Imaging Detectors

a review of detector technology for space research

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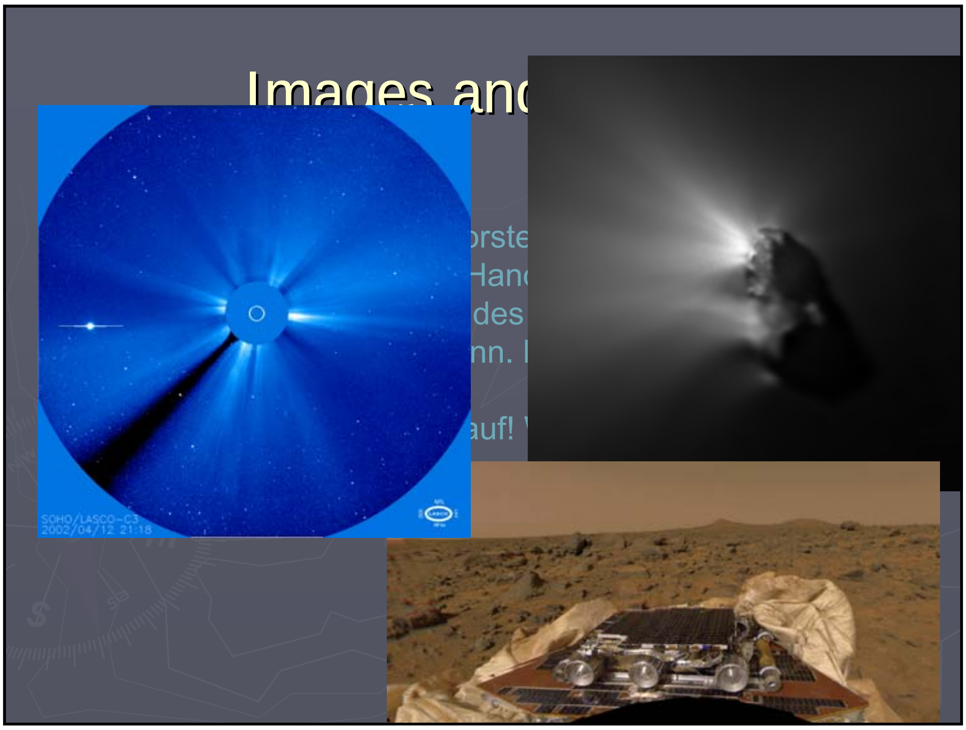
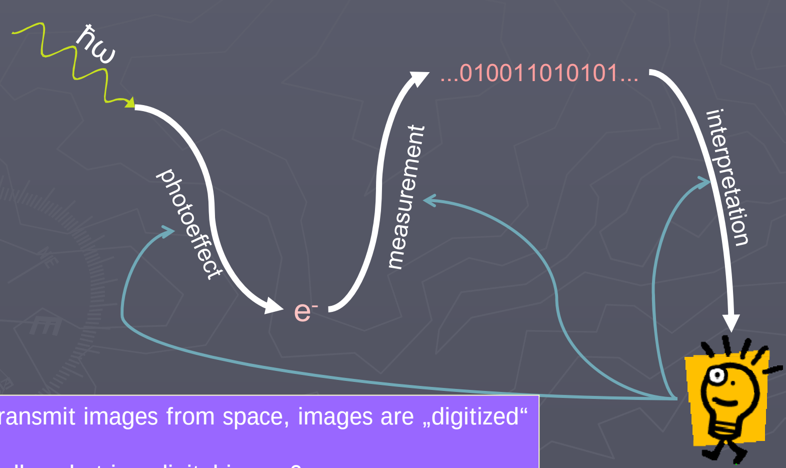
IMPRS lecture on 7. December 2006
with contributions from previous lectures of I. Pardowitz and A. Gandorfer

Outline

- digital cameras: general remarks, terminology
- sensor arrays: materials
- general performance characteristics
- CCDs vs CMOS-APS sensors
- UV detectors for solar observations
  - hybrid sensors with wide bandgap materials
  - microchannel plate detectors
    - analog read-out MCP detectors
    - Intensified APS detectors

