 2-D array of pixels.
- Optical and IR focal plane arrays both collect charges via electric fields.
- In the z-direction, optical and IR use a p-n junction to “sweep” charge toward pixel collection nodes.

Absorption depth of SI and HgCdTe

HgCdTe (direct bandgap)



Silicon (indirect bandgap)



Indirect bandgap material: Electron needs change in momentum in addition to an energy change !

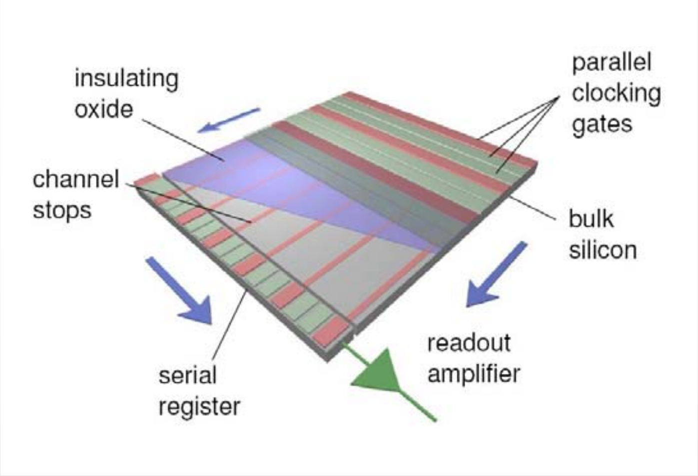
Absorption depth = The depth of detector material that absorbs 63.2% of the radiation

1 absorption depth(s)	63.2% of light absorbed
2	86.5%
3	95.0%
4	98.2%

For high QE, thickness of detector material should be ≥ 3 absorption depths

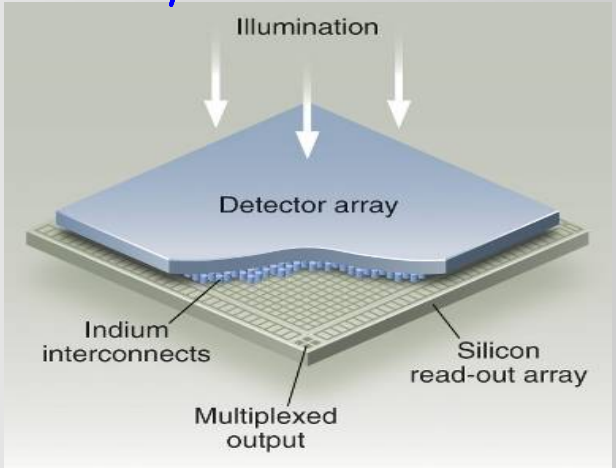
IR detector material is very thin 10 to 15 micron, SI detector can be very thick (i.e. 300 microns)

3 phase CCD



- CCD needs charge transfer towards amplifier
- Red electrodes high potential and green the low potentials.
- A pixel is the region between two channel stops
- During the exposure two gates are held at high potentials to integrate charge in the pixel
- Pixels are read **after** the integration
- CCD pixel share the same amplifier

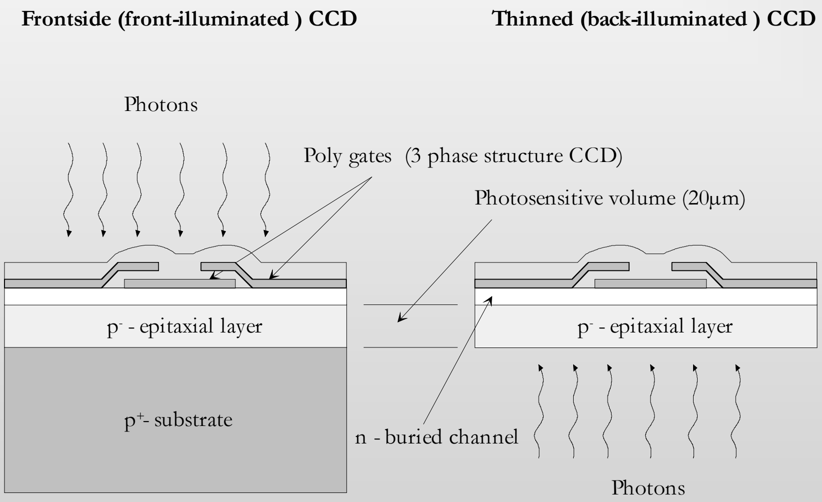
Hybrid CMOS/IR



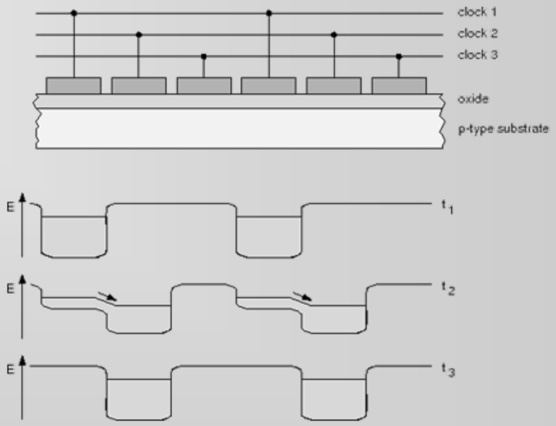
- Detector material hybridized to SI multiplexer (optical or IR material)
- No 'charge coupling'
- Indium interconnects are used
- Charge to voltage conversion takes place in parallel at the sense node of each pixel
- CMOS have amplifier per unit cell
- Pixels can be read **during** the integration

Principle of CCD Sensors

- BI CCDs have the best spectral response available
- The CCD is inverted, the bulk silicon ground down and Anti-Reflection (AR) coating is added. A number of optimized AR coating options are available

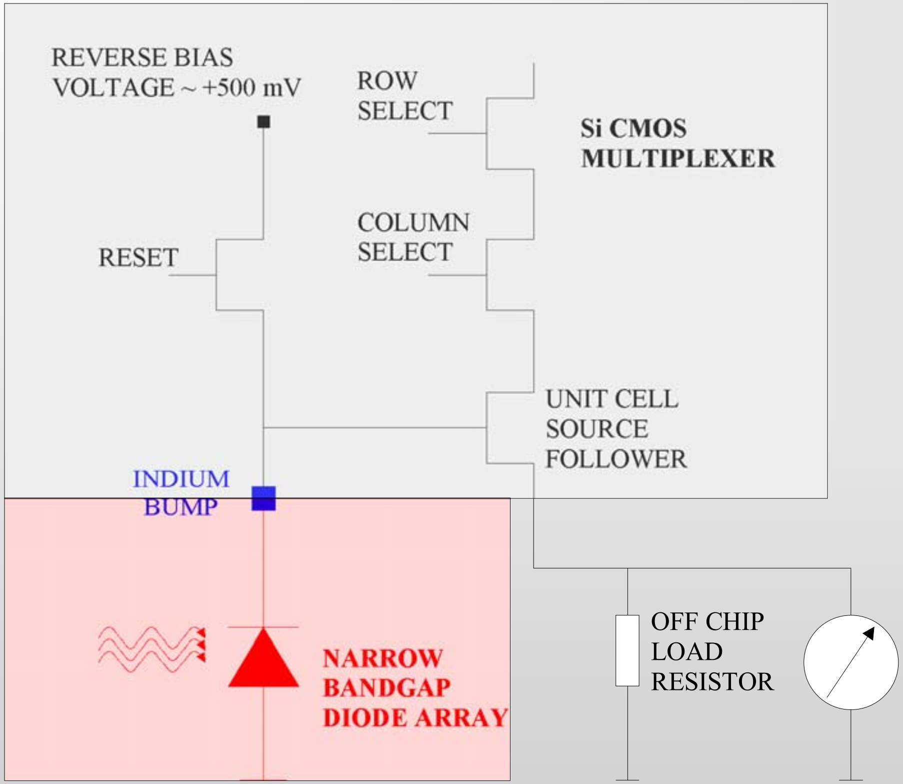


- During the integration time charge is collected under one or two of the gates.
- After an exposure the charge needs to be moved towards the output structure of the CCD. A simple scheme of clock pulses is applied to the gates to move the charge from one pixel to the next. Such clock cycles are repeated to readout an entire N-pixel linear registers for parallel or serial movement



- Then the voltage gets amplified by a MOSFET transistor.

Principle of Hybrid Active Pixel Sensors



Structure

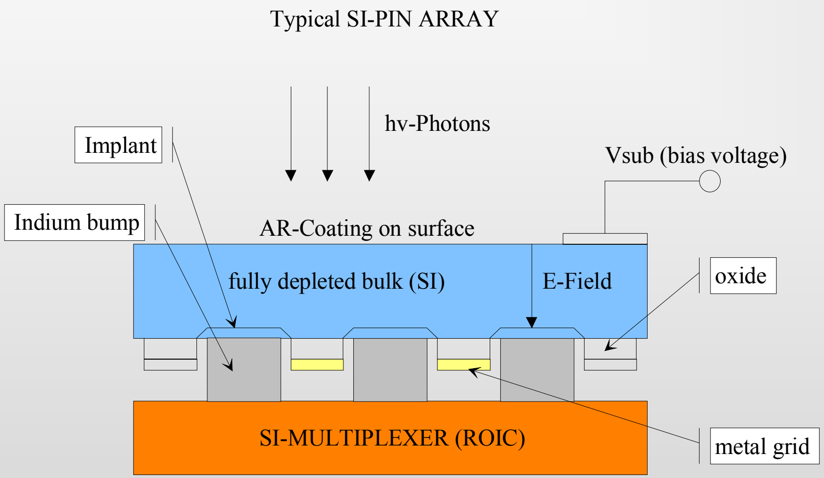
- Silicon readout multiplexer
- Narrow band-gap infrared diode array
- Hybridization with In bumps

Operation

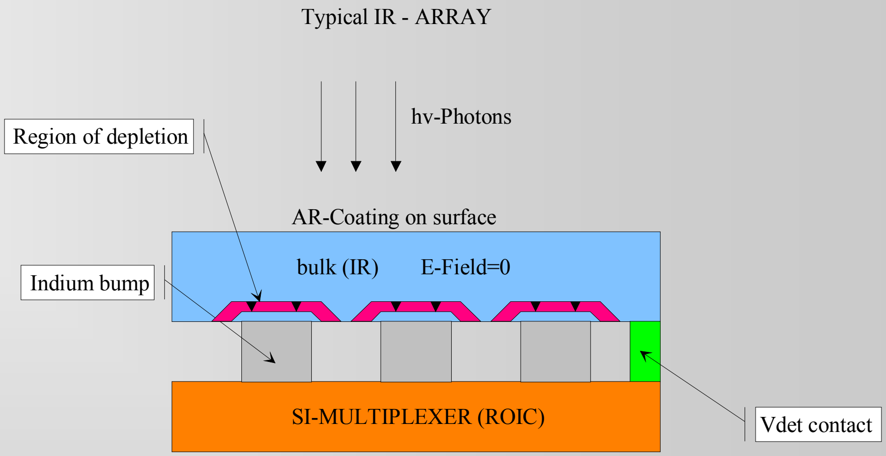
- charge diode capacity by reverse bias voltage
- floating capacity is discharged by absorbed photons
- Read voltage across diode capacity several times during integration by addressing unit cell source follower

