Imaging and Imaging Detectors

Introduction

Detectors we have dealt with so far: non-imaging detectors.

This lecture: imaging optical photons and X-rays

Any imaging system has two parts:

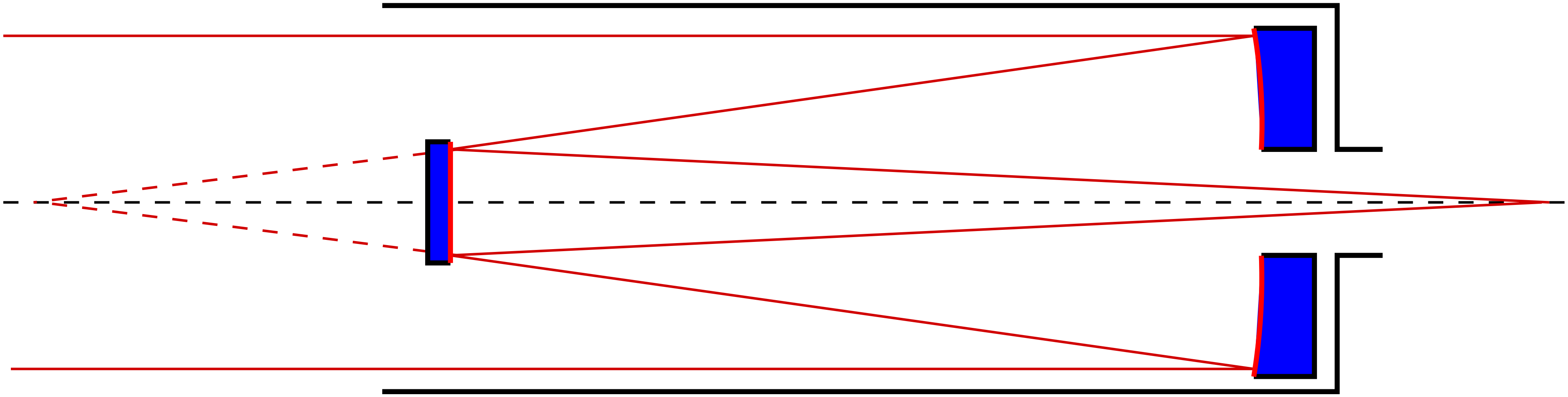
1. Imaging optics

   In most applications, mirrors are used for imaging, although other techniques (variants of shadow cameras) are used, e.g., for γ-rays

2. Spatially resolved detector

   i.e., a detector capable of measuring where a photon hits it in the focal plane. This can be a photographic plate or film, but is normally a charge coupled device (CCD).

Optical Imaging, I



Cassegrain telescope, after Wikipedia

Reminder: Optical telescopes are usually reflectors:

primary mirror → secondary mirror → detector

Main characteristics of a telescope:

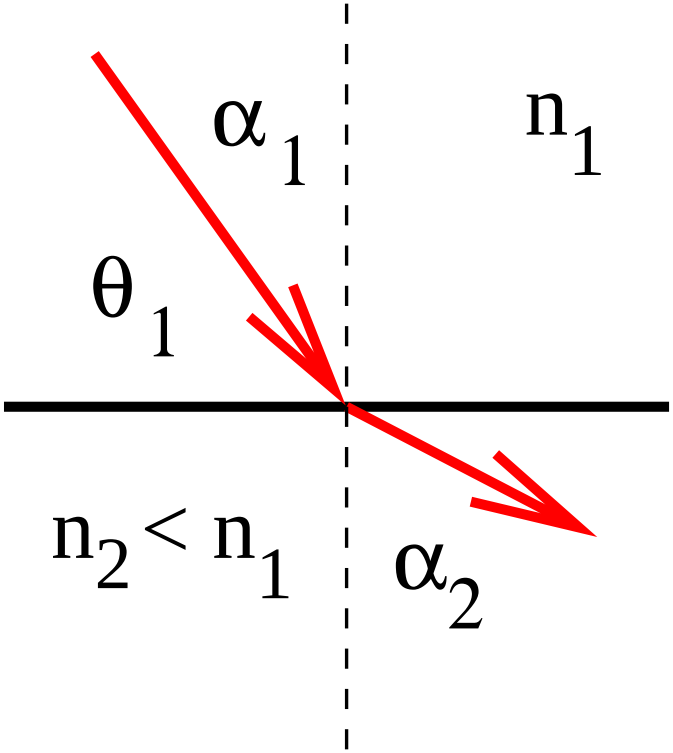
- collecting area (i.e., open area of telescope, $\sim \pi d^2/4$, where d: telescope diameter)
- fpr small telescopes: angular resolution,

$$\theta = 1.22\,\frac{\lambda}{d} \tag{4.1}$$

but do not forget the seeing!

Optical Imaging, II

Optical telescopes are based on principle that reflection “just works” with metallic surfaces. For X-rays, things are more complicated. . .



Snell’s law of refraction:

$$\frac{\sin\alpha_1}{\sin\alpha_2} = \frac{n_2}{n_1} = n \tag{4.2}$$

where n index of refraction, and $\alpha_{1,2}$ angle wrt. surface normal. If $n \gg 1$: Total internal reflection

Total reflection occurs for $\alpha_2 = 90^\circ$, i.e. for

$$\sin\alpha_{1,\mathrm{c}} = n \quad \Longleftrightarrow \quad \cos\theta_\mathrm{c} = n \tag{4.3}$$

with the critical angle $\theta_\mathrm{c} = \pi/2 - \alpha_{1,\mathrm{c}}$.

Clearly, total reflection is only possible for $n < 1$

Light in glass at glass/air interface: $n = 1/1.6 \Longrightarrow \theta_\mathrm{c} \sim 50^\circ \Longrightarrow$ principle behind optical fibers.

Optical Imaging, III

X-rays: theory gives index of refraction vacuum versus material as

$$n = 1 - N_\mathrm{A}\frac{Z}{A}\frac{r_\mathrm{e}}{2\pi}\rho\lambda^2 =: 1 - \delta \tag{4.4}$$

N_A: Avogadro's number, $r_\mathrm{e} = 2.8 \times 10^{-15}\,\mathrm{m}$, Z: atomic number, A: atomic weight ($Z/A \sim 0.5$), ρ: density, λ: wavelength (X-rays: $\lambda \sim 0.1$–$1\,\mathrm{nm}$).