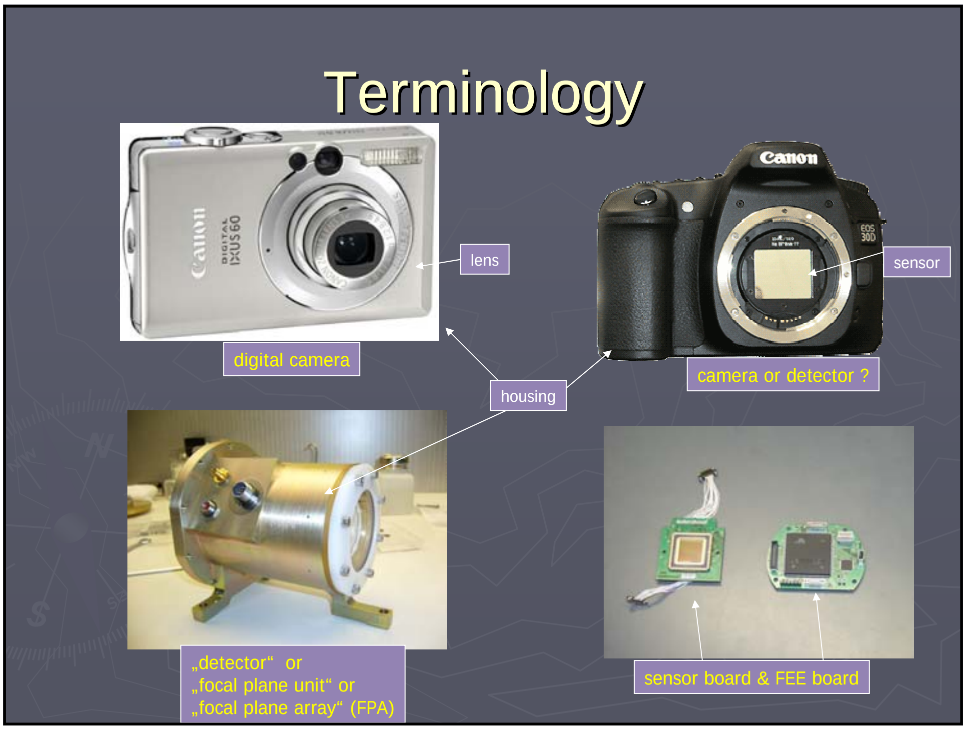


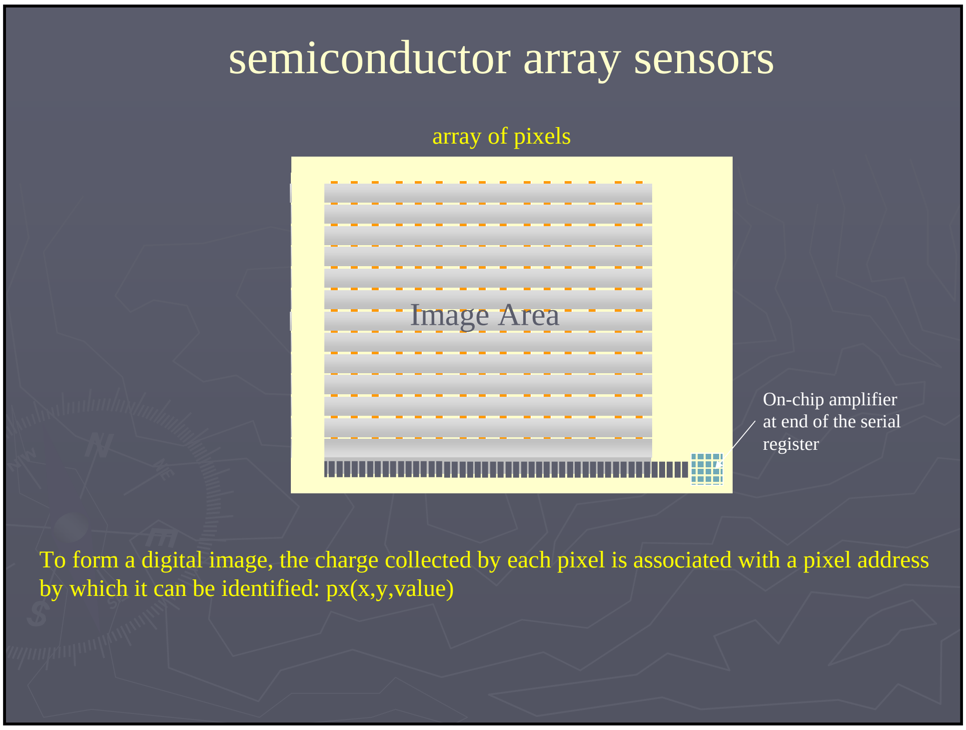
From photon to knowledge



To transmit images from space, images are „digitized“

Actually, what is a digital image?


Terminology
lens
sensor
digital camera
camera or detector ?
housing
„detector“ or
„focal plane unit“ or
„focal plane array“ (FPA)
sensor board & FEE board


semiconductor array sensors
array of pixels
Image Area
On-chip amplifier
at end of the serial
register
To form a digital image, the charge collected by each pixel is associated with a pixel address by which it can be identified: px(x,y,value)

remark

Note that the pixel size of a sensor array is of the order of 10 to 20 um squared.

If you design an optical system (a telescope), the image scale must be such that the resolution element corresponds with the pixel size and the field of view corresponds with the array size.

The parameter to adjust is the Focal Length.

Photodetector materials

Material	E_{gap} (eV)	λ [nm]	band
Si	1,12	1100	Visible
GaAs	1,42	875	Visible
Ge	0,66	1800	NIR
InGaAs	0,73-0,47	1700-2600	NIR
InAs	0,36	3400	NIR
InSn	0,17	5700	IR
HgCd	0,7-0,1	1700-12500	NIR-FIR

Other detector materials

- PtSi (3-5 um)
- HgCdTe (3-5 or 8-10 um)
- CdZnTe
- GaN (360 nm)
- AlGaN (360 to 260 nm)
- C (diamond) (220 nm)

infrared materials

ultraviolet materials

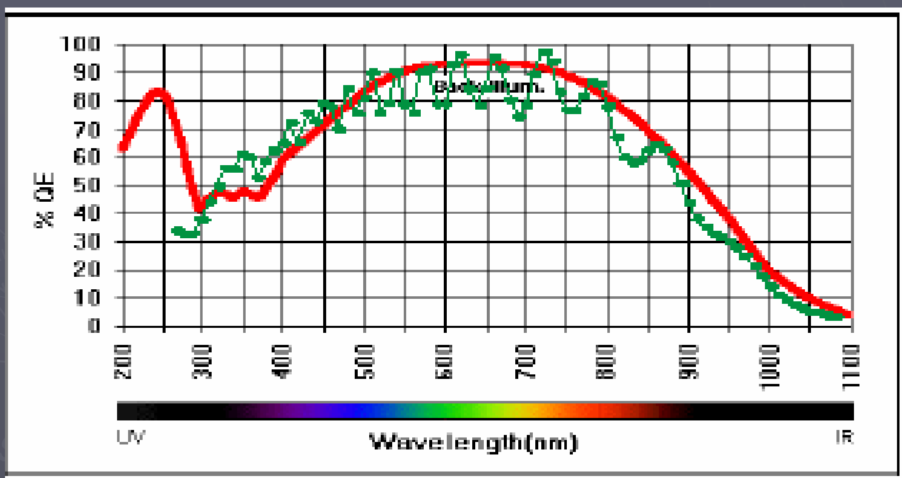
Performance Parameters(1)

- Spectral range
- QE = quantum efficiency
- Noise (dark noise, read-out noise, photon noise)
- Dynamic range (full well capacity – dark signal)
- CCE = Charge Collection Efficiency
- CTE = Charge Transfer Efficiency
- Dark current / dark signal (need cold T ?)

Performance Parameters (2)

- Array size (pixel size and # of pixels)
- Frame rate (speed, determines image cadence)
- Radiation hardness
- Power requirements
- Technology
- Price

QE = quantum efficiency



types of sensor arrays

Si-based sensors:

- charge coupled devices (CCDs, Si sensors)
- CMOS sensors
  - expanding the sensitivity range to the UV
  - backside illumination
  - deep depletion
- choice of materials
- sensor architecture
- Hybrid detectors

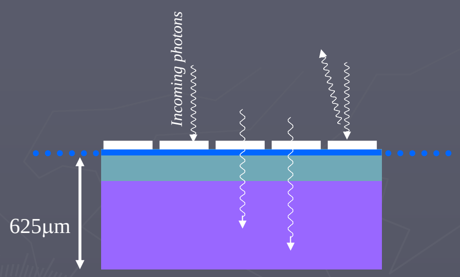
→

CCDs

diode arrays

CMOS active pixel arrays (APS)

Thick Front-side Illuminated CCD



p-type silicon

n-type silicon

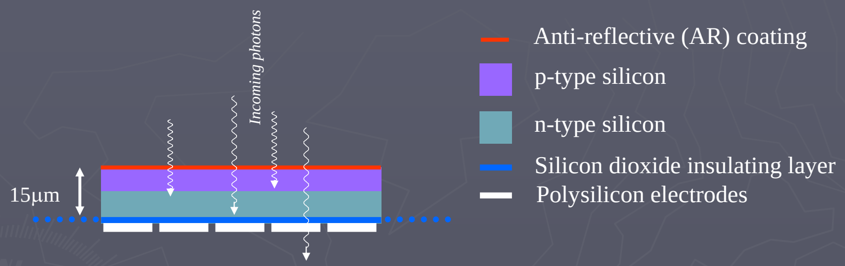
Silicon dioxide insulating layer

Polysilicon electrodes

These are cheap to produce using conventional wafer fabrication techniques.