Difference between optical and IR Hybrid Active Pixel Sensors

Typical SI Hybrid with fully depleted bulk



Typical IR array with per pixel depleted bulk

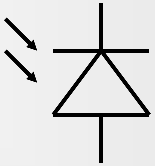
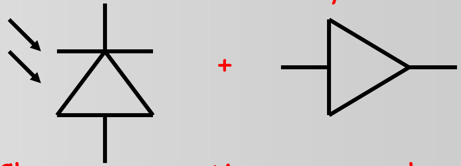
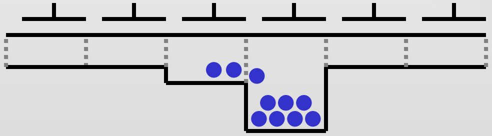
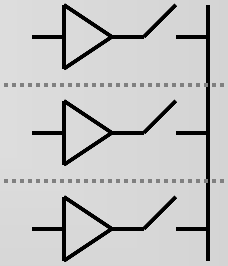
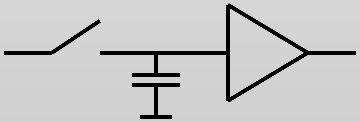


Implant boron ions to form n-on-p junctions

SI-PIN array is a fully depleted bulk detector

IR array is a per pixel depleted detector.

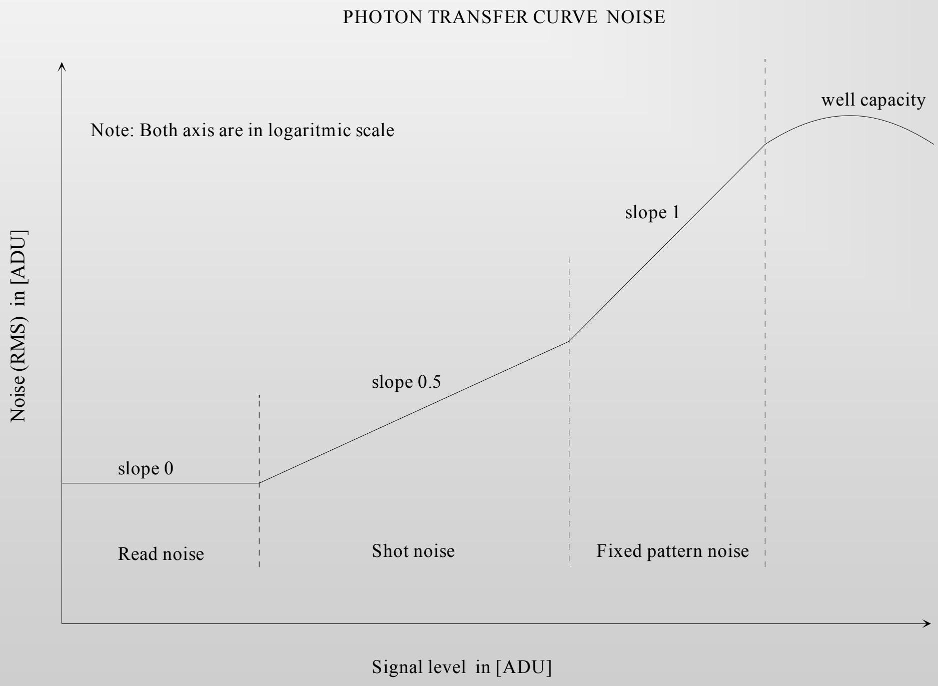
Summary of detector architecture

	CCD	CMOS
Pixel	*Photodiode*  Charge generation & charge integration	*Photodiode* + *Amplifier*  Charge generation, charge integration & charge-to-voltage conversion
Array Readout	 Charge transfer from pixel to pixel	 Multiplexing of pixel voltages: Successively connect amplifiers to common bus
Sensor Output	 Output amplifier performs charge-to-voltage conversion	Various options possible: - no further circuitry (analog out) - add. amplifiers (analog output) - A/D conversion (digital output)

Photon Transfer (1)

How do I know how much electrons the pixel has collected since we only record digital values ?
=> The photon transfer curve

Measurement of detector parameters such as noise, system gain, full well capacity, quantum efficiency, dark current, sensitivity and linearity are usually covered using the photon transfer curve.



A photon transfer curve has three different noise regimes:

1. readnoise
2. shot noise
3. fixed pattern noise.

Photon Transfer (2)

Read noise is the noise associated with the detectors output amplifier and the readout electronics (i.e. its signal processing, digitization etc.). This is the intrinsic system noise of a dark frame or image (no light). It is independent of the photons or input signal. The slope is 0 on a logarithmic scale.

Shot noise occurs when the input signal increases and the noise of the detector is dominated by shot noise. Shot noise is proportional to the square root of that signal. The slope is 0.5 on a logarithmic scale.

Fixed Pattern noise arises at high levels of illumination. This noise results from differences in sensitivity of pixels. This is also called the Pixel Response Nonuniformity (PRNU).

Due to processing and mask alignment variations during manufacture each pixel has a slightly different charge collection capacity and responsivity. This noise is proportional to the number of photons. The slope is 1 on a logarithmic scale.

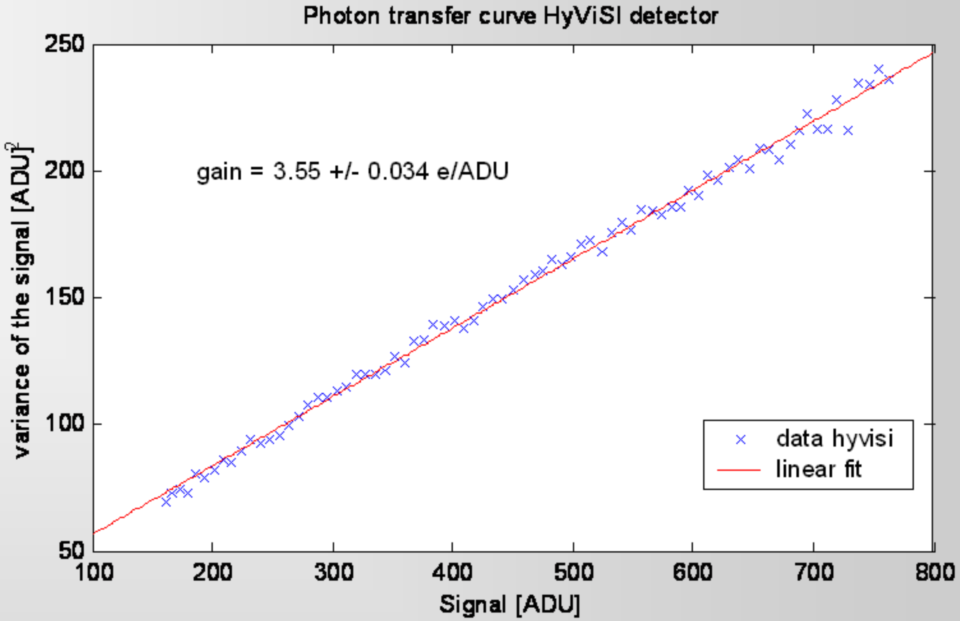
Photon Transfer (3)

The photon transfer curve plots read noise as a function of the signal for an area of *n* by *n* pixels in a frame.

To obtain the y-axis of the curve, the variance is computed. The variance is the square of the standard deviation of a single observation from the mean of the pixels.

$$\sigma^2 = \frac{\sum_{i=1}^{i=N_p} (S_i - S)^2}{Np}$$

Example:



To obtain the x-axis of the curve one computes the mean, dark subtracted signal S. That is

$$S = \frac{\sum_{i=1}^{i=N_p} S_i - S_{dark}}{Np}$$

where S_i is the signal value of the *i*th pixel and

N_p is the number of pixels in the *n* by *n* pixel area.

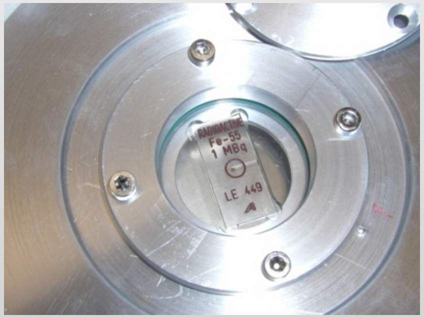
S_{dark} is the signal of a dark frame taken from the same data set.

FE-55

FE-55 is a radioactive source that emits X rays at three energy levels (5.9 KeV (Mn Kα line), weaker peak at 6.5 KeV (Mn Kβ) and the third at 4.12KeV (Kα escape line).

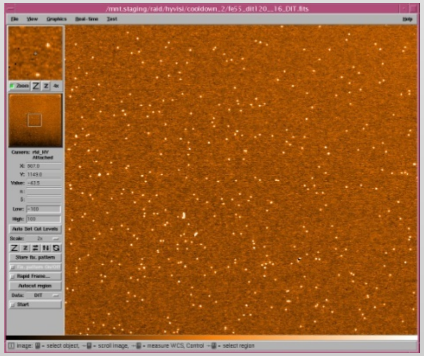
When these Xrays are absorbed by silicon they produce large photoelectron events Kα 1620 electrons, Kβ 1778 electrons and the Kα escape peak 1133 electrons.

