UiO : Department of Informatics
University of Oslo

INF5442 – Image Sensor Circuits and Systems

Lecture 2 – Photon detection and pixel circuits

1-September-2014

Agenda

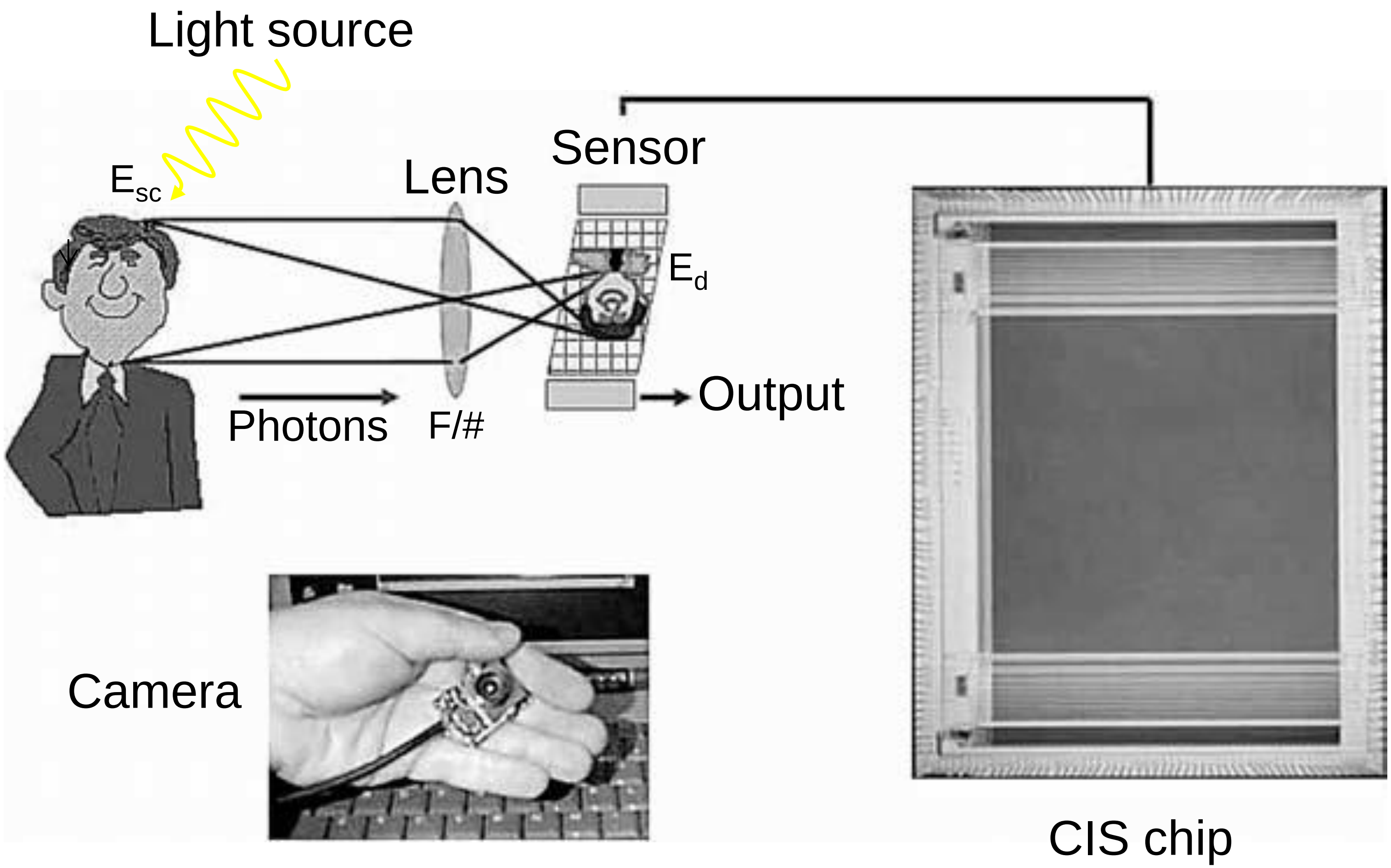
- Key takaways from previous week

- Lecture2 – Photon detection and pixel circuits
  - References: Nakamura, Ch. 3

Recap from previous week

- Photon energy, $E_{photon} = h\, c / \lambda$ (J)
- RGB and YUV color representation
- Light level on sensor: $E_d = E_{sc} / 4F^2$ (lx or W/m^2)
- Camera field of view: $FOV = 2\Theta' = \tan^{-1}(y'/f)$

CMOS Image Sensor (CIS)



Ref: J Nakamura, ch-3

Optical format and effective array size

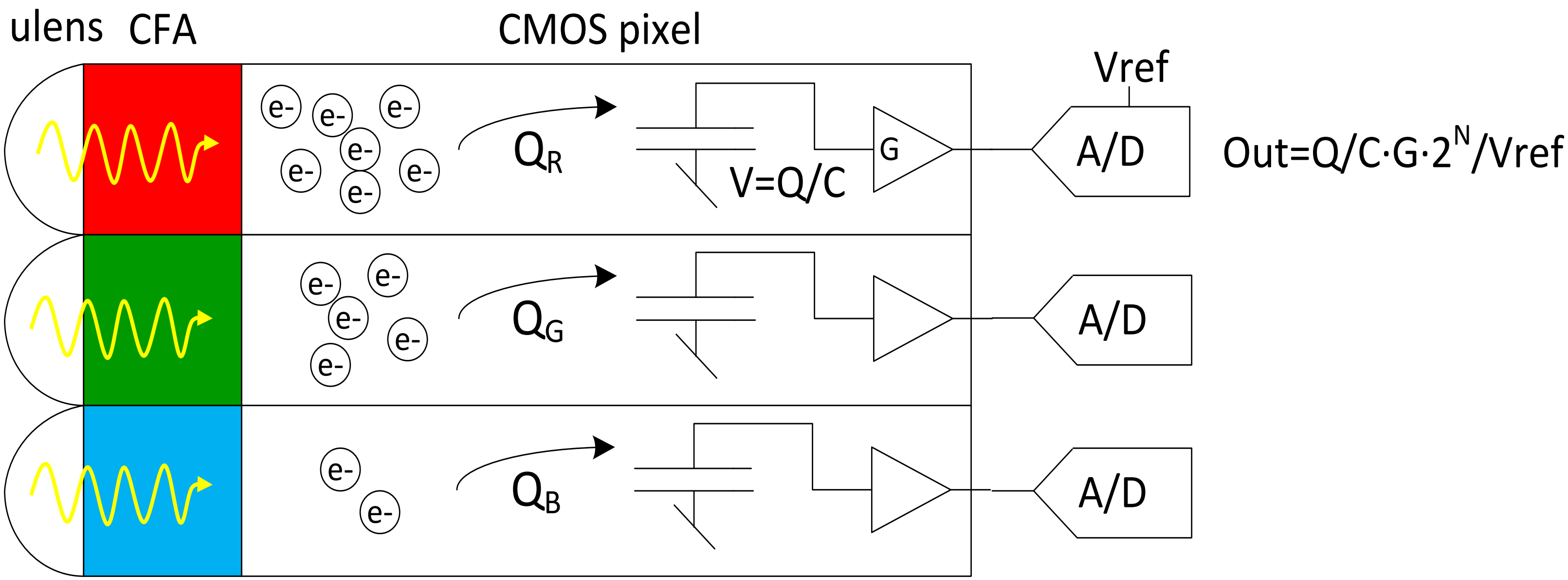
Format (type)	Diagonal (mm)	H (mm)	V (mm)
1	16.0	12.80	9.60
2/3	11.0	8.80	6.60
1/1.8	8.89	7.11	5.33
1/2	8.00	6.40	4.80
1/2.5	7.20	5.76	4.32
1/2.7	6.67	5.33	4.00
1/3	6.00	4.80	3.60
1/3.2	5.63	4.50	3.38
1/4	4.50	3.60	2.70
1/5	3.60	2.88	2.16
1/6	3.00	2.40	1.80

For DSLR

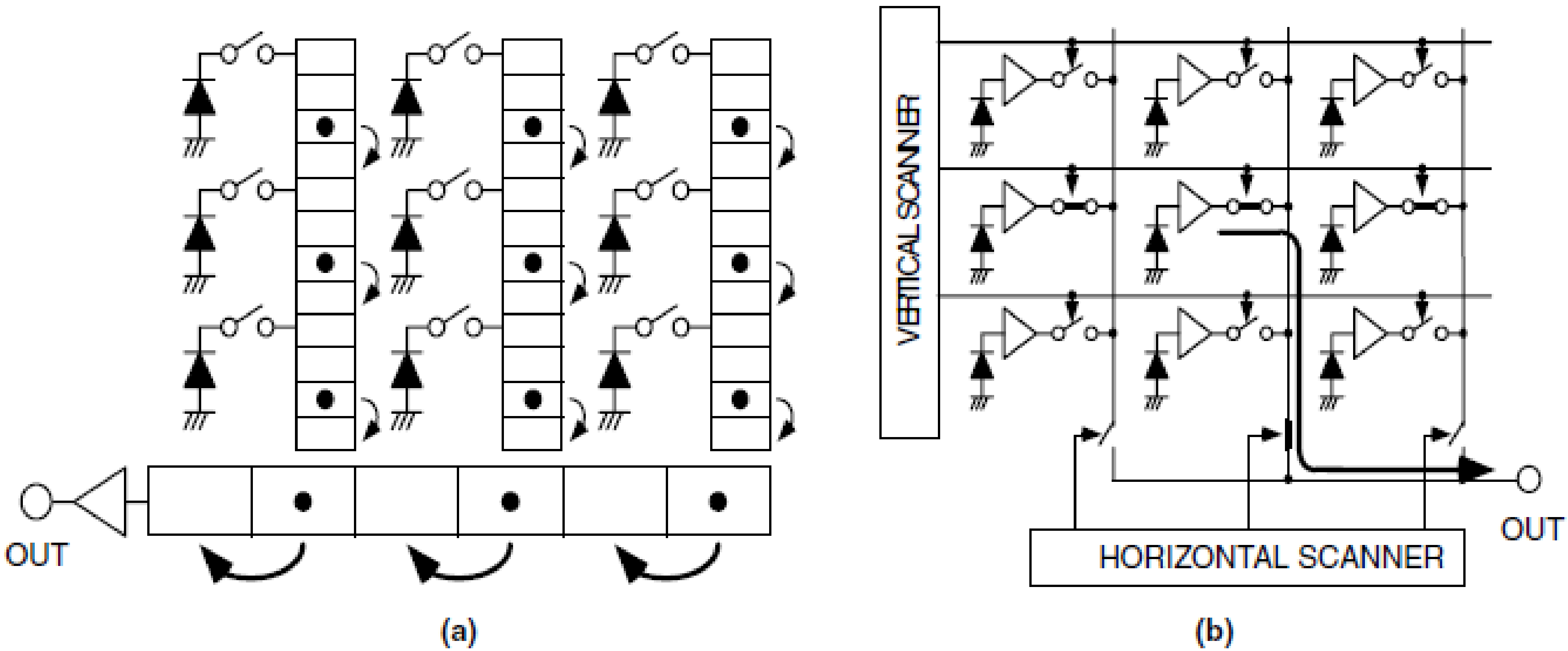
Format	Diagnal (mm)	H (mm)	V (mm)
35 mm	43.27	36.00	24.00
APS-DX	28.37	23.7	15.6
APS-C	27.26	22.7	15.1
APS-H	33.93	28.7	19.1
Four-thirds	21.63	17.3	13.0