Critical angle for X-ray reflection:

$$\cos\theta_\mathrm{c} = 1 - \delta \tag{4.5}$$

Since $\delta \ll 1$, Taylor ($\cos x \sim 1 - x^2/2$):

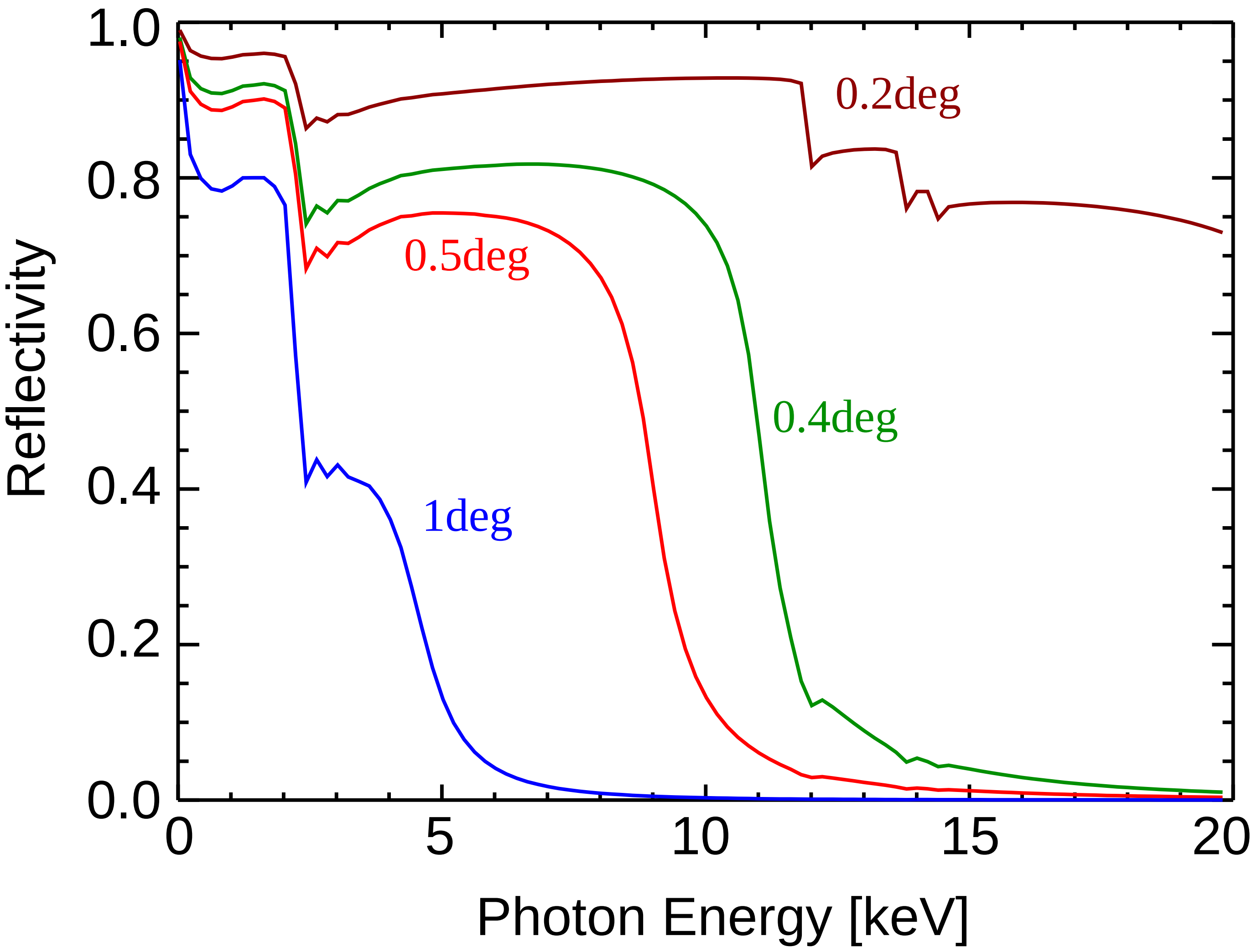
$$\theta_\mathrm{c} = \sqrt{2\delta} = 56'\rho^{1/2}\frac{\lambda}{1\,\mathrm{nm}} \tag{4.6}$$

So for $\lambda \sim 1\,\mathrm{nm}$: $\theta_\mathrm{c} \sim 1^\circ$.

To increase θ_c: need material with high ρ

$\Longrightarrow$ gold (*XMM-Newton*) or iridium (*Chandra*).

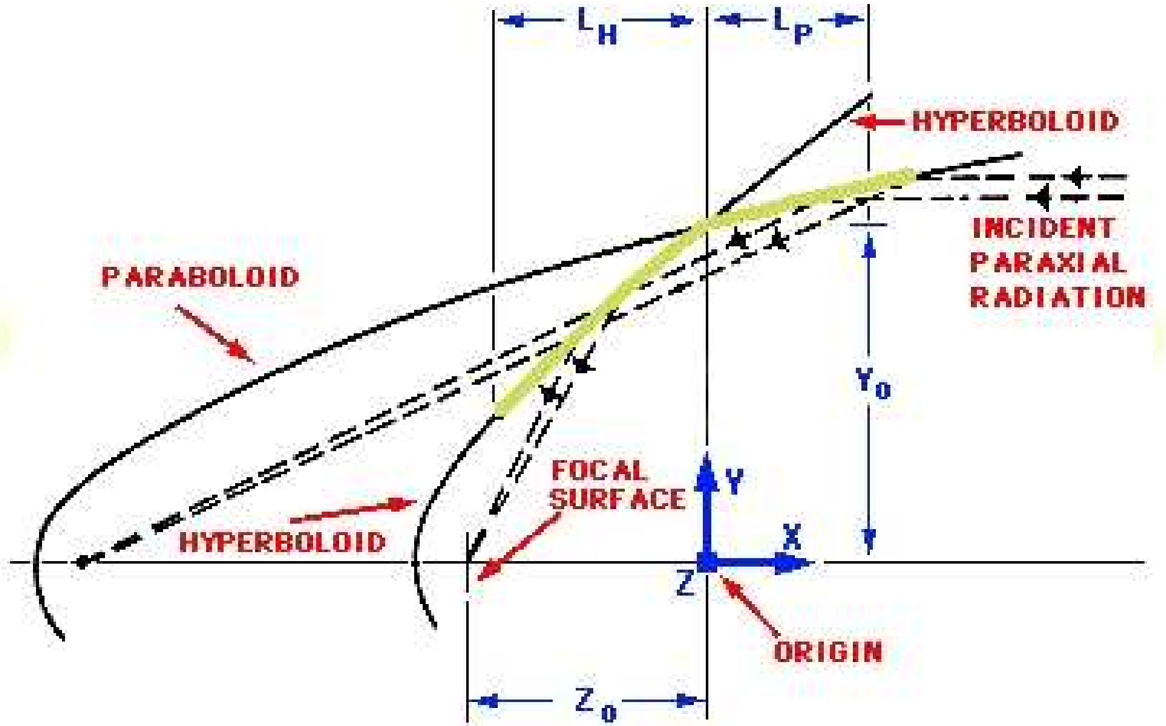
Optical Imaging, IV



Reflectivity for Gold

X-rays: Total reflection only works in the soft X-rays and only under grazing incidence ⟹ grazing incidence optics.