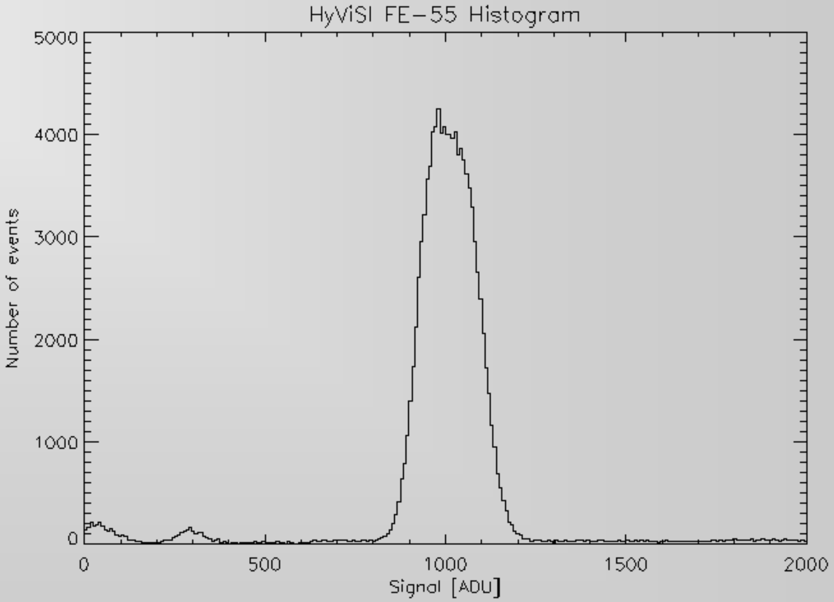
The Kα line was used to calibrate the conversion gain



FE-55 source installed on the window

FE-55 events on the detector (120s integration time)



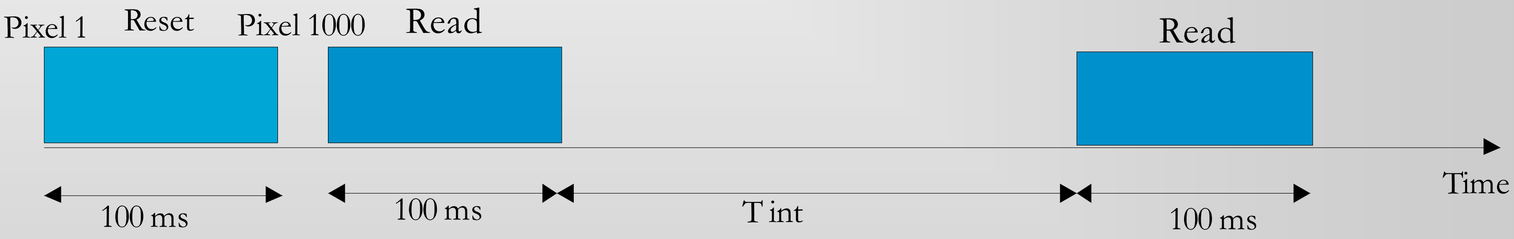


HyViSI FE-55 histogram: Conversion factor 1.65 e/ADU

CMOS Detectors readout scheme

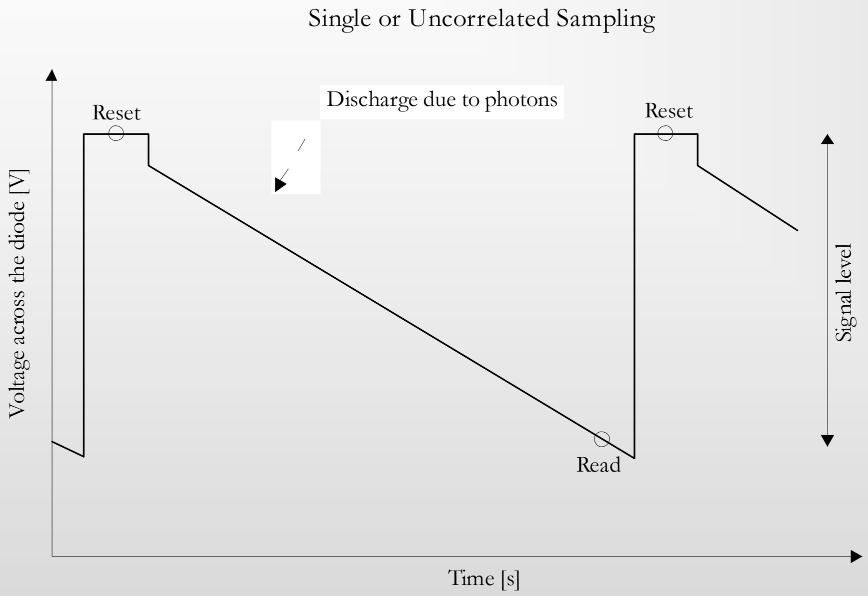
To define the exposure time IR detectors do not require a shutter. If shutters are used those would have to be cold and operate very fast due to short exposure times in the infrared due to high background radiation.

IR detectors are read out non-destructive (sampling does not alter the charge on the photodiode junction). When a detector is reset the signal shifts to the pedestal level. Then the diode discharges either by photocurrent or dark current. Resets are done usually pixel by pixel.



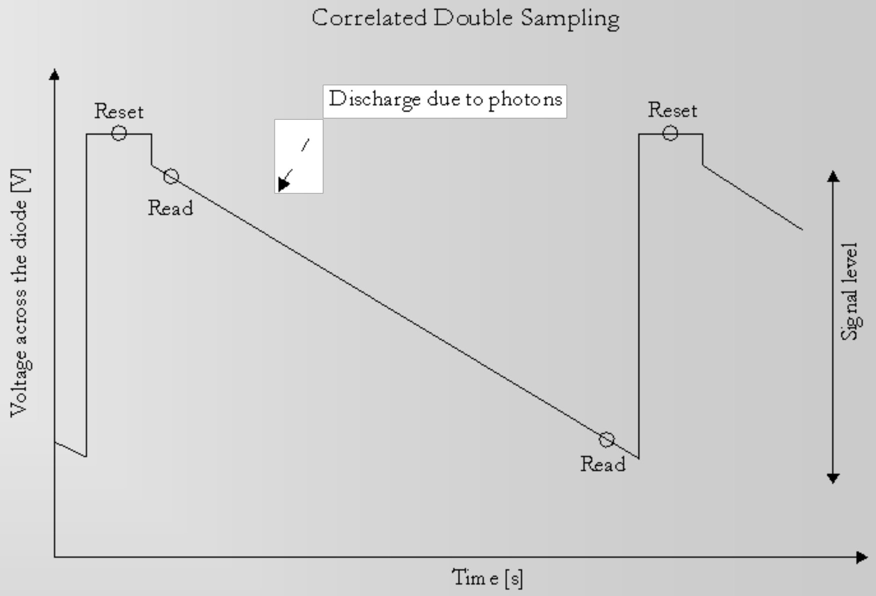
The following sample/reset modes are mainly used in astronomy (Diagram on a pixel by pixel basis)

IR Detectors readout scheme



Single (reset read) or uncorrelated Sampling

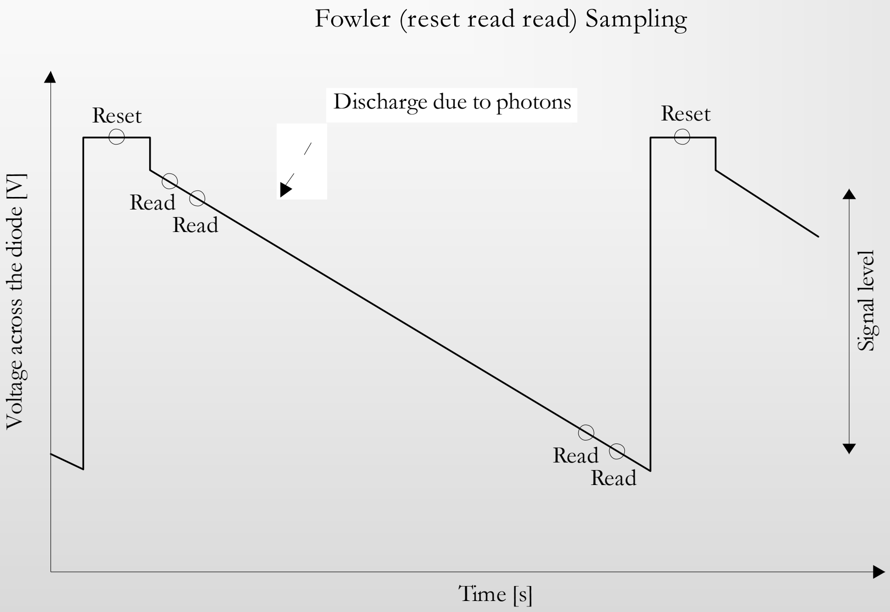
Cannot remove KTC noise or drifts in the detector but can measure saturation or full well capacity of the detector pixels (use also for dark current measurements by not resetting the device). Provides high dynamic range.
KTC noise = drifts in voltage due to Temp effects.

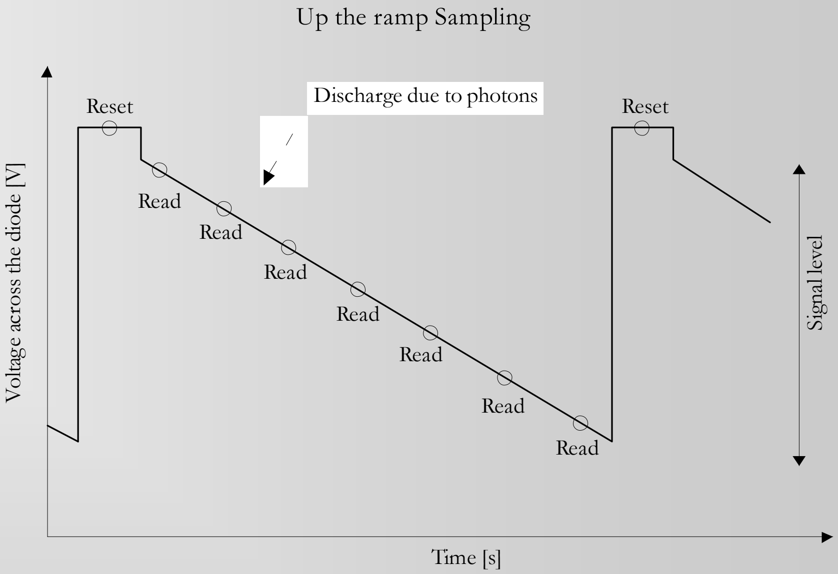


Correlated Double Sampling (CDS)

This mode removes KTC noise but cannot detect saturation of the pixels. It is the standard readout mode.

IR Detectors readout scheme





Fowler (reset-read-read) Sampling

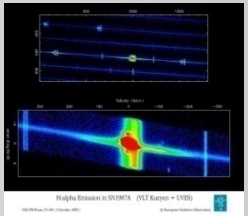
Readnoise decreases as $\frac{1}{\sqrt{n}}$

with n being the numbers of samples.
Is better in readnoise limited conditions than DC.
Saturation not known.

Up-the-Ramp Sampling

Fit line to get the mean flux rate = slope.
This mode is good if some pixels saturate before the end of the exposure time.