Ref: Nakamura, ch-3

From photons to bits conceptually



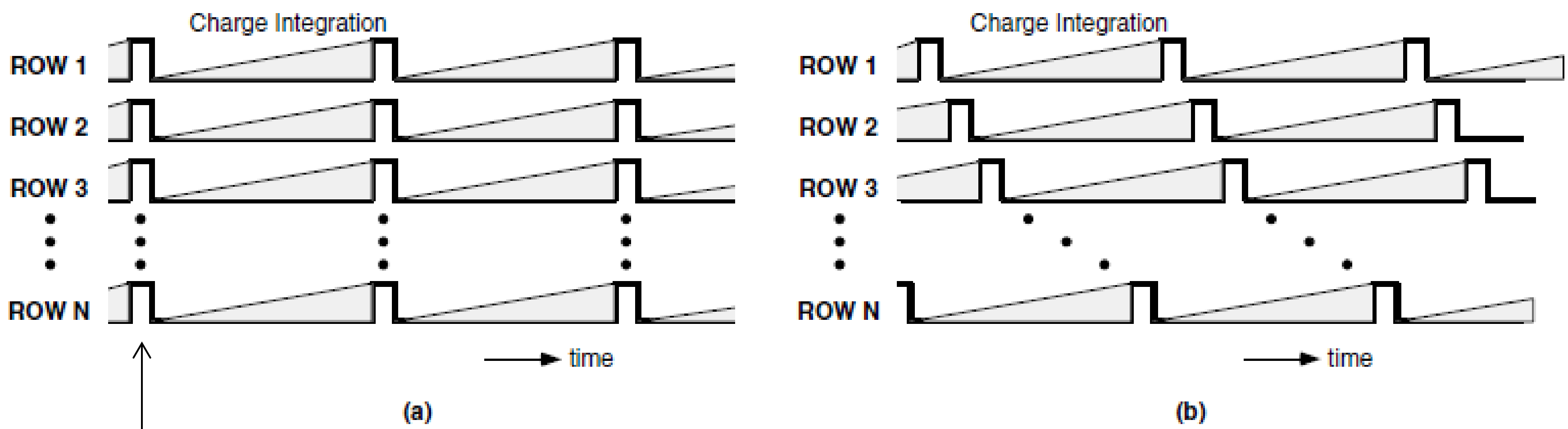
CCD vs CMOS image sensors



CCD CMOS

Ref: J Nakamura, ch-3

CCD vs CMOS capture timing



CCD

CMOS

Global shutter, ie all pixel rows start and stop image capture simultaneously

Rolling shutter, ie fixed time delay between each row

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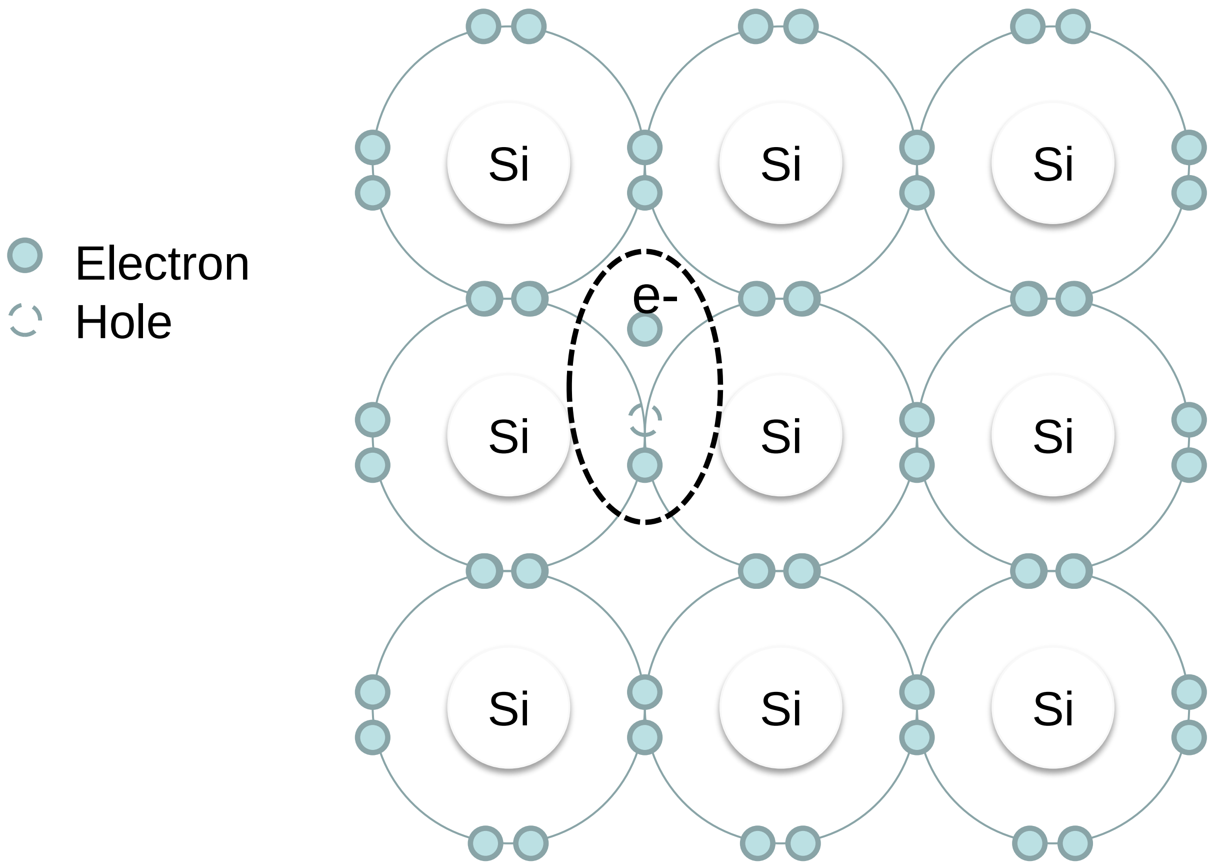
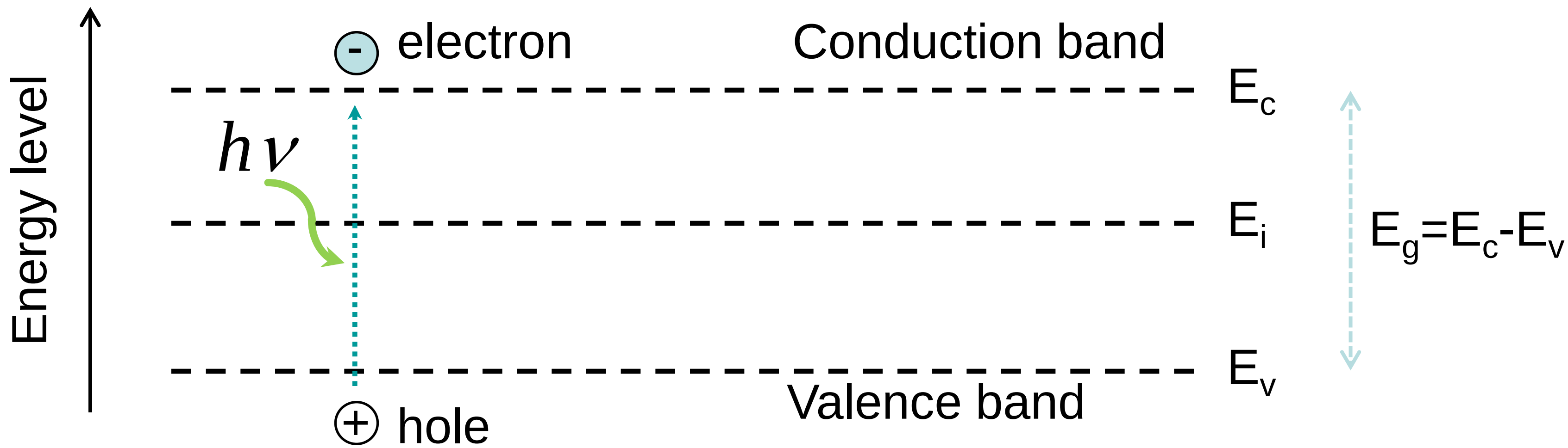
PHOTON DETECTION IN SILICON

Photon absorption in Silicon generates electron-hole pairs



Pixels measure light intensity by absorbing photons. Each detected photon generates an electron-hole pair.

Detection of photons i Silicon (Photoelectric effect)



Photon energy (Joule) : $E = h\nu = h\dfrac{c}{\lambda}$

Condition for detection : $h\nu \geq E_g \Rightarrow \lambda \leq \dfrac{hc}{E_g}$

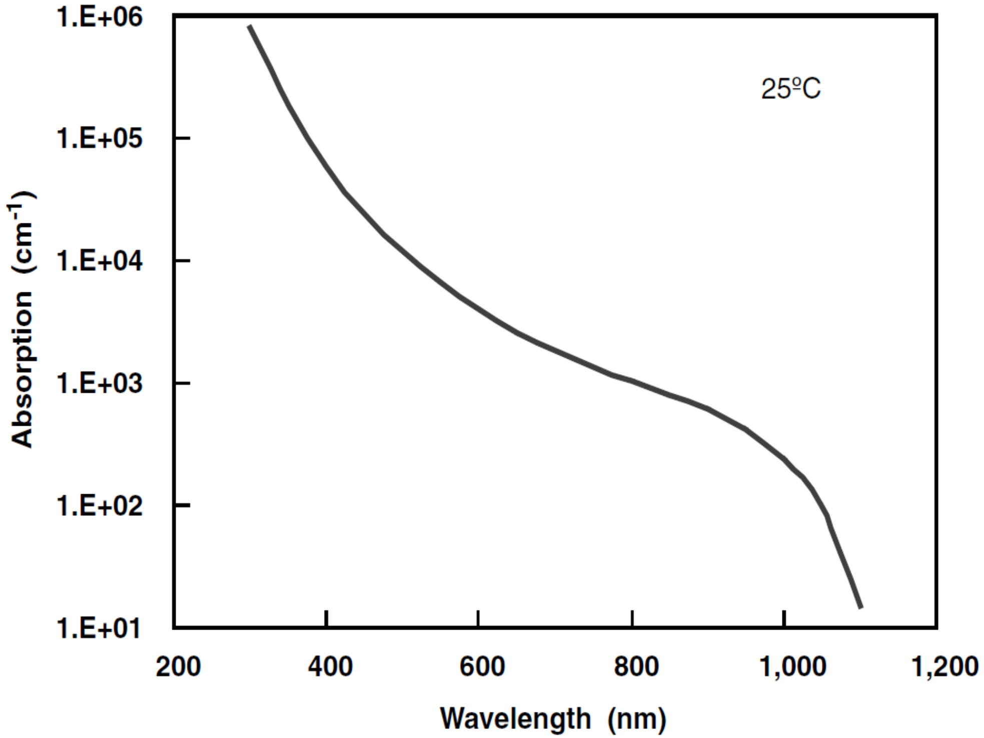
Band-gap in Silicon: $E_g \approx 1{,}8 \cdot 10^{-19}\, J$

Cut-off wavelength in Silicon : $\boxed{\lambda_{cut\text{-}off} \approx 1{,}1 \text{ um}}$

Absorption of light in Silicon

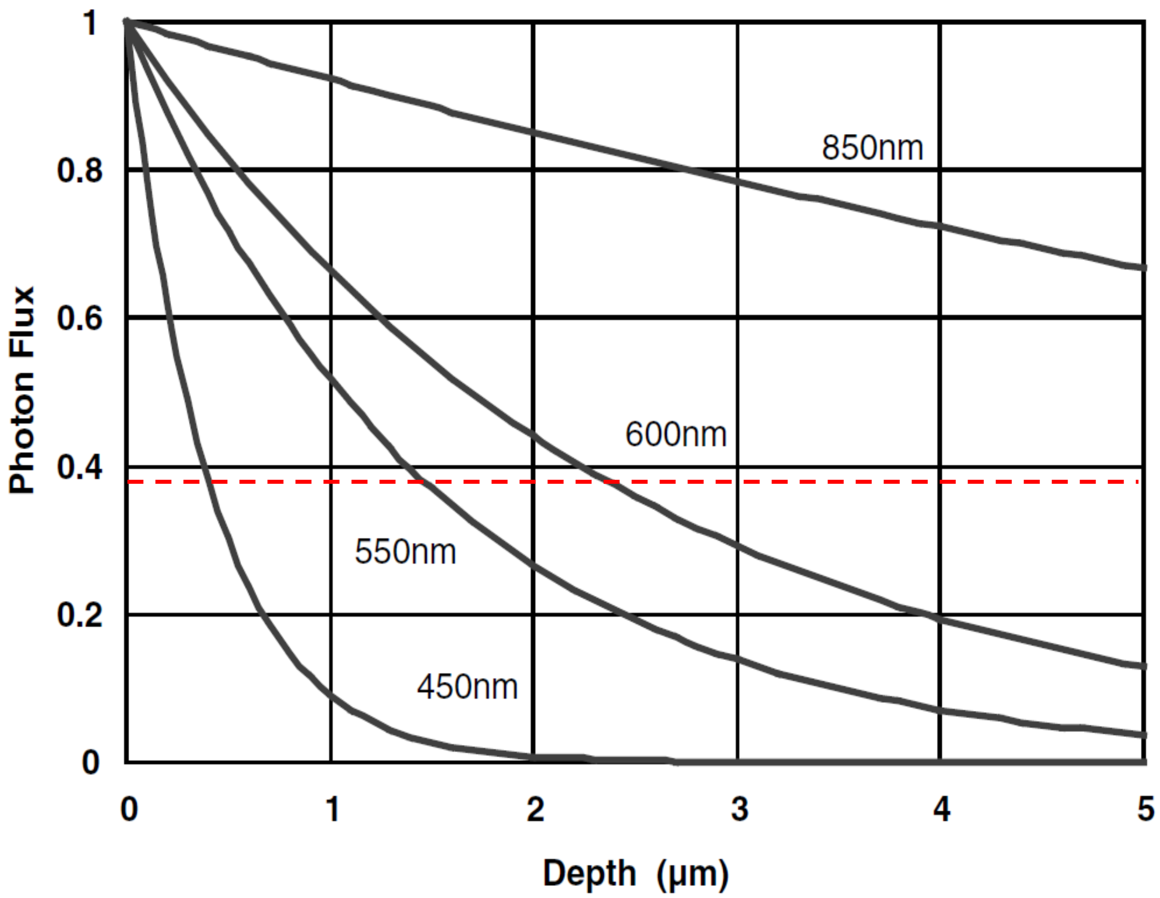
$\Phi(x)$: photon flux, α: absorption coefficient (cm^{-1})
x: distance from silicon surface (cm)

$$\Phi(x) = \Phi_0 exp(-\alpha x)$$



Ref: J Nakamura, ch-3

Absorption of light in Silicon (intensity versus depth)



