TNU/SAGI summer school 2024

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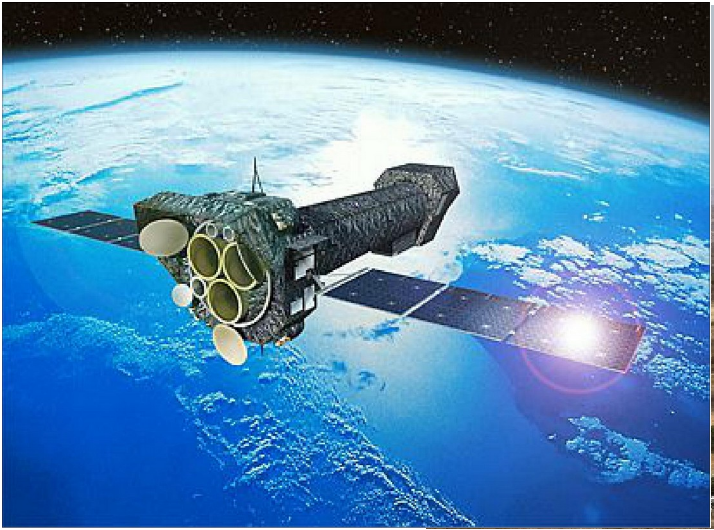
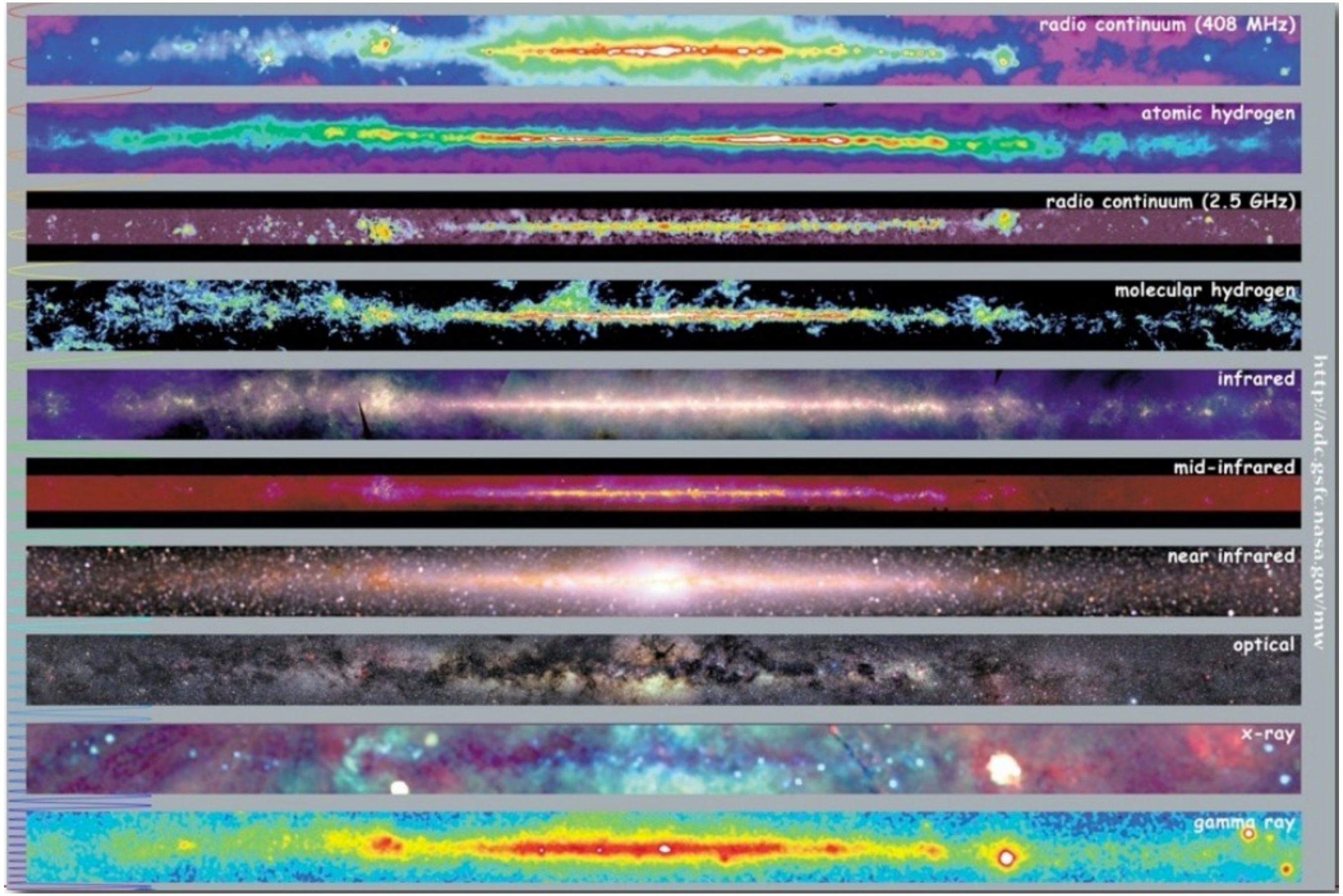