OPTICAL DETECTORS for imaging and spectroscopy



ESO's Scientific CCDs

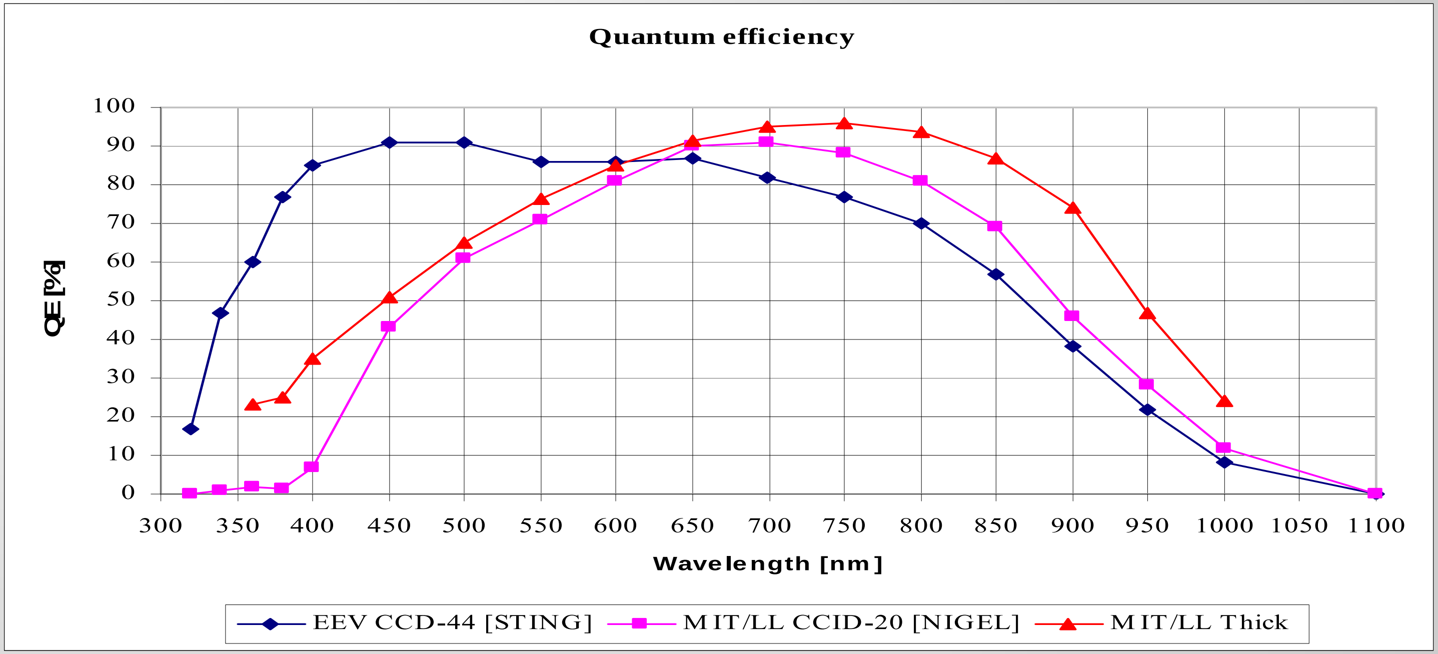
In 1996, ESO began an aggressive programme to procure new generation CCDs:

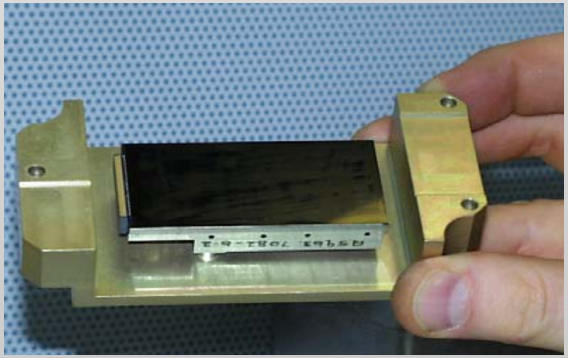
2k x 4k, 15 micron pixels, 3-side (and 4-side) buttable
Dark current < 1 electron/pixel/hr
High speed, low noise amplifiers (2 e$^-$ at 50 kps, 5 e$^-$ at 625 kps)
Readout speed up to 1 Million pixels per second
Typical CTE: 0.999999 (six 9's)
Very flat (less than 20 micron peak-to-valley)
Excellent cosmetic quality (≤ 4 bad columns)
Full well capacity: 130 000 to 225000 electrons

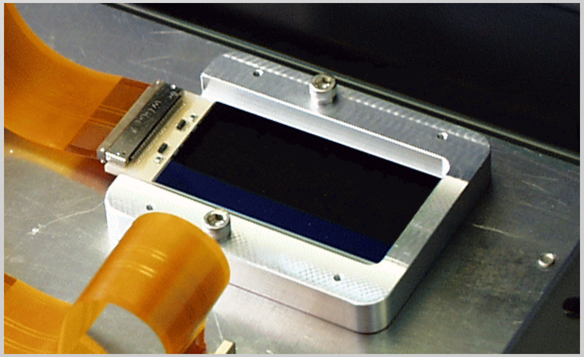
Two manufacturers produce these devices, with different spectral response:

E2V
MIT Lincoln Laboratory

Typical quantum efficiency of thinned E2V and MIT/LL CCDs

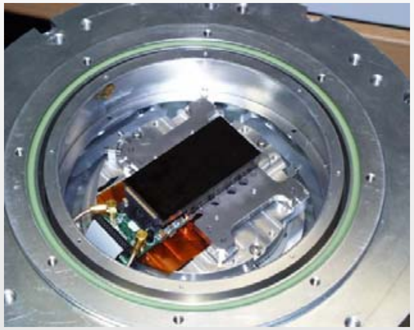




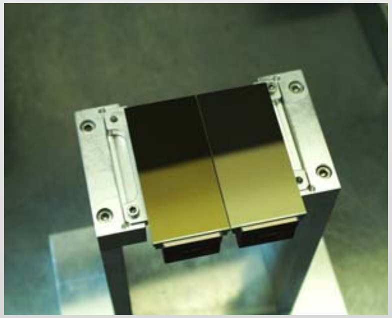


Examples of CCD detectors systems

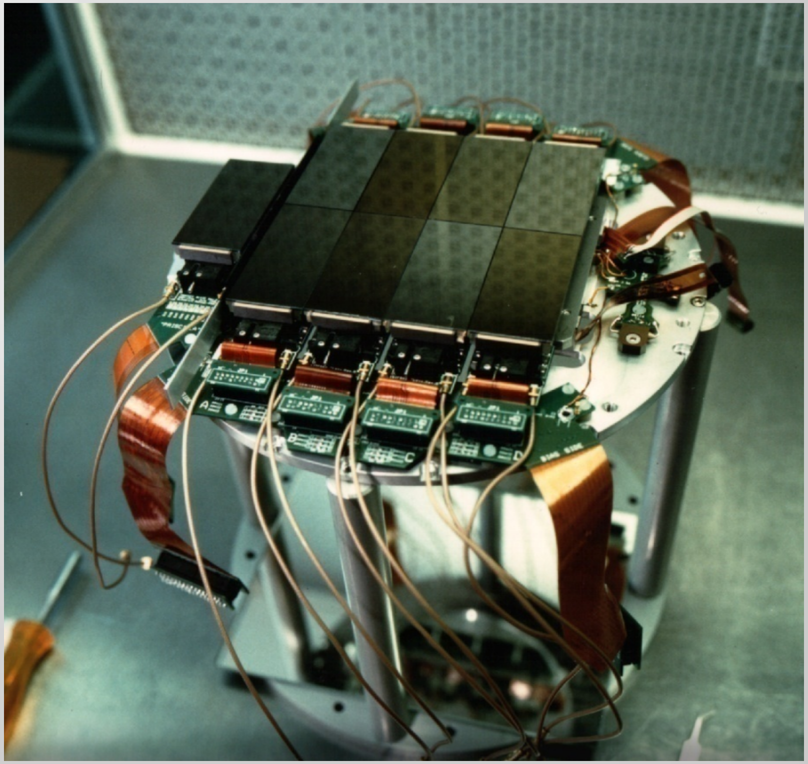
…from single detectors to very big mosaics…..



Single E2V
2kx4k CCD



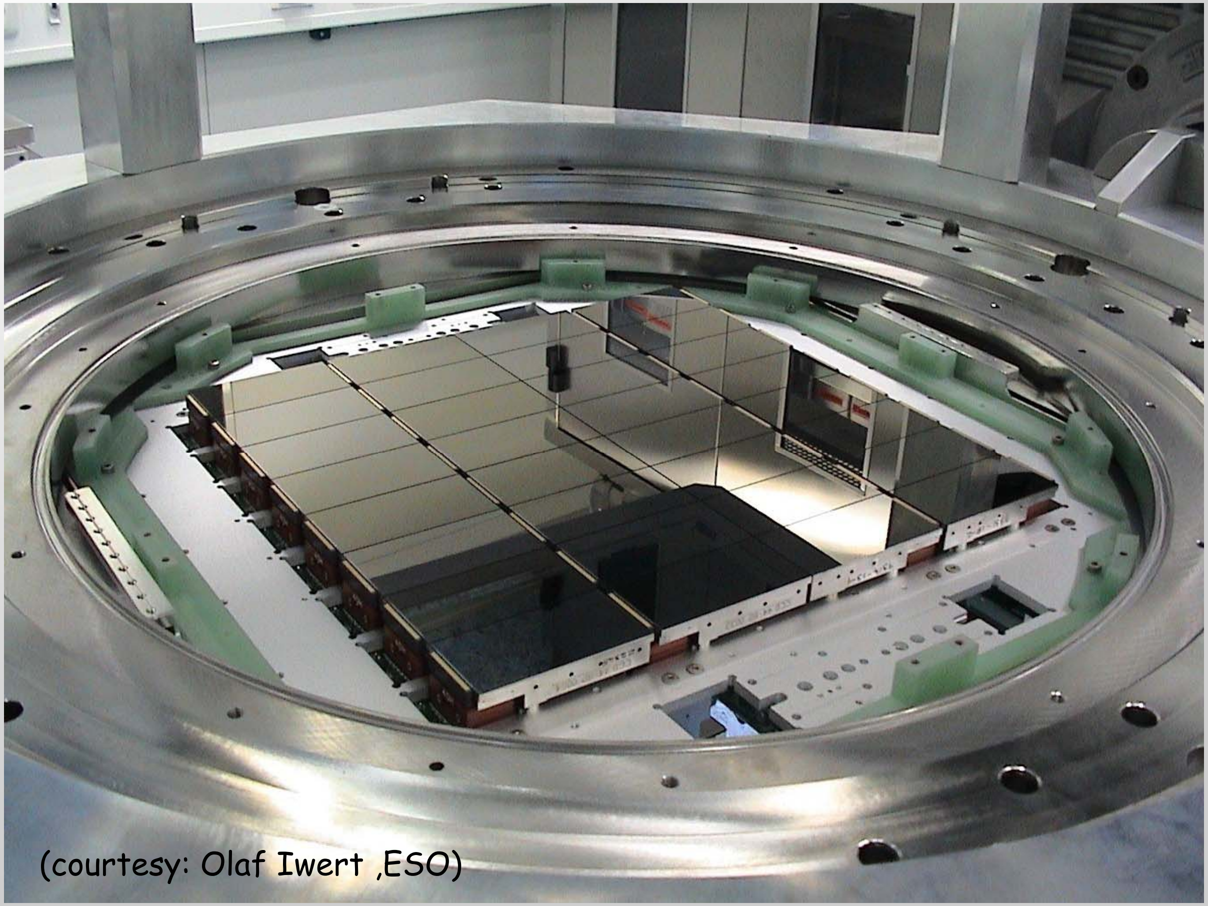
Mosaic of two
E2V 2kx4k CCD



Wide Field Imager
8k x 8k mosaic, 72 million pixels

and even bigger…..