Wolter Telescopes, I

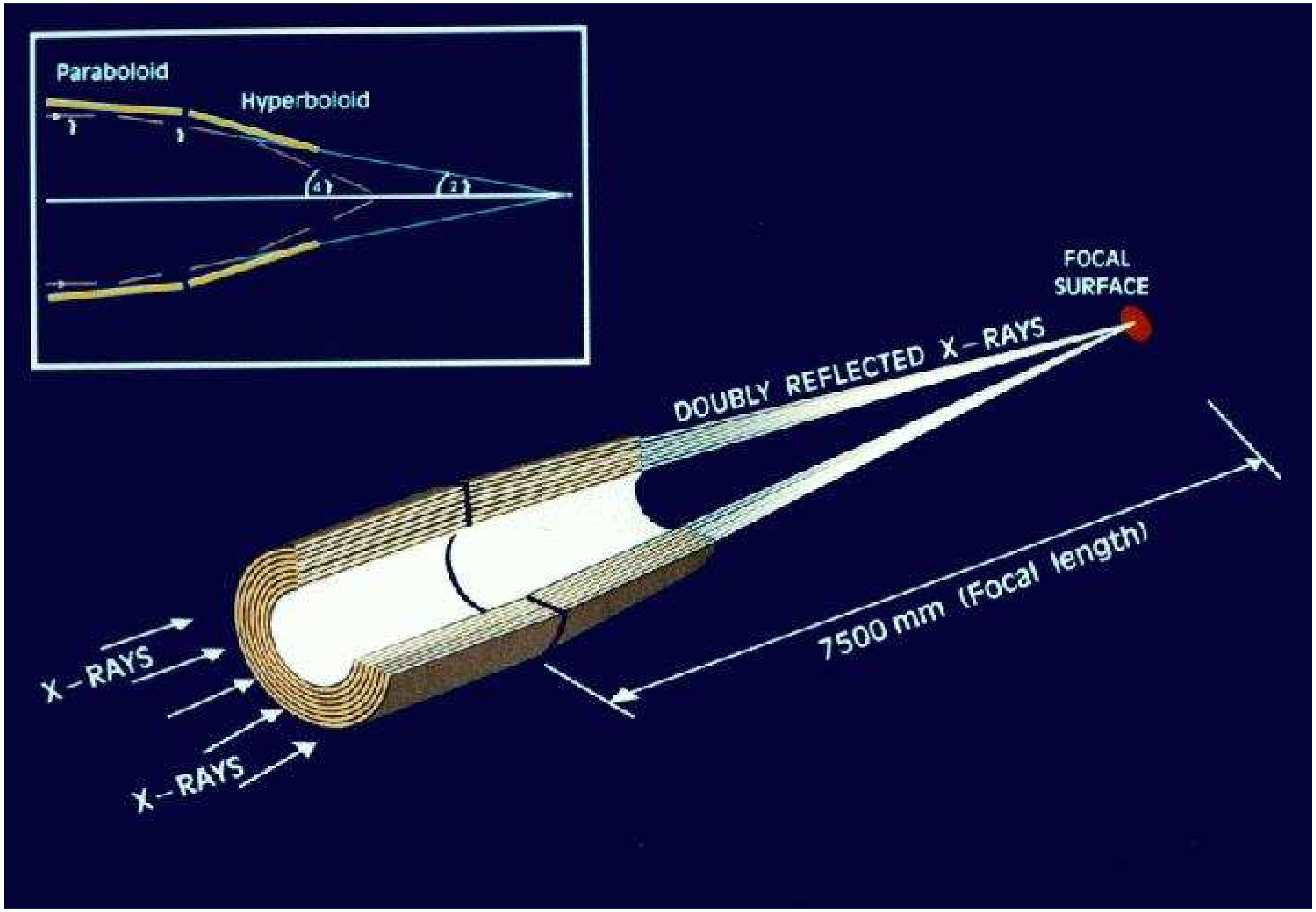


To obtain manageable focal lengths ($\sim$ 10 m), do imaging with telescope using two reflections on a parabolic and a hyperboloidal mirror

(Wolter, 1952, for X-ray microscopes, Giacconi, 1961, for UV- and X-rays).

But: small collecting area ($A \sim \pi r^2 l / f$ where f: focal length)

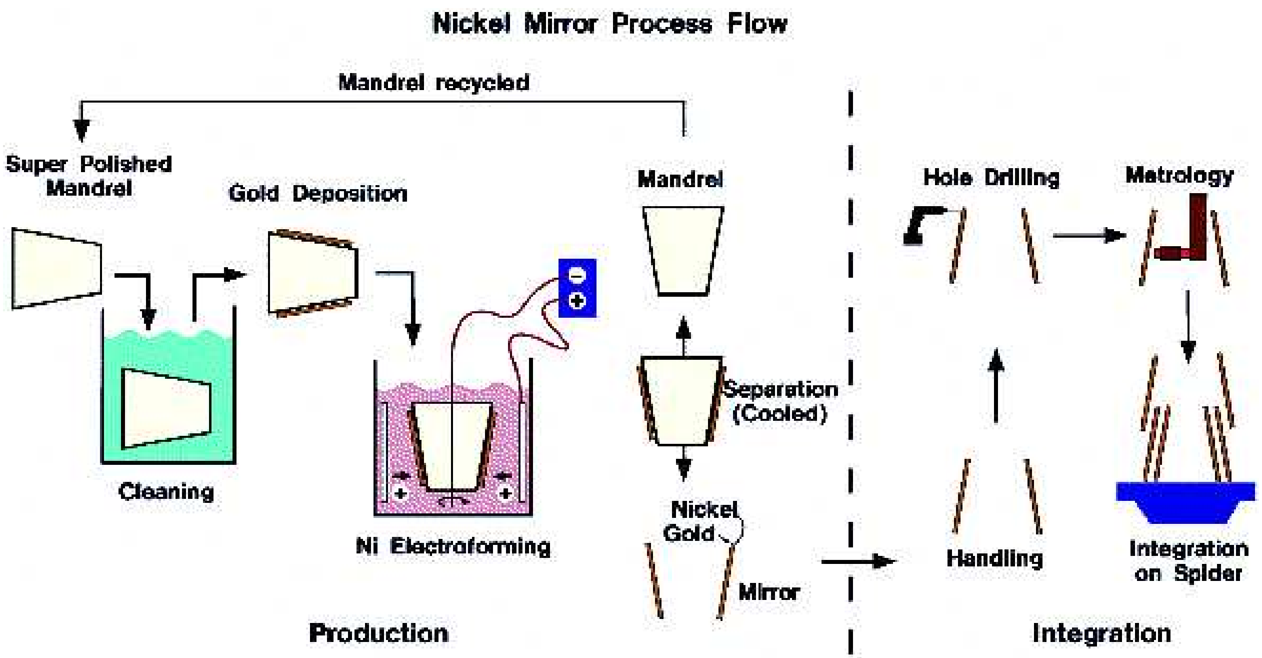
Wolter Telescopes, II



ESA/XMM

Solution to small collecting area: nested mirrors

Mirror manufacture, I



Recipe for making an X-ray mirror:

1. Produce mirror negative ("Mandrels"): Al coated with Kanigen nickel (Ni+10% phosphorus), super-polished [0.4 nm roughness]).
2. Deposit 250 nm Au onto Mandrel
3. Deposit 1 mm Ni onto mandrel ("electro-forming", 10 μm/h)
4. Cool Mandrel with liquid N. Au sticks to Nickel
5. Verify mirror on optical bench.

Total production time of one mirror: 12 d, for XMM: 3×58 mirrors.

Mirror manufacture, II

Gold plastered mandrel for one of the XMM mirrors before electroforming the Ni shell onto the gold.