High energy Astronomy: An instrument perspective

Speaker: Nhàn T. Nguyễn-Đặng (Tübingen, Germany)

X-ray astronomical instruments



The milky way measured in different ranges of the electromagnetic spectrum

X-ray astronomical instruments

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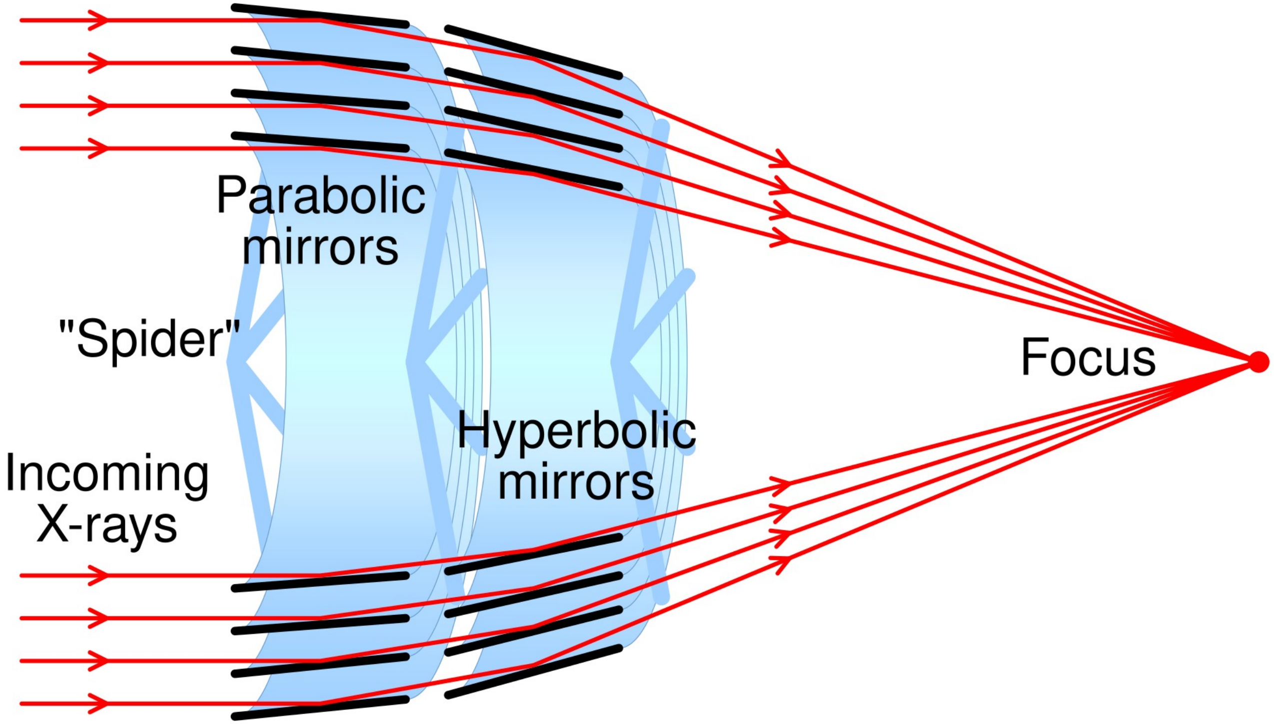
Credit: wikipedia