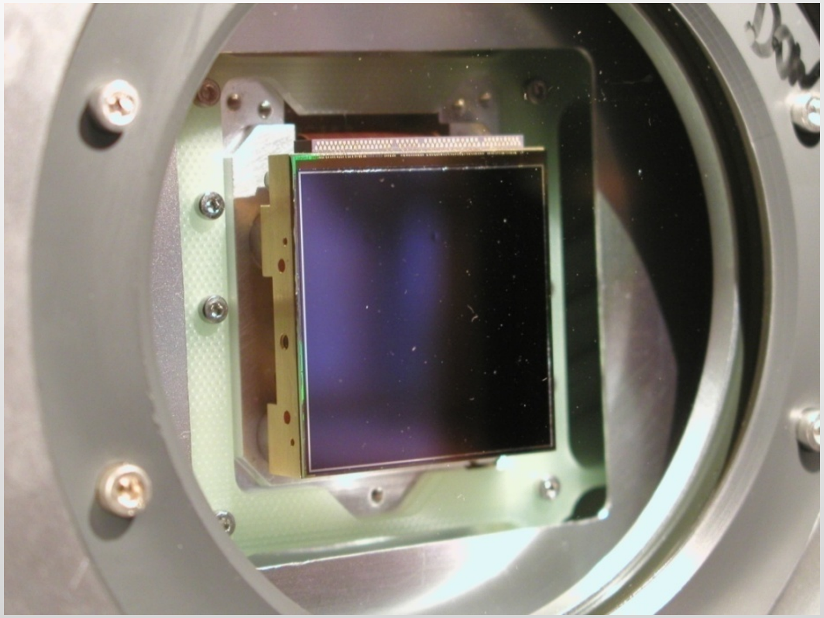
OmegaCAM detector mosaic



(courtesy: Olaf Iwert ,ESO)

32 CCDs - 16 x 16 k - 1x1° FOV + 4 tracker - **288** million pixels

SI-PIN/Visible hybrid Hawaii2RG detector

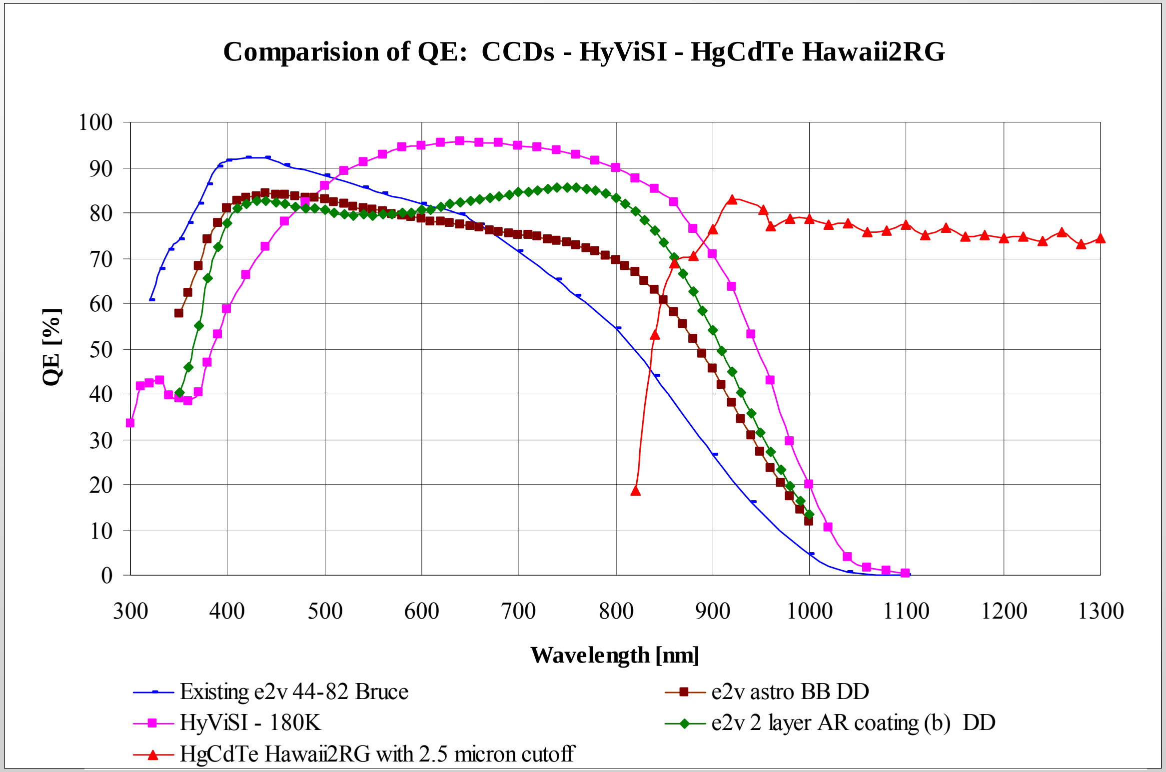


It is a complementary metal oxide semiconductor (CMOS) alternative to charge coupled devices (CCDs) for photons at optical wavelength.

2k x 2k format with 18 micron pixels

A silicon pin hybrid detector has close synergy with IR (HgCdTe) detectors.

HyViSI quantum efficiency (compared to CCDs)



The HyViSI detector outperforms all CCDs above 500 nm and shows a higher overall QE compared to the CCDs.

The e2v astro is a curve provided by e2v for a broad band deep depletion device.

The green curve the QE for a 2 layer AR coating of the deep depletion CCD.

The blue curve is the QE of the CCD currently installed in Giraffe at the VLT.

Red curve is a IR Hawaii2RG HgCdTe detector

Infrared detectors used in Astronomy

Infrared astronomy is currently benefiting from three different technologies providing high performance hybrid active pixel sensors:

In the near infrared from 1 to 5 μm two technologies:

InSb and $Hg_{(1-x)}Cd_xTe$ grown by LPE or MBE on Al_2O_3, Si or CdZnTe substrates.

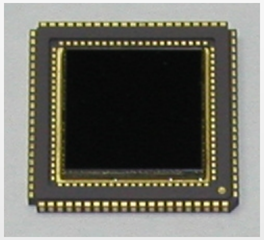
The width of the band-gap of the alloy $Hg_{(1-x)}Cd_xTe$ can be tuned by varying the composition x of the alloy. In this way the cut-off wavelength λ_c of the sensor can be changed as explained before.

In the mid infrared spectral range from 8 to 28 μm:

Blocked impurity band Si:As arrays

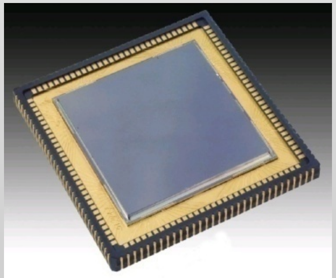
Present IR arrays

Hawaii 1



Rockwell 1024x1024
2.5µm HgCdTe detector array
4 Quadrant architecture
4 Output amplifiers
18.5 µm pixels
LPE HgCdTe on sapphire (PACE-1)
Use of external JFETs possible

Quantum efficiency (70% - 80%)
Dark current 0.01 e-/s (65K)
Read noise about 10 - 15 e- rms CDS
Residual image effect
Some multiplexer glow
Fringing
500 ms – 1 s frame time

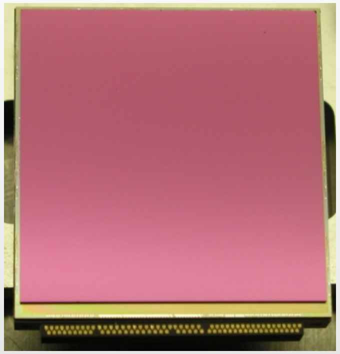


1024x1024 InSb detector array
4 Quadrant architecture
32 Output amplifiers
27 µm pixels
Thinned, AR coated InSb
Three generations of multiplexers
Frame time ~ 70 ms

Quantum efficiency high (70% - 90%)
Dark current 0.01 - 1.0 e-/s
Read noise about 40 e- rms CDS,
10 e- rms Fowler sampling
Charge capacity 200,000 e-
Residual image effect

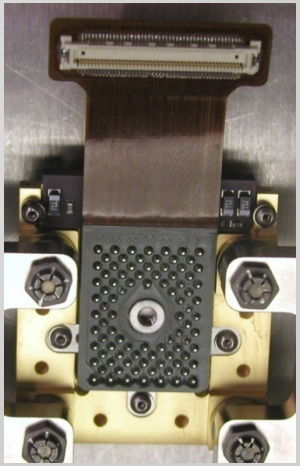
Present IR arrays

Hawaii 2RG



Most Sophisticated ROIC Yet Developed for Astronomy

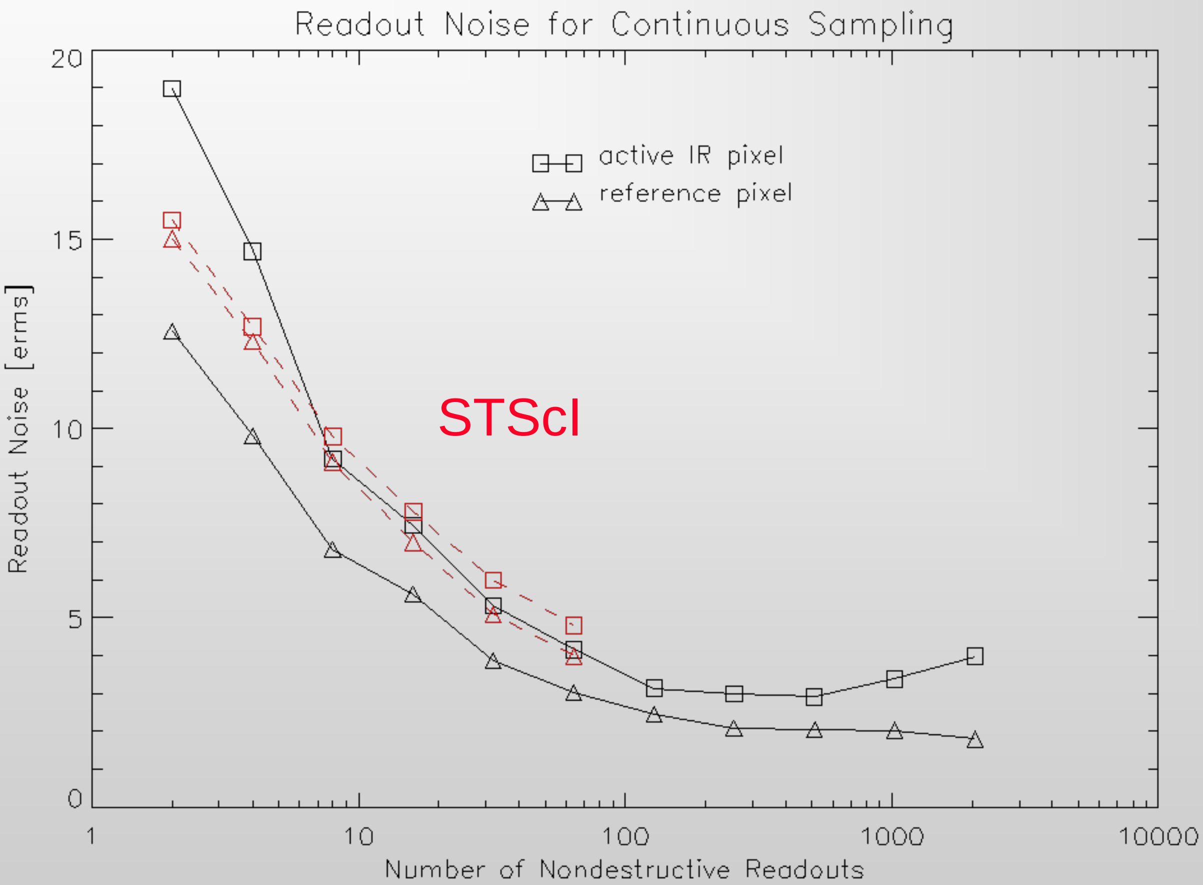
Noise: 17 electrons for a normal DC read
QE (array mean) > 80 %
Dark current < 0.006 e/s/pixel at 77K and 2.5 um cutoff
Spectral range 0.3 - 5.3 um
Guide mode and reference pixels



