Light Detectors Physics 157

Photomultiplier tubes Photodiodes Readouts and Amplifiers

Outline

- Role of detectors
- Photomultiplier tubes (photoemission)
- Modulation transfer function
- Photoconductive detector physics
- Detector architecture

Where detectors are used in science & technology

Scientific: Imaging Spectroscopy

Technical: Acquisition / guiding Active optics Adaptive optics Interferometry (fringe & tip/tilt tracking)

Photomultiplier tube

Electron multiplier



Photomultiplier tube





Optical and Infrared Astronomy (0.3 to 25 μ m)

Two basic parts

Telescope to collect and focus light



Optical and Infrared Astronomy (0.3 to 25 μ m)

More recent instrumentation:

Telescope to collect and focus light



Instrument goal is to measure a 3-D data cube



But array detectors are 2-dimensional!

- Our detectors are BLACK & WHITE
- Cannot measure color, only intensity

So the optics of the instrument are used to map a portion of the 3-D data cube on to the 2-D detector

Detector zoology



We will concentrate on 2-D focal plane arrays.

- Optical silicon-based (CCD, CMOS)
- Infrared IR material plus silicon CMOS multiplexer

The Ideal Detector

- Detect 100% of photons
- Each photon detected as a delta function
- Large number of pixels
- Time tag for each photon
- Measure photon wavelength
- Measure photon polarization

- \checkmark Up to 99% quantum efficiency
- ✓ One electron for each photon
- \checkmark 1 billion pixels by 2008
- ☑ No framing detectors
- ☑ No defined by filter (except STJs)
- on 🗵 No defined by filter

Plus READOUT NOISE and other "features"

5 basic steps of optical/IR photon detection

- 1. Get light into the detector Anti-reflection coatings
- 2. Charge generation Popular materials: Silicon, HgCdTe, InSb
- 3. Charge collection
 - Electrical fields within the material collect photoelectrons into pixels.
- 4. Charge transfer

If CMOS, no charge transfer required. For CCD, move photoelectrons to the edge where amplifiers are located.

5. Charge amplification & digitization

Amplification process is noisy. In general CCDs have lowest noise, CMOS detectors have higher noise. Quantum <u>Efficie</u>ncy

> Point Spread Function

Sensitvity

Step 1: Get light into the detector

Good optics No lost light No stray light Anti-reflection coatings

Step 2: Charge Generation



Silicon Similar physics

for IR materials

Step 2: Charge Generation Photon Detection

For an electron to be excited from the conduction band to the valence band

 $hv > E_g$

h = Planck constant (6.6310-34 Joule·sec) v = frequency of light (Hz) = λ/c E_g = energy gap of material (electron-volts)



$$\lambda_{c}$$
 = 1.238 / E_g(eV)

Material Name	Symbol	E_{g} (eV)	λ_{c} (µm)
Silicon	Si	1.12	1.1
Mer-Cad-Tel	HgCdTe	1.00 - 0.09	1.24 - 14
Indium Antimonide	InSb	0.23	5.9
Arsenic doped Silicon	Si:As	0.05	24

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Material Name	Symbol	E _g (eV)	$λ_{c}$ (μm)	Operating Temp. (K)
Silicon	Si	1.12	1.1	160 - 300
Mer-Cad-Tel	HgCdTe	1.00 - 0.09	1.24 - 14	20 - 80
Indium Antimonide	InSb	0.23	5.9	30
Arsenic doped Silicon	Si:As	0.05	24	4

Step 3: Charge Collection

- Intensity image is generated by collecting photoelectrons 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, use an electric field to "sweep" charge toward pixel collection nodes.



Photovoltaic Detector Potential Well



Silicon CCD & HgCdTe and InSb are photovoltaic detectors. They use a pn junction to generate E-field in the z-direction of each pixel. This electric field separates the electron-hole pairs generated by a photon.



<u>For silicon</u>

n - region from phosphorous doping

> p - region from boron doping

<u>n-channel CCD</u> collects electrons

> <u>p-channel CCD</u> collect holes

Step 3: Charge Collection

- Optical and IR focal plane arrays are different for charge collection in the x and y dimensions.
- IR collect charge at each pixel and have amplifiers and readout multiplexer
- CCD collect charge in array of pixels. At end of frame, move charge to edge of array where one (or more) amplifier (s) read out the pixels.