ESA picture 96.05.006-070

Mirror manufacture, III

. . . insertion of Mandrel into electroforming bath

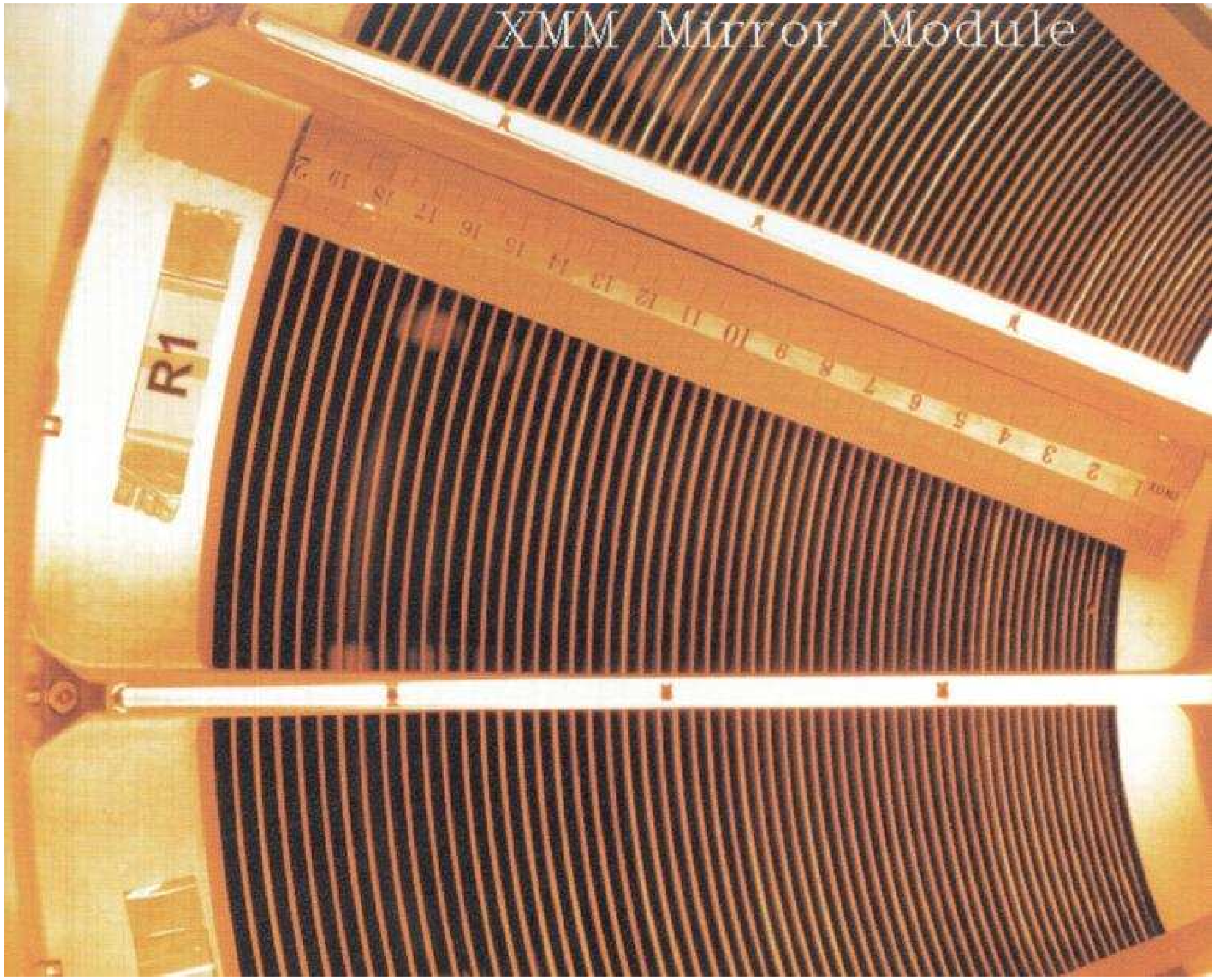
ESA picture 96.12.002-016

Mirror manufacture, IV

. . . and the mirror is done

ESA picture 96.12.002-093

XMM-Newton



Top of the XMM mirrors:

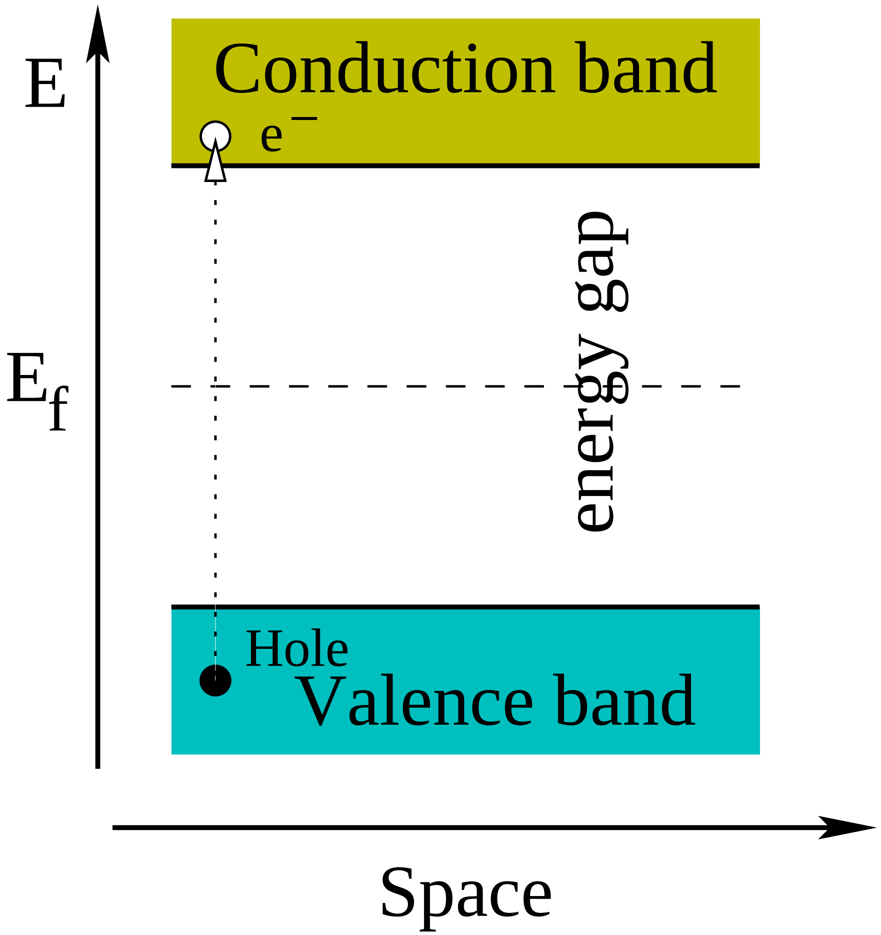
3 mirror sets, each consisting of 58 mirrors,

- Thickness between 0.47 and 1.07 mm
- Diameter between 306 and 700 mm,
- Masses between 2.35 and 12.30 kg,
- Mirror-Height 600 mm
- Reflecting material: 250 nm Au.

photo: Kayser-Threde

The *XMM-Newton* Spacecraft (photo: ESA)

Reminder: Semi-Conductors, I



Semiconductors: separation of valence band and conduction band ~1 eV (=energy of visible light).