2048 x 2048 resolution with 18 μm square pixels
Close buttable package
1, 4, or 32 output mode selectable
Slow mode (100 kHz) and fast mode (5 MHz with additional column buffers) selectable, both usable with internal and external buffers

Number of outputs	Frame time in slow mode	Frame time in fast mode
1	*42 s*	*840 ms*
4	*10.5 s*	*210 ms*
32	*1.3 s*	*26 ms*

Hawaii 2RG noise performance



Fowler sampling:
number of readouts n proportional to integration time: 825 ms/readout

for 256 Fowler pairs
3 e- rms on IR pixels
1.8 e- rms on reference pixels

shielding multiplexer glow very efficient

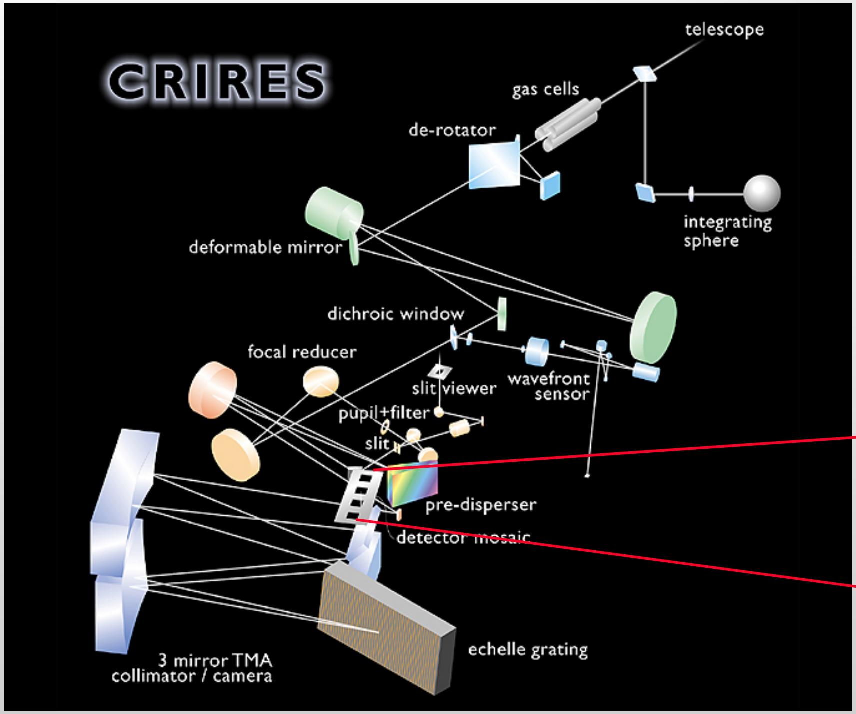
large number of nondestructive readouts possible with 32 channels

(courtesy: Gert Finger,ESO)

Examples of IR detectors systems

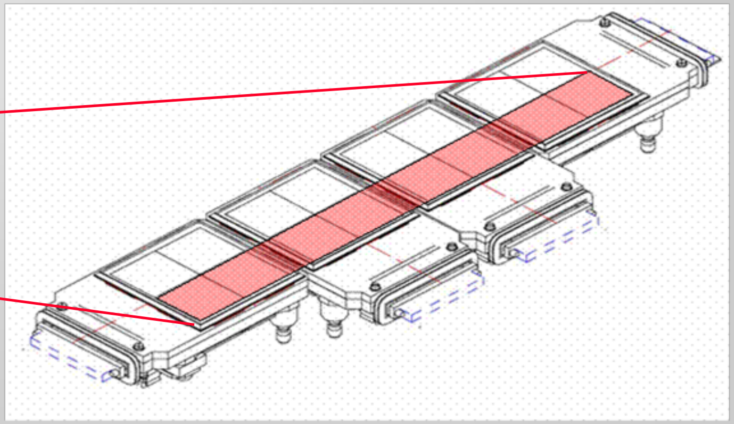
The CRIRES 1024 x 4096 pixels Aladdin InSb focal plane array

Cryogenic Echelle Spectrograph

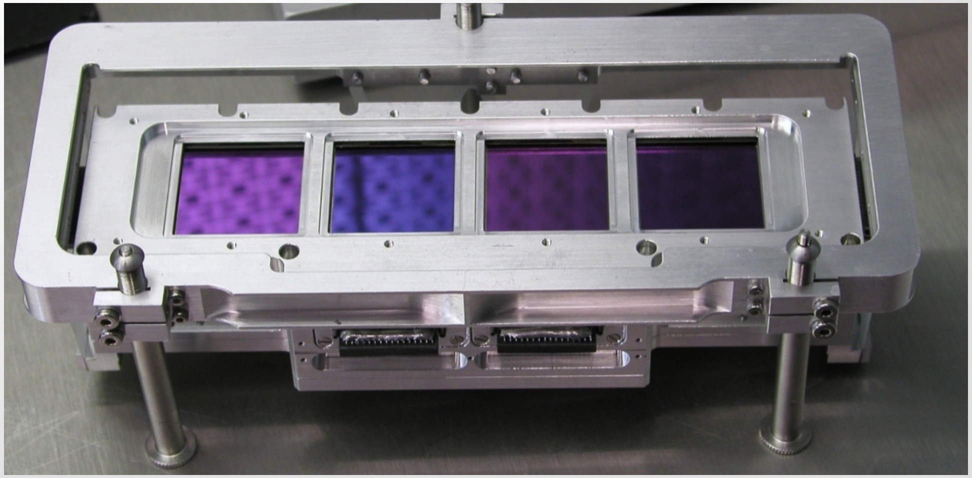


curvature AO: 0.1 arcsec / pixel
512 pixels in spatial direction
High resolution R=100000 echelle
prism predisperser for order sorting and
photon background suppression

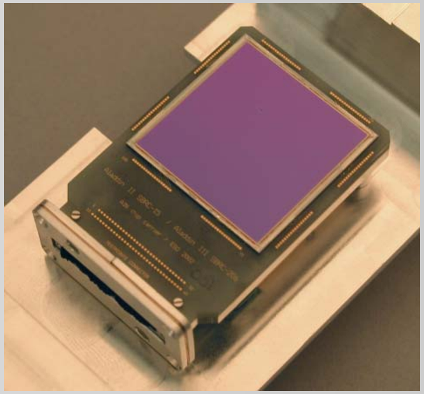
Four **Aladdin** 1Kx1K InSb arrays



The CRIRES 1024 x 4096 pixels Aladdin InSb focal plane array

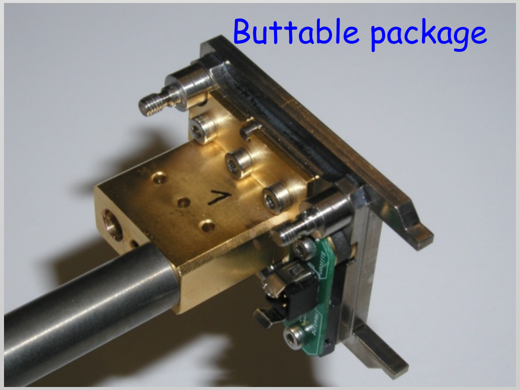


Aladdin III in new package



A new 3 side quasi buttable package
for the Aladdin II /III

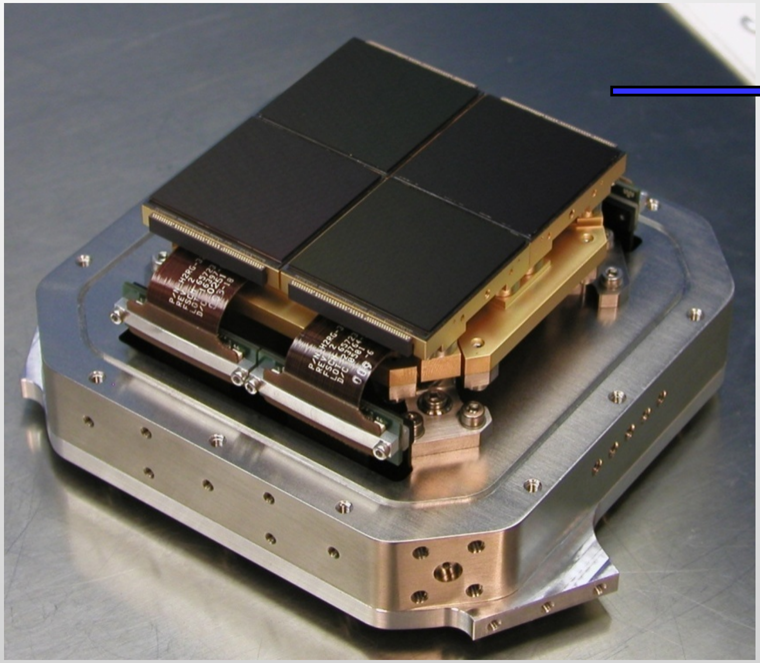
(ESO development)