They have a low Quantum Efficiency due to the reflection and absorption of light in the surface electrodes. Very poor blue response. The electrode structure prevents the use of an Anti-reflective coating that would otherwise boost performance.

Thinned Back-side Illuminated CCD



The silicon is chemically etched and polished down to a thickness of about 15microns. Light enters from the rear and so the electrodes do not obstruct the photons. The QE can approach 100% .

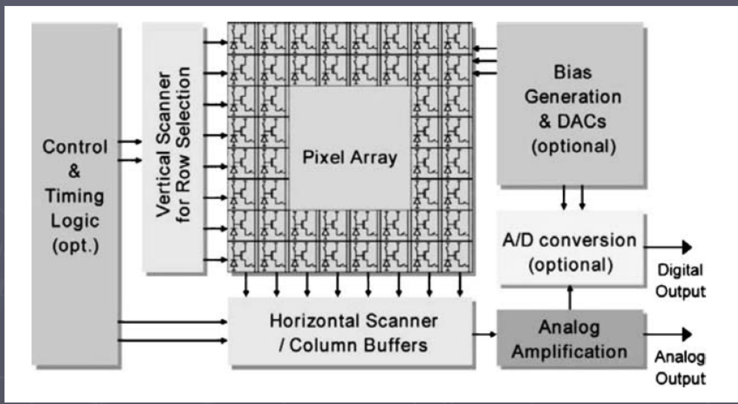
These are very expensive to produce since the thinning is a non-standard process that reduces the chip yield. These thinned CCDs become transparent to near infra-red light and the red response is poor. Response can be boosted by the application of an anti-reflective coating on the thinned rear-side. These coatings do not work so well for thick CCDs due to the surface bumps created by the surface electrodes.

Almost all Astronomical CCDs are Thinned and Backside Illuminated.

CCD versus CMOS sensors

	CCD Approach	CMOS Approach
Pixel	Photodiode Charge generation and charge integration	Photodiode + Amplifier Charge generation, charge integration and 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)

generic architecture of a CMOS sensor

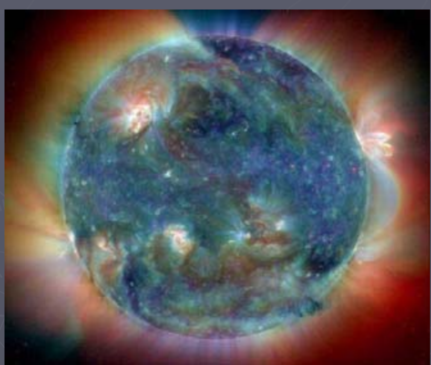


- ✓ flexibility of read-out scheme (pixels can be adressed individually)
- ✓ no shutter is needed

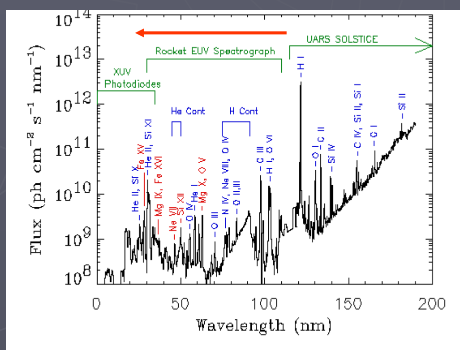
find more info about CCDs and APS in the lectures of Gandorfer and Pardowitz at the IMPRS web site!

UV detectors for solar observations

at these wavelengths no window materials exist
➔ **open detectors** are needed



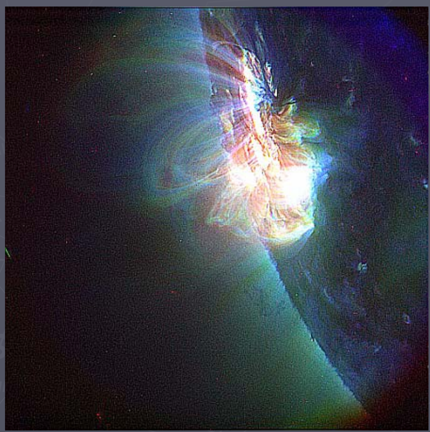
TRACE-image of the Sun in the EUV



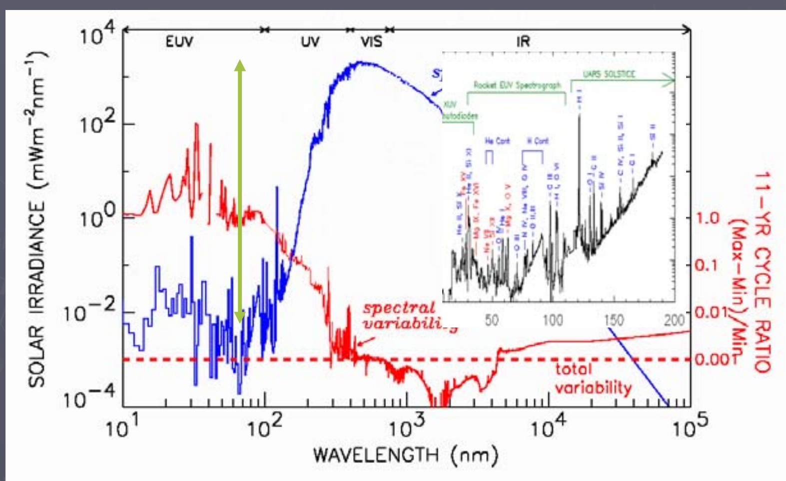
Emission spectra of the Sun in the VUV

The quest for higher resolution and radiation hardness

0.5 Arcsec
~ 350 km at Sun



Solar spectral irradiance (and variability)

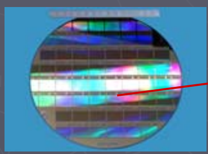


5.5 magnitudes!