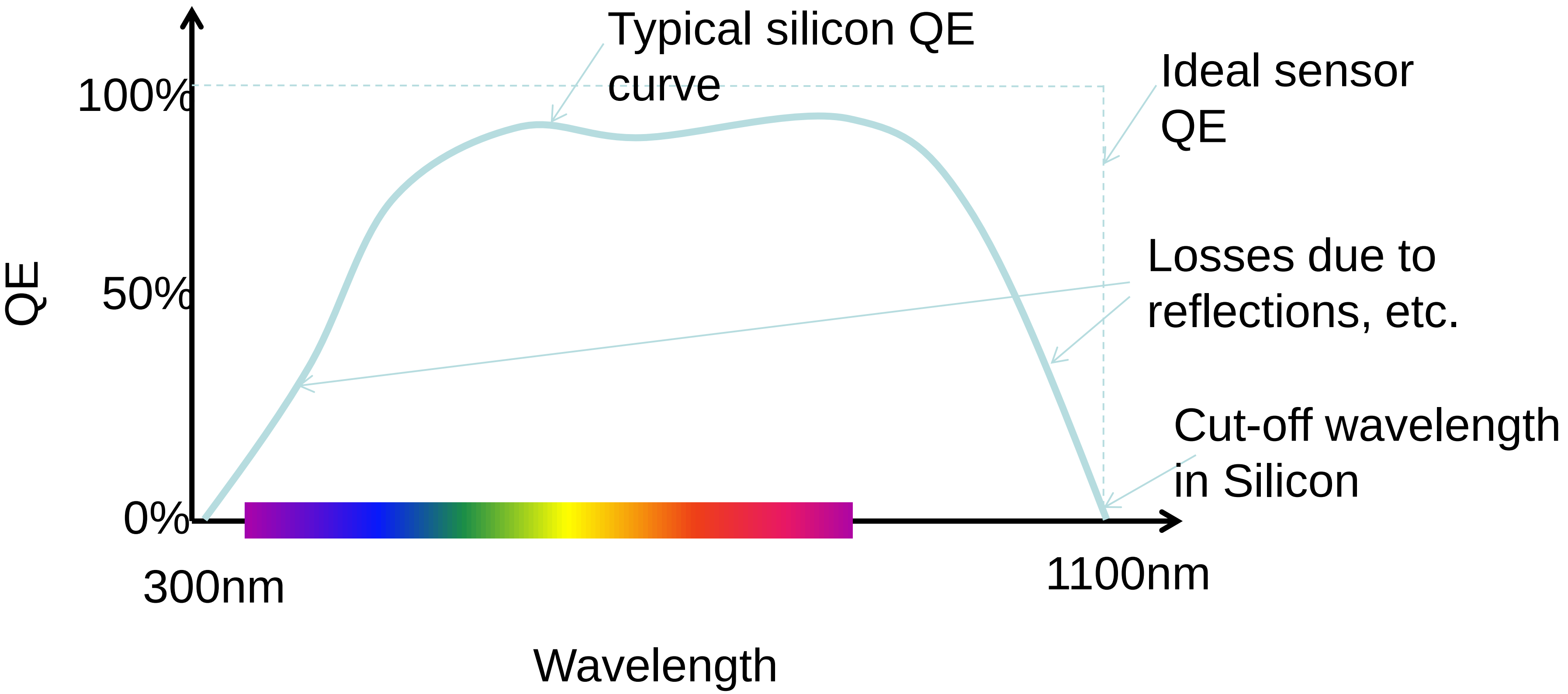
$\Theta(1/a) = 1/e$

Light penetration depth, $1/\alpha$

Ref: J Nakamura, ch-3

Quantum efficiency (QE)

QE = likelihood of detecting a photon



More referenses

- Books
  - Physics of Semiconductor Devices by Simon M. Sze and Kwok K. Ng (Oct 27, 2006)
  - Solid-State Imaging with Charge-Coupled Devices (Solid-State Science and Technology Library) by Albert J. P. Theuwissen (Mar 31, 1995)

- Internet
  - Wikipedia
  - http://pveducation.org/pvcdrom/pn-junction/conduction-in-semiconductors

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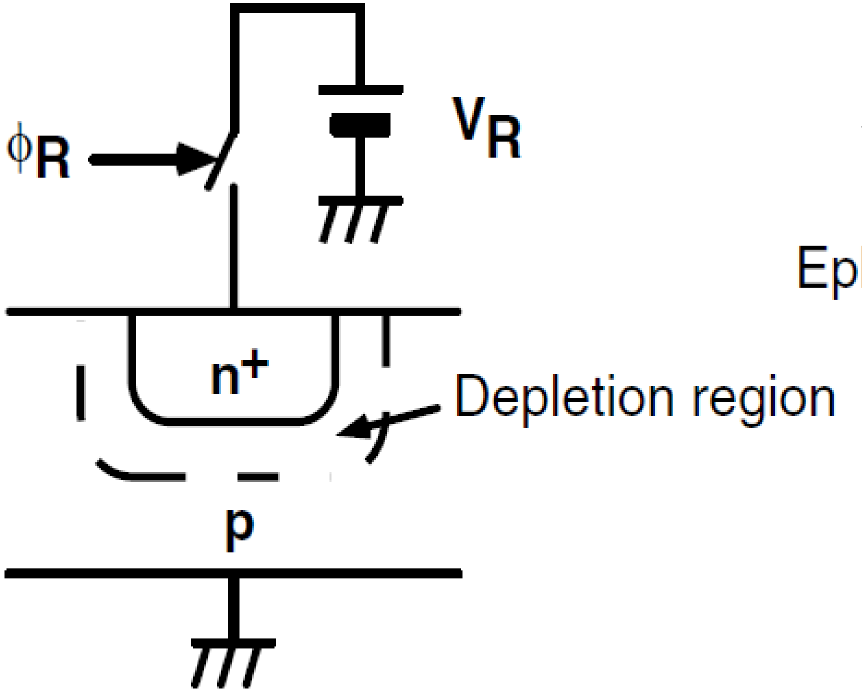
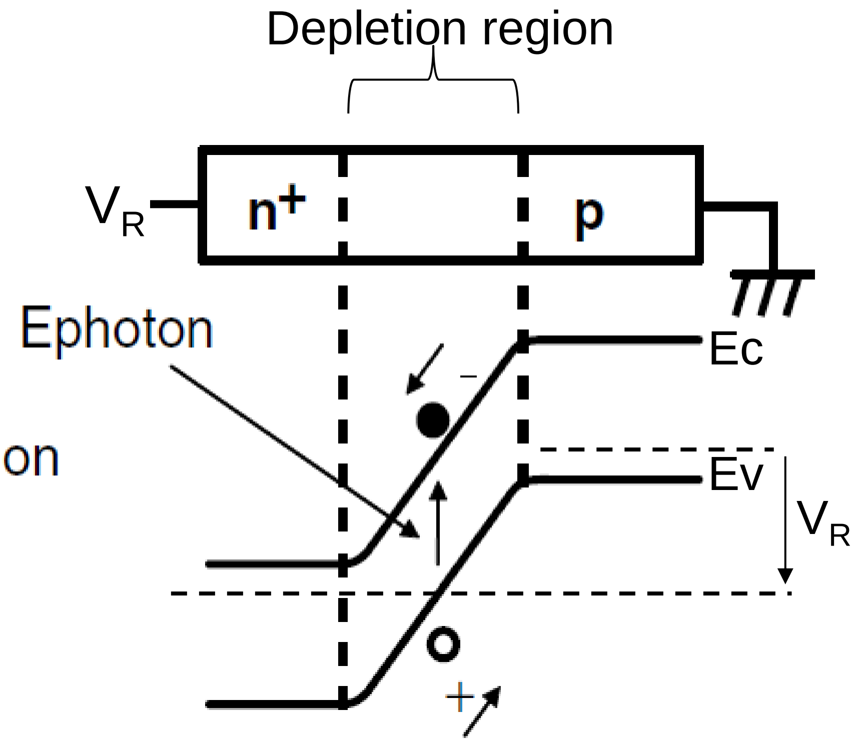
PHOTODIODE STRUCTURE AND PIXEL CIRCUITS

Light detection in reverse biased photodiode

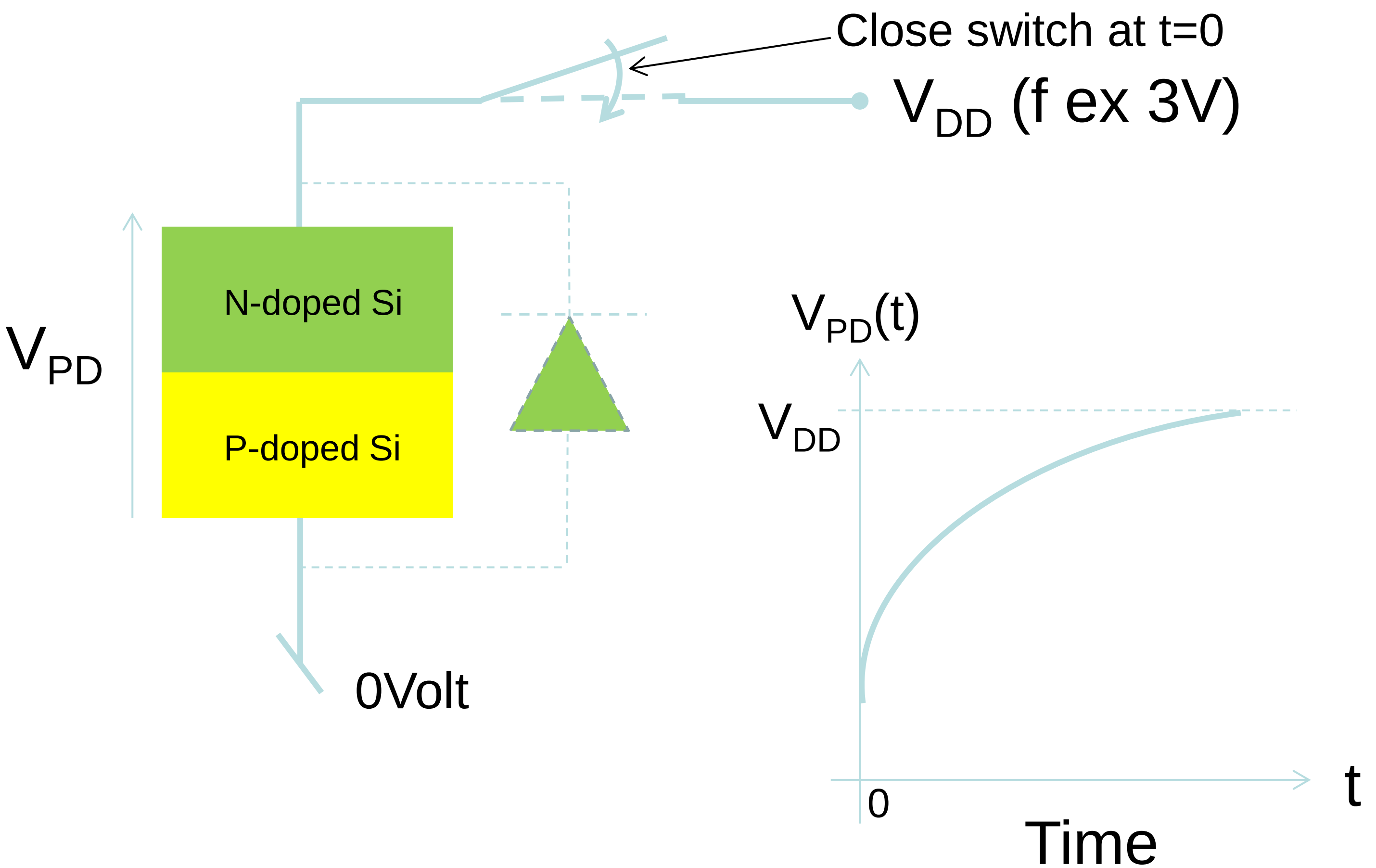




Ref: Nakamura et al

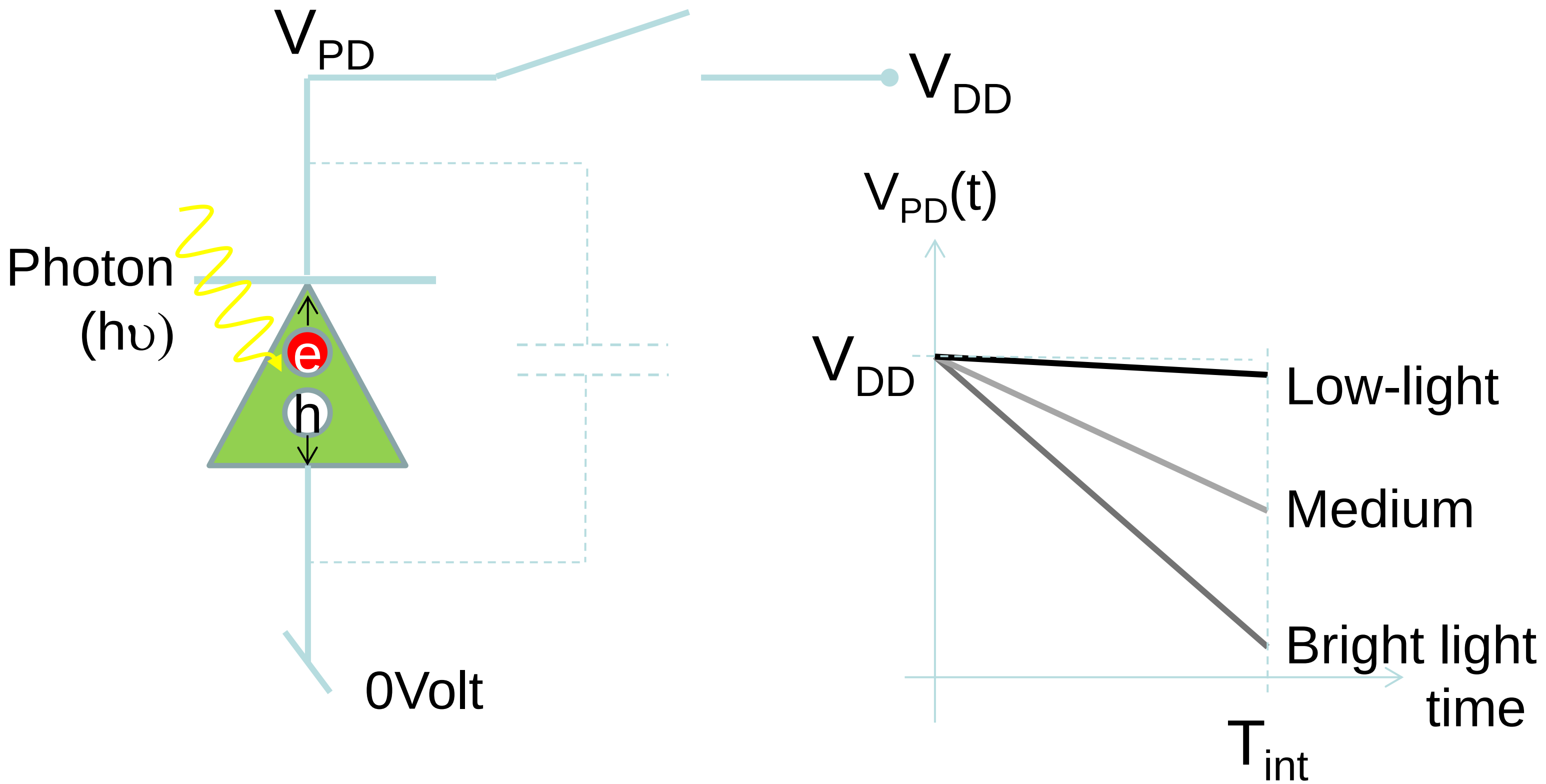
Photodiode detection principle (1/3)

