Lecture 9 Outline

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

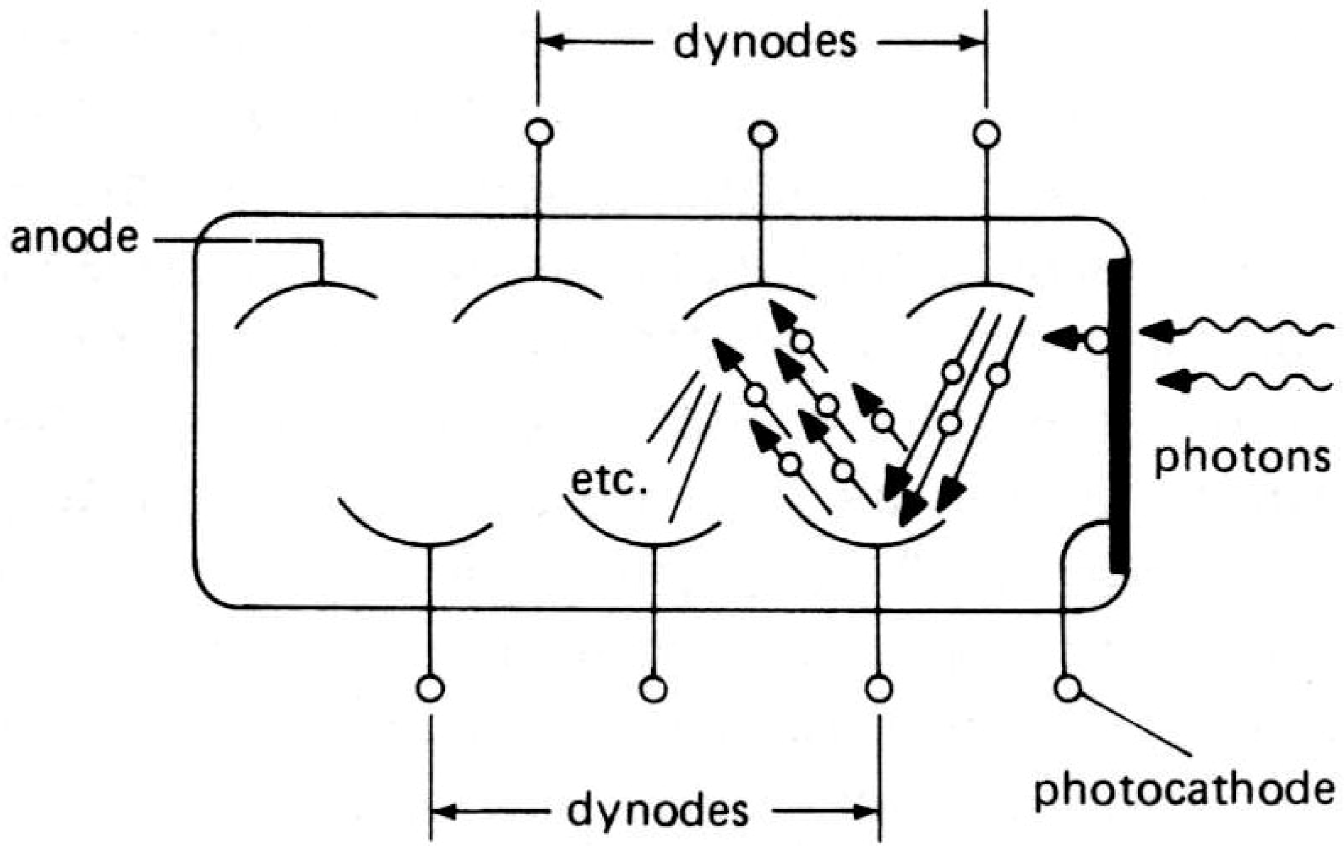
Where detectors are used in science & technology

Scientific: Imaging
Spectroscopy

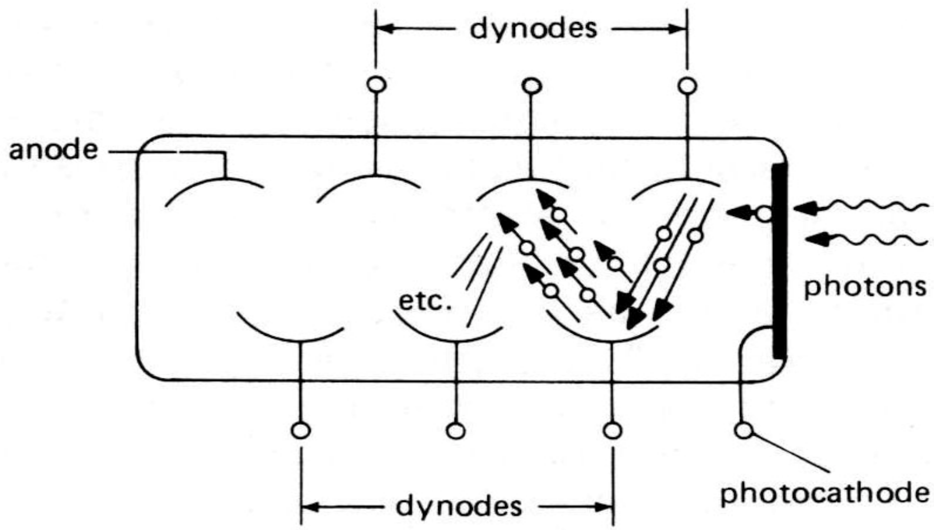
Technical: Acquisition / guiding
Active optics
Adaptive optics
Interferometry
(fringe & tip/tilt tracking)

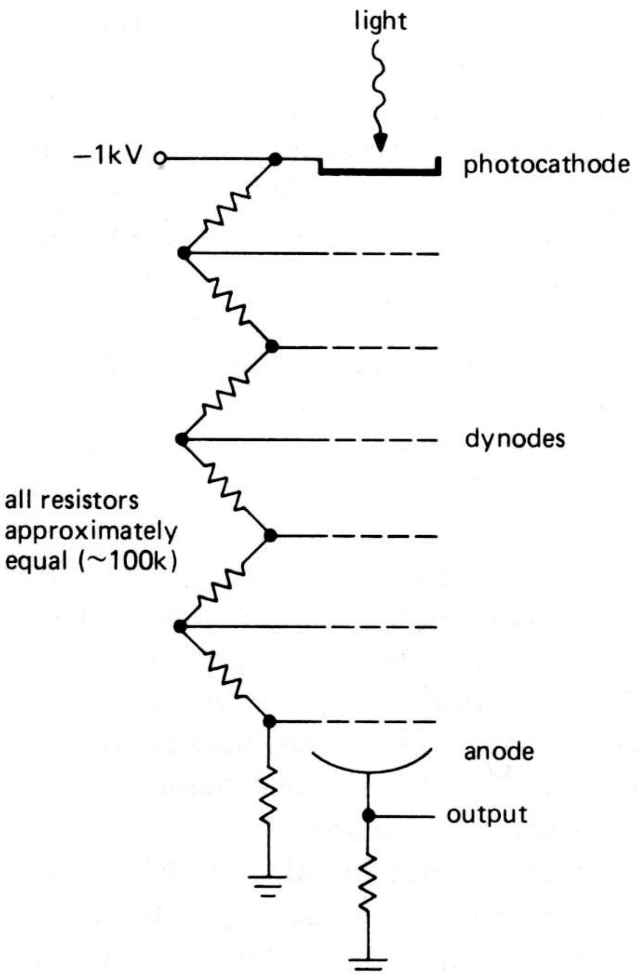
Photomultiplier tube

- Electron multiplier



Photomultiplier tube



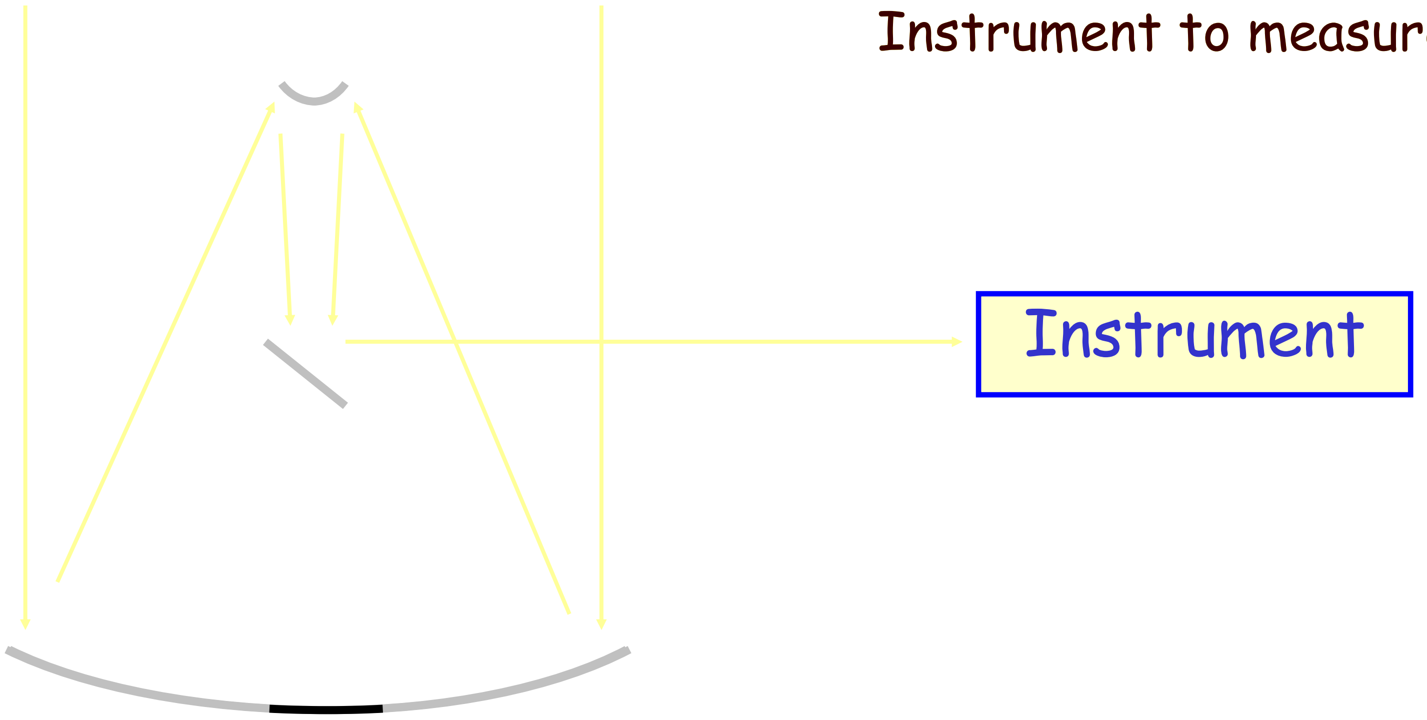


Optical and Infrared Astronomy
(0.3 to 25 μm)

