MICRO-523: Optical Detectors

Week Six: CCD cameras (Solutions Ex6)

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EPFL

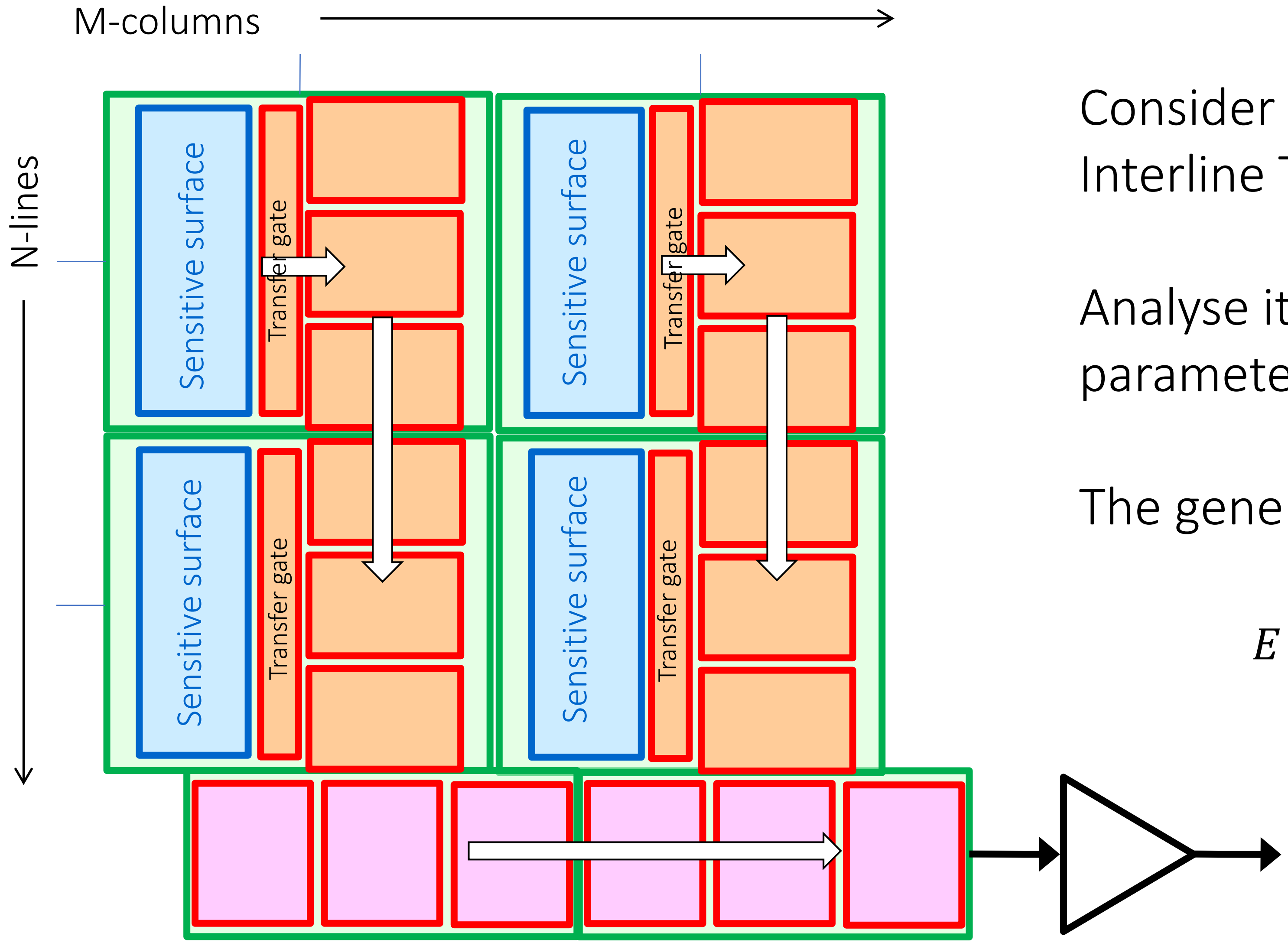
Outline

6.1 Consumption of CCDs

6.2 Fill factor

6.3 Charge transfer efficiency

Exercise 6.1: Consumption of CCDs



Consider a CCD camera with Interline Transfer.

Analyse its consumption using the parameters given below.