Step-1: Reset diode (remove old signal) by connecting it to power supply (VDD)



Photodiode detection principle (2/3)

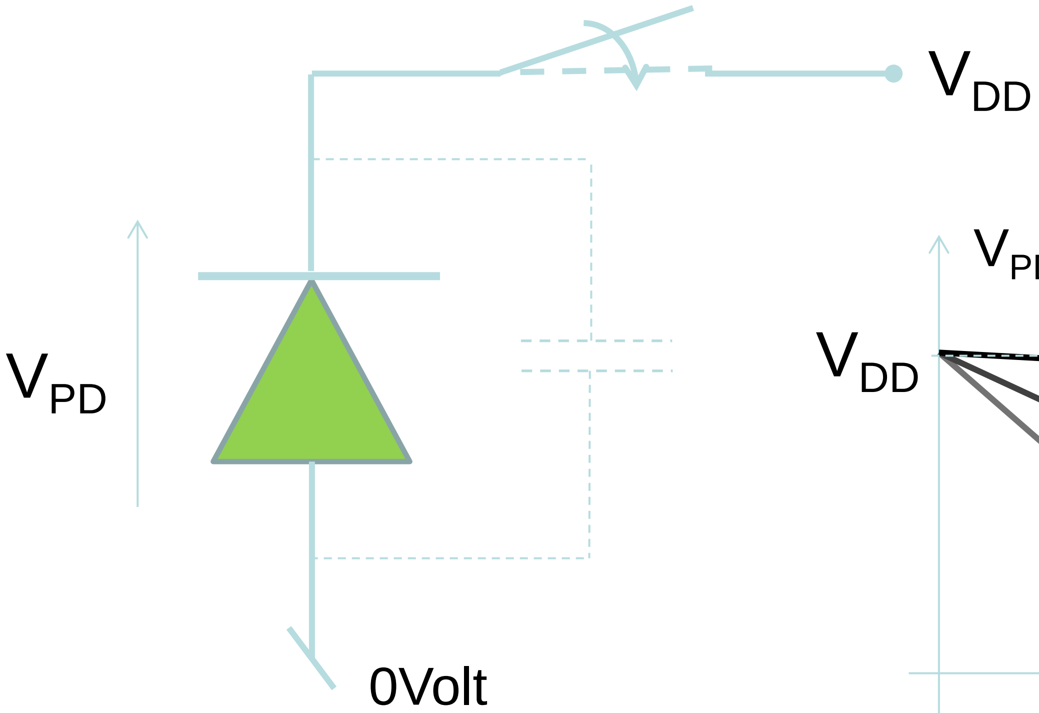
Step-2: Accumulate signal during exposure time (T_{int} f ex 10ms)

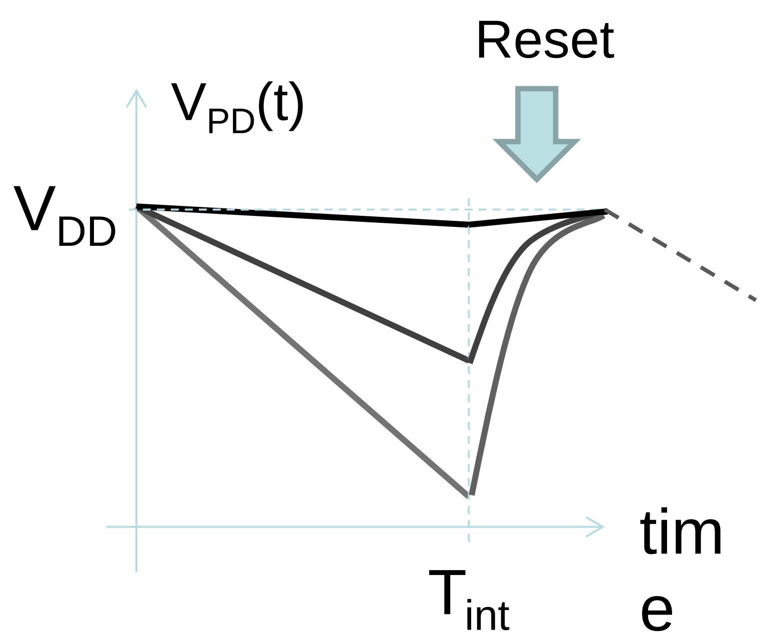


$$\Delta V_{PD} = V_{DD} - V_{PD}(T_{\text{int}})$$

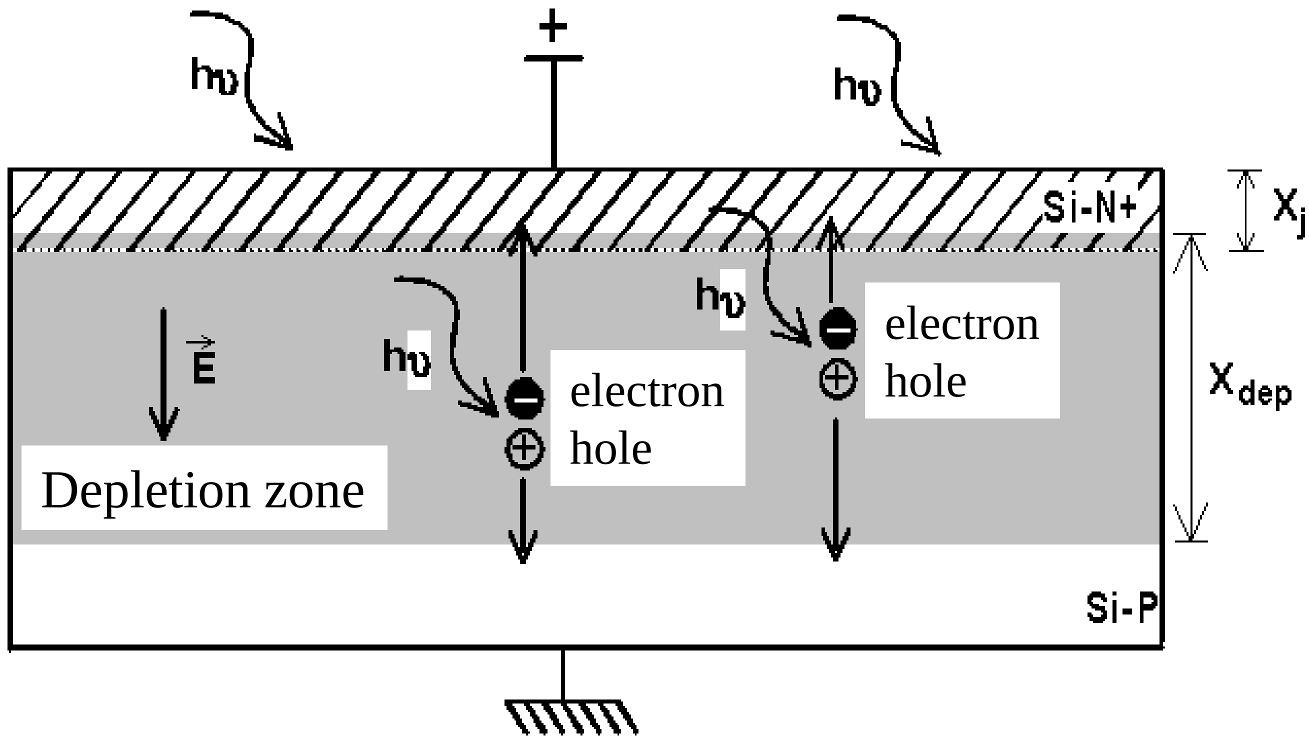
Photodiode detection principle (3/3)

Step-3: Sample output, then reset and start new exposure

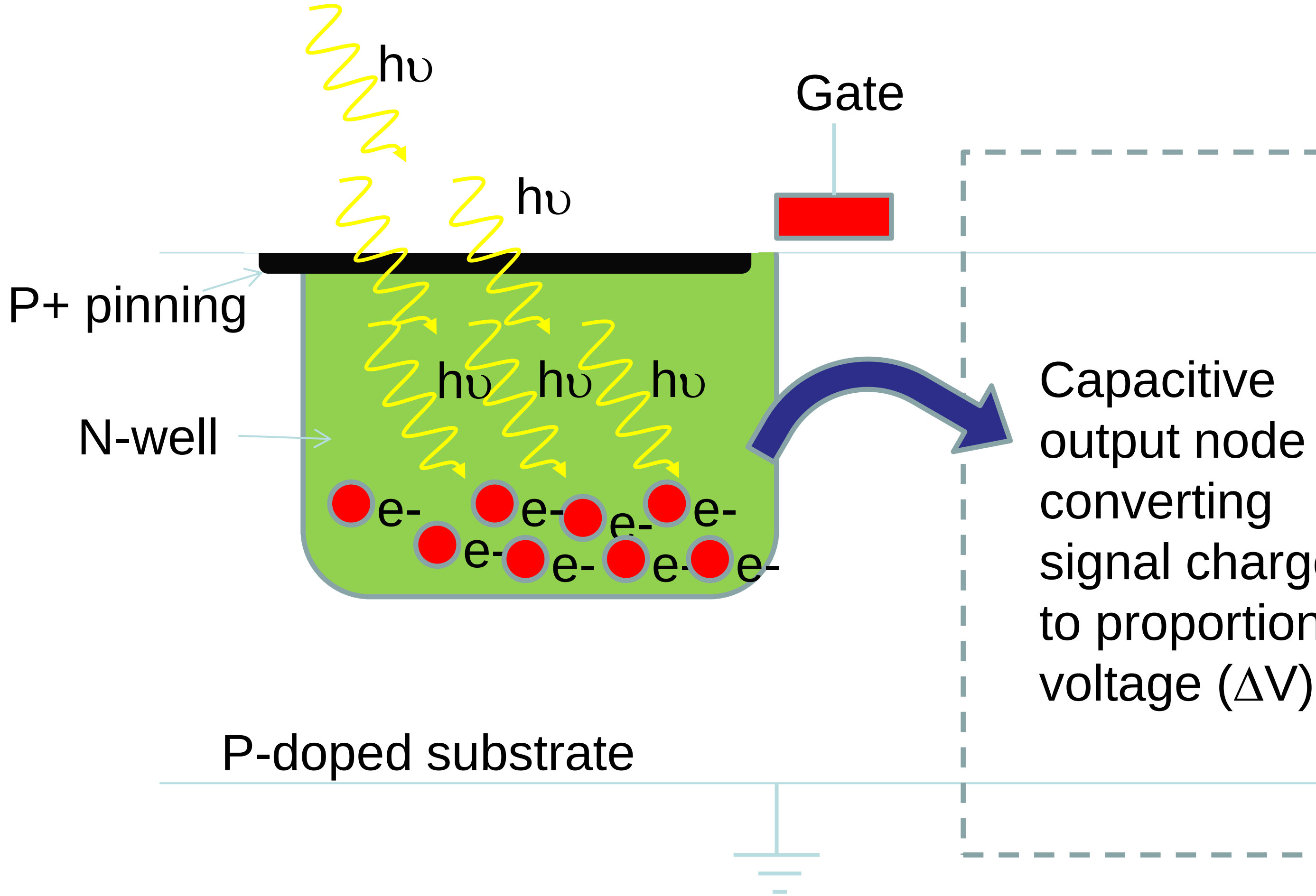




Photodiode detection principle

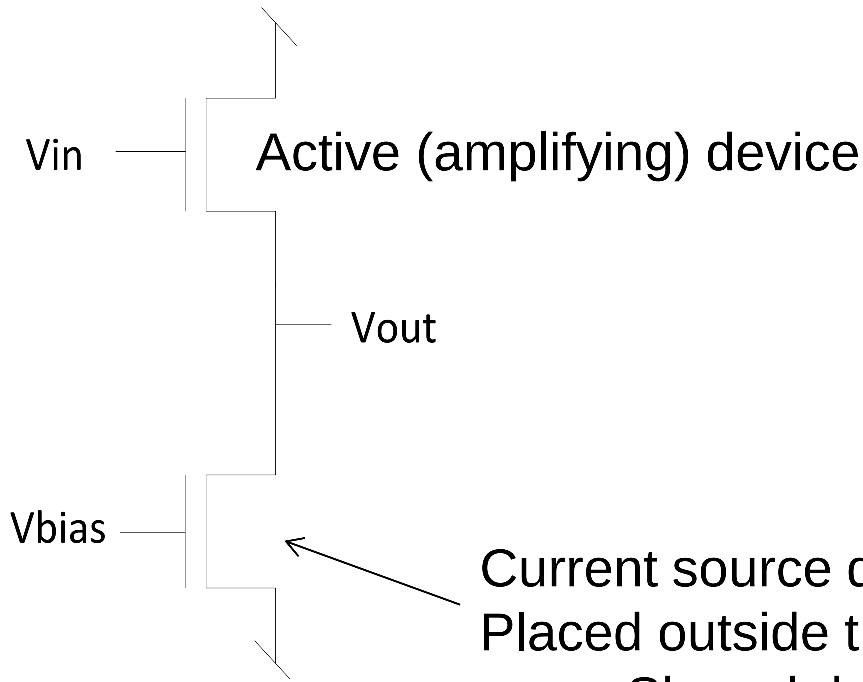


Pinned photodiode structure



Capacitive output node converting signal charge to proportional voltage (ΔV)