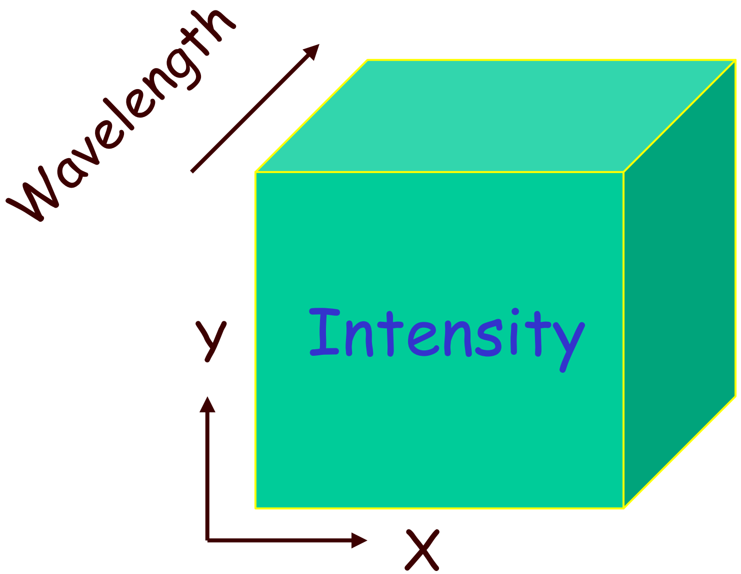
Two basic parts

Telescope to collect and focus light

Instrument to measure light



Instrument goal is to measure a 3-D data cube

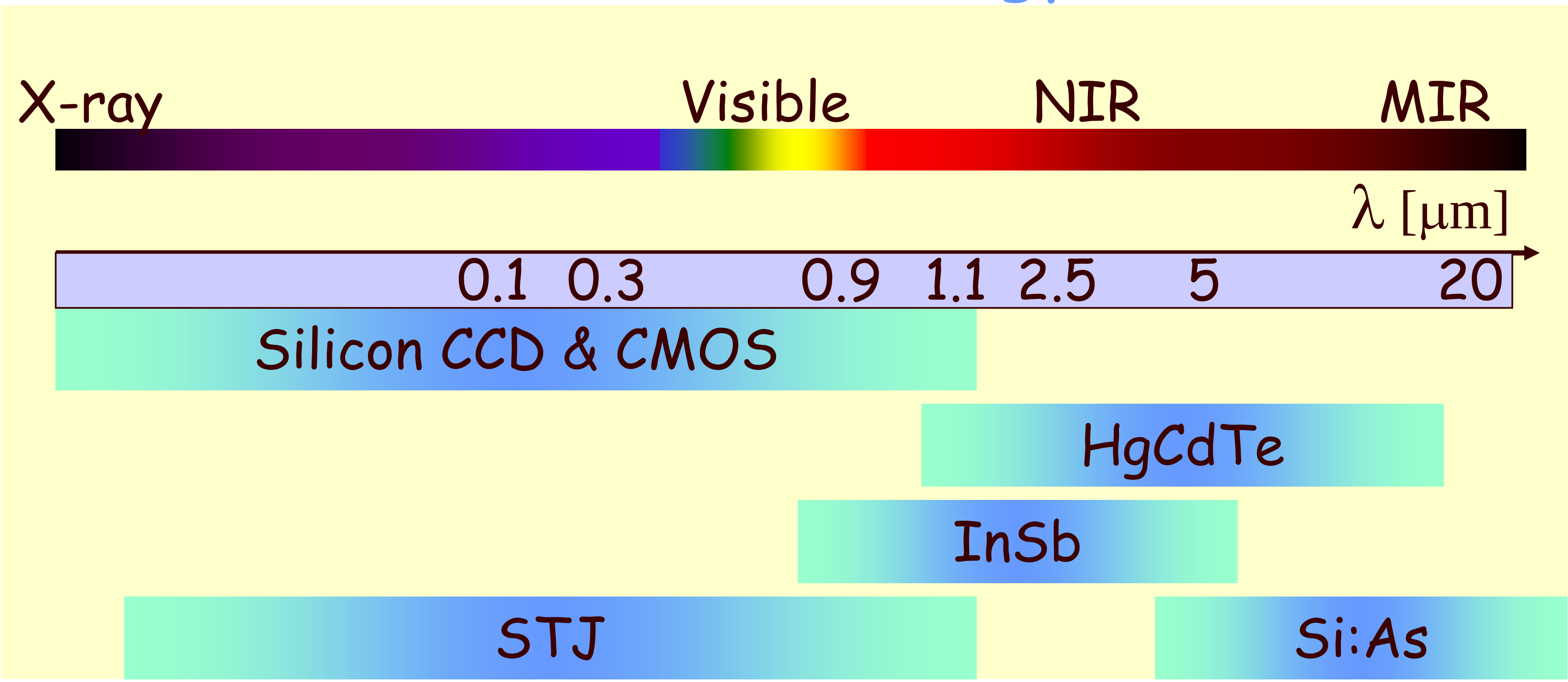


But array detectors are 2-dimensional !

- 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 .

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

The Ideal Detector

• Detect 100% of photons	✓ Up to 99% quantum efficiency
• Each photon detected as a delta function	✓ One electron for each photon
• Large number of pixels	✓ 1 billion pixels by 2008
• Time tag for each photon	☒ No - framing detectors
• Measure photon wavelength	☒ No – defined by filter (except STJs)
• Measure photon polarization	☒ 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 Efficiency

Point Spread Function

Sensitivity

Step 1: Get light into the detector

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

- Anti-reflection coatings will be discussed in next lecture.

Modulation Transfer Function

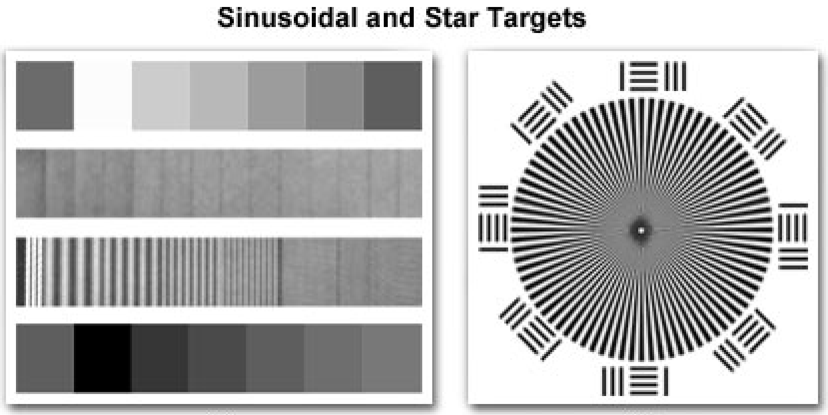
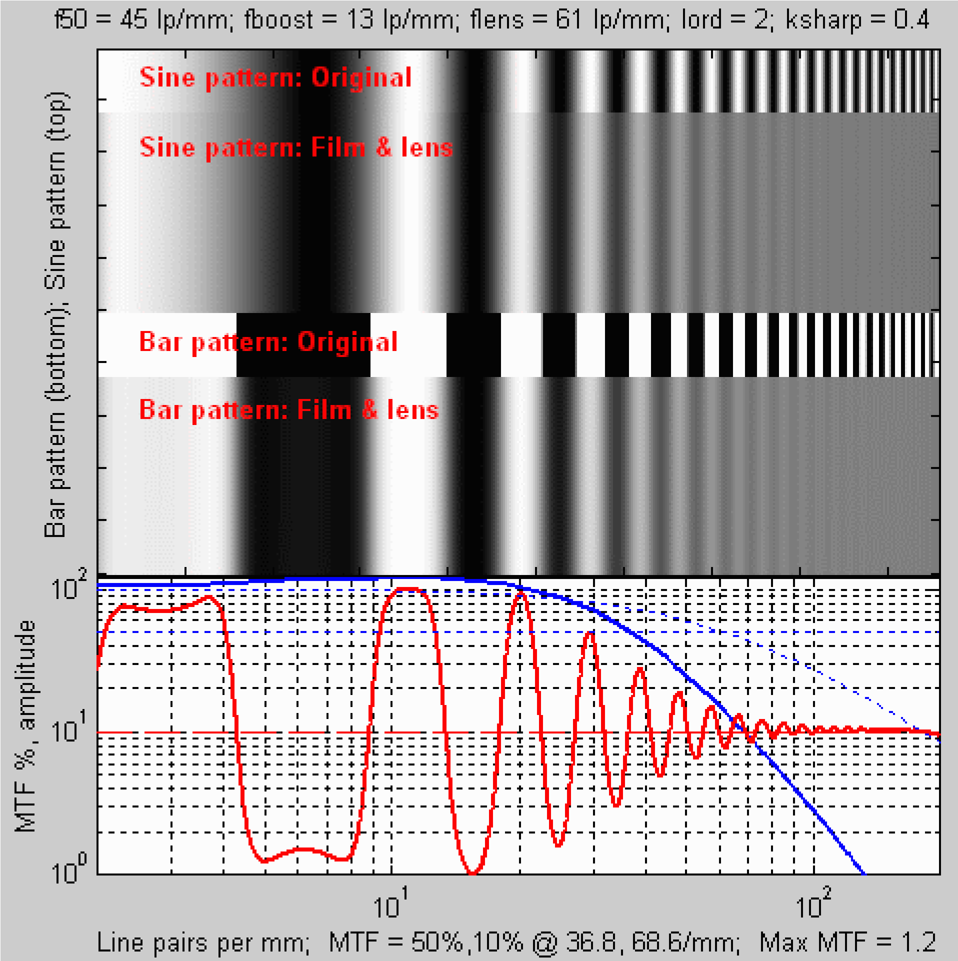