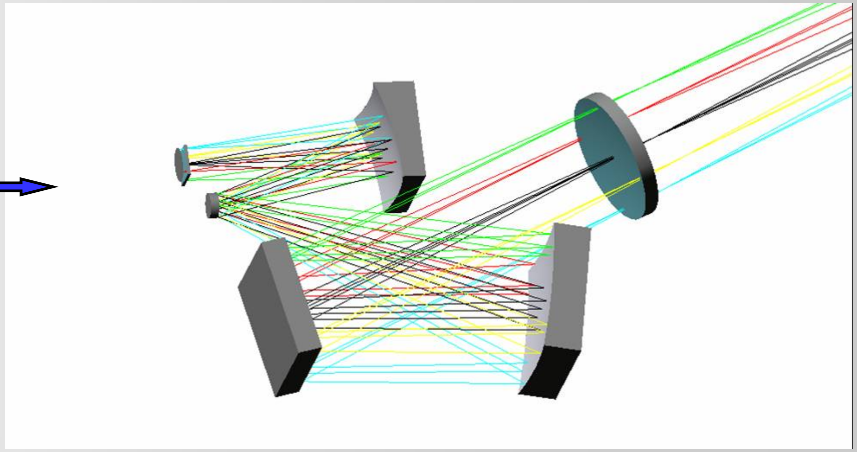


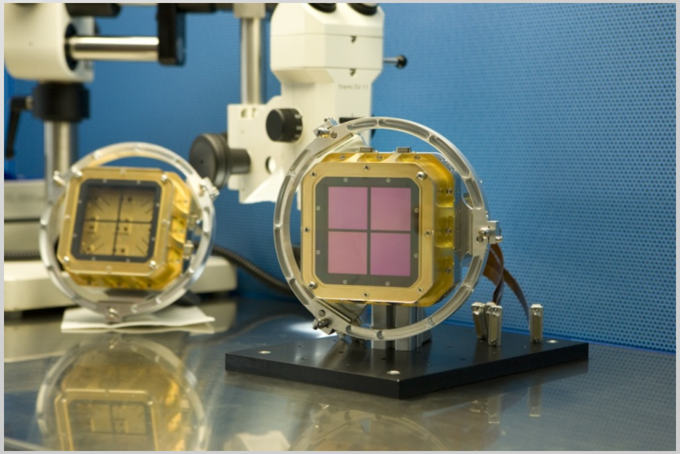
Buttable package

AlN chip carrier

HAWK-I – HgCdTe Array Wide field K-band Imager for the VLT







Mosaic out of 4 Hawaii 2RG MBE detectors, 128 parallel channel system

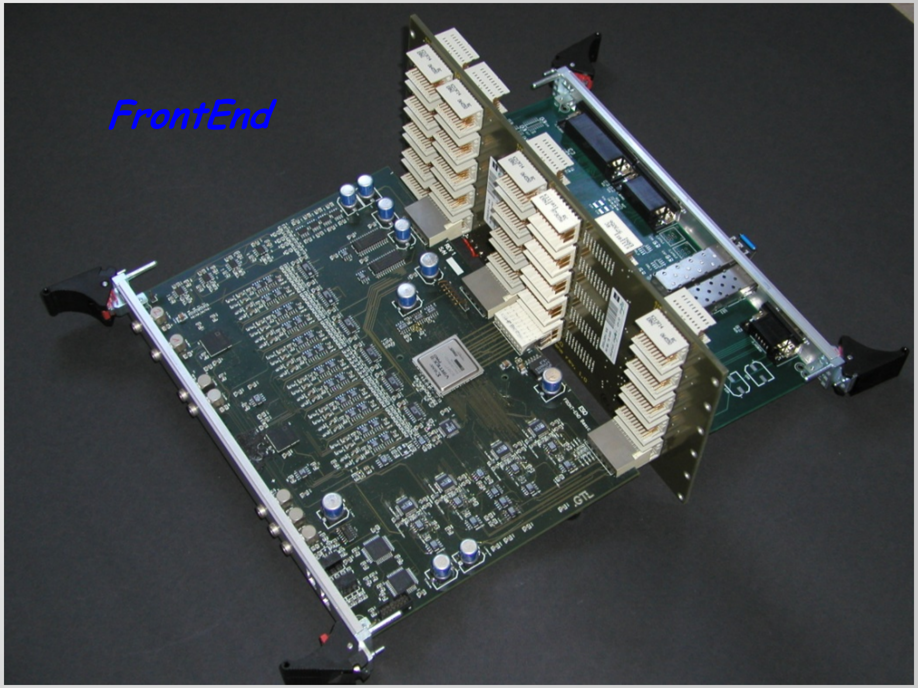
Wavelength range: 0.85 - 2.5 µm

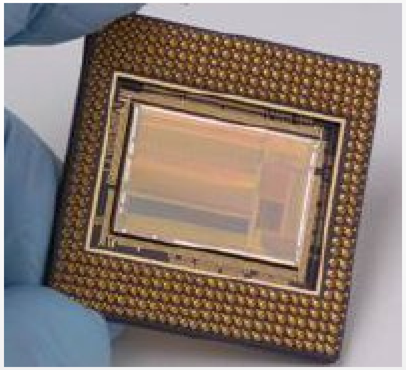
VIRGO 16 x 2Kx2K HgCdTe mosaic for VISTA (4m survey Telescope)

- VISTA built by RAL & UKATC
- FOV 1.65 degrees
- 2Kx2K HgCdTe grown by LPE on CdZnTe substrate (VIRGO)
- Pixel size 20 µm
- 16 parallel outputs
- Pixel rate 400 KHz
- Frame rate 1.5 Hz
- 3-side buttable
- Reference cells included in video data stream

The ESO baseline controller for CCDs and IR detectors (NGC)

- NGC is a modular system for IR detector and CCD readout with a Back-end, a basic Front-end unit containing a complete four channel system on one card and additional boards like 32 channel ADC units and more...
- There is no processor, no parallel inter-module data bus on the front-end side. Advanced FPGA link technology is used to replace conventional logic.
- Connection between Back and Front-end with high speed fiber links at 2.5GBit/s
- Connection between Front-end modules with high speed copper links at 2.5GBit/s.





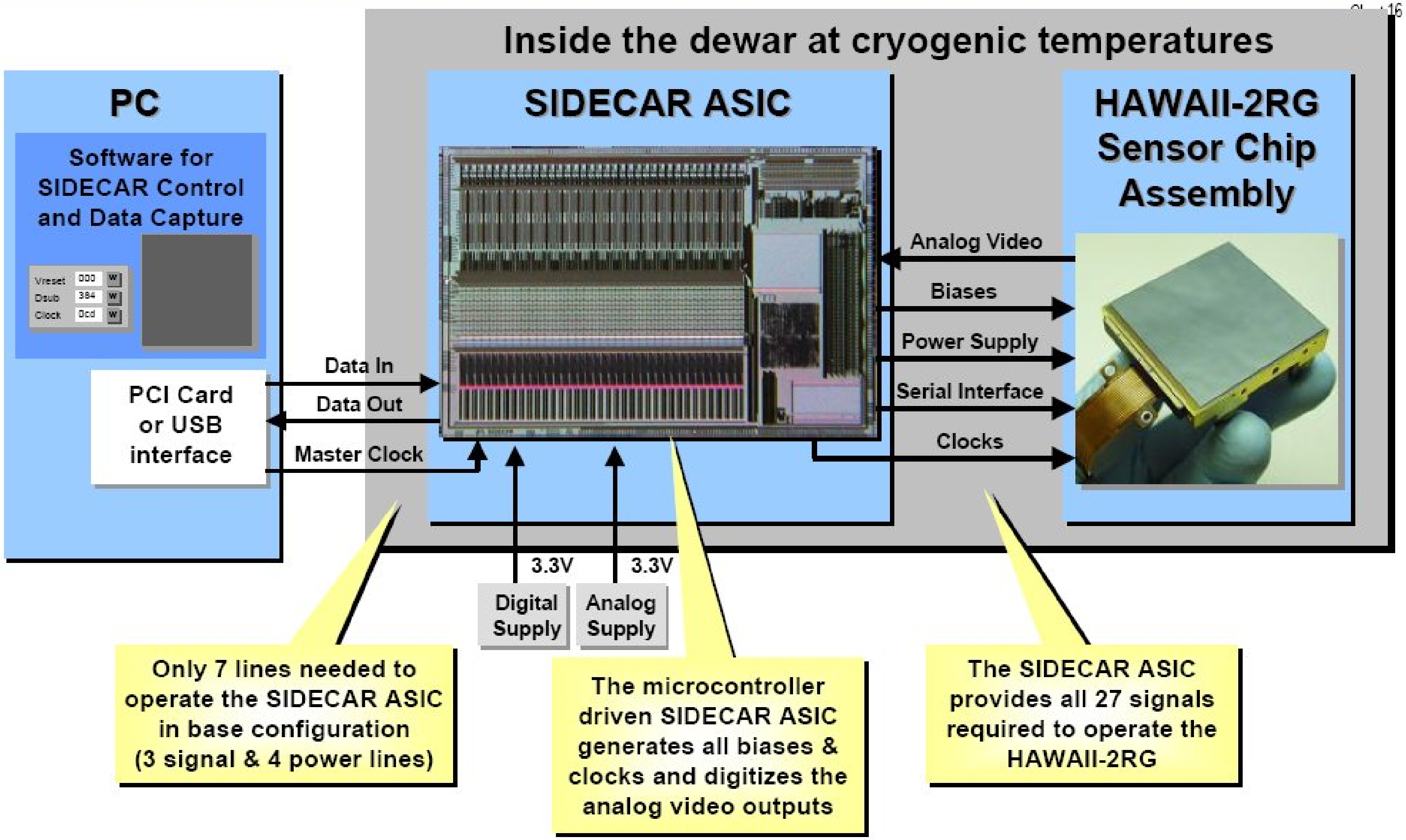
SIDECAR ASIC

SIDECAR™
- system image, digitizing, enhancing, controlling, and retrieving -

ASIC
- Application Specific Integrated Circuit -

The ASIC is a controller on a single Chip designed for use in all Teledyne Imaging Sensors (former Rockwell) FPAs including 2048 x 2048 HAWAII-2RG™