NMOS source follower circuit used in CMOS active pixel sensors



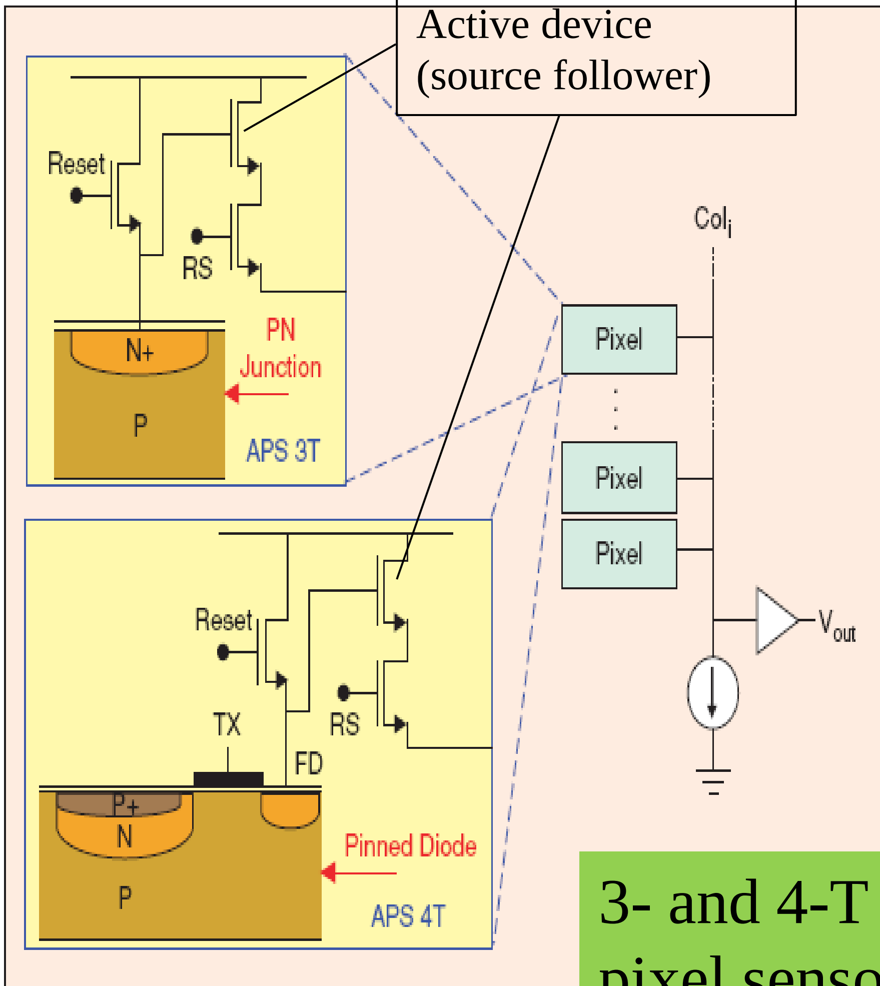
Current source device. Placed outside the pixel array. Shared device used by every pixel in the same column.

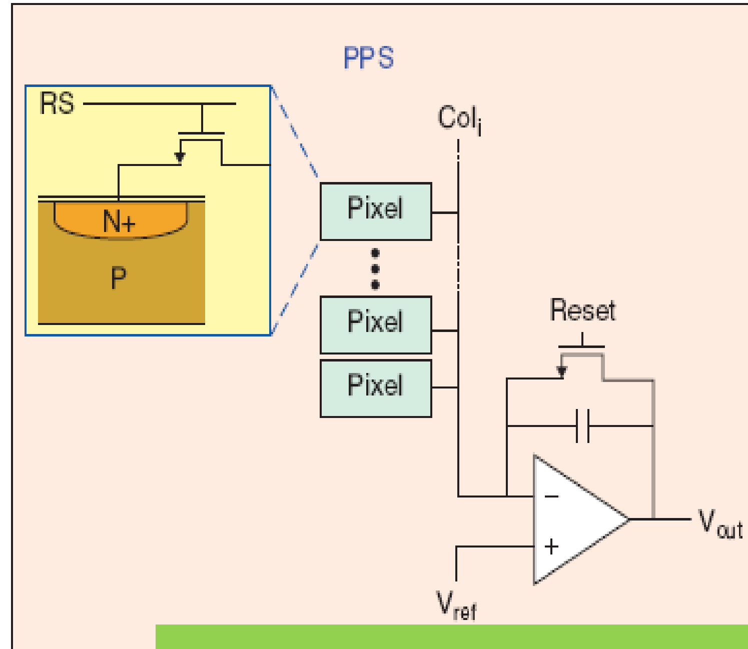
Gain equation:

$$\frac{\Delta V_{out}}{\Delta V_{in}} = \frac{g_m/g_d}{1 + g_m/g_d} \approx 0.8$$

Pixel Circuits

Active device
(source follower)





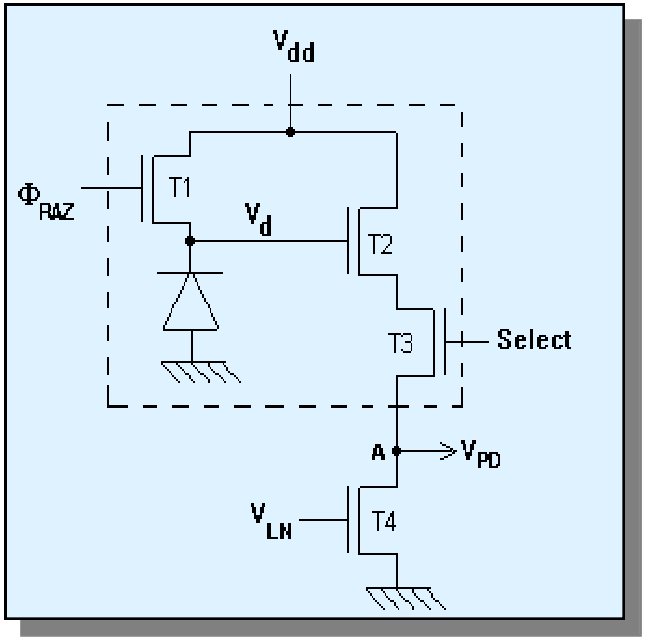
1-T Passive Pixel Sensor

3- and 4-T active pixel sensor.

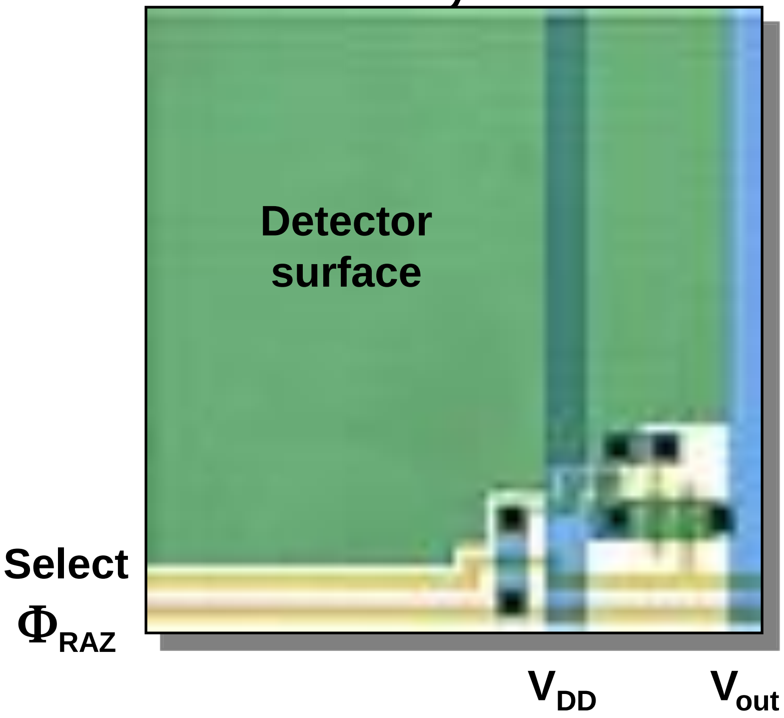
Ref: A.E.Gamal, et al. “CMOS Image Sensors”, IEEE Circuits and Device Magazine, May. 2005