- Wilhelm Röntgen and the first medical X-ray image (of his wife)

- First Nobel prize receiver.

- X-ray: high-energy radiation that can penetrate matters.

X-ray astronomical instruments



Credit: By Cmglee - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=82992872

X-ray telescope:

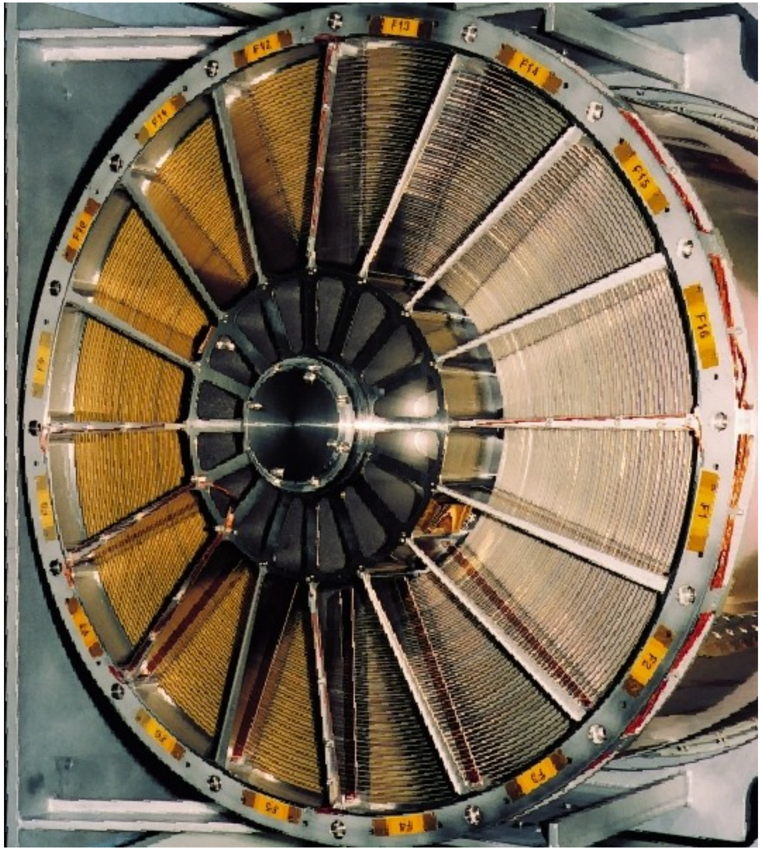
- Collimator.

- Mirrors (require: low incident angles).