Figure 6



Modulation Transfer Function

- Relation to point-spread function (PSF)

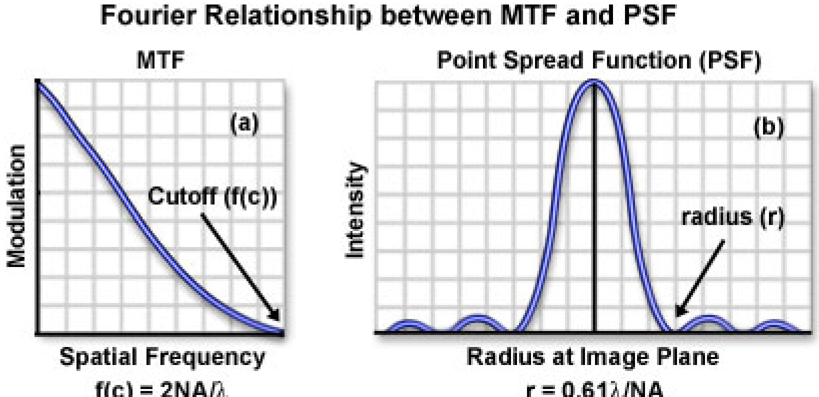
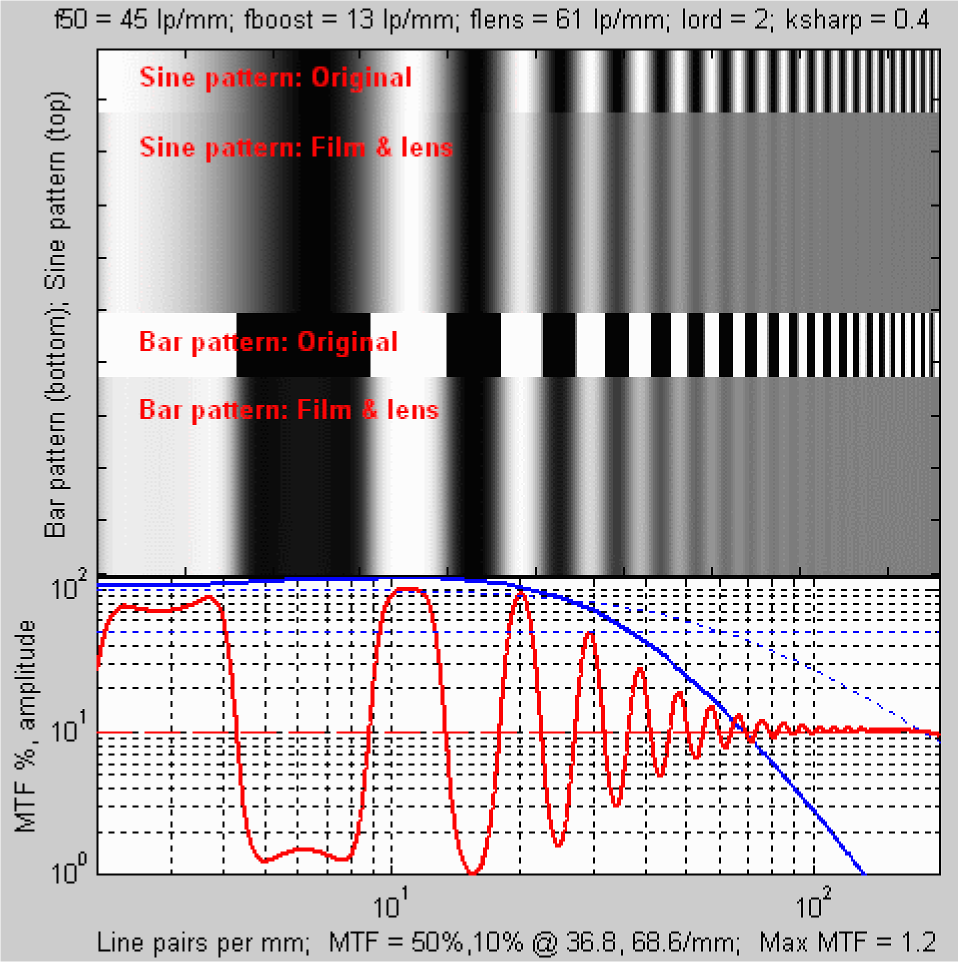
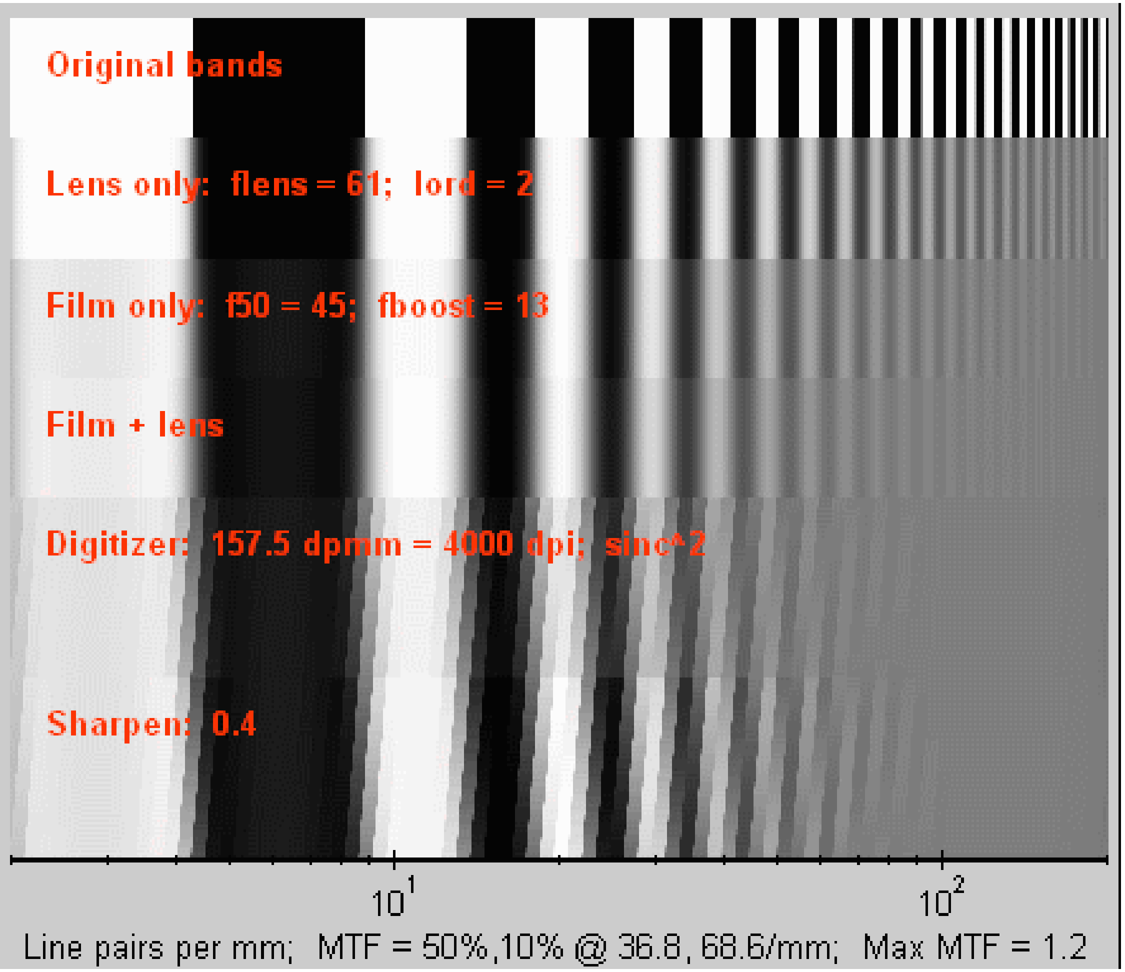