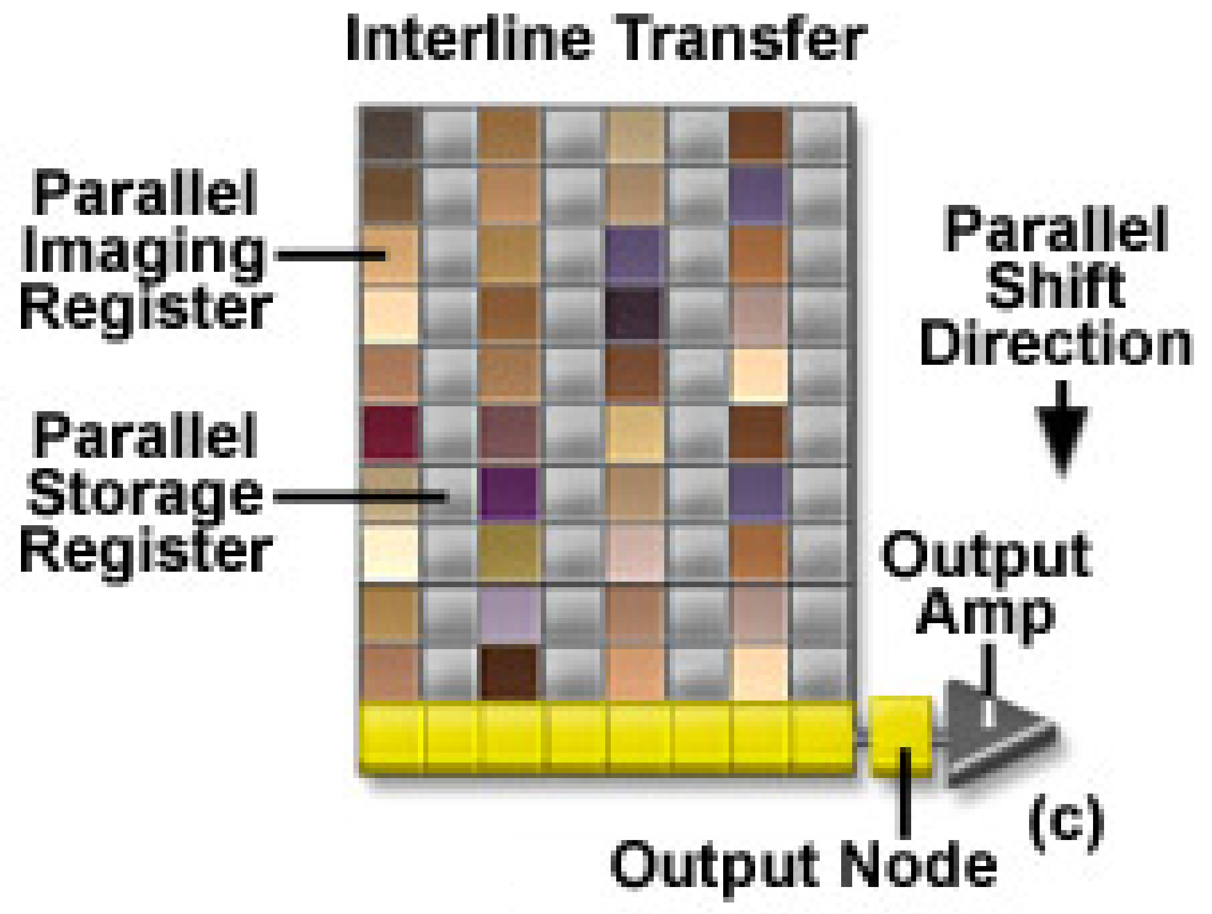
The generic formula for energy is:

$$E = \frac{1}{2} C V^2$$

Exercise 6.1: Data

N = 1000 lines, M = 1000 columns	(1Mpix camera)
Photosensitive capacity:	C_1=30 fF
3 CCD cells per pixel for vertical registers, as well as for horizontal output register.	
Capacity of cell in vertical and horizontal readout registers	C_0=10fF.
Voltage to create the wells	V=10V
Frame rate:	r = 25 images / s

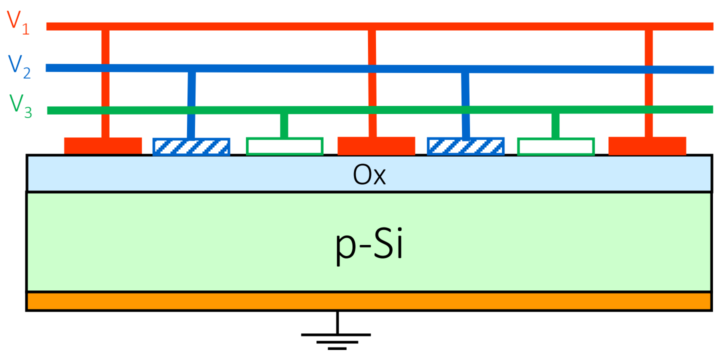
Exercise 6.1: Interline transfer



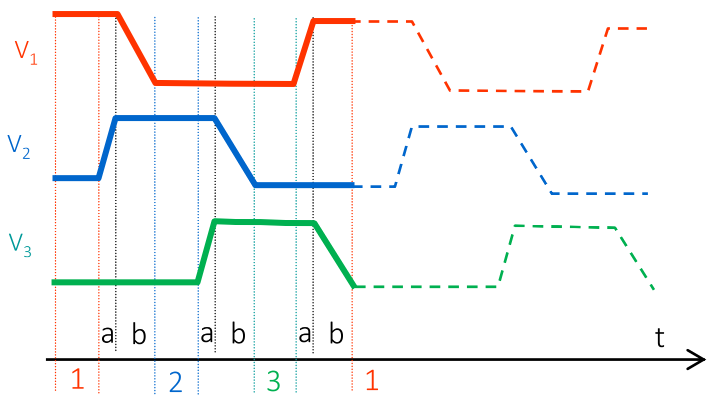
- http://micro.magnet.fsu.edu/primer/java/digitalimaging/ccd/interline/index.html