Science-grade CMOS APS development at RAL and E2V

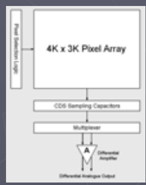
4k x 3k Pixel Sensor Development for ESA's Solar Orbiter

- 5 μm pixel size.
- 12 bit dynamic range.
- 4-transistor CDS pixel for low noise.
- 0.25 μm CMOS process.
- EUV sensitivity by back-thinning or front-etch.



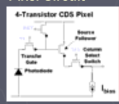
8-inch Wafer 0.25 μm CMOS

4kx3k pixel sensor die



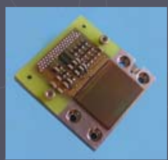
Architecture

Pixel Circuit

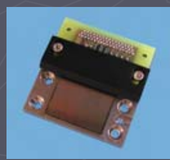


CAD Simulation

CAD Layout



Sensor mounted on an invar block and wire-bonded to a PCB



Bond-wire protection-cover fitted

scintillator coating on CMOS-APS

(downconversion from EUV to visible)

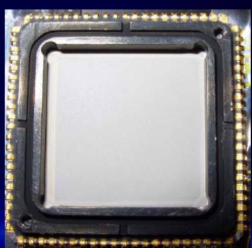
APS CMOS: "HAS" from Fillfactory (B)

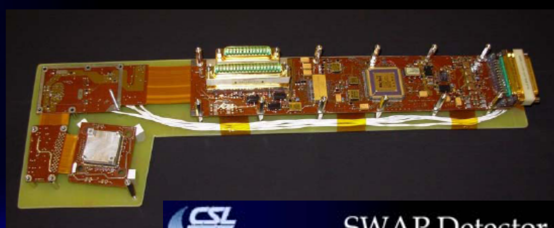
- 1024 x 1024 18 μm pixels
- New development (ESA project
- SWAP uses prototype devices s

Scintillator coating (545 nm)

Readout electronics with 12 bit ADC

- need cooling to reduce dark signal
- need filters to suppress visible
- thin film filters for EUV (0.1 μm thick) are fragile and reduce signal



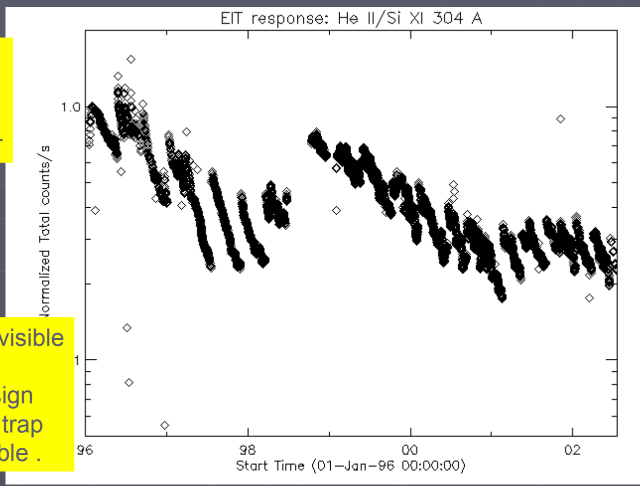


SWAP Detector

Drawbacks of current Si-based sensors

the EUV-teleskope
EIT on SOHO:

back-thinned CCD sensor

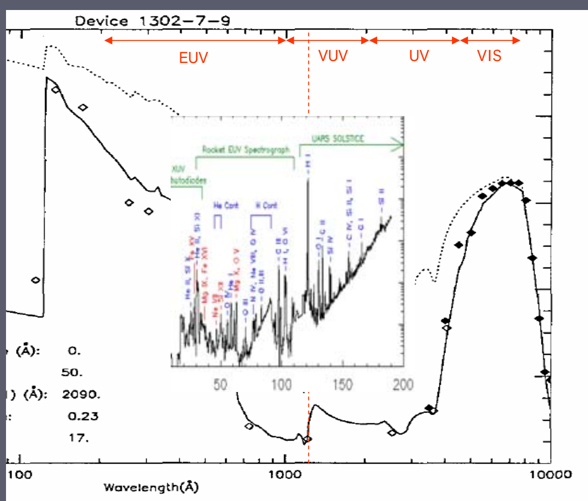


- need filters to suppress visible
- need cooling.
- complicates thermal design
- results in contamination trap

==> Efficiency very unstable .

The problem of silicon in the VUV

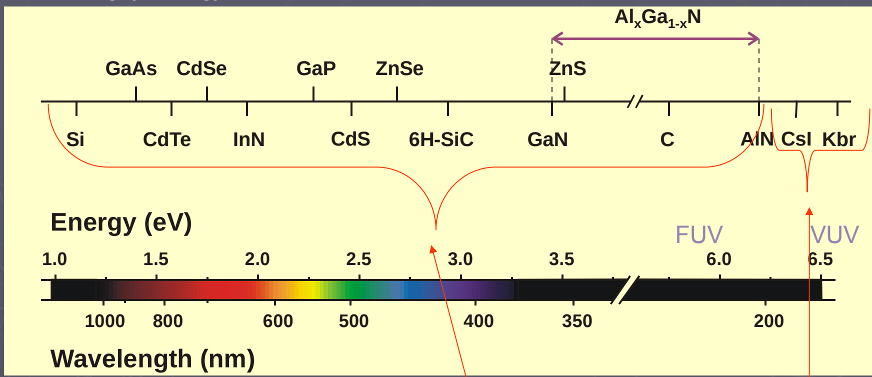
The efficiency of silicon at 121nm (the hydrogen Lyman-Alpha line) wavelength is minimal.



Measured QE for silicon device (open diamonds, data taken at -70 0C; filled diamonds, data taken at room temperature in a diode mode). Dotted curve, maximum theoretical QE for 100% CCE; solid curve, best-fit semiempirical model using all data.