Figure 3

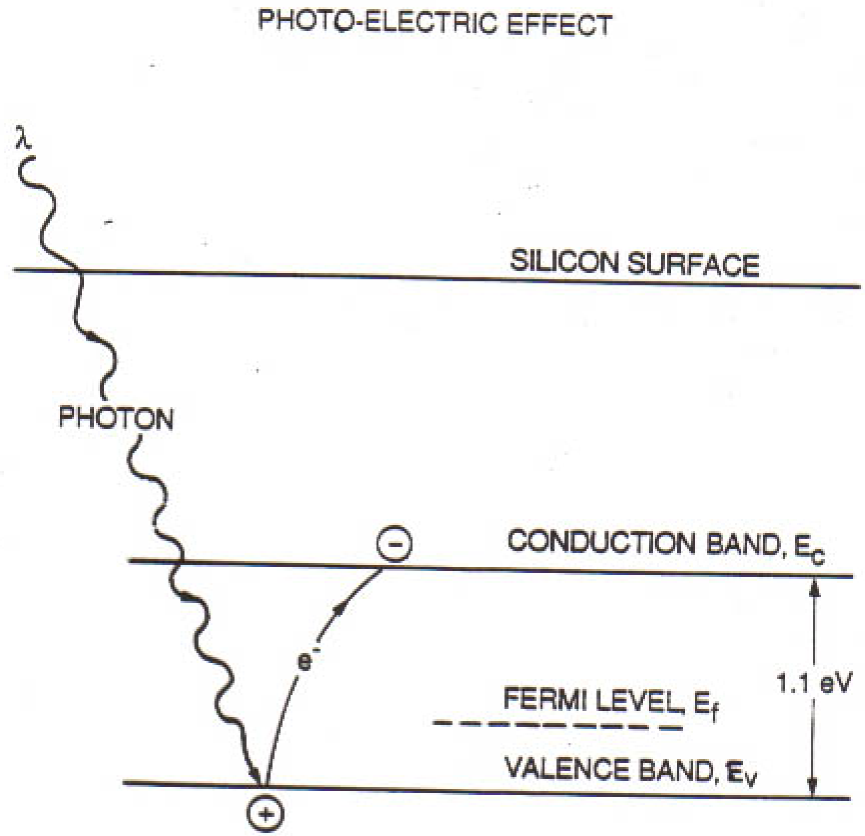


MTF

- Effects of processing



Step 2: Charge Generation



$$e^- = \frac{\text{ENERGY OF PHOTON (eV)}}{3.65\ \text{eV}/e^-}$$

$$\lambda\ (\text{Å}) = \frac{12390}{\text{ENERGY OF PHOTON (eV)}}$$

Silicon

Similar physics for IR materials

Detector Current Responsivity

S = photocurrent /incident power

$$S = QE\, \lambda q G / hc$$

Rieke 2.13

where $G = \tau / T$ τ = carrier lifetime

T = transit time

(for photomultipliers, the photo-conductive gain G can be >>1 !)

Minimum Noise Equivalent Power

Detector internal Johnson noise limited:

$< I_J >^2 = 4kT\,\Delta f\,/\,R$

$NEP > I_J\,/\,S\ = [2hc/QE\lambda qG](kT/R)^{1/2}$ $W/Hz^{1/2}$

but most applications are not internal noise limited...

Noise Equivalent Power

Include shot noise from input photons (so-called generation-recombination noise):

$$NEP_{G-R} > I_J / S = [2hc/\lambda](\phi/QE)^{1/2} \quad W/Hz^{1/2}$$

sum:

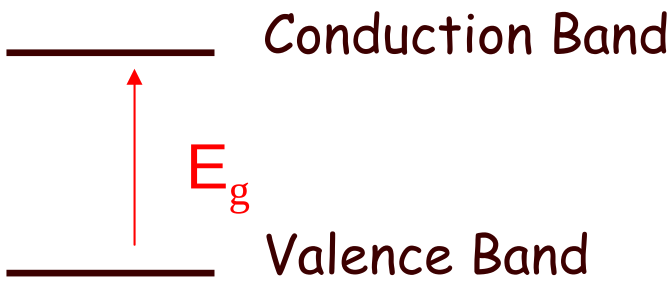
$$NEP^2 = NEP^2_{G-R} + NEP^2_J + NEP^2_{1/f}$$

Step 2: Charge Generation
Photon Detection

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

$$h\nu > E_g$$

h = Planck constant (6.6310-34 Joule•sec)
ν = 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

Step 2: Charge Generation

Photon Detection

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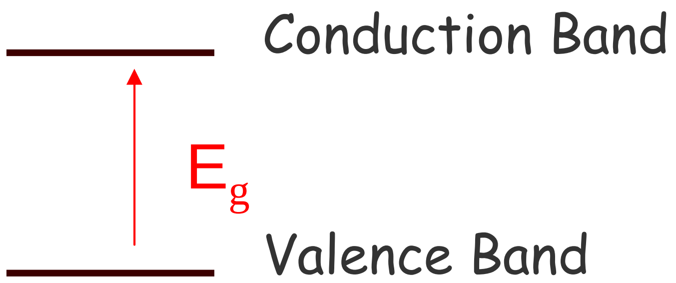
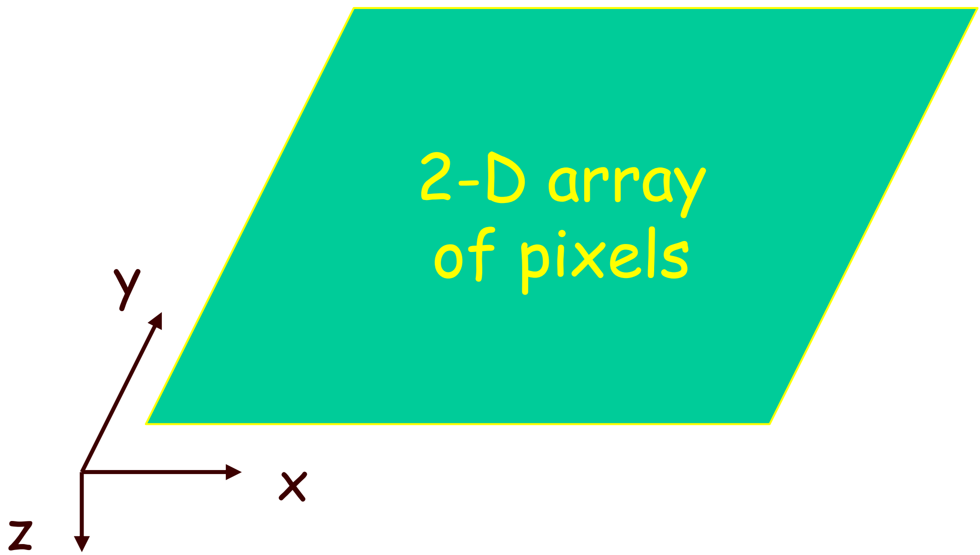


$$\lambda_c = 1.238 / E_g\,(eV)$$

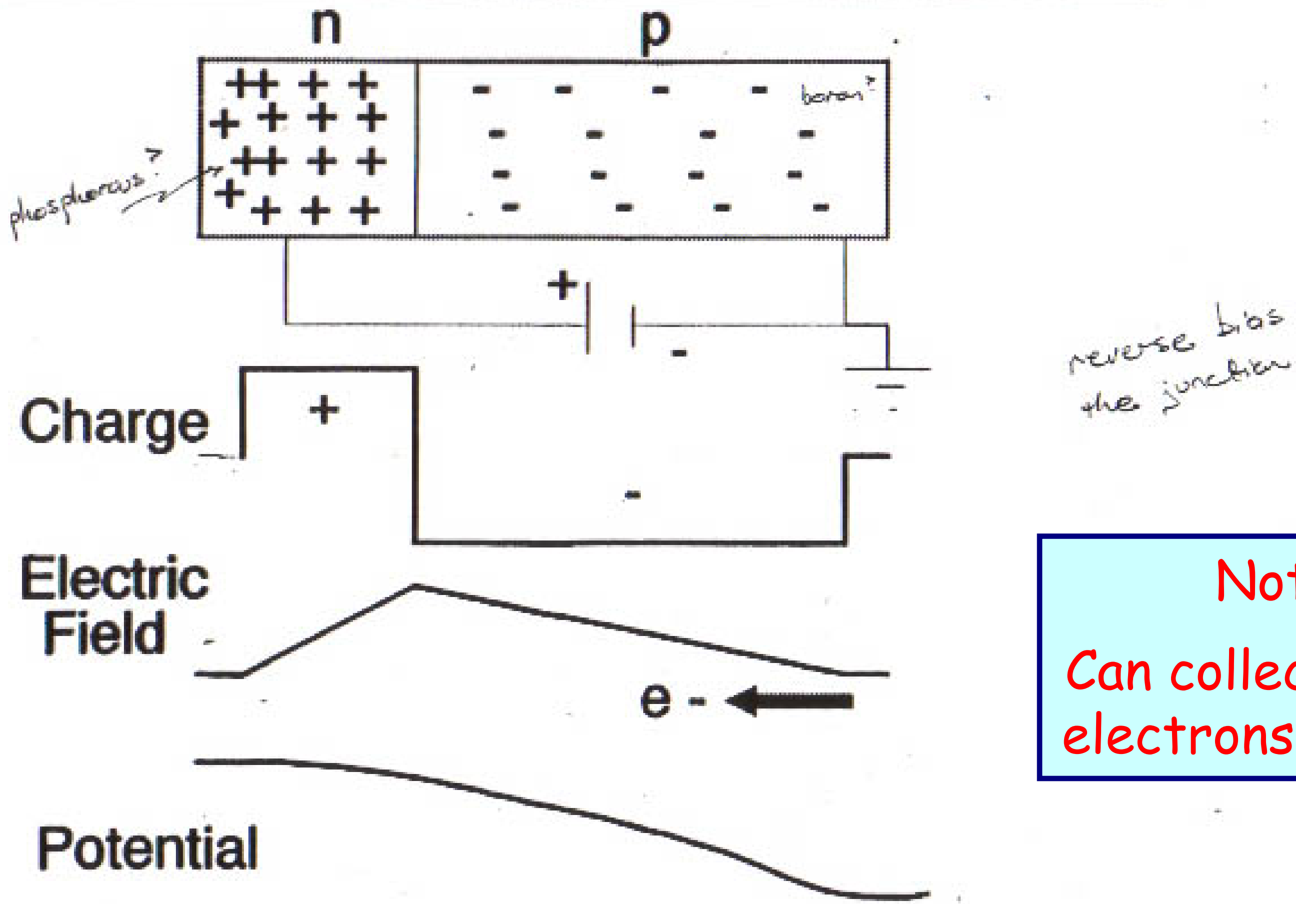
Material Name	Symbol	E_g (eV)	λ_c (μm)	Operating Temp. (K)
Silicon	Si	1.12	1.1	163 - 300
Mer-Cad-Tel	HgCdTe	1.00 – 0.09	1.24 – 14	20 - 80
Indium Antimonide	InSb	0.23	5.9	30
Arsenic doped Silicon	Si:As	0.05	24	4

