Observing Photons in Space

M.C.E. Huber, A. Pauluhn, J.L. Culhane, J.G. Timothy, K. Wilhelm & A. Zehnder (Eds.)
Outline

Imaging Detectors:
► 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
UV Technology developments
Images and...
To transmit images from space, images are „digitized“

Actually, what is a digital image?
Terminology

digital camera

lens

camera or detector?

camera or detector?

housing

digital camera

sensor

digitizer board & FEE board

“detector” or “focal plane unit” or “focal plane assembly” (FPA)
Focal plane assembly for space instrumentation

- Inner Support Tube
- Outer Support Tube
- Heater & Thermistor Connector
- Ribbon Harness
- FPA Housing
- Instrument Mount Light Tight Seal
- Decontamination Heater
- CCD Element
- INVAR Chip Carrier
- Decontamination Cup
- Thermal Shield
- Cold Finger
- Connector
- CCD Ribbon Harness
- Thermal Radiator
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 μm.

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

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{\text{gap}}$(eV)</th>
<th>$\lambda$ [nm]</th>
<th>band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>1100</td>
<td>Visible</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.42</td>
<td>875</td>
<td>Visible</td>
</tr>
<tr>
<td>Ge</td>
<td>0.66</td>
<td>1800</td>
<td>NIR</td>
</tr>
<tr>
<td>InGaAs</td>
<td>0.73-0.47</td>
<td>1700-2600</td>
<td>NIR</td>
</tr>
<tr>
<td>InAs</td>
<td>0.36</td>
<td>3400</td>
<td>NIR</td>
</tr>
<tr>
<td>InSn</td>
<td>0.17</td>
<td>5700</td>
<td>IR</td>
</tr>
<tr>
<td>HgCd</td>
<td>0.7-0.1</td>
<td>1700-12500</td>
<td>NIR-FIR</td>
</tr>
</tbody>
</table>
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
X-ray materials
ultraviolet materials
„wide band gap“ materials
Photodetector materials

band gap energy of materials:

Energy (eV)
1.0 1.5 2.0 2.5 3.0 3.5 6.0
1000 800 600 500 400 350 200

Wavelength (nm)

charge creation and photo-conduction

photo-emission in vacuum
QE = quantum efficiency
Types of sensor arrays

Si-based sensors:
- charge coupled devices (CCDs)
- CMOS – APS active pixel sensors
  - expanding the sensitivity range to the UV
  - thinned backside illumination
  - deep depletion
- choice of materials
- sensor architecture
- hybrid devices

CCDs
diode arrays
CMOS active pixel arrays (APS)
Front-side Illuminated CCD

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.

find more info about CCDs at http://www.ing.iac.es/%7Esmt/CCD_Primer/CCD_Primer.htm
The silicon is chemically etched and polished down to a thickness of about 15 microns. 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.

Almost all astronomical CCDs are Thinned Backside Illuminated.
an X-ray CCD focal plane unit
Active pixel sensor
CMOS-APS

functional principle

one pixel
pixel array
## CCD versus CMOS sensors

<table>
<thead>
<tr>
<th>Pixel</th>
<th>CCD Approach</th>
<th>CMOS Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Photodiode</strong></td>
<td><strong>Photodiode</strong> + <strong>Amplifier</strong></td>
</tr>
<tr>
<td></td>
<td>Charge generation and charge integration</td>
<td>Charge generation, charge integration and charge-to-voltage conversion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Array Readout</th>
<th>CCD Approach</th>
<th>CMOS Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charge transfer from pixel to pixel</td>
<td>Multiplexing of pixel voltages: Successively connect amplifiers to common bus</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor Output</th>
<th>CCD Approach</th>
<th>CMOS Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Output amplifier performs charge-to-voltage conversion</td>
<td>Various options possible:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- no further circuitry (analog out)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- add. amplifiers (analog output)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- A/D conversion (digital output)</td>
</tr>
</tbody>
</table>
flexibility of read-out scheme (pixels can be addressed individually)

no shutter is needed
CMOS APS development

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.

Architecture

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

Bond-wire protection-cover fitted

8-inch Wafer 0.25 μm CMOS

4kx3k pixel sensor die
Drawbacks of current Si-based sensors

- Need for filters to suppress visible light.
- Need for cooling.
- Complicates thermal design.
- Results in contamination trap.

\[ \Rightarrow \text{Efficiency very unstable.} \]
UV detectors for solar observations

TRACE-image of the Sun in the EUV

Emission spectra of the Sun in the VUV
The Sun on 24 September 1996

Fe IX/X 17.2 nm (SOHO/EIT)

H I Lyman-ε (SOHO/SUMER)
VUV spectrograph SUMER on SOHO

Raster scan of sunspot:
- vis 6330Å
- cont. ~1250Å
- N V 1238Å
- O V 629Å
- Fe XII 1242Å

Raster scan of polar region:
- no background noise
- no cosmic ray spikes

Udo Schühle
IMPRS Oct. 2010
higher resolution and radiation hardness

0.5 Arcsec
~ 350 km at Sun
Solar spectral irradiance (and variability)

5.5 magnitudes!
quantum efficiency of Si CCD

increased QE by back-side thinning
Backside thinning of CCDs and APSs

UV to NIR

VUV to soft X-ray
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. Dotted curve: maximum theoretical QE for 100% CCE; solid curve, best-fit semi-empirical model.
Wide band gap material detectors can be selected to be solar blind. Highly efficient in the VUV and EUV.
hybrid sensors

photosensitive substrate + silicon read-out circuit = hybrid sensor

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

IR UV X-ray

readout circuit array (ROIC):
silicon based integrated circuit (CMOS array) with individually addressable pixels
to be mated by „flip-chip technique“ via indium bump contacts
Photodetector types