Photocathode materials

band gap energy of materials:



charge creation and photoconduction

photoemission in vacuum

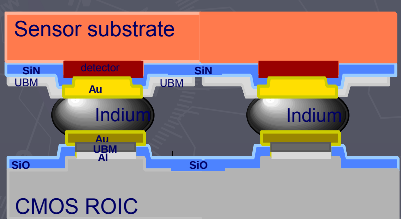
hybrid sensors

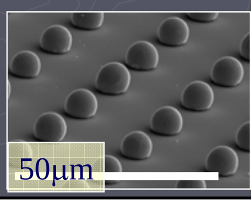
photosensitive substrate
+
silicon read-out circuit
=
hybrid sensor

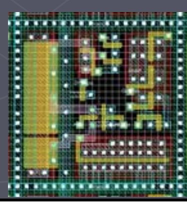
substrate:
array of photosensitive material,
e.g., HgCdTe or AlGaN

readout circuit array, ROIC:
silicon based integrated circuit (CMOS array)
with individually adressable pixels

to be mated by „flip-chip technique“
via indium bump contacts

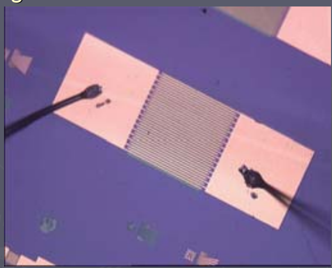






hybrid design with wide band gap material

e. g. GaN MSM-Photoconductor

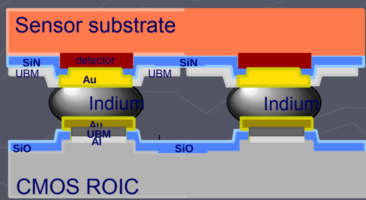


Can be selcted to be solar blind

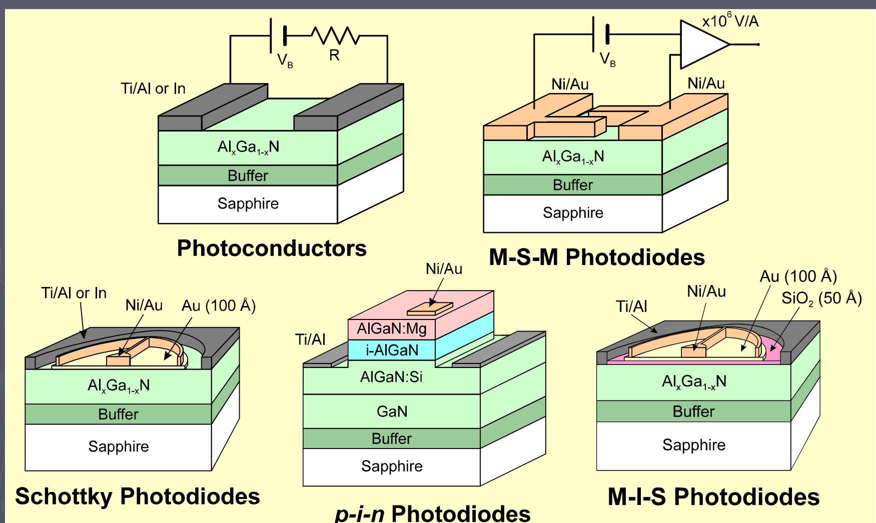
Highly efficient in the VUV and EUV

Sensor substrate: Diamond or AlGaN

ROIC: silicon based CMOS structure



$Al_xGa_{1-x}N$ Photodetector types

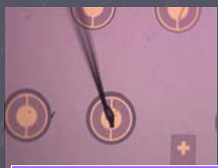


WBGS detectors

Wide band gap detectors - two different substrate materials: AlGaN and Diamond

AlGaN test devices

MSM GaN device



Schottky GaN device

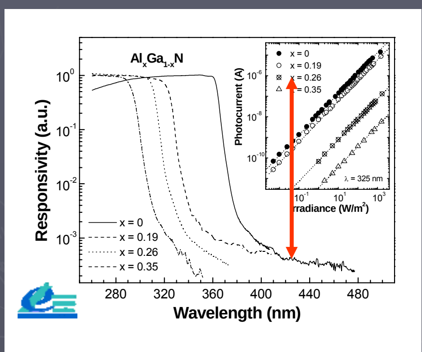
Diamond devices

MSM and PIN diodes

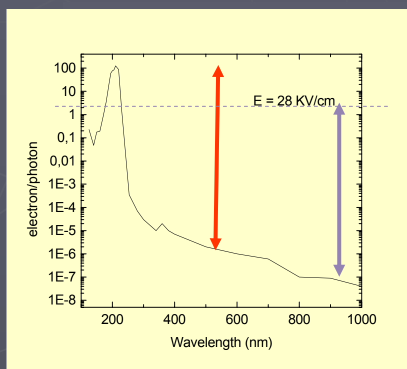
soon flying on PROBA2-LYRA

- Only single pixel devices.
- Large arrays to be developed

Solar-blindness of present WBGS detectors



Pau *et al.* 2003. **Nitride**

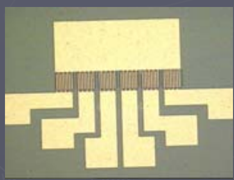


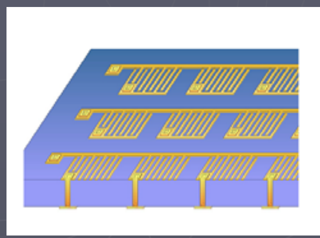
Diamond Pace *et al.* 2000.

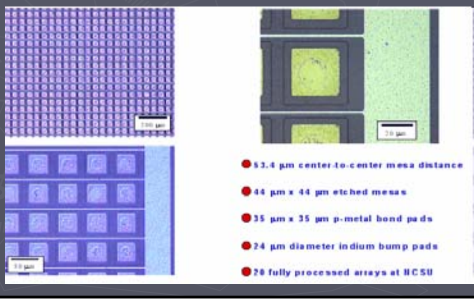
- ✓ less filters are needed to suppress the visible-NIR continuum
- ✓ negligible dark signal at room temperature
- ✓ no cooling required

imaging arrays of WBGS

build a micro-array of photoconductors



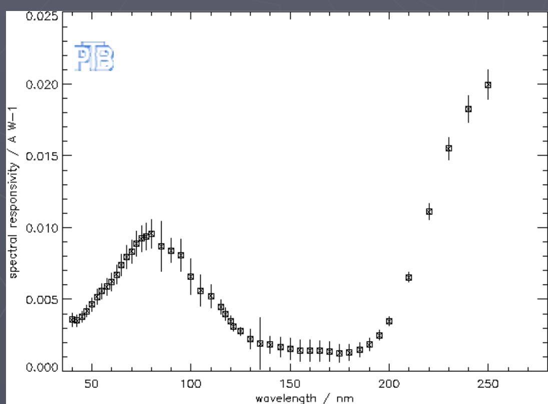




EUV efficiency of GaN Schottky device

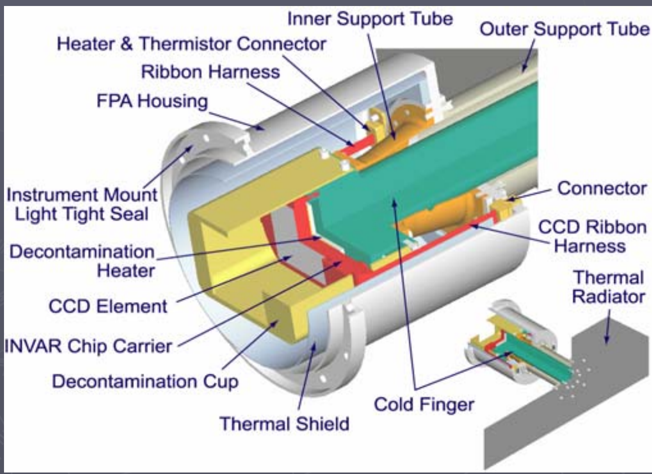
• Absolute responsivity measured at the electron storage ring BESSY II