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



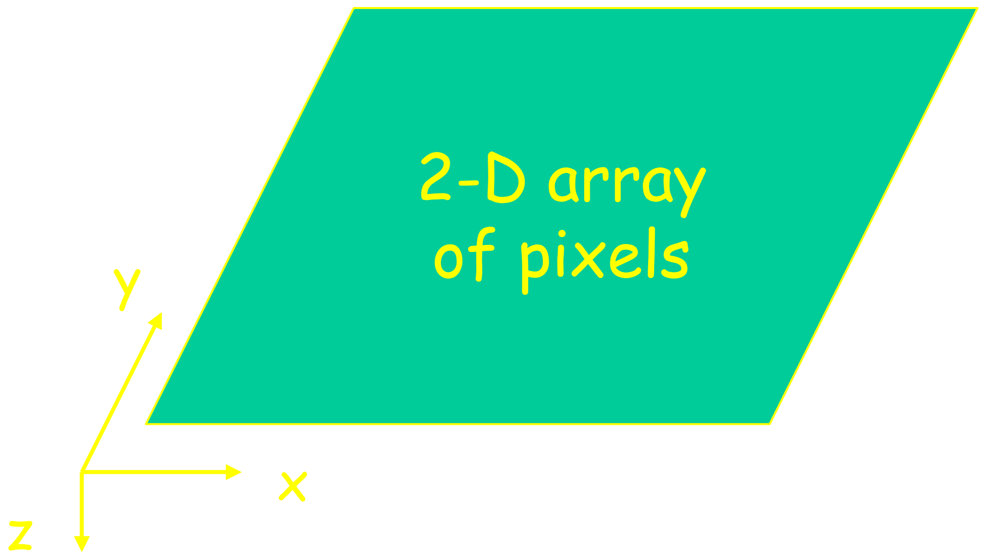
Note:

Can collect either electrons or holes

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.

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.



Periodic Table

1 H Hydrogen 1.0																	2 He Helium 4.0
3 Li Lithium 6.9	4 Be Beryllium 9.0											5 B Boron 10.8	6 C Carbon 12.0	7 N Nitrogen 14.0	8 O Oxygen 16.0	9 F Fluorine 19.0	10 Ne Neon 20.2
11 Na Sodium 23.0	12 Mg Magnesium 9.0											13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 S Sulfur 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 Iron 55.9	27 Co Colbalt 58.9	28 Ni Nickel 58.7	29 Cu Copper 63.5	30 Zn Zinc 65.4	31 Ga Gallium 69.7	32 Ge Germanium 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 Yttrium 88.9	40 Zr Zirconium 91.2	41 Nb Niobium 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 Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
55 Cs Caesium 132.9	56 Ba Barium 137.4	57-71	72 Hf Hafnium 178.5	73 Ta Tantalum 181.0	74 W Tungsten 183.9	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl 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
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57 La Lanthanum 138.9	58 Ce Cerium 140.1	59 Pr Praseodymium 140.9	60 Nd Neodymium 144.2	61 Pm Promethium 147.0	62 Sm Samarium 150.4	63 Eu Europium 152.0	64 Gd Gadolinium 157.3	65 Tb Terbium 158.9	66 Dy Dysprosium 162.5	67 Ho Holmium 164.9	68 Er Erbium 167.3	69 Tm Thulium 168.9	70 Yb Ytterbium 173.0	71 Lu Lutetium 175.0
89 Ac Actinium 132.9	90 Th Thorium 232.0	91 Pa Protactinium 231.0	92 U Uranium 238.0	93 Np Neptunium 237.0	94 Pu Plutonium 242.0	95 Am Americium 243.0	96 Cm Curium 247.0	97 Bk Berkelium 247.0	98 Cf Californium 251.0	99 Es Einsteinium 254.0	100 Fm Fermium 253.0	101 Md Mendelevium 256.0	102 No Nobelium 254.0	103 Lr Lawrencium 257.0

Types of Elements Key:

- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanides
- Actinides
- Poor metals
- Semi-metals
- Non-metals
- Noble gases

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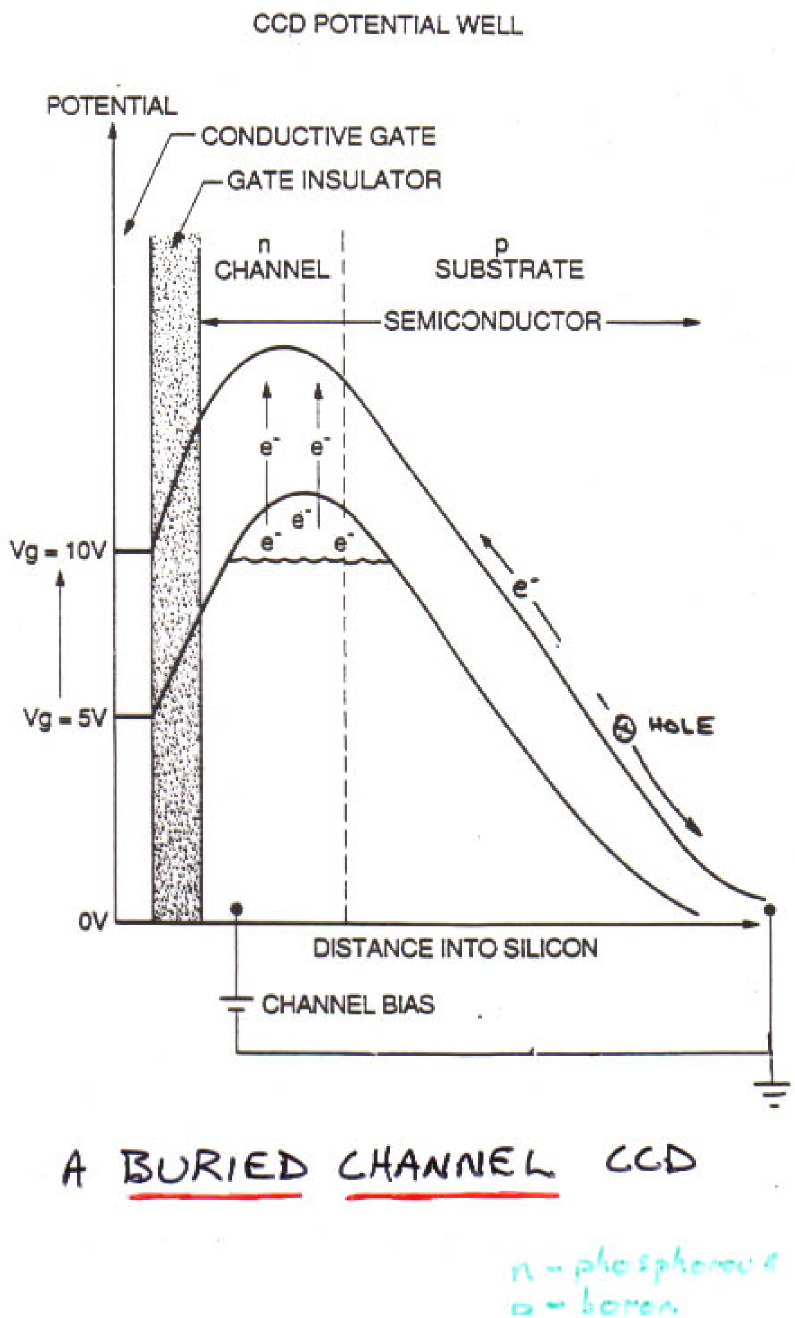