Absorption of photon in Si: Energy of photon released

Number of electron-hole pairs produced:

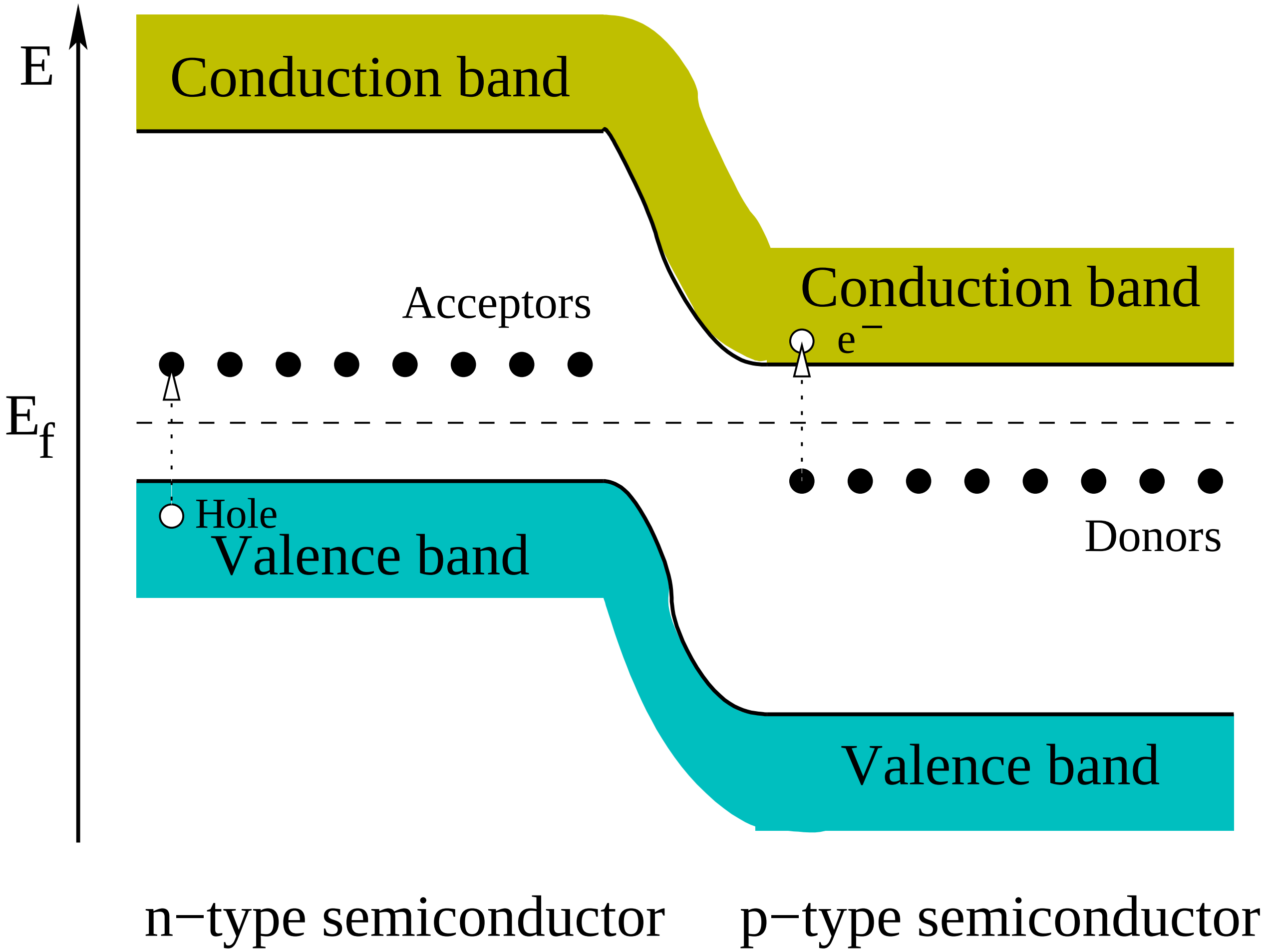
$$N \sim \frac{h\nu}{E_{\text{gap}}} \qquad (4.7)$$

in other words:

- optical light: ~1 electron-hole pair
- X-rays (keV): ~1000 electron-hole pairs

Problem: electron-hole pairs recombine immediately in a normal semiconductor.

Reminder: Semi-Conductors, II



"Doping" the semiconductor moves the valence- and conduction bands.

Connecting a "n-type" and a "p-type" semiconductor gives a pn-junction.

Electron-hole pairs created at pn-junction will be separated by field gradient

$\Longrightarrow$ electrons can then be collected in potential well away from the junction and read out.

Reminder: Semi-Conductors, III

Number of electron-hole pairs produced determined by band gap $+$ “dirt effects”

(“dirt effects”: e.g., energy loss going into bulk motion of the detector crystal [“phonons”])

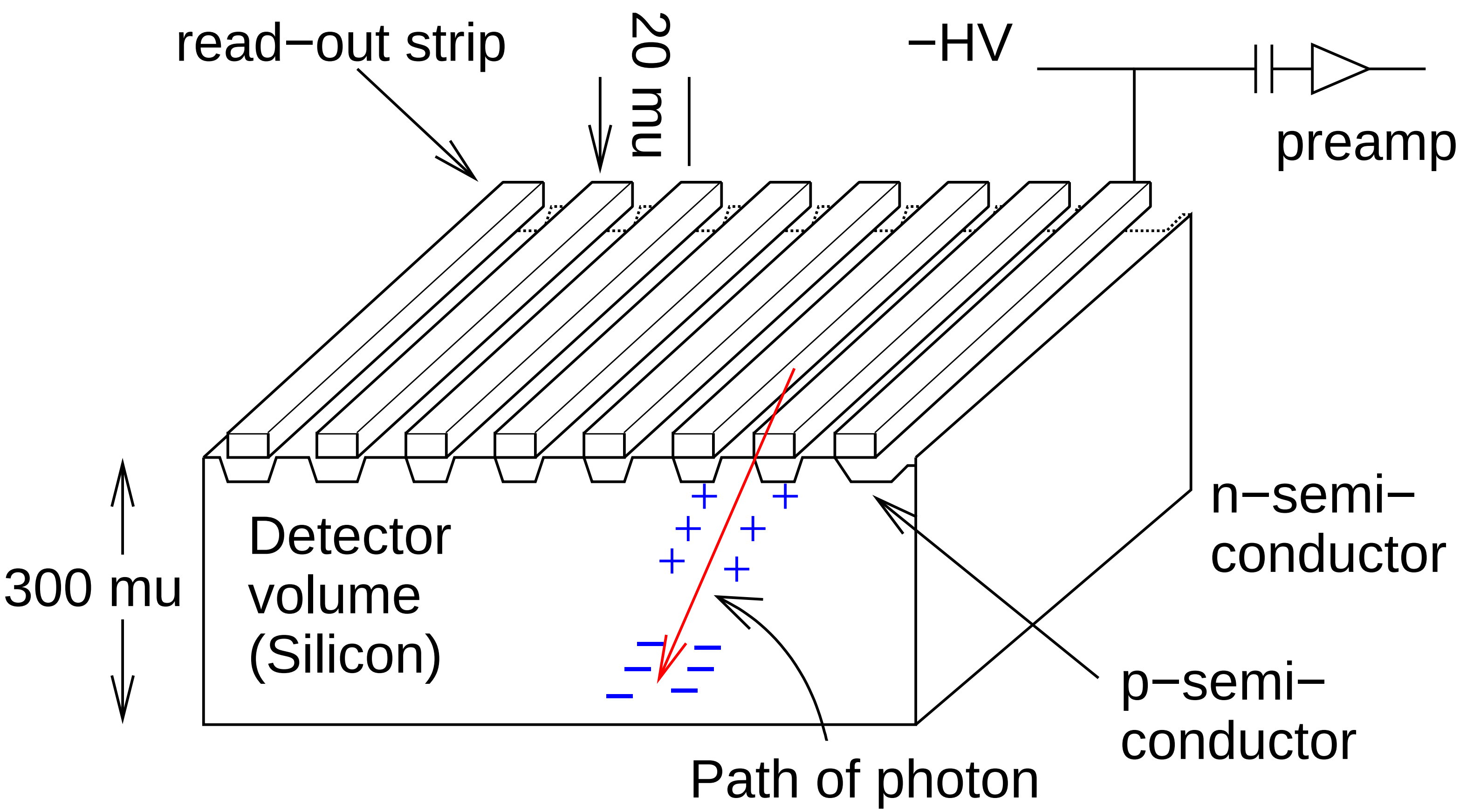
Material	Z	Band gap (eV)	E/pair (eV)
Si	14	1.12	3.61
Ge	32	0.74	2.98
CdTe	48–52	1.47	4.43
HgI2	80–53	2.13	6.5
GaAs	31–33	1.43	5.2