• Compared to a calibrated PtSi reference diode



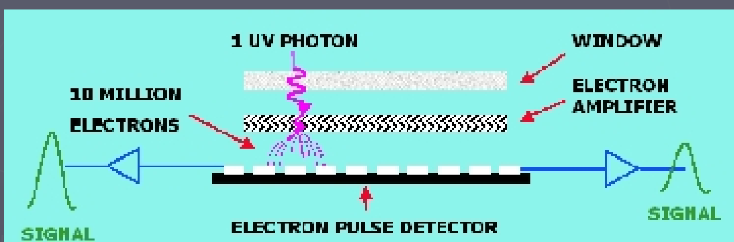
All detectors have poor sensitivity between 50 nm and 150 nm!

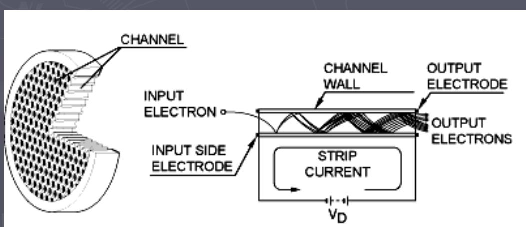
Focal plane array for space instrumentation



Multichannel plate (MCP) detectors

(photoemission detectors, photon counting detectors)

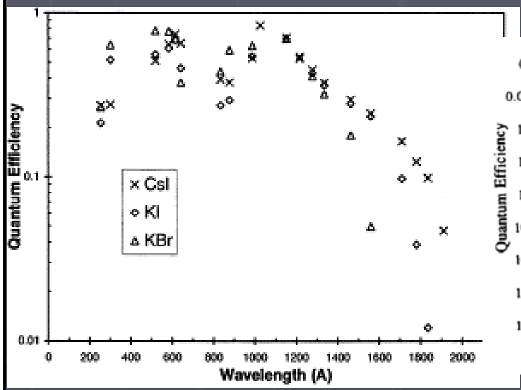




each MCP operates at
a gain of ~100 electrons

photocathodes on MCPs

alkali halide photocathodes increase the quantum efficiency in selected wavelength ranges:
CsI, CsCl, LiF, KCl, KBr, RbI, etc.



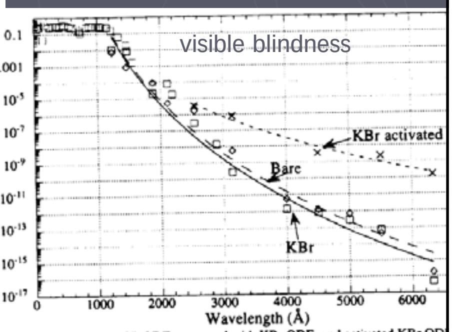
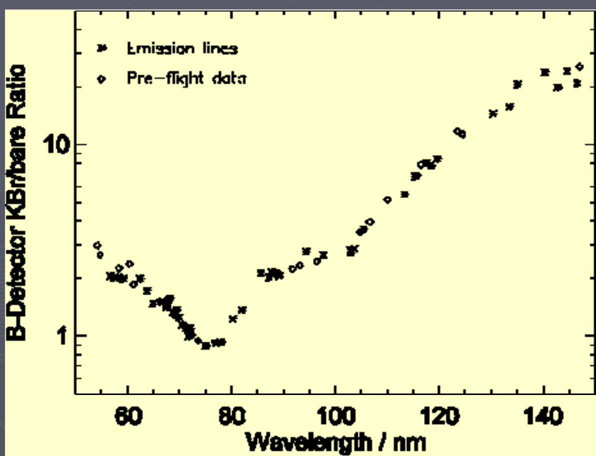


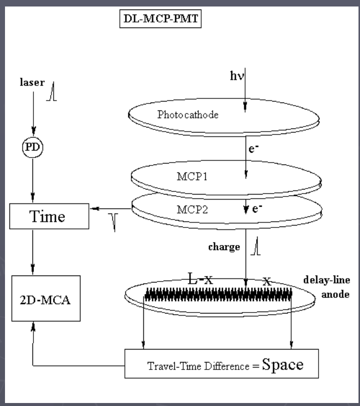
Figure 13. Bare MCP QDE compared with KBr QDE, and activated KBr QD