3T Active Pixel Structure

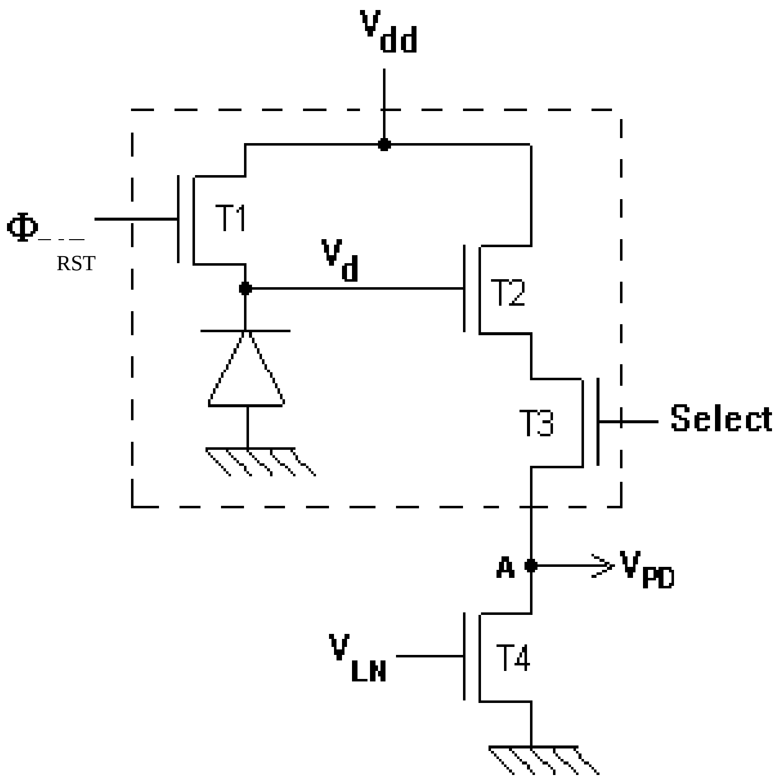
Schematics

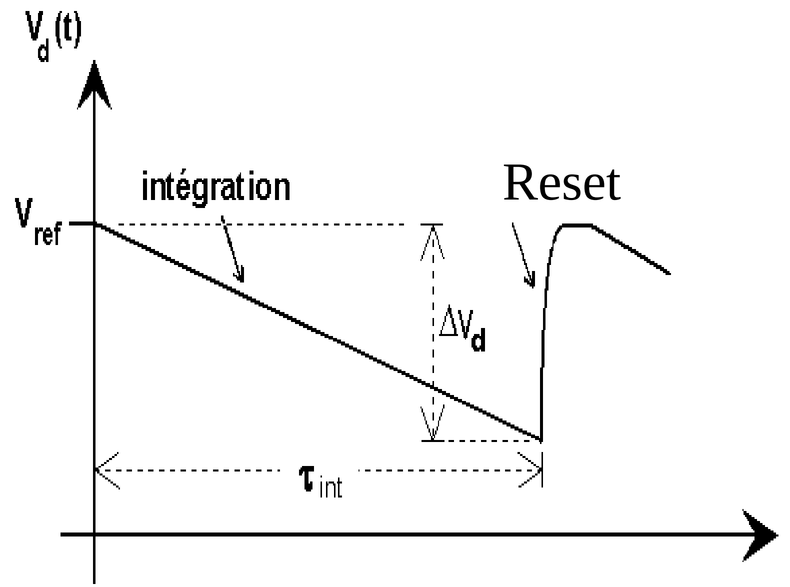


Layout



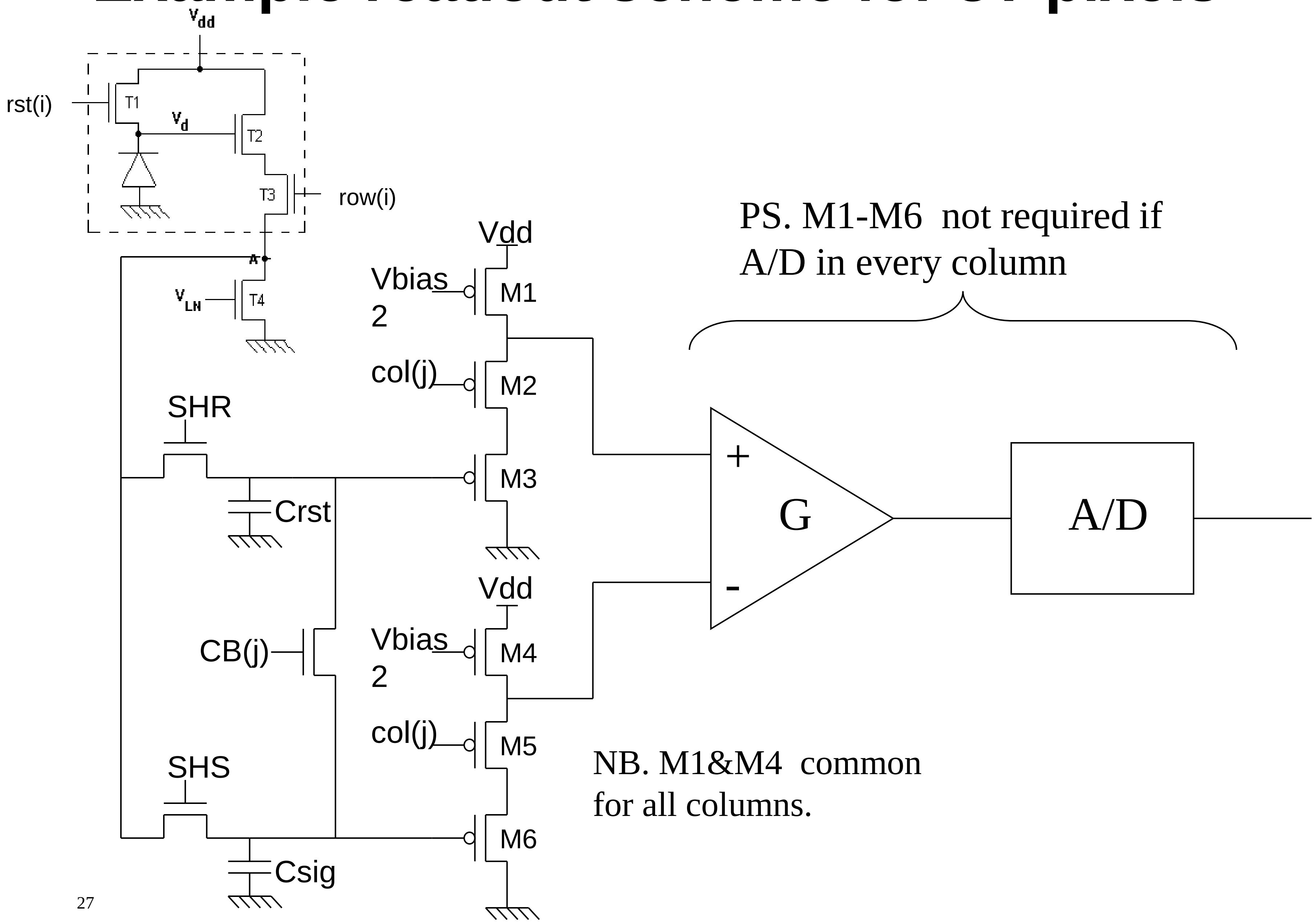
3T active pixel





$$V_d(t) = V_{ref} - \frac{1}{C_d} \cdot \int_0^t I_{phot}(u) \cdot du$$

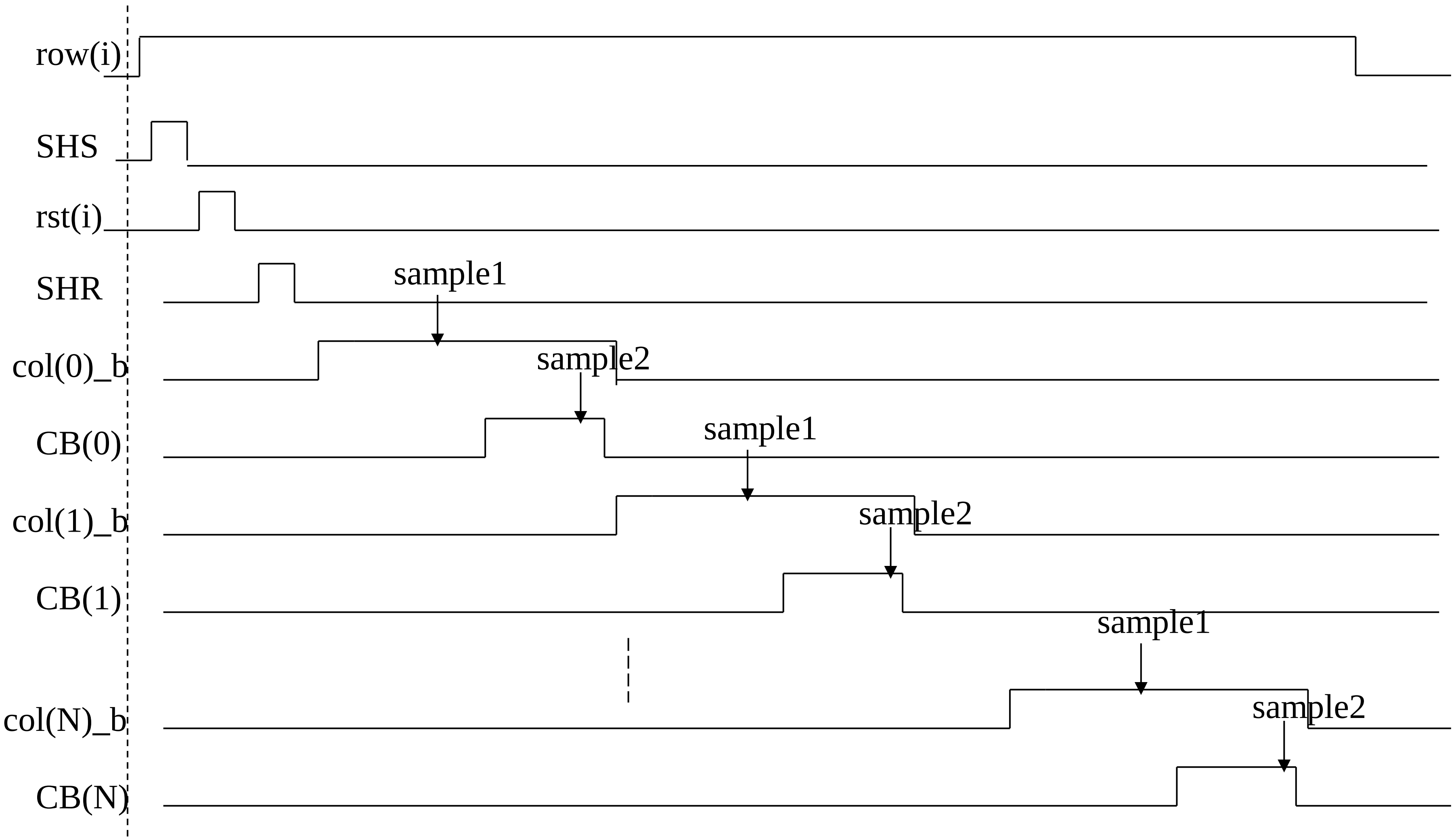
Example readout scheme for 3T pixels



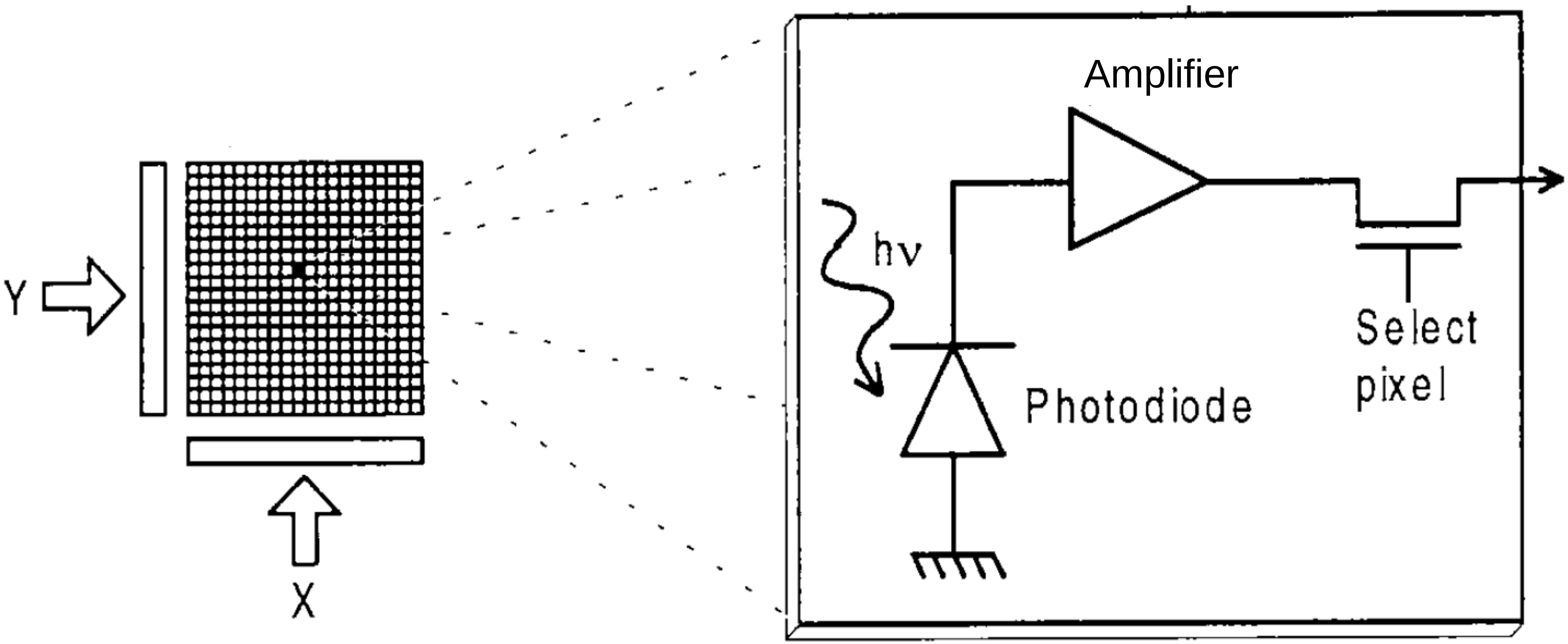
PS. M1-M6 not required if A/D in every column

NB. M1&M4 common for all columns.