For silicon

n – region from phosphorous doping

p – region from boron doping

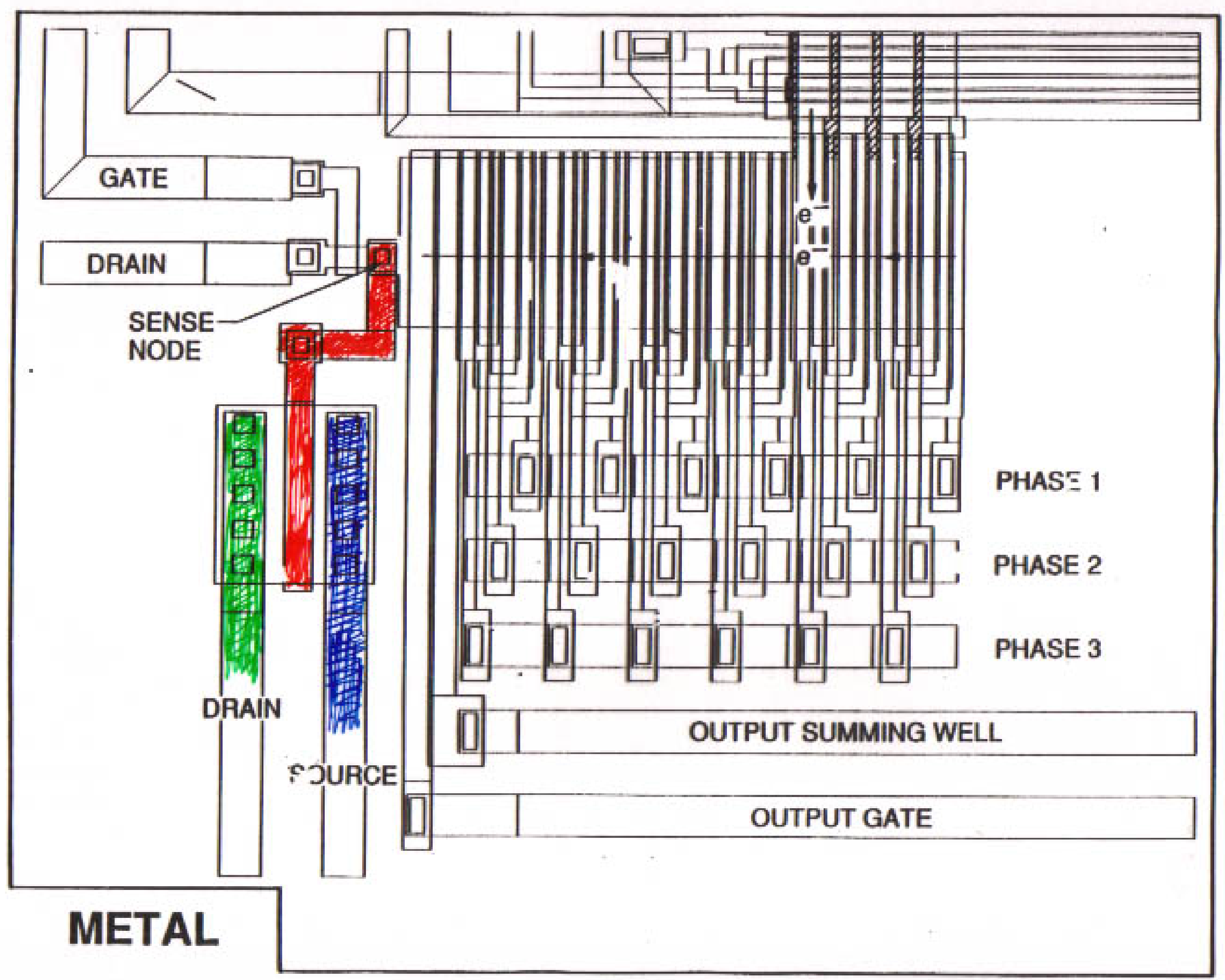
n-channel CCD collects electrons

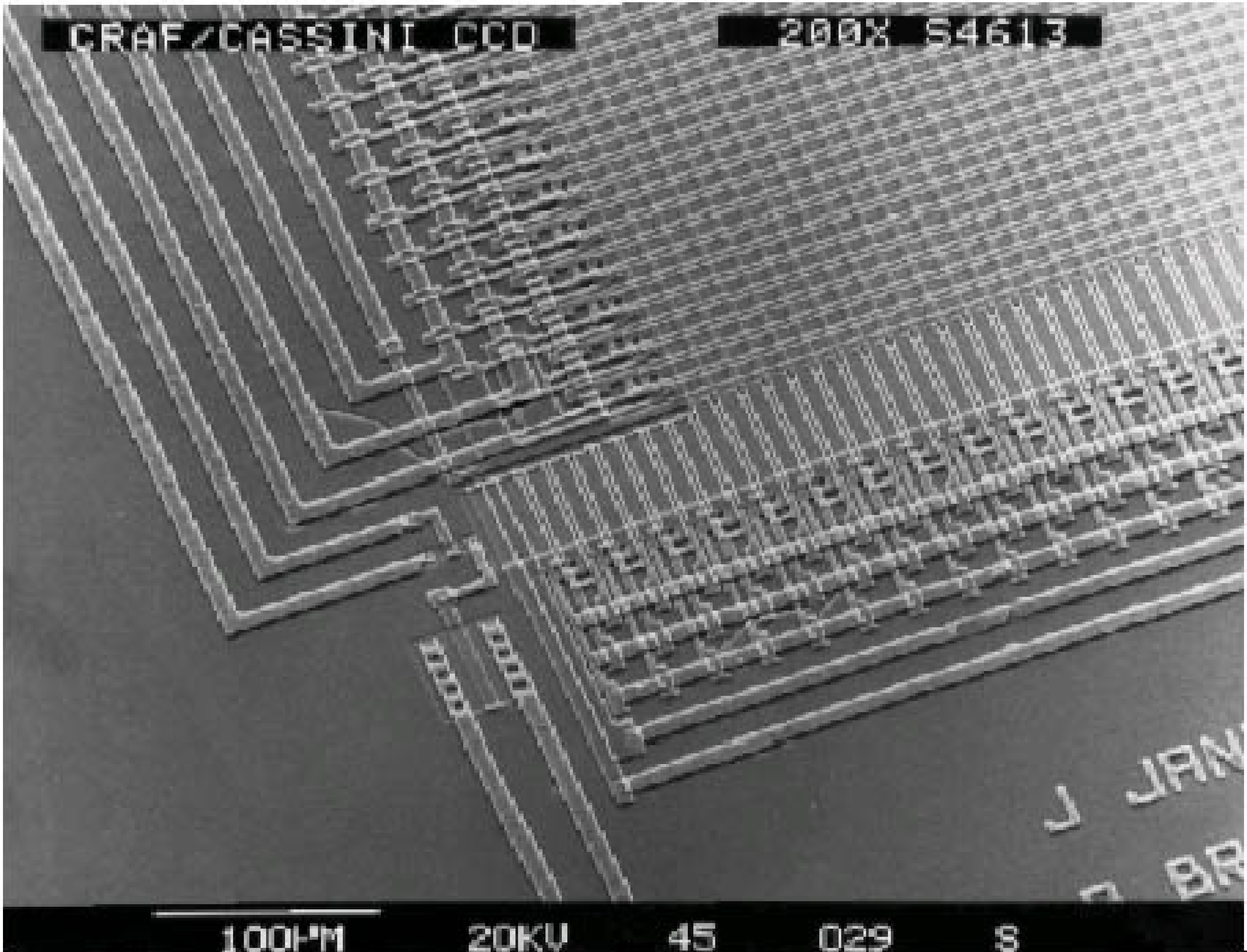
p-channel CCD collect holes

Steps 4 and 5: Charge transfer and amplification

- Transfer different for CCDs and IR detectors (will cover next time).
- Both use MOSFETs (metal-oxide-semiconductor field effect transistors) to amplify the signal.