- Detectors

- Space-based missions

X-ray astronomical instruments



XMM-Newton

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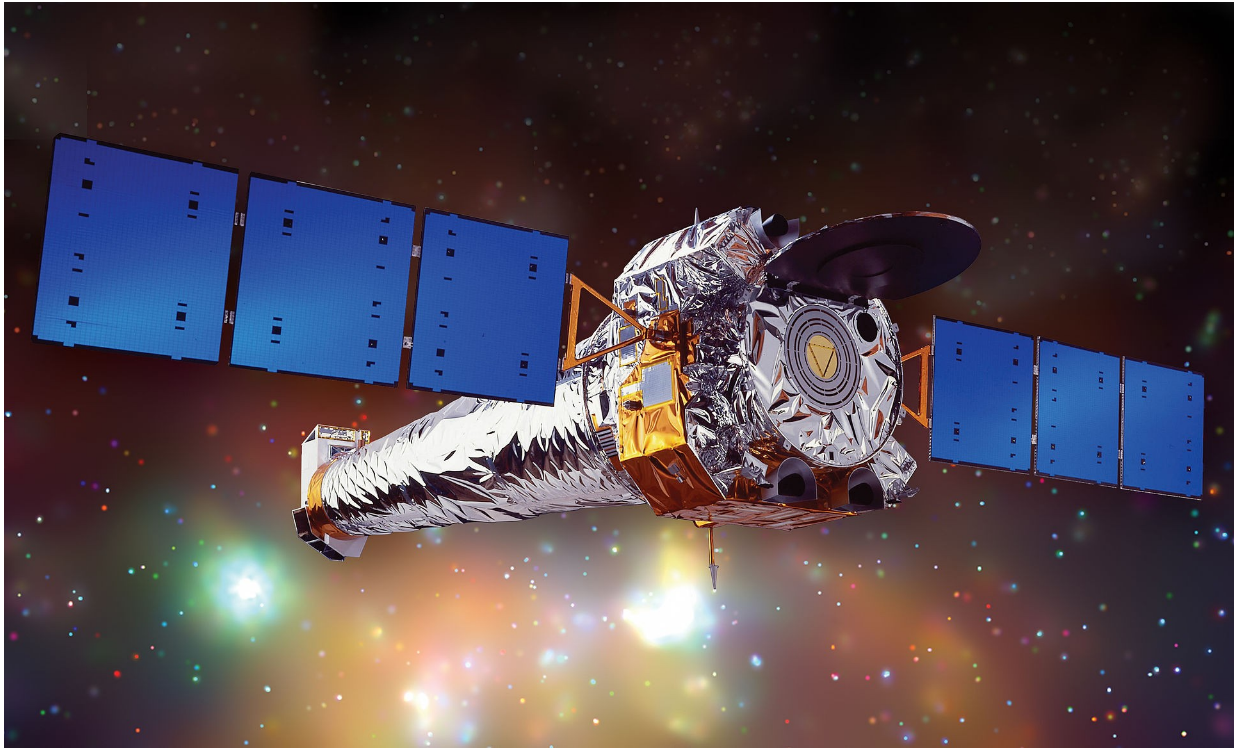
X-ray astronomical instruments

Credit: By NASA/CXC/NGST - http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=11185 (image link), Public Domain, https://commons.wikimedia.org/w/index.php?curid=38252467