ASIC Based Compact System



Inside the dewar at cryogenic temperatures

PC

Software for SIDECAR Control and Data Capture

PCI Card or USB interface

SIDECAR ASIC

HAWAII-2RG Sensor Chip Assembly

Data In

Data Out

Master Clock

Analog Video

Biases

Power Supply

Serial Interface

Clocks

3.3V

3.3V

Digital Supply

Analog Supply

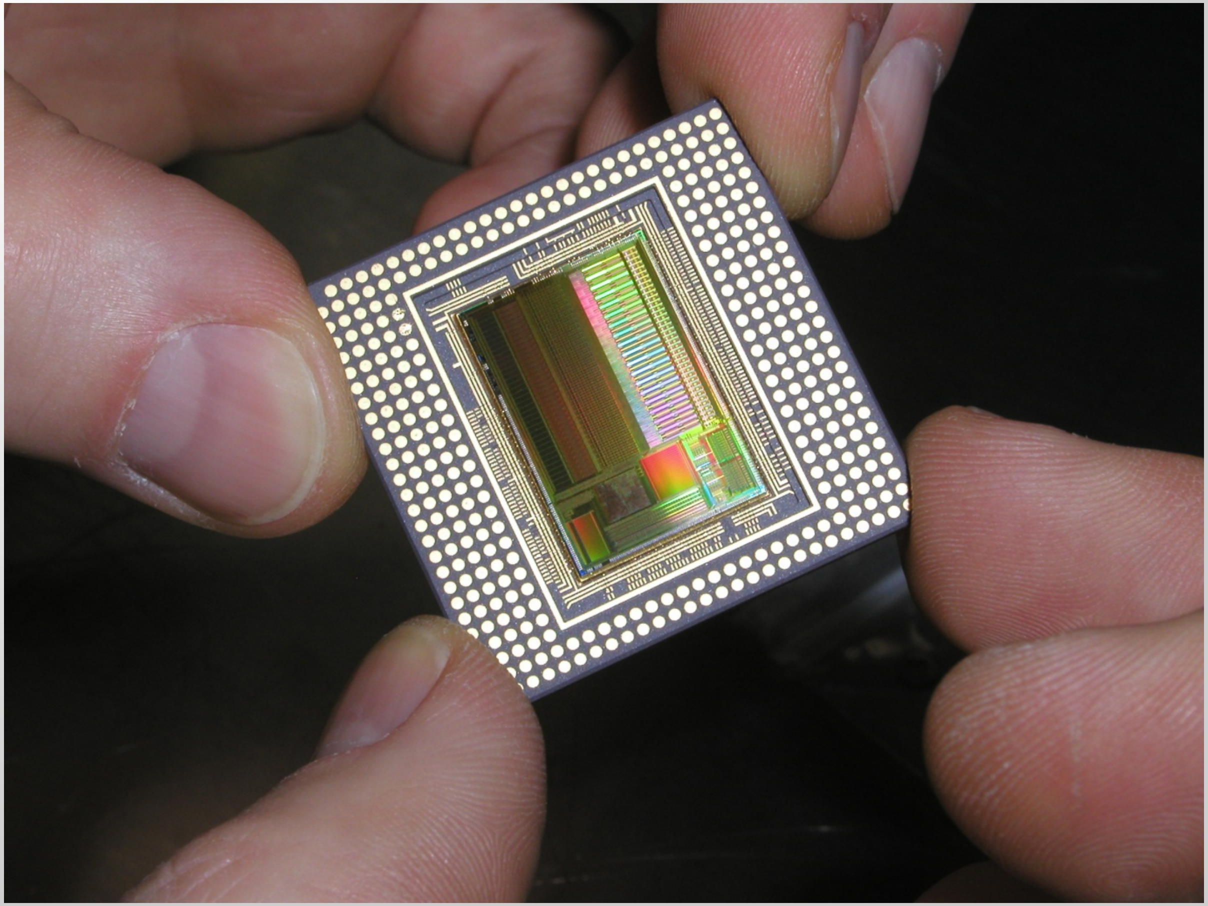
Only 7 lines needed to operate the SIDECAR ASIC in base configuration (3 signal & 4 power lines)

The microcontroller driven SIDECAR ASIC generates all biases & clocks and digitizes the analog video outputs

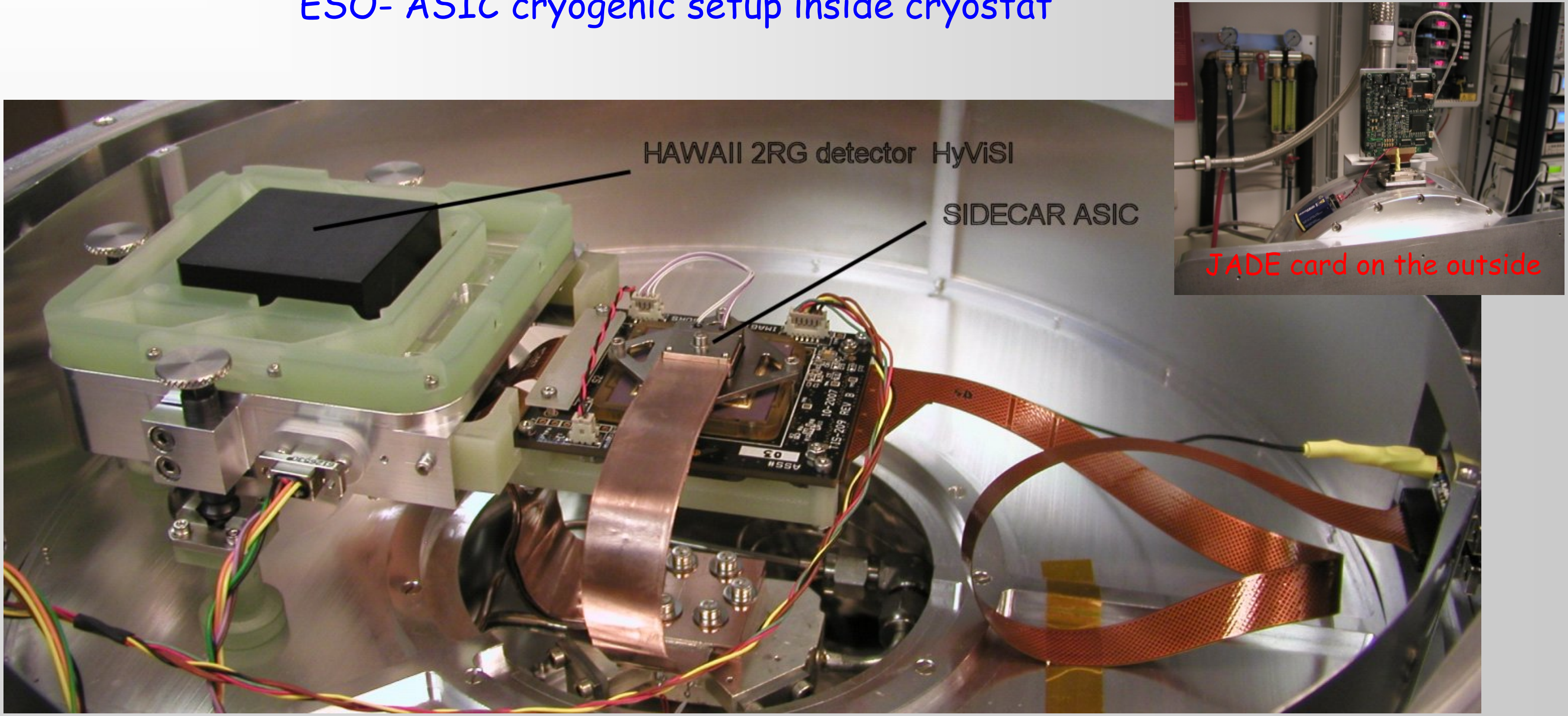
The SIDECAR ASIC provides all 27 signals required to operate the HAWAII-2RG

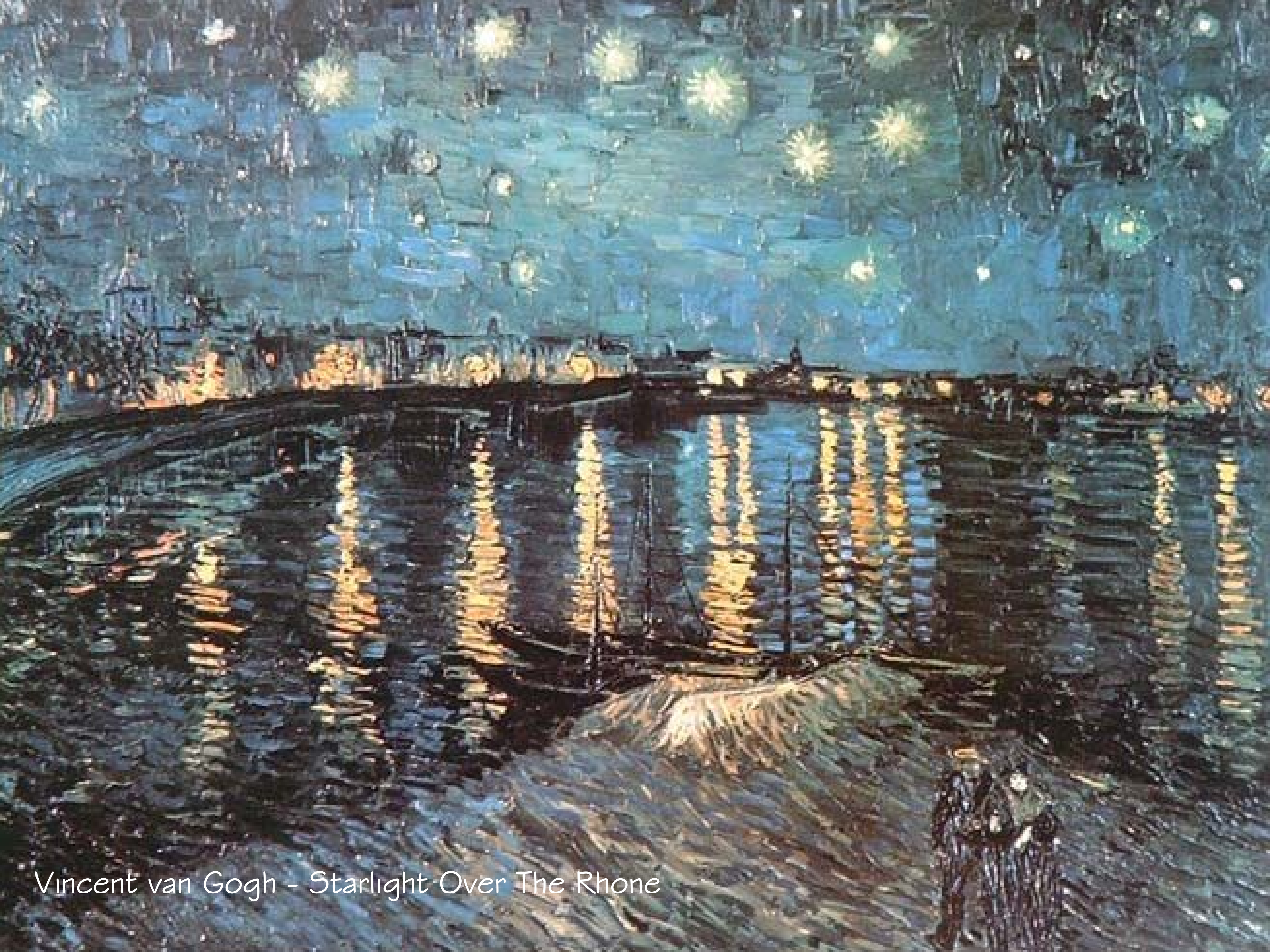
TELEDYNE IMAGING SENSORS
A Teledyne Technologies Company

ASIC @ ESO – LCC package



ESO- ASIC cryogenic setup inside cryostat





Vincent van Gogh - Starlight Over The Rhone