CCD - Serial register and amplifier

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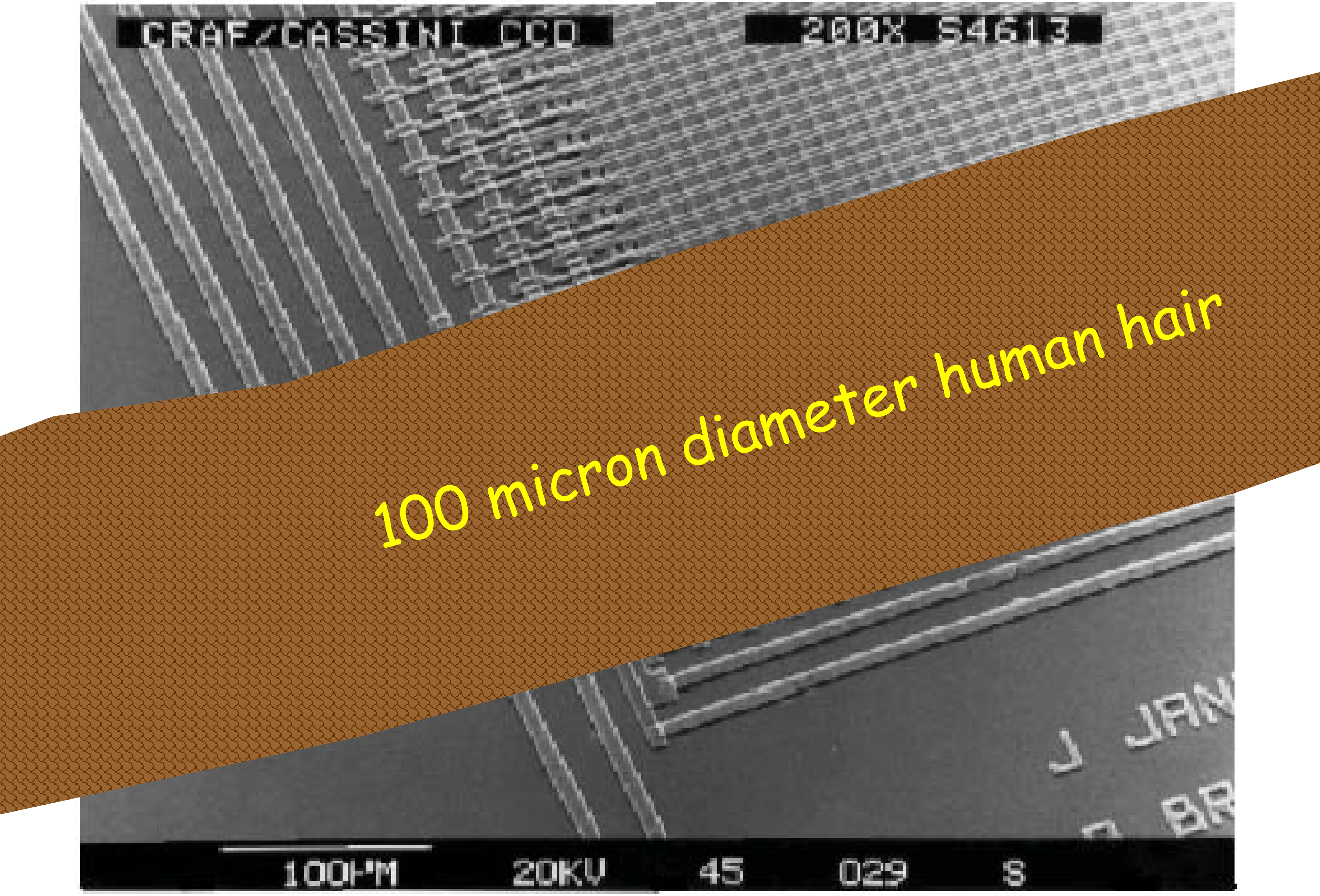
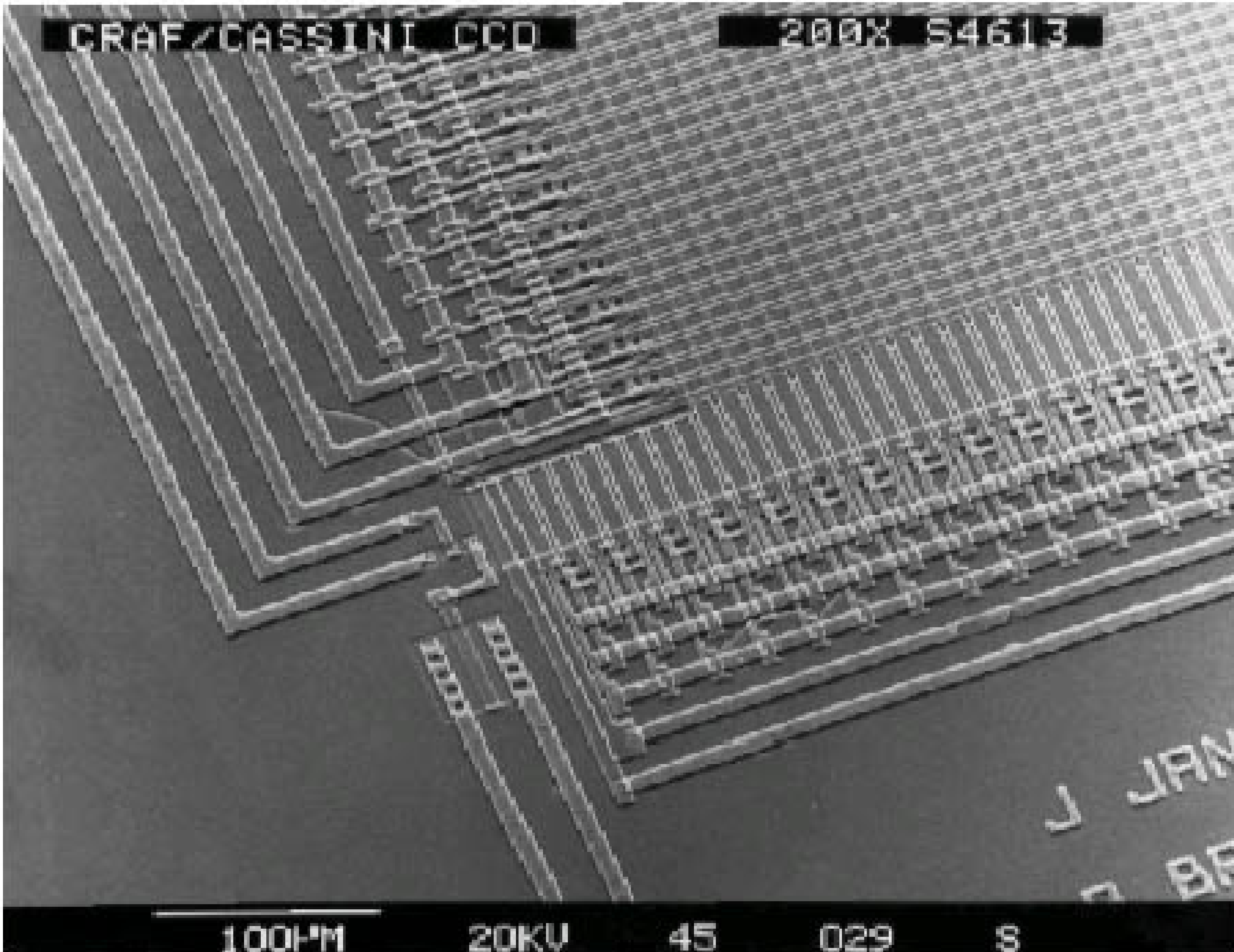
200X S4613
J JAN
BR
100UM 20KV 45 029 S