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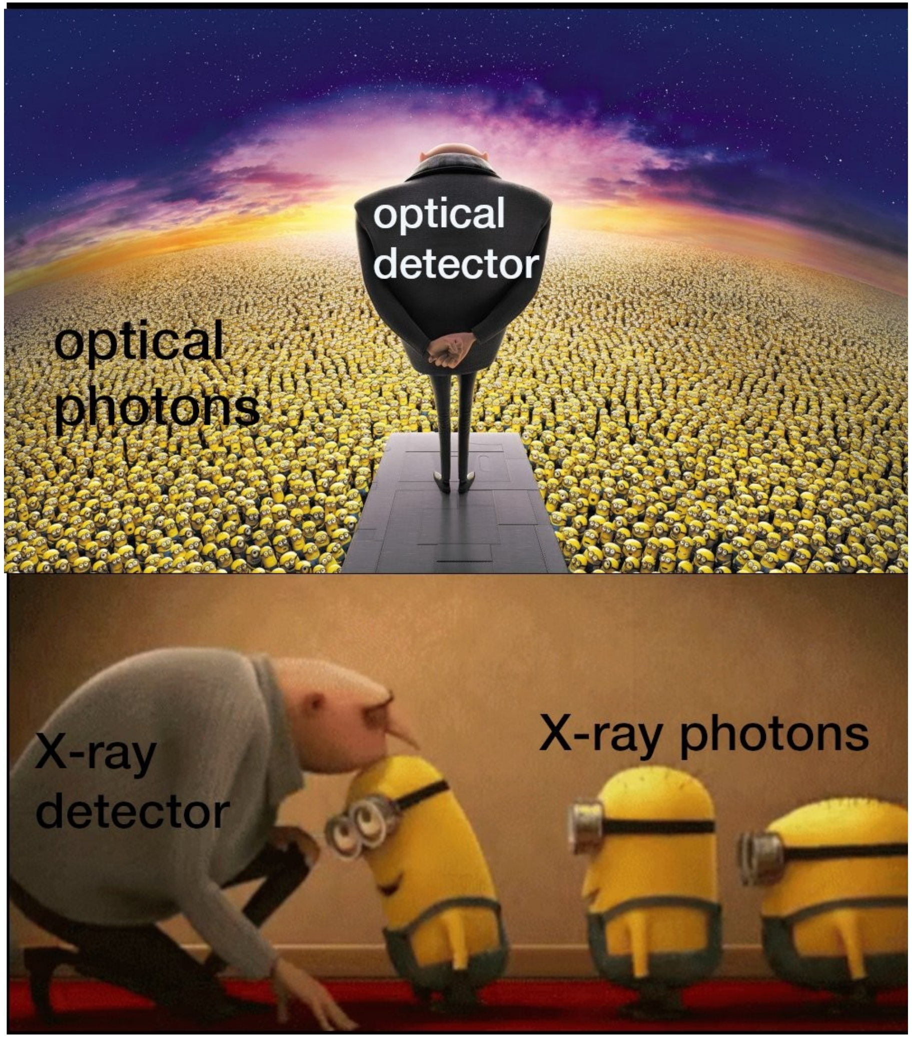