(so $\sim$1 electron for optical photons, $\sim$1000 electrons for X-rays)

Since band gap small: thermal noise $\Longrightarrow$ need cooling

(ground based: liquid nitrogen, -200°C, in space: cryostats)

Strip Detectors

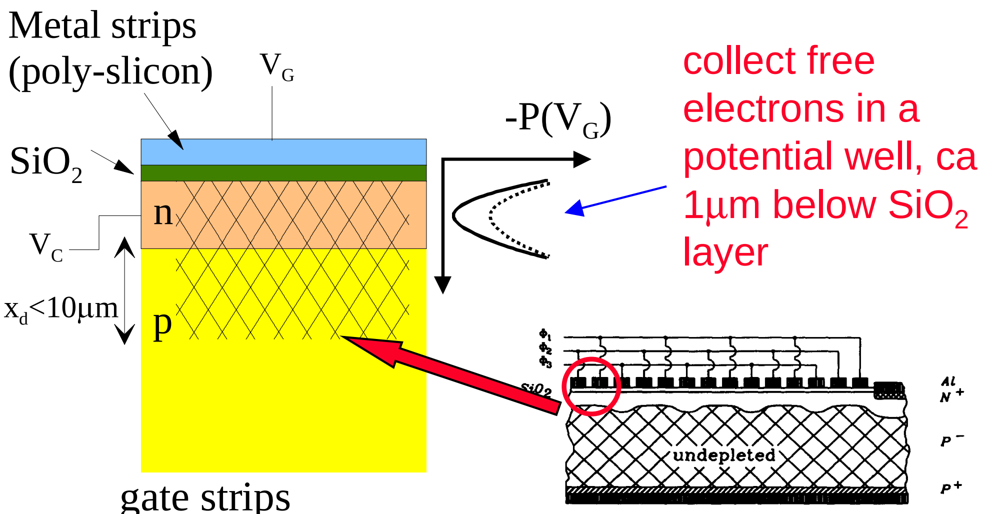


after Grupen

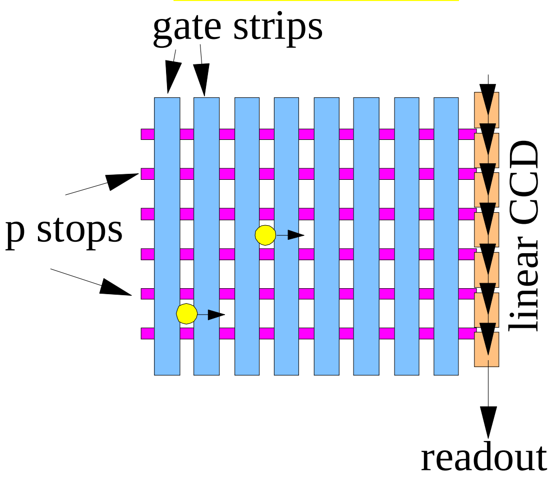
First attempt at spatial resolution obtained by segmenting the p-doped layer: microstrip detectors

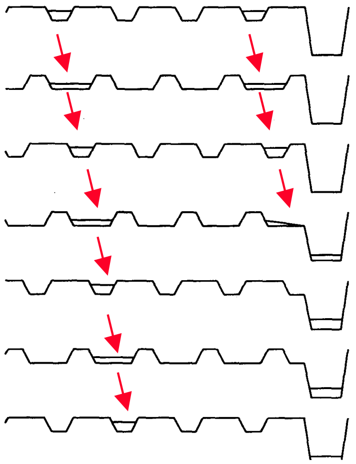
◆ Charge Coupled Devices (CCD)

MOS structure with segmented metal layer



collect free electrons in a potential well, ca. 1µm below SiO_2 layer





→ **all pixels are readout via one (few) output node(s)**

→ **very few electronic channels but long readout time!**

Charge transport by periodic change of gate voltage triplets (ϕ_1,ϕ_2,ϕ_3)

CCDs, II

optical CCDs: measure intensity $\Longrightarrow$ need *long* exposures

X-ray CCDs: measure individual photons $\Longrightarrow$ need fast readout

bright sources: several 1000 photons per second $\Longrightarrow$ readout in μs!

In X-rays: spectroscopy possible. Typical resolution reached today:

$$\frac{\Delta E}{E} = 2.355\sqrt{\frac{3.65\,\mathrm{eV}\cdot F}{E}} \qquad (4.8)$$