CRAF/CASSINI CCD
200X S4613
100 micron diameter human hair
100µM 20KV 45 029 S


CRAF/CASSINI CCD
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BR
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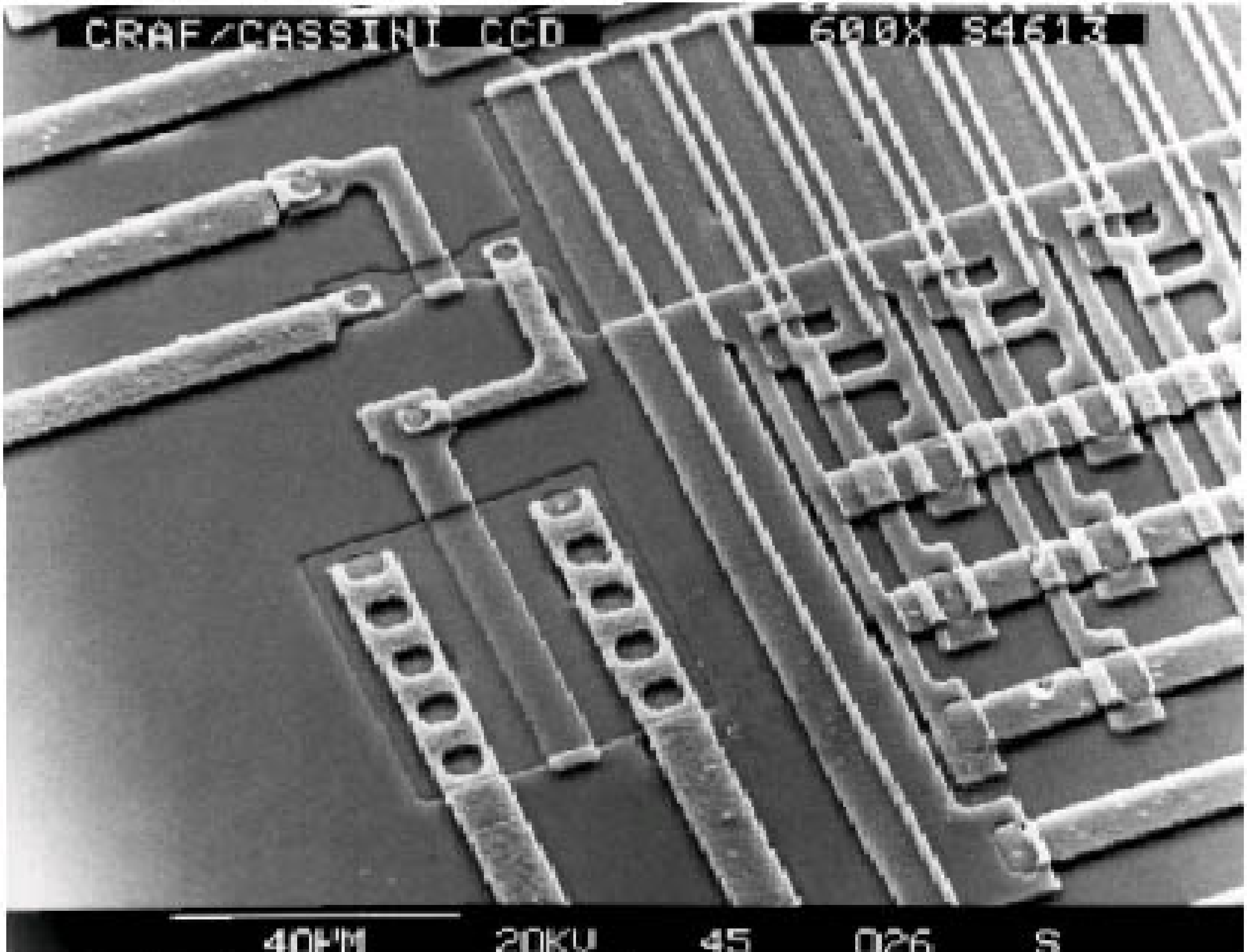
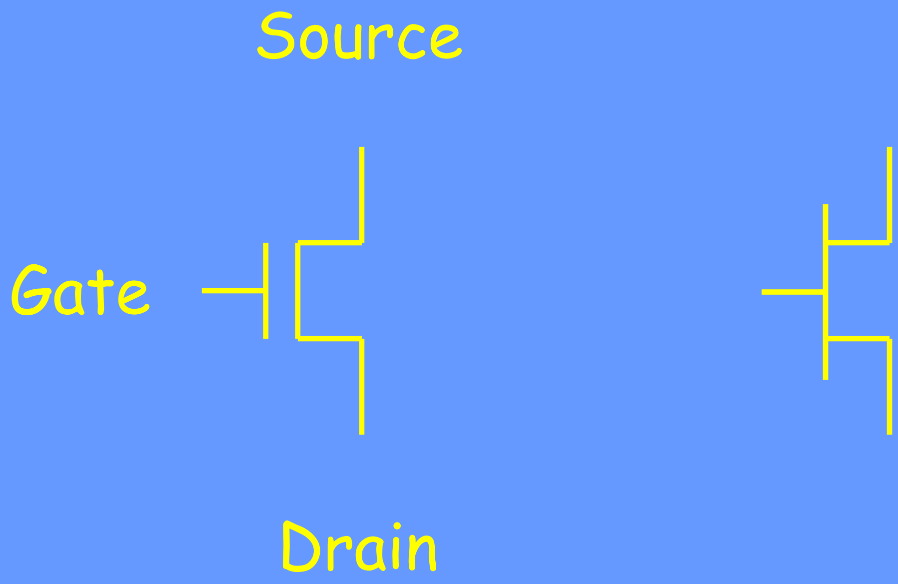
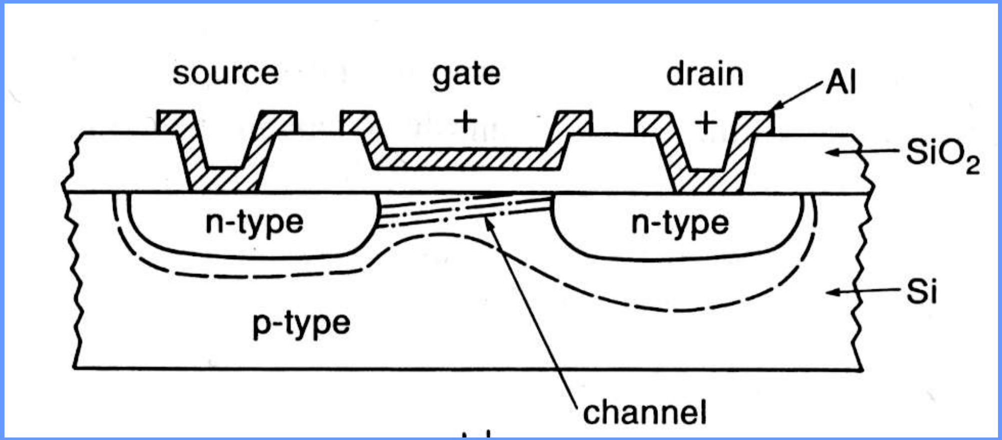
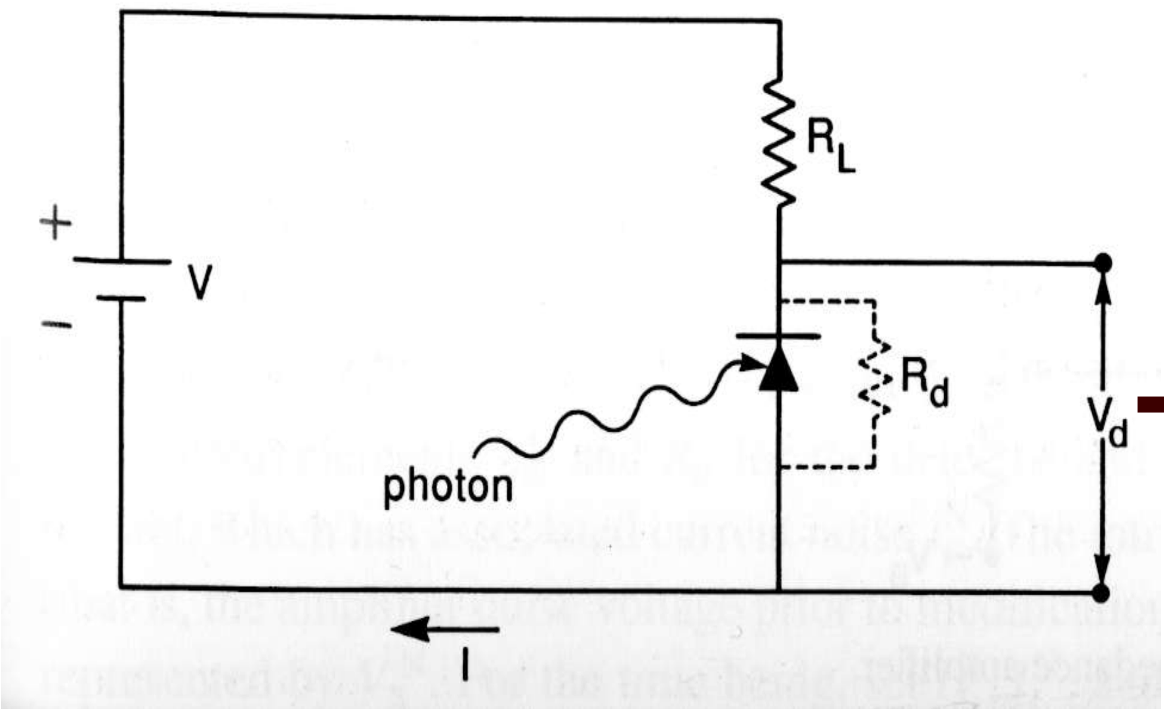

CRAF/CASSINI CCD
600X S4613
40µM
20KV
45
026
S

MOSFET

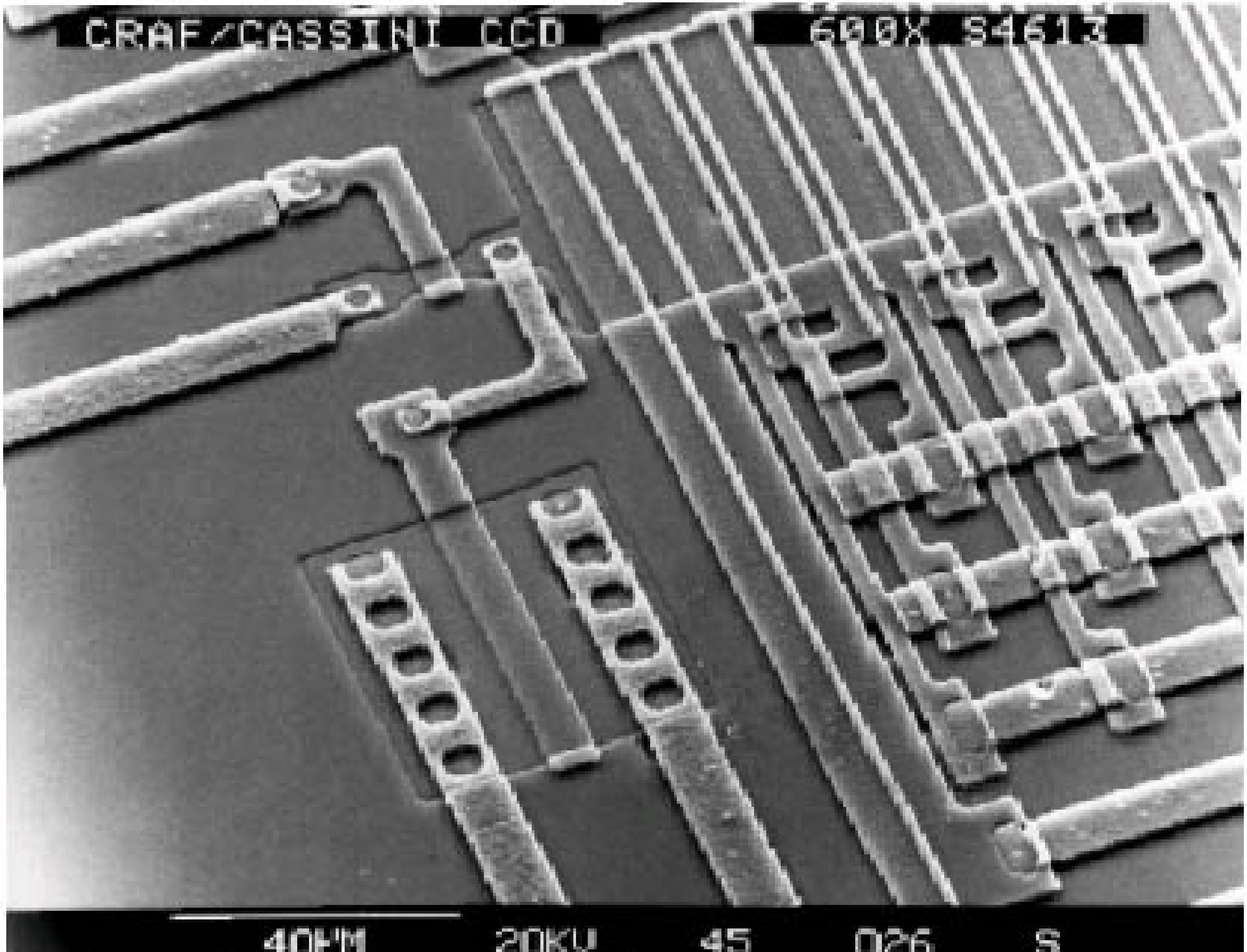

Source
Gate
Drain


source
gate
drain
Al
+
+
SiO2
n-type
n-type
p-type
Si
channel

READOUT



MOSFET amplifier


CRAF/CASSINI CCD
600X S4613
40HM
20KV
45
026
S

Amplifier Responsivity

$$Q = CV$$

$$V = Q / C$$

Capacitance of MOSFET = 10^{-13} F (100 fF)

Responsivity of amplifier = 1.6 μV / e^-

More recent amplifier designs have higher responsivity, 5 – 10 μV/e^-, which give lower noise, but less dynamic range.