“pixel architecture”

**Photoconductors**

- Ti/Al or In
- Al$_x$Ga$_{1-x}$N
- Buffer
- Sapphire

**Schottky Photodiodes**

- Ti/Al or In
- Al$_x$Ga$_{1-x}$N
- Buffer
- Sapphire

**M-S-M Photodiodes**

- Ni/Au
- Al$_x$Ga$_{1-x}$N
- Buffer
- Sapphire

**p-i-n Photodiodes**

- Ti/Al
- AlGaN:Mg
- i-AlGaN

**M-I-S Photodiodes**

- Ni/Au
- Au (100 Å)
- SiO$_2$ (50 Å)
- Al$_x$Ga$_{1-x}$N
- Buffer
- Sapphire
imaging arrays of Wide Band Gap material

build a micro-array of photoconductors
Solar-blindness of present WBGS detectors

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

Pau et al. 2003.

Nitride

Diamond

Pace et al. 2000.
Multichannel plate detectors
(photoemission detectors, photon counting detectors)

Each MCP operates at a gain of ~100 electrons
photocathodes on MCPs

- Multichannel plates are "wide band gap" detectors.
- Photocathode materials with different band gap energies may be applied.
- Alkali halide photocathodes increase the quantum efficiency in selected wavelength ranges: CsI, CsCl, LiF, KCl, KBr, RbI, multi-alkali, etc.

These are also wide band gap materials
Selective photocathode

Photocathode on front MCP

test image at 121.6 nm

- simple technology:
  deposition by vacuum evaporation even after final assembly!
photocathodes on MCPs

SUMER KBr photocathode

- Emission lines
- Pre-flight data
Readout 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
Flatfield pattern & resolution

- Pore structure limiting the resolution
- Multifiber bundle boundaries
- Moire pattern by superposition of MCPs
Example: flatfield of SUMER XDL detector

- Image geometric distortion
- ADC nonlinearity
- Multifiber bundles (hexagonal)
- Moire pattern (from 3 MCPs)
- Dead pores
Intensified CCD

MCP coupled to CCD via lens or fiber-optic taper
Microchannel plate intensifiers

MCP based intensifiers

Phosphor screen anode on fiber optic coupler
Solar-blind intensified imaging array detector

= MCP intensifier coupled with a pixel sensor

- MCP intensifier
- Fiber optic coupler
- HV supply
- KBr coating
- Photocathode
- window
- Al-filter + Phosphor screen
- APS
- FEE

hv

hv

APS sensor array on PCB

HV power supply
Intensified APS

STAR 1000 visible CMOS-APS sensor

MCP stack
fiber optic blocks
APS sensor board
FEE board
Fiber optic coupling

Image intensifier can be coupled to any sensor (CCD or APS) on the market
Fiber optic tapers

Typical Taper Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Type</td>
<td>SCHOTT 24 Glass</td>
</tr>
<tr>
<td>Element Size (µm)</td>
<td>6, 10, 18, 25</td>
</tr>
<tr>
<td>Numerical Aperture – small end</td>
<td>1.0</td>
</tr>
<tr>
<td>Stray Light Control (EMA)</td>
<td>Available with or without EMA</td>
</tr>
<tr>
<td>Collimated Transmission White Light for Base Material:</td>
<td></td>
</tr>
<tr>
<td>3mm thick</td>
<td>85%</td>
</tr>
<tr>
<td>10mm thick</td>
<td>44%</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion (x10^-7 / °C)</td>
<td>68</td>
</tr>
<tr>
<td>Phosphor Compatible</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Fused Fiber Optic Tapers by Schott

Image Minification or Magnification

typical de-magnification of 3:1 is standard (5:1 possible)

Performance of the sensor array with readout electronics (without intensifier)

Image of a target. The yellow line is the location of the profile shown below.
Resolution limitations of intensifier
Resolution of the optical system adapted to I-APS detector

![Graph showing MTF vs. Spatial Frequency for different intensifiers and a telescope match telescope with detector.](image-url)
test images with extreme UV lamp

grid mask image at 123.6 nm

grid mask image at 58.4 nm
Resolution test with I-APS Detector

- imaging a wire grid
- 35 µm wire width
- 12 µm pore MCPs
- 15 µm APS pixels

![Graph showing resolution of the grid wire]

- Grid width = 35 microns
- Half width = 45 microns
Performance testing with Lyman-α lamp

quasi flat image at 121.6 nm

pinhole mask image
performance test with Lyman-α lamp and extreme UV lamp

(tests possible under vacuum only!)
The Sun on 24 September 1996

Fe IX/X 17.2 nm (SOHO/EIT)

H I Lyman-ε (SOHO/SUMER)
Who is doing what?

**Industrial company (e.g., Proxitronic):**
- Intensifier
- Fiber optic block
- Coupling of intensifier with fiber optic block and image sensor

**MPS:**
- Coating of MCP photokathode
- Front-end readout electronics
- Mechanical housing
- Space qualification (vibration, thermal vac, thermal balance)
- Performance characterization
- Calibration
Performance Parameters (1)

- Array size (pixel size and # of pixels)
- Frame rate (speed, determines image cadence)
- Radiation hardness
- Power requirements
- Technology
- Price (may be 0.5 million €)
Performance Parameters (2)

- Spectral range
- Radiometric response (QE)
- Flat field response (uniformity)
- Linearity of response
- Dark current / dark signal (need cold T)
- Noise (dark noise, read-out noise, photon noise)
- Dynamic range (full well capacity – dark signal)
- CTE = Charge Transfer Efficiency (for CCDs)