photocathodes on MCPs

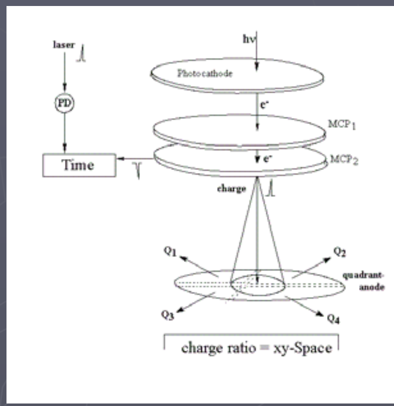
SUMER KBr photocathode



Readout schemes of microchannel plate detectors

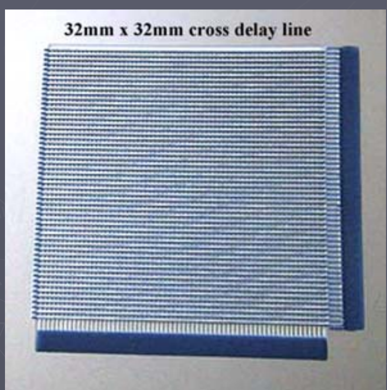


Cross delay line anode + time to digital converter



Cross strip anode + charge ratio centroiding

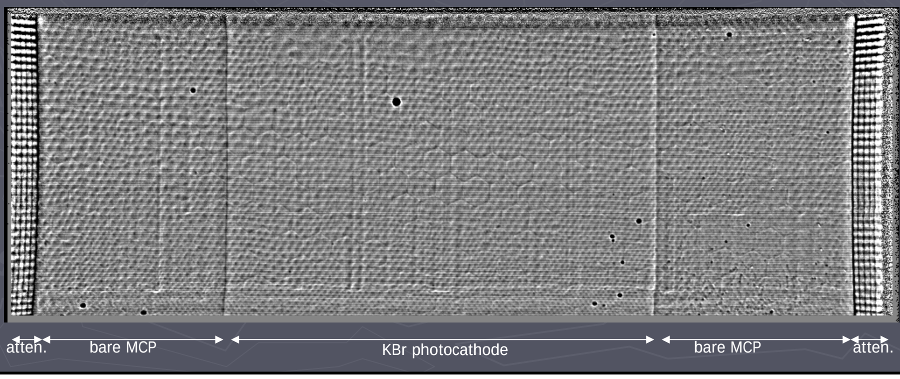
Anode design options



- Wedge and strip anode
- Cross Delay line anode
- Cross strip anode
- CCD sensor
- CMOS APS sensor

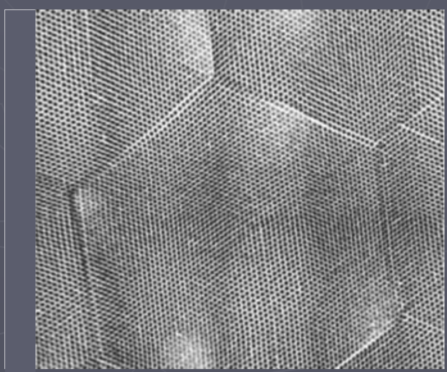
Example: flatfield of SUMER XDL detector

- Distortion
- ADC nonlinearity
- Multifiber bundles (hexagonal)
- Moire pattern (from 3 MCPs)
- Dead pores



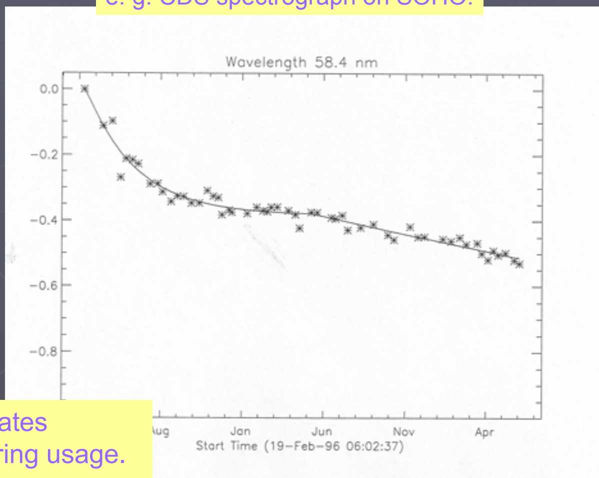
Flatfield pattern & resolution

- Pore structure limiting the resolution
- Multifiber bundle boundaries
- Moire pattern by superposition of MCPs



Instability of channel plate detectors

e. g. CDS spectrograph on SOHO:



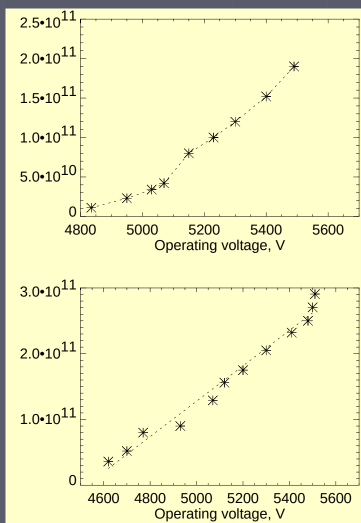
The gain of channel plates reduces constantly during usage.

Instability of channel plate detectors

voltage increase to compensate the gain evolution of the SUMER detectors using stack of three MCPs (10^6 electrons per pulse)

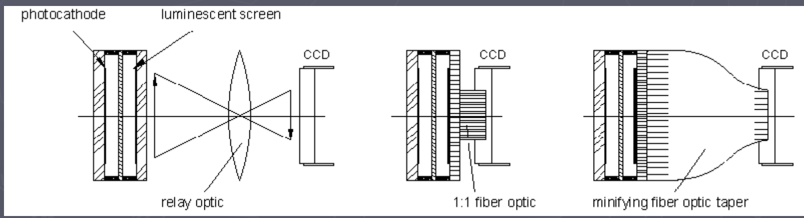
➔

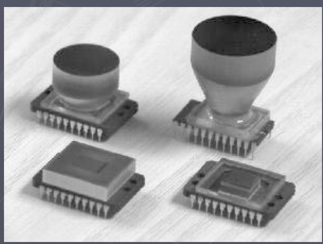
this is now understood and can be avoided using only one MCP (at low gain) and CCD sensor