1 H Hydrogen																	2 He Helium
3 Li	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oogen	9 F Fluorine	10 Ne Neon
0.9 11 Na Sodium 23.0	12 Mg Magnesium 9.0											13 Al Auminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 Sultur 32 1	17 Cl Chlorine 35.5	18 Ar Argon 40.0
19 K Potassium 39.1	20 Ca Calcium 40.2	21 Sc Scandium 45.0	22 Ti Titanium 47.9	23 V Vanadium 50.9	24 Cr Chromium 52.0	25 Mn Manganese 54.9	26 Fe fon 55.9	27 Co Colbalt 58.9	28 Ni Nickel 58.7	29 Cu Copper 63.5	30 Zn 2nc 65.4	31 Gallium 69.7	32 Gemanium 72.6	33 As Arsenic 74.9	34 Se Selenium 79.0	35 Br Bromine 79.9	36 Kr Krypton 83.8
37 Rb Rubidium 85.5	38 Sr Strontium 87.6	39 Y Yittrium 88.9	40 Zr Zirconium 91.2	41 Nb Nobium 92.9	42 Mo Molybdenum 95.9	43 TC Technetium 99	44 Ru Ruthenium 101.0	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag silver 107.9	48 Cd Cadmium 112.4	49 In hdium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 bdine 126.9	54 Xe Xen on 131.3
55 CS Caesium 132.9	56 Ba Barium 137.4	57-71	72 Hf Hathium 178.5	73 Ta Tantalum 181.0	74 W Tung <i>s</i> ten 183.9	75 Re Rhenium 186.2	76 OS 0smium 190.2	77 I r hidium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 TI Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium 210.0	85 At Astatine 210.0	86 Rn Radon 222.0
87 Fr Francium 223.0	88 Ra dium 226.0	89-103	104 Rf Ritherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 262	108 HS Has sium 265	109 Mt Meitnerium 266	110 Uun Ununnilium 272						I I	pes of Elemer	ts Key:
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57 La Lanthanum	58 Ce Cerium	59 Pr Prase odym ium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Brbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium		oor metak emi-metak	
138.9 89 Actinium	140.1 90 Th Thorium	140.9 91 Pa Protactinium	144.2 92 Uranium 239.0	147.0 93 Np Neptunium	150.4 94 Pu Plutonium 242.0	152.0 95 Am Americium	167.3 96 Cm Curium 247.0	158.9 97 Bk Berkelium 247.0	162.5 98 Cf Calitomium 251.0	164.9 99 ES En steinium	167.3 100 Fm Fernium 252.0	168.9 101 Mendelevium 258.0	173.0 102 No Nobelium 254.0	175.0 103 Lr Lawrencium	и —	on-metak oble gases	