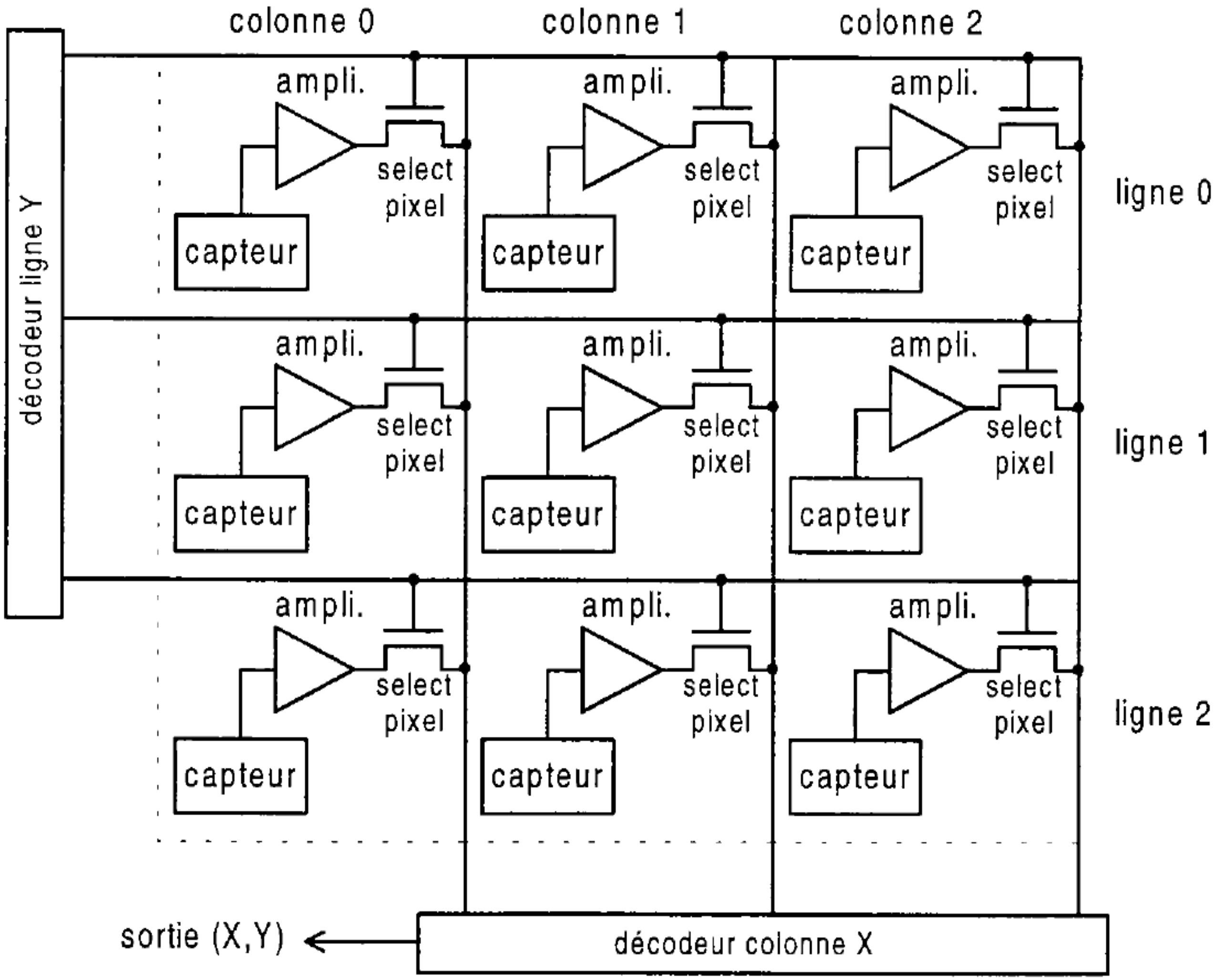
Timing diagram for 3T row readout



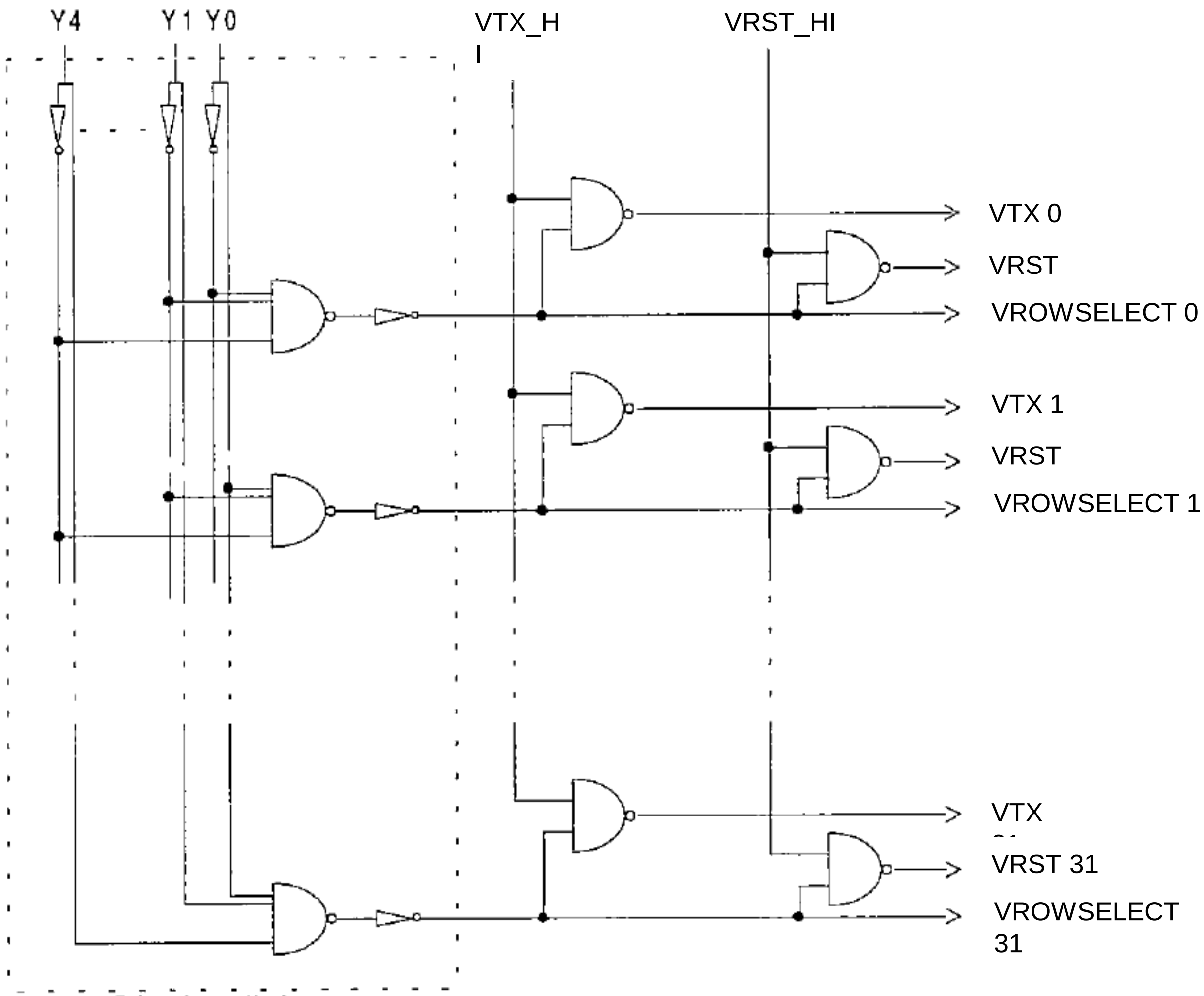
CMOS Active Pixel Sensor



CMOS Active Pixel Sensor

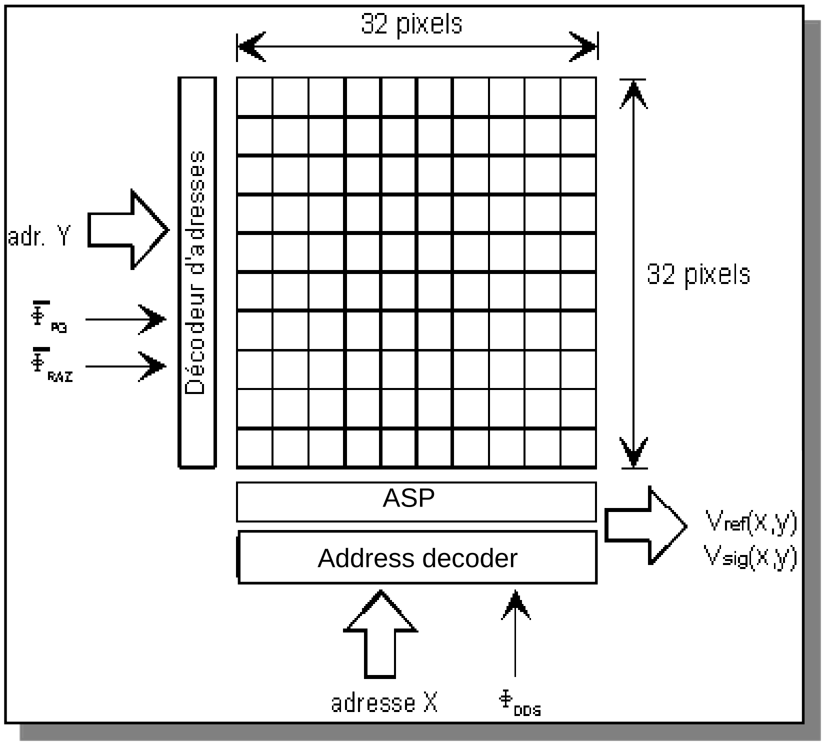


Row decoder circuit

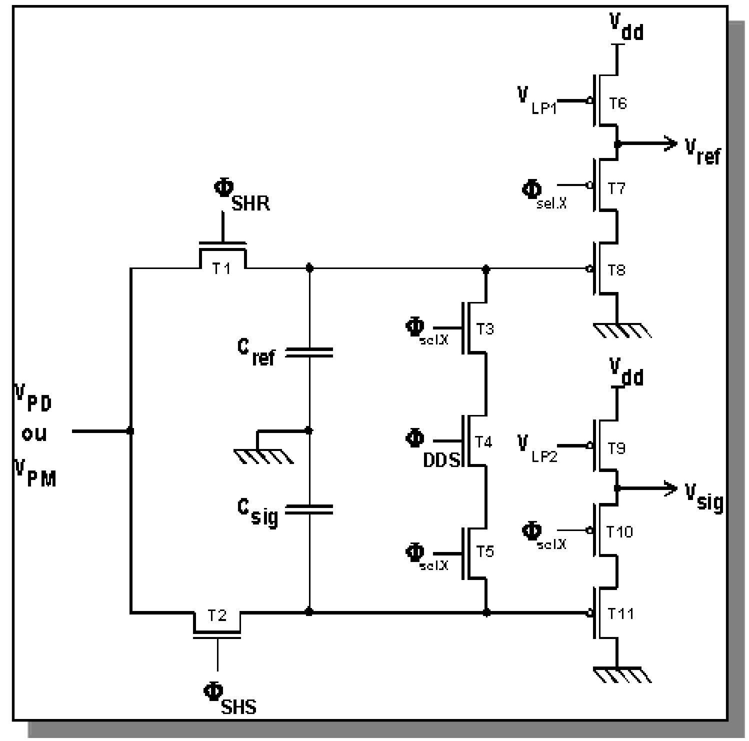


APS Detector Organization

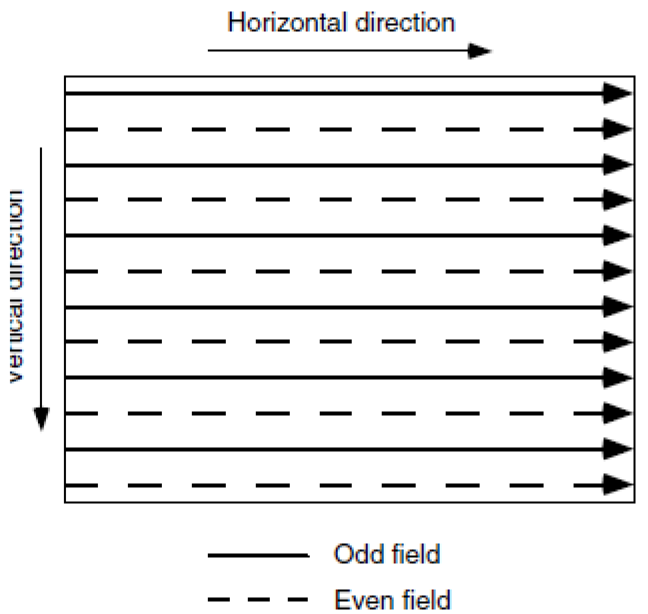
Image sensor



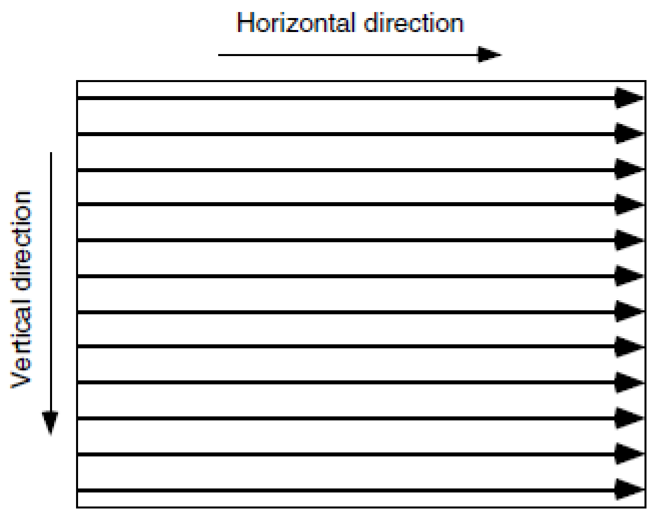
ASP+Address decoder



Interlaced scan versus progressive scan



(a)



(b)

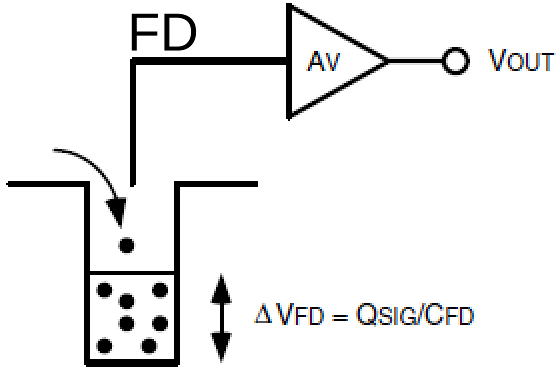
Interlaced scan
(output even and odd fields sequentially, ie trade off vertical resolution against bandwidth and power)

Progressive scan
(output every pixel row in every frame for maximum resolution)

Ref: J Nakamura, ch-3

Conversion gain

Charge detection scheme:



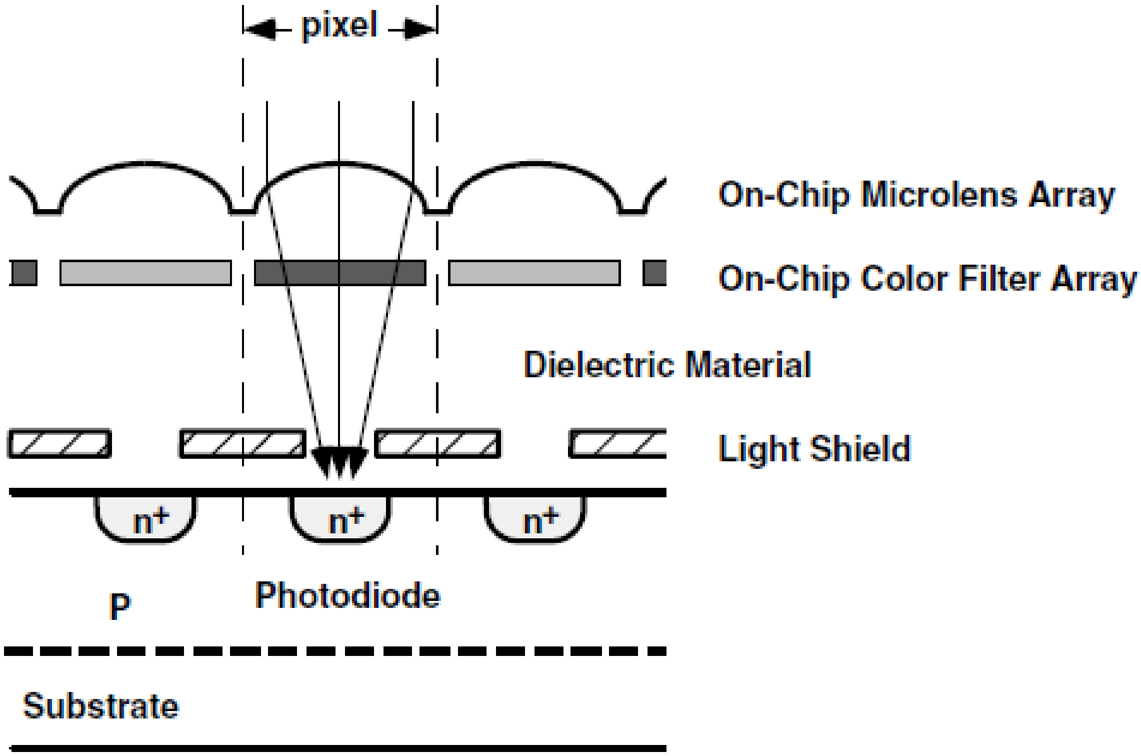
Conversion gain: $$C.G. = \frac{q}{C_{FD}} \quad [\mu V/\text{electron}]$$

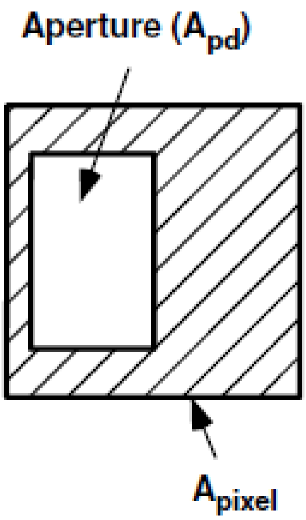
$q = 1.6 \times 10^{-19}$ C
C_{FD} = floating diffusion capacitance