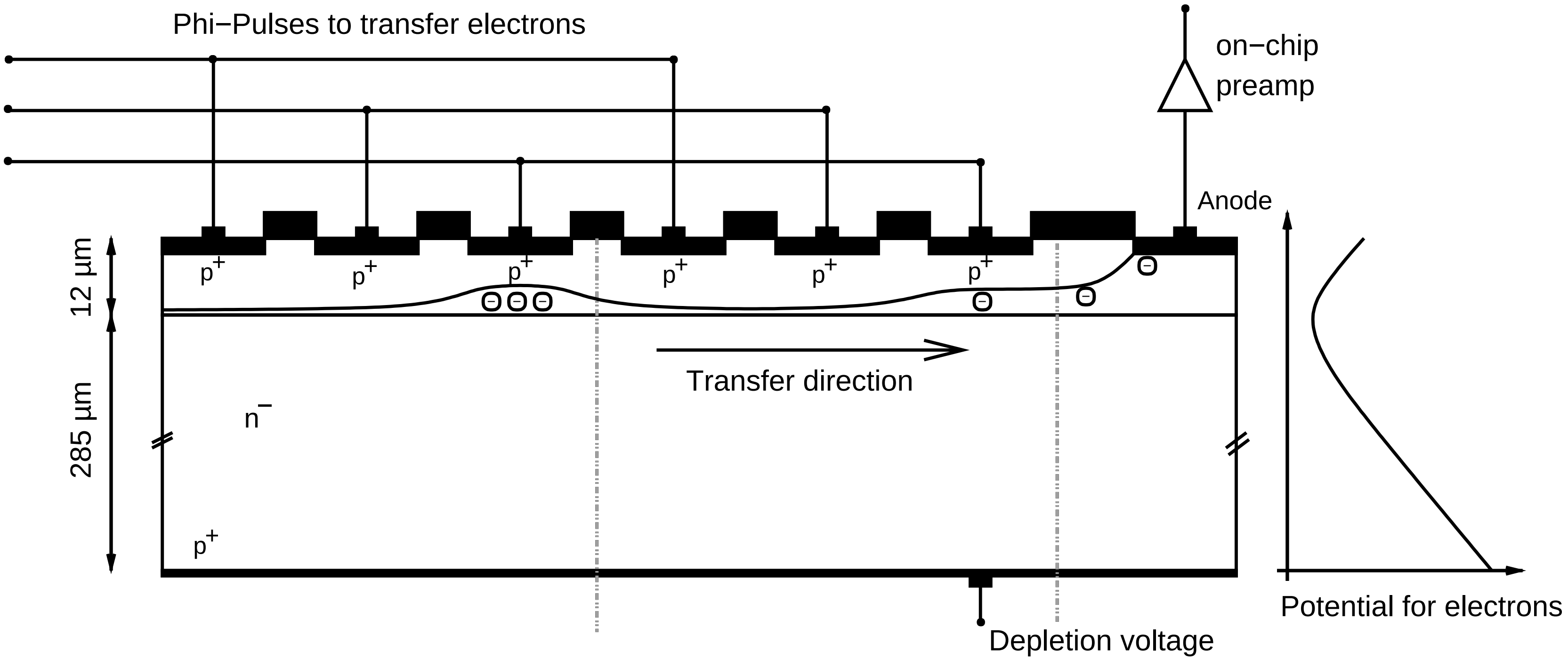
with $F \sim 0.1 \Longrightarrow \sim 0.4\%$, so much better than proportional counters.

(but same $\Delta E/E \propto E^{-1/2}$ proportionality because of Poisson!)

For both optical and X-rays: sensitivity close to 100%

Si based CCDs are currently the best available imaging photon detectors for optical and X-ray applications.

CCDs, III



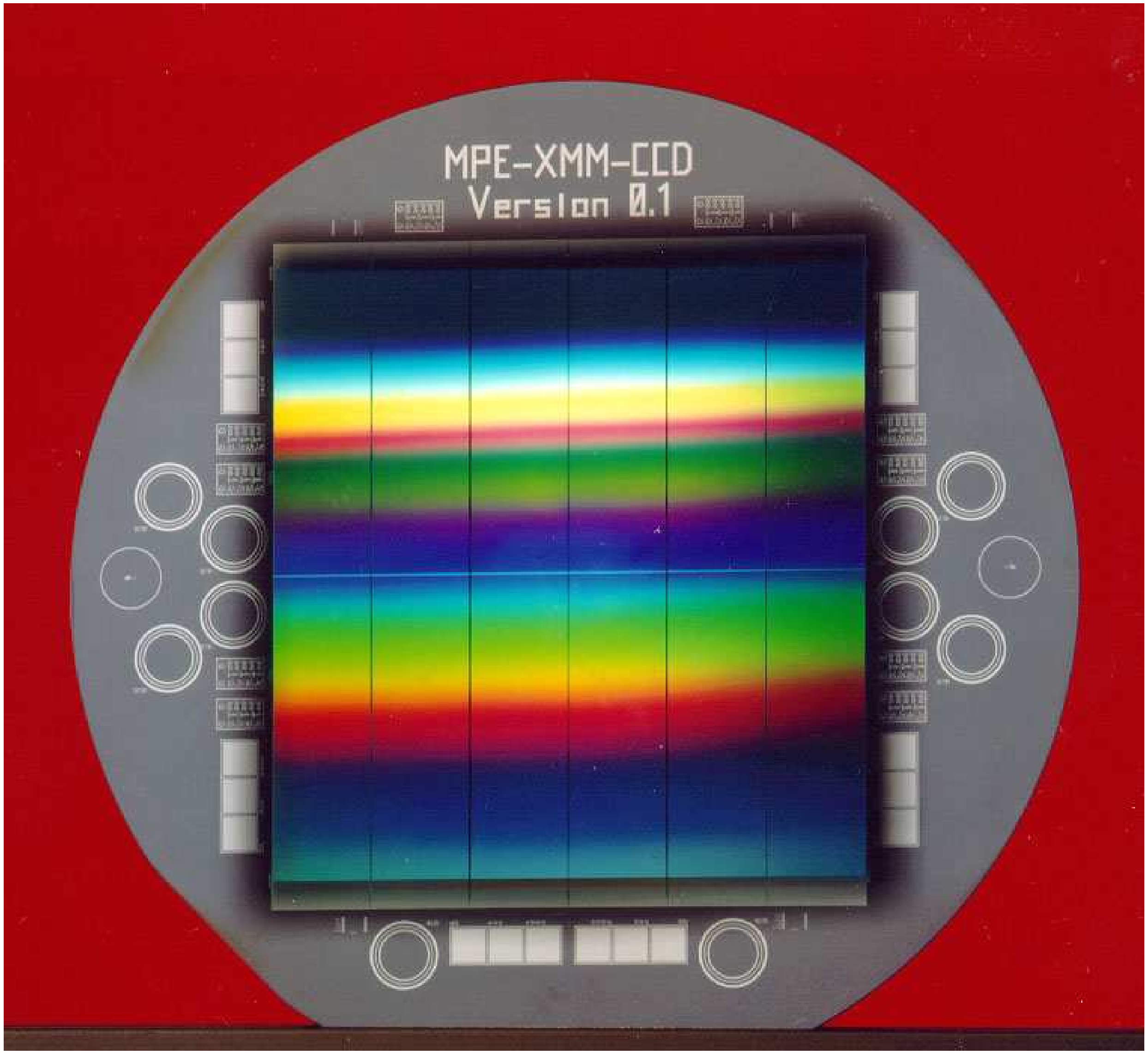
Schematic structure of the *XMM-Newton* EPIC pn CCD.

Problem: Infalling structure has to pass *through* structure on CCD surface $\Longrightarrow$ loss of low energy response, also danger through destruction of CCD structure by cosmic rays. . .

Solution: Irradiate the back side of the chip. Deplete whole CCD-volume, transport electrons to pixels via adequate electric field ("backside illuminated CCDs")