1 H Hydrogen																	2 He Helium
1.0 3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Dingen	9 F Fluorine	4.0 10 Ne Neon
6.9 11 Na Sodium	9.0 12 Mg Magnesium											10.8 13 Auminum	12.0 14 Si Silicon	14.0 15 Phosphorus	16.0 16 S Sultur	19.0 17 Chlorine	20.2 18 Ar Argon
19 K Potassium 39.1	20 Ca Calcium 40.2	21 Sc Scandium 45.0	22 Ti Titanium 47.9	23 V Vanadium 50.9	24 Cr Chromium 52.0	25 Mn Manganese 54,9	26 Fe Iron 55.9	27 Co Colbalt 58.9	28 Ni Nickel 58,7	29 Cu Copper 63.5	30 Zn Zn 0 65.4	31 Gallium 69.7	28.1 32 Gemanium 72.6	31.0 33 Ass Arsenic 74.9	32.1 34 See Selenium 79.0	35 35 Bromine 79,9	36 Kr Knpton 83.8
37 Rb Rubidium 85.5	38 Sr Strontium 87.6	39 Y Yittrium 88.9	40 Zr Zirconium 91.2	41 Nb Nobium 92.9	42 Mo Molybde num 95.9	43 Tc Technetium 99	44 Ru Ruthenium 101.0	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In hdium 114.8	50 Sn Tn 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 	54 Xe Xen on 131.3
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											He Helium 4.0
						5	6	7	8	9	10
						В	С	N	Ο	F	Ne
						Boron 10.8	Carbon 12.0	Nitrogen 14.0	Oxygen 16.0	Fluorine 19.0	Neon 20.2
						13	14	15	16	17	18
						AI	Si	Р	S	CI	Ar
						Auminum 27.0	Silicon 28.1	Phosphorus 31.0	Sultur 32.1	Chlorine 35.5	Argon 40.0
	26	27	28	29	30	31	32	33	34	35	36
ו	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
ese	i ron 55.9	Colbalt 58.9	Nickel 58.7	Соррег 63.5	Zinc 65.4	Gallium 69.7	Germanium 72.6	Arsenic 74.9	Selenium 79.0	Bromine 79.9	Krypton 83.8
	44	45	48	47	48	49	50	51	52	53	54
L 7	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Те		Xe
um	Ruthenium 101.0	Rhodium 102.9	Palladium 106.4	Silver 107.9	Cadmium 112.4	hdium 114.8	Tin 118.7	Antimony 121.8	Tellurium 127.6	lodine 126.9	Xen on 131.3
	76	77	78	79	80	81	82	83	84	85	86
è	Os	lr	Pt	Au	Hg	TI	Pb	Bi	Po	At	Rn
т 2	Osmium 190.2	hidium 192.2	Platinum 195.1	Gold 197.0	Mercury 200.6	Thallium 204.4	Lead 207.2	Bismuth 209.0	Polonium 210.0	Astatine 210.0	Radon 222.0
	108	109	110								
1	Hs	Mt	Uun								
m	Hassium	Meitnerium	Ununnilium						<u>Τγ</u>	pes of Elemer	<u>ds Key:</u>
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											He
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						B	Ċ	Ň	Ò	Ē	Ne
						Boron	Carbon	Nitro den	Dogen	Fluorine	Neon
						10.8	12.0	14.0	16.0	19.0	20.2
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						AI	Si	Р	S	CI	Ar
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						27.0	28.1	31.0	32.1	35.5	40.0
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L F	Ru	Rh	Pd	Aq	Cd	In	Sn	Sb	le		Xe
um	Ruthenium	Rhodium 102 g	Palladium 108-4	Silver	Cadmium 112-4	hdium 114.8	Tin 118.7	Antimony 121.8	Tellurium 127 B	lodine 128 g	Xenon 1313
	76	77	78	79	80	81	82	83	84	85	86
è	Os	lr	Pt	Au	Hq	TI	Pb	Bi	Po	At	Rn
m	Osmium	hidium	Platinum	Gold	Mercury	Thallium	Lead	Bismuth	Polonium	Astatine	Radon
2	190.2	192.2	195.1	197.0	200.6	204.4	207.2	209.0	210.0	210.0	222.0
	108	109	110								
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Alkalimetak

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						5	6	7	8	9	10
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	26	27	28	29	30	31	32	33	34	35	36
1	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
ese	iron 55 O	Colbalt 58.0	Nickel 58.7	Copper 63.5	Znc 85.4	Gallium eo 7	Germanium 72 B	Arsenic 74 o	Selenium 70 0	Bromine 70 0	Kripton 93.9
	44	45	46	47	48	49	50	, 1 .8 51	, s.o 52	, e.e 53	54
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Alkalimetak



<u>For silicon</u>

n - region from phosphorous doping

> p - region from boron doping

<u>n-channel CCD</u> collects electrons

> <u>p-channel CCD</u> collect holes

Steps 4 and 5: Charge transfer and amplification

- Transfer different for CCDs and IR detectors.
- Both use MOSFETs (metal-oxidesemiconductor field effect transistors) to amplify the signal.

CCD - Serial register and amplifier











MOSFET

Drain

READOUT

Amplifier Responsivity

Capacitance of MOSFET = 10^{-13} F (100 fF) Responsivity of amplifier = 1.6μ V / e⁻

More recent amplifier designs have higher responsivity, 5 - 10 μ V/e⁻, which give lower noise, but <u>less</u> dynamic range.