Voltage swing at FD node: $\Delta V_{FD} = CG\ S_{electrons}$

Ref: J Nakamura, ch-3

Photodiode in a pixel

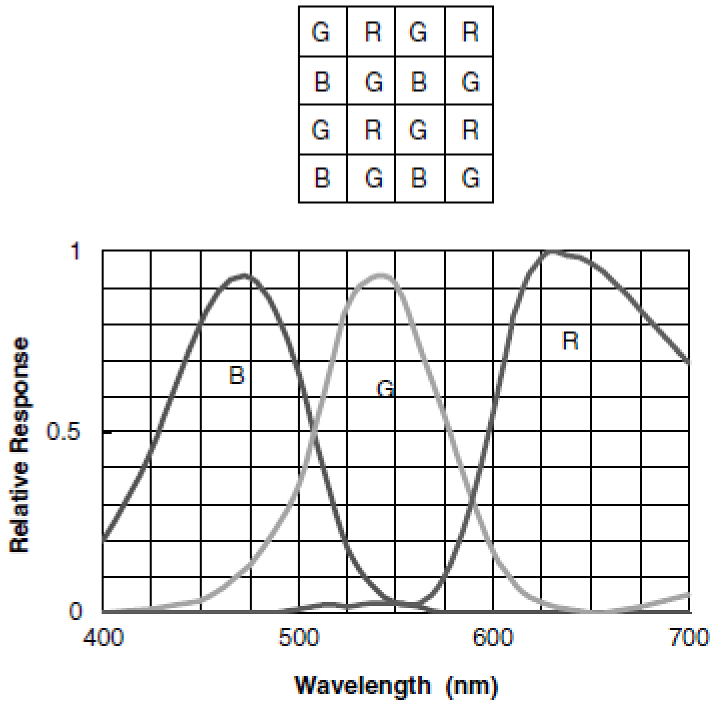




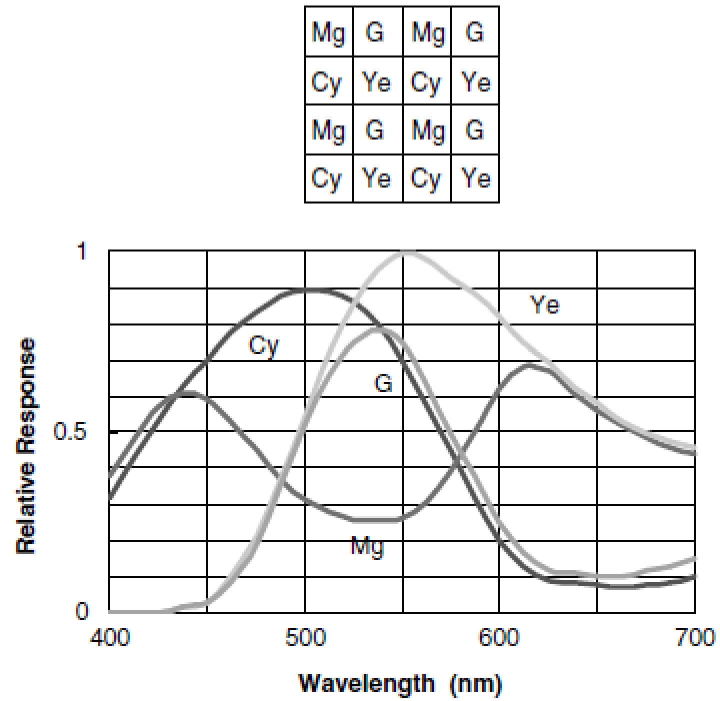
$$\text{Fill factor} = (A_{pd} / A_{pix}) \times 100 \quad [\%]$$

Ref: J Nakamura, ch-3

Bayer CFA versus CMY CFA



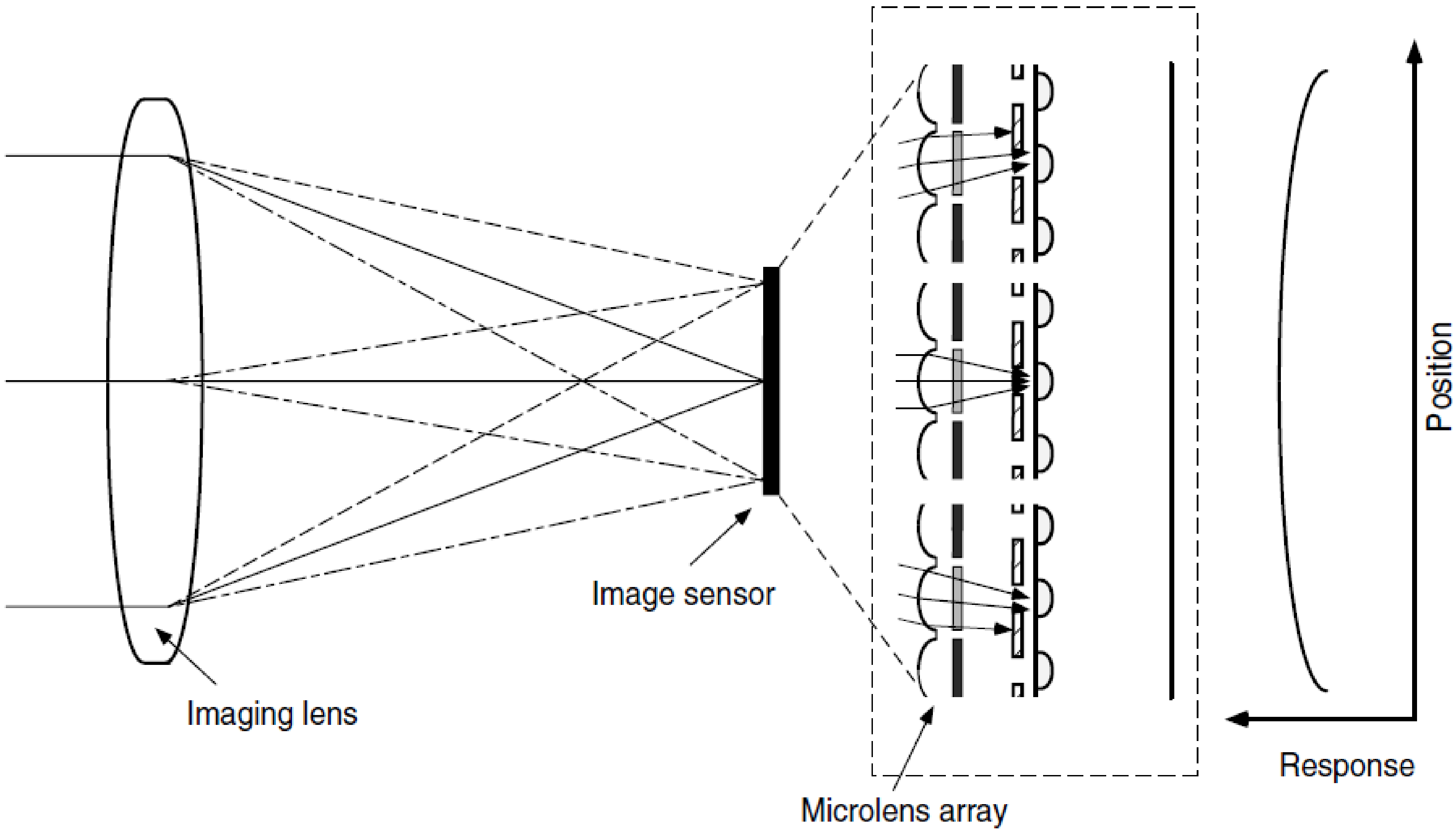
Bayer CFA



Complimentary CFA

Ref: J Nakamura, ch-3

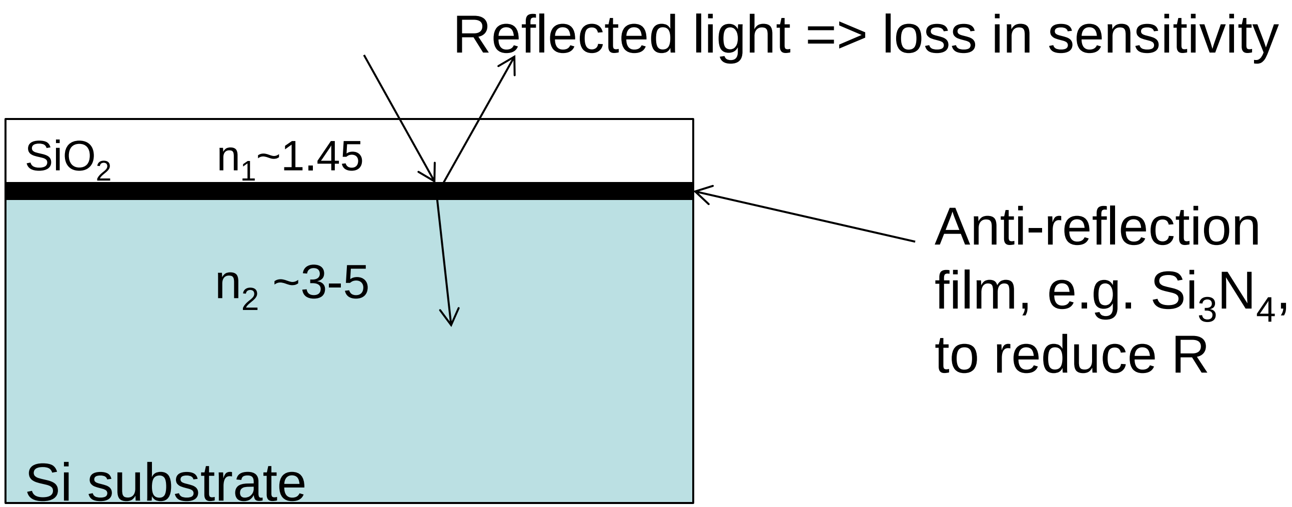
Shading caused by incident light angle



Sensors with pixels <2.8um can have different shading curve for R, G, and B. In which case a 3-channel compensation scheme is utilized before color interpolation.

Ref: J Nakamura, ch-3

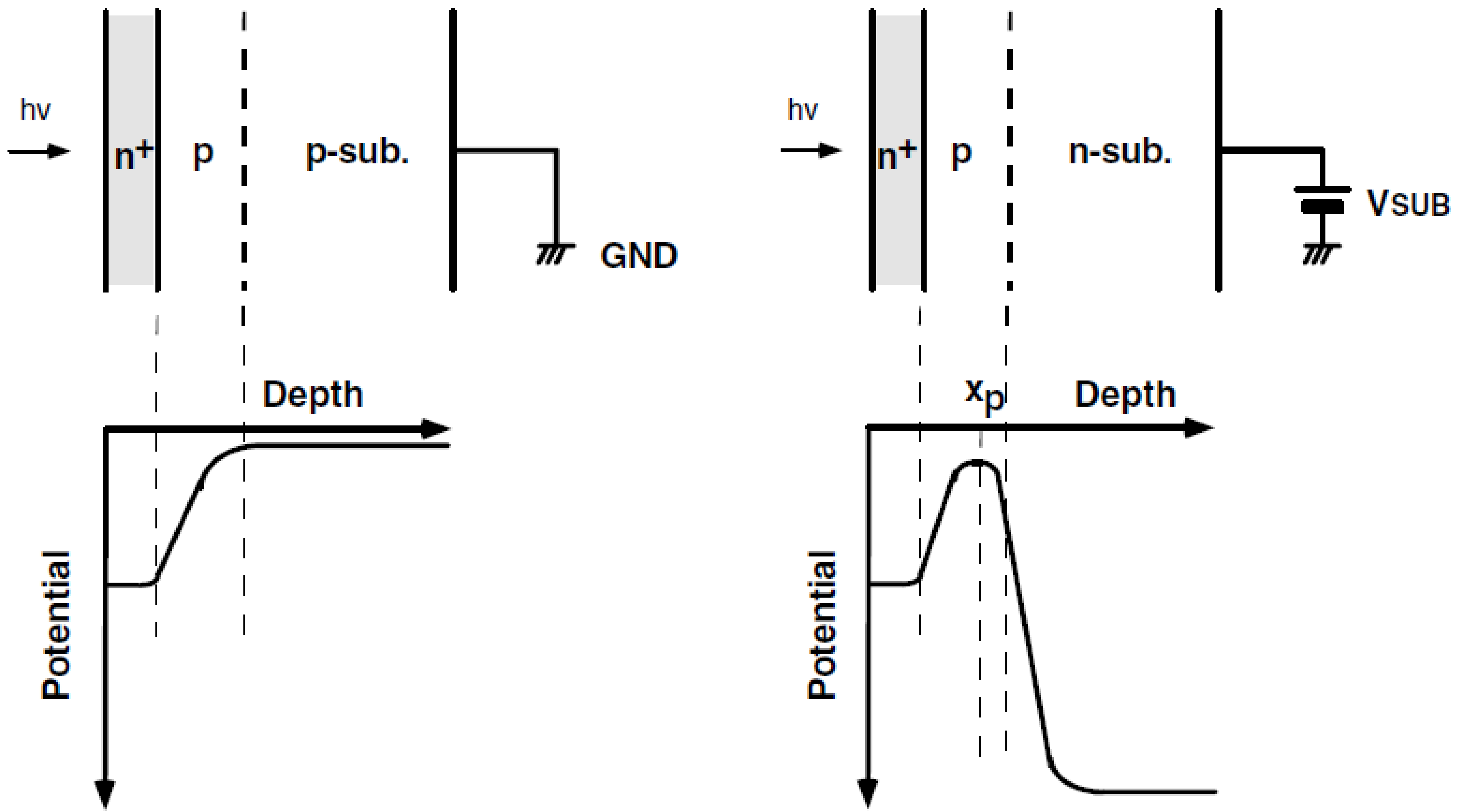
Reflection at the SiO_2/Si interface



For perpendicular light: $R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$ ⇒ Anti-reflection coating reduce the refractive index deltas at the interfaces

Ref: J Nakamura, ch-3

NP photodiode on p-sub (CIS) vs n-sub (CCD)



Ref: J Nakamura, ch-3

Photodiode full well capacity (FWC)

- Maximum number of electrons that can be stored in the pixel
- Sometimes called pixel saturation level

$$N_{sat} = \frac{1}{q} \int_{V_{reset}}^{V_{\max}} C_{PD}(V) \cdot dV \quad \text{[electrons]}$$

C_{PD} = photodiode capacitance (F)
V_{reset} = photodiode reset level (V)
V_{max} = photodiode voltage when potential well is filled (V)

Ref: J Nakamura, ch-3