Note: solution works mainly for X-rays

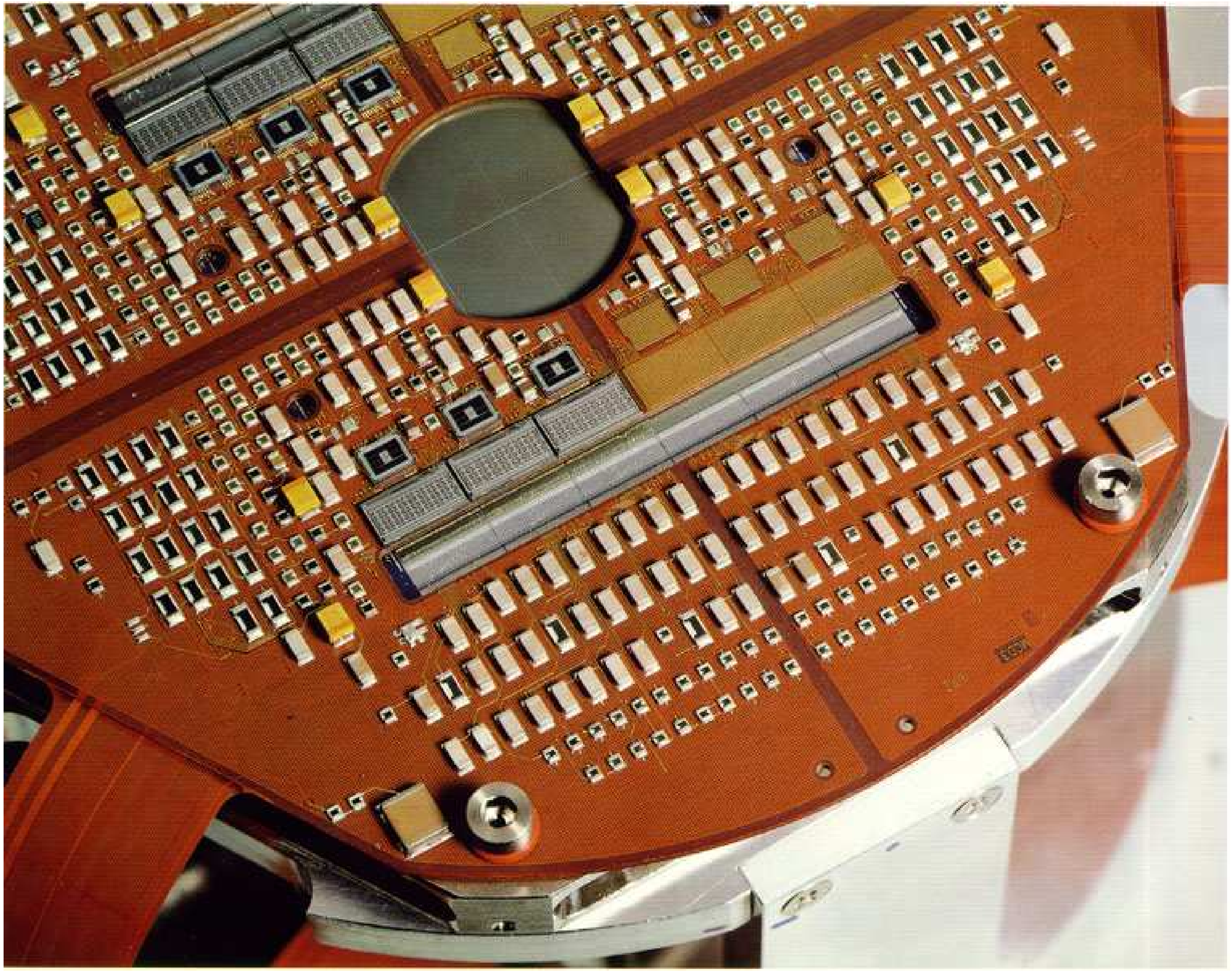
XMM-Newton: EPIC-pn CCD



XMM-Newton: Array of individual backside illuminated CCDs on one Silicon wafer $\Longrightarrow$ requires extreme care during production

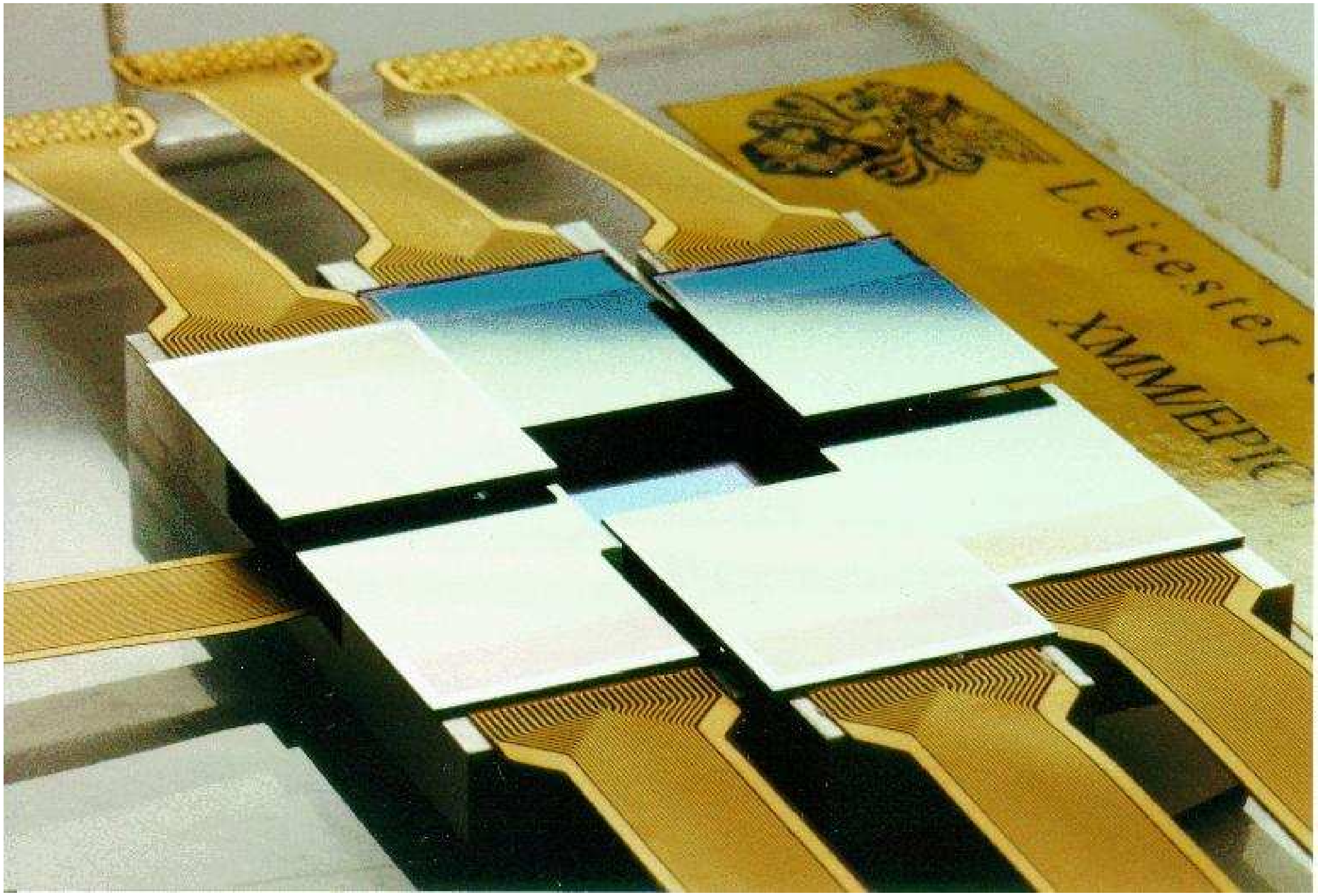
at the time of production one of the most complex Silicon structures ever made (diameter: 65.5 mm)

XMM-Newton: EPIC-pn CCD



Backside of the EPIC-pn camera head

XMM-Newton: EPIC-pn CCD



XMM-Newton (EPIC-MOS; Leicester): 7 single CCDs with 600 × 600 pixels, mounting is adapted to curved focal plane of the Wolter telescope.