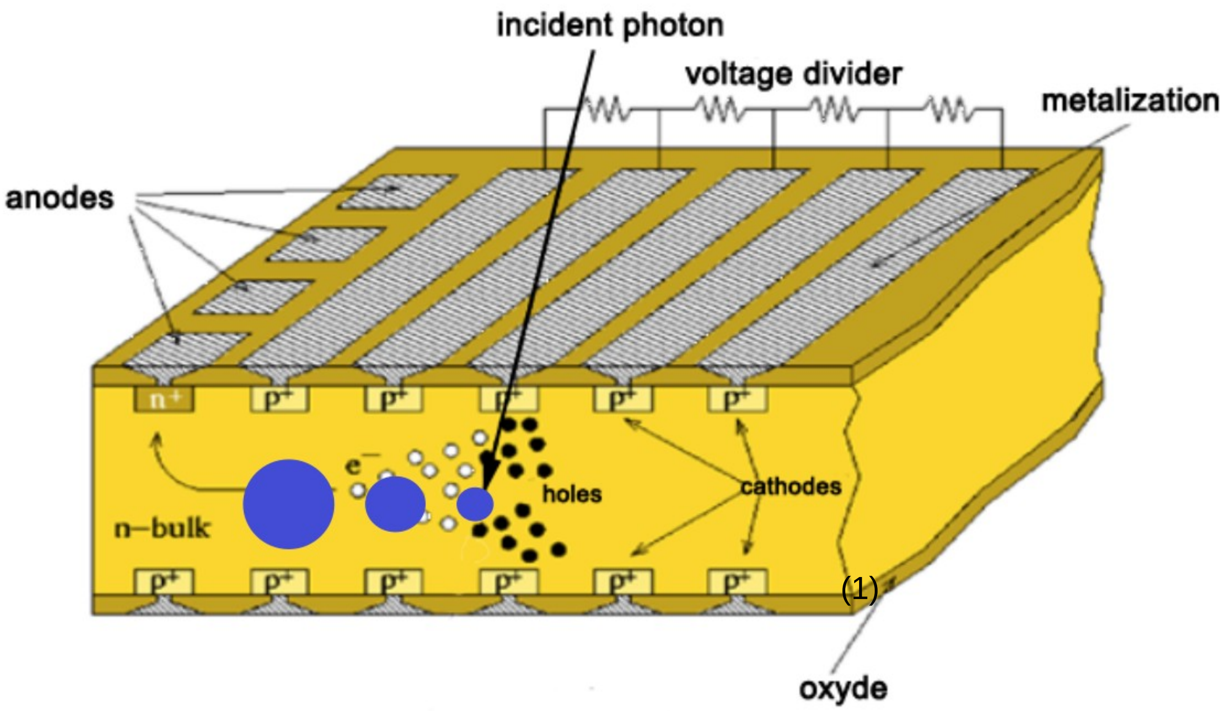
Credit: MaiteCeballos

The different between optical vs. X-ray detectors: every X-ray hit counts!

How do we record the X-ray photons? => X-ray detectors.

Example: Silicon drift detector.

Silicon drift detectors



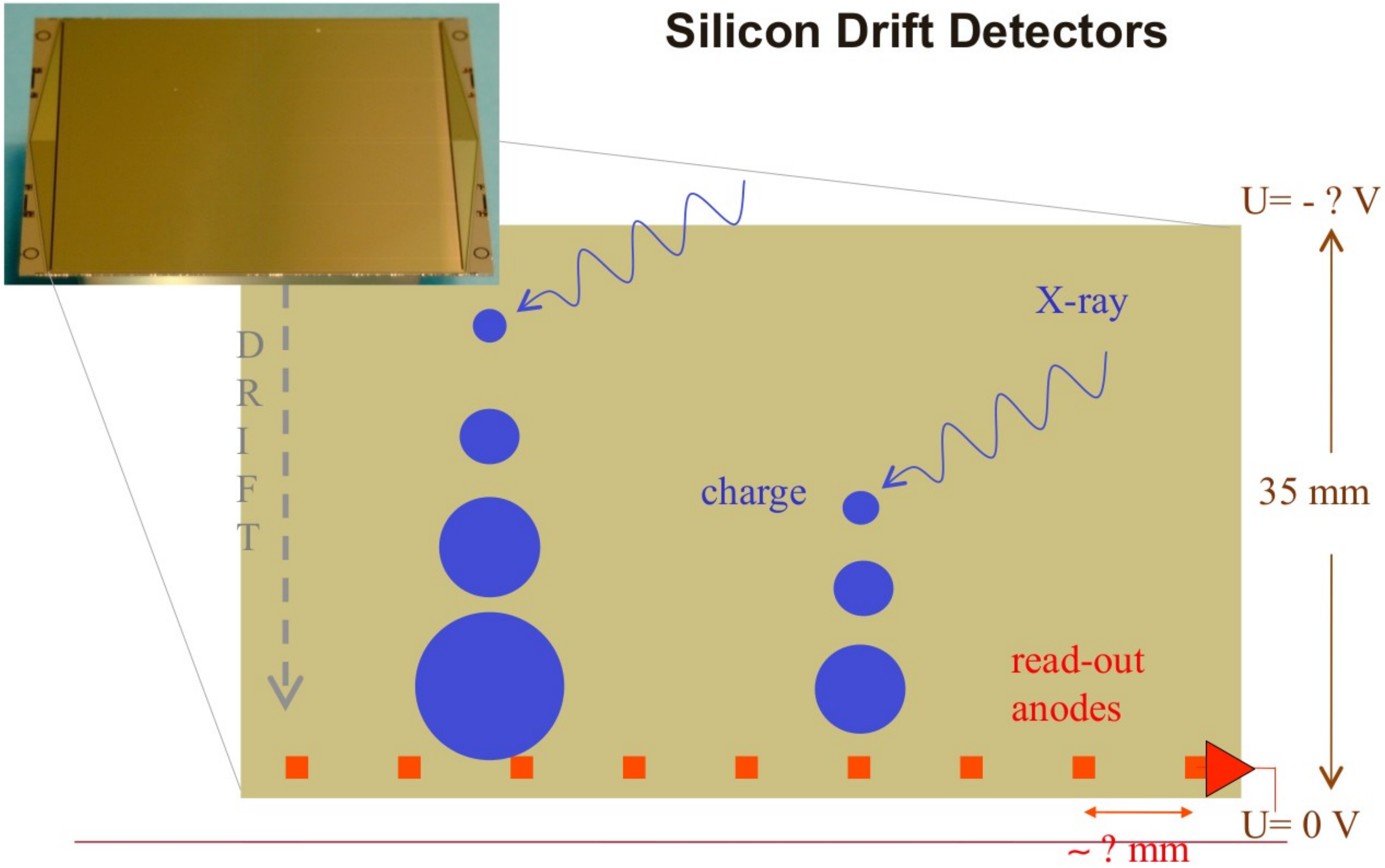
- Silicon sensor, drift field, central collection electrodes.