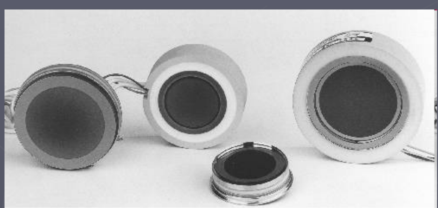
Intensified CCD

MCP coupled to CCD via lens or fiber-optic taper



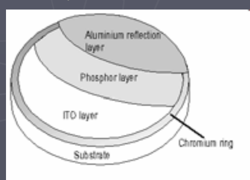


Microchannel plate intensifiers



MCP based intensifiers

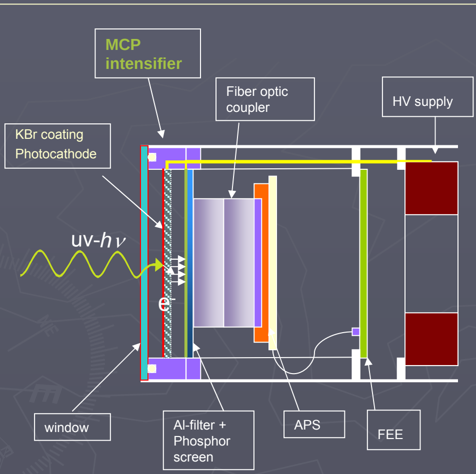
Phosphor screen anode

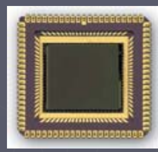


Phosphor screen anode on fiber optic coupler

Solar-blind intensified APS detector

= MCP intensifier coupled with a CMOS active pixel sensor

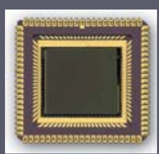




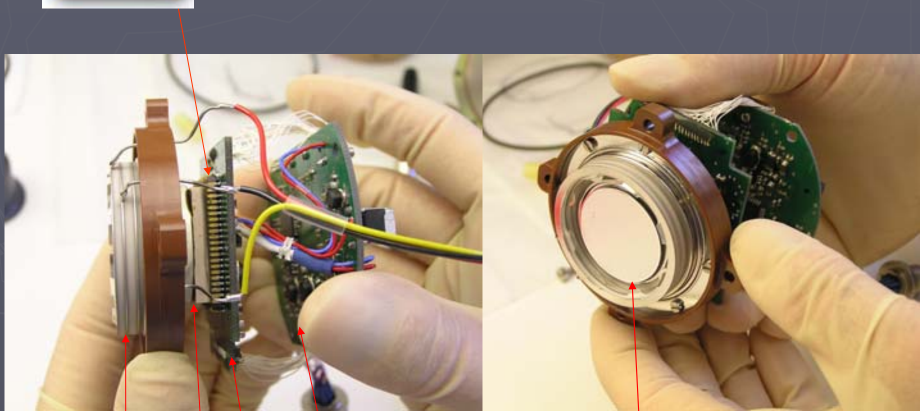
APS sensor array on PCB

HV power supply

STAR 1000
visible CMOS-APS sensor



Intensified APS



MCP stack

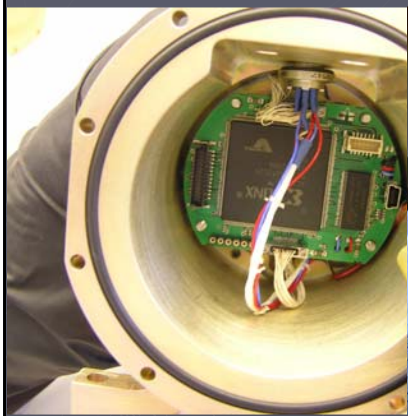
fiber optic blocks

APS sensor board

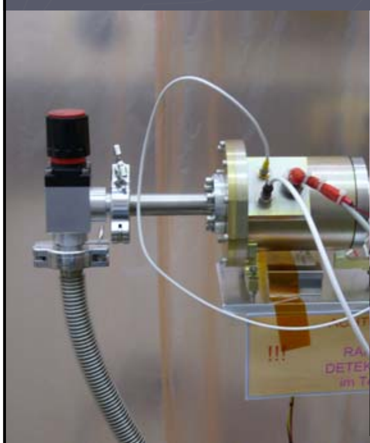
FEE board

anode (phosphor screen)

detector unit assembly and vibration test

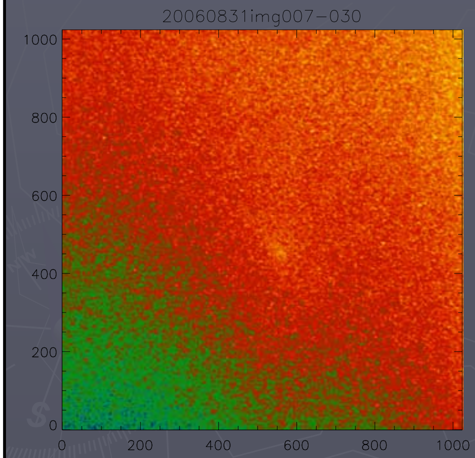


perfomance test with Lyman-α lamp and extreme UV lamp

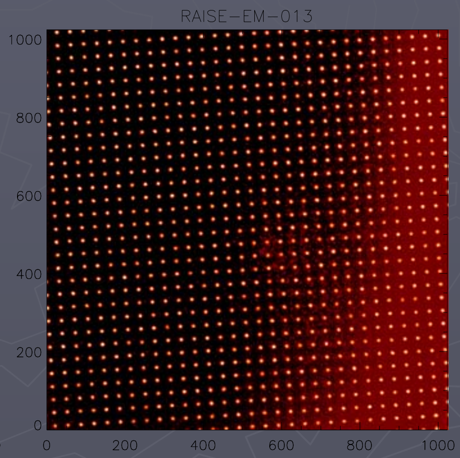


note: this is a „open“ MCP detector (without window)

test images with Lyman-α lamp

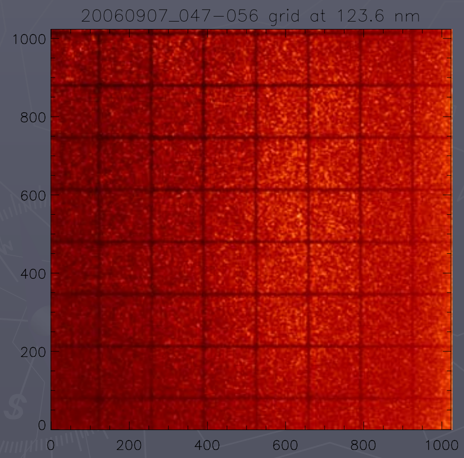


quasi flat image at 121.6 nm

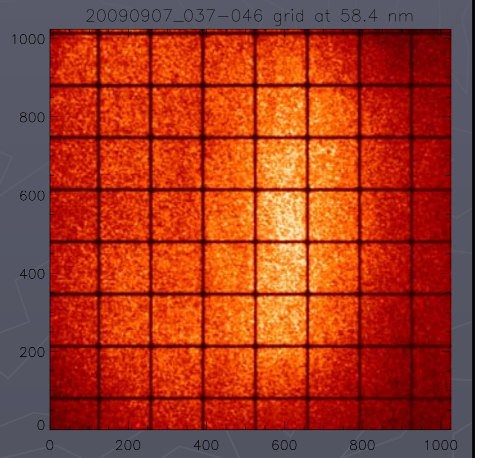


pinhole mask image

test images with extreme UV lamp



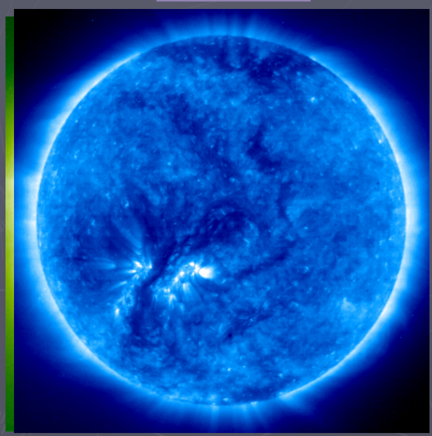
grid mask image at 123.6 nm



grid mask image at 58.4 nm

The Sun on 24 September 1996

Fe IX/X 17.2 nm
(SOHO/EIT)



H I Lyman-ε
(SOHO/SUMER)