- X-ray hits semiconductor material => create hole-electron pair => charge cloud.

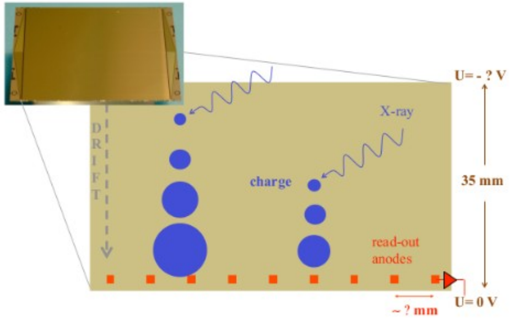
- Charge carriers drift along the electric field.

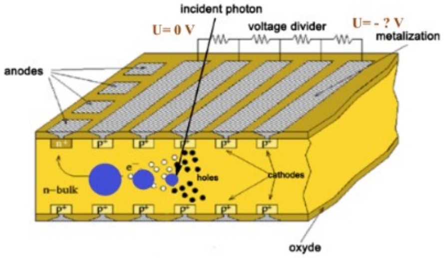
- Measure the energy of an incoming photon by the amount of ionization it produces in the detector material.

X-ray astronomical instruments



Silicon drift detectors (SDDs) are used both in particle physics (for example in the *ALICE* experiment at CERN) and in astrophysics (in *SuperAGILE* as well as in the planned *eXTP* and *Athena* missions). They are characterized by a large effective area, customizable geometric shape and a simple readout design with few anodes. The rectangular geometry shown in the schematic has an extent of 10 cm (length) × 3.5 cm (width) × 450 μm (thickness). A strong electric field is applied between the top and bottom surfaces, so that generated negative charge carriers drift to the read-out anode.





a) The drift velocity is very important for the time resolution performance of the detector. For a time resolution (i.e. maximum drift time) of 10 μs , calculate the voltage that must be applied between the two electrodes. Use the electron mobility in silicon

$$\mu_{\mathrm{e,Si}} = \frac{v_{\mathrm{drift}}}{E} = 1400\,\frac{\mathrm{cm}^2}{\mathrm{V}\cdot\mathrm{s}} \qquad (1)$$

at $T = 300\,\mathrm{K}$. As can be seen, direct information about the interaction location is only obtained in one dimension.

b) While drifting, the originally very compact charge cloud (Gaussian distribution, $\sigma_0 = 20\,\mu$m, corresponding to the range of a 50 keV electron in silicon) widens, following:

$$\sigma(t) = \sqrt{2 \cdot D \cdot t + \sigma_0^2} \qquad (2)$$

with the diffusion coefficient $D = \mu_e \cdot k_B \cdot T/e$ and the elementary charge e.

(i) Using this detector type, how could one obtain information about the position of the photon interaction in drift direction even if the interaction time is only known to not better than $\pm 10\,\mu$s?
<u>*Hint:*</u> The anodes can be readout individually. Give a formula for the position in drift direction.

(ii) Calculate the width σ of the charge cloud at the location of the anodes at a drift distance of 1.0 cm and 3.5 cm and a photon energy of 6.4 keV (cf. Exercise 10 about energy resolution). What would be a reasonable distance between the individual anodes?

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a) The maximum drift time is $t_{\text{max}} = 10\,\mu$ s. The drift velocity is:

$$v_{\text{drift}} = \frac{d_{\text{max}}}{t_{\text{max}}} = \frac{35\ \text{mm}}{10\,\mu\text{s}} \tag{3}$$

The electric field strength:

$$E = \frac{v_{\text{drift}}}{\mu_{e,\text{Si}}} = \frac{35\ \text{mm}}{10\ \mu\text{s} \cdot 1400\text{cm}^2} \tag{4}$$

Finally, the potential difference or voltage to apply between the two electrodes:

$$U = E \cdot d_{\text{max}} = \frac{v_{\text{drift}}}{\mu_{e,\text{Si}}} \cdot d_{\text{max}} = \frac{\text{V.s}}{1400\ \text{cm}^2} \cdot \frac{3.5^2\ \text{cm}^2}{10\,\mu\text{s}} = 875\,\text{V} \tag{5}$$

b) We have:

$$\sigma(t) = \sqrt{2Dt + \sigma_0^2} = \sqrt{2\mu_e k_B \frac{T}{q} \cdot t + \sigma_0^2} \tag{6}$$

with $\sigma_0 = 20\,\mu\text{m}$ and the total charge generated $q = n \cdot e$. As the charged particle moves inside the Silicon detector, the variance $\sigma_{(t)}$ increases according to time t. Therefore, base on the size of the charge cloud, we can estimate how long it has been drifted, which leads to solving the drift velocity and the position of incoming signal.

(i) To determine the location, the width of the charge cloud σ_A at the time of the readout can be calculated back:

$$d = v_{\text{Drift}} \cdot t = \underset{(1)}{E} \cdot \mu_e \cdot t = \frac{U}{d_{\max}} \cdot \mu_e \cdot \frac{\sigma_A^2 - \sigma_0^2}{2D} = \frac{U}{d_{\max}} \cdot \frac{\sigma_A^2 - \sigma_0^2}{2k_B T} \cdot (n \cdot e) \tag{7}$$

(ii) We have again:

$$\sigma(t) = \sqrt{2Dt + \sigma_0^2} = \sqrt{2\mu_e k_B \frac{T}{e} \cdot t + \sigma_0^2} = \sqrt{2\mu_e k_B \frac{T}{e} \cdot \frac{d}{v_{\text{Drift}}} + \sigma_0^2}$$
$$\Leftrightarrow \quad \sigma(d) = \sqrt{2k_B T \frac{1}{e} \cdot \frac{d \cdot d_{\max}}{U} + \sigma_0^2} \tag{8}$$

Plugging the numbers in:

$$\sigma(d_{\text{Drift}} = 1\,\text{cm}) = \sqrt{2 \cdot 8.617 \cdot 10^{-5}\,\text{eV/K} \cdot 300\,\text{K} \cdot \frac{1.0 \cdot 3.5\,\text{cm}^2}{e \cdot 875\,\text{V}} + (20\,\mu\text{m})^2}$$
$$= 145.08\,\mu\text{m}$$
$$\sigma(d_{\text{Drift}} = 3.5\,\text{cm}) = \sqrt{2 \cdot 8.617 \cdot 10^{-5}\,\text{eV/K} \cdot 300\,\text{K} \cdot \frac{3.5 \cdot 3.5\,\text{cm}^2}{e \cdot 875\,\text{V}} + (20\,\mu\text{m})^2}$$
$$= 269.97\,\mu\text{m}$$

Hence, the reasonable distance between individual anodes is in the range of a few hundreds μm

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Thank you for your attention!