Exercise 6.1: CCD register: Charge transfer

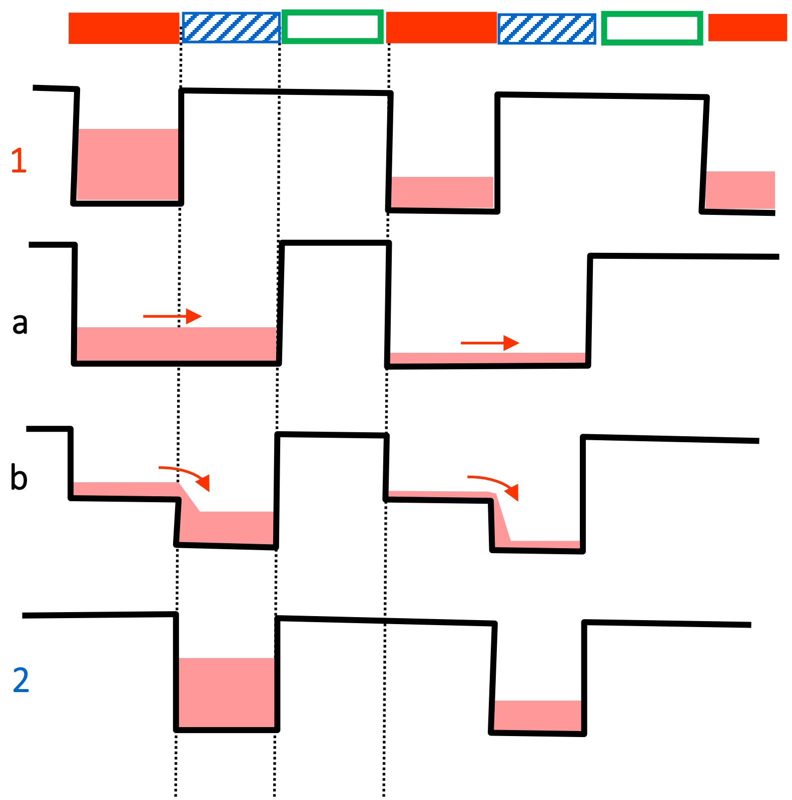
CCD structure: 3 phases



Driving sequence



Charge transfer



Exercise 6.1: a) Consumption of the photosensitive zone and of the 1st transmission

$$E = \frac{1}{2} C \cdot V^2$$

$$E_{photosens} = 2\,(N \cdot M) \cdot \frac{1}{2} C_1 \cdot V^2 = 3\ [\mu J]$$

$$E_{trans} = 2(N \cdot M) \cdot \frac{1}{2} C_0 \cdot V^2 = 1\ [\mu J]$$

$N = M = 1000$

$C_0 = 10\ fF$

$C_1 = 30\ fF$

$V = 10\ V$

Exercise 6.1: b1) Consumption of the vertical registers

A one pixel jump for one pixel: $E = 2 \cdot 3 \cdot \frac{1}{2} C_0 \cdot V^2 = 3\ [pJ]$

$N = M = 1000$

$C_0 = 10\ fF$

$C_1 = 30\ fF$

$V = 10\ V$

A one line jump for all N·M pixels in the matrix $E = 2 \cdot (N \cdot M) \cdot \left(3 \cdot \frac{1}{2} C_0 V^2\right) = 3\ [\mu J]$

An N line jump for all N·M pixels in the matrix $E = 2\, N \cdot (N \cdot M) \cdot \left(3 \cdot \frac{1}{2} C_0 V^2\right) = 3\ [mJ]$

Exercise 6.1: b2) Consumption of the output register

$N = M = 1000$
$C_0 = 10\ fF$
$C_1 = 30\ fF$
$V = 10\ V$

A one pixel jump for one pixel: $E = 6 \cdot \frac{1}{2} C_0 \cdot V^2 = 3\ [pJ]$

A one pixel jump for all M pixels in a line: $E = 2 \cdot M \cdot \left(3 \cdot \frac{1}{2} C_0 V^2\right) = 3\ [nJ]$

An M pixel jump for all M pixels in a line: $E = 2\ M \cdot M \cdot \left(3 \cdot \frac{1}{2} C_0 V^2\right) = 3\ [\mu J]$

Repeat to output N lines: $E = 2\ N \cdot (M^2) \cdot \left(3 \cdot \frac{1}{2} C_0 V^2\right) = 3\ [mJ]$

Exercise 6.1: c-d) Total consumption

$$N = M = 1000$$
$$C_0 = 10\ fF$$
$$C_1 = 30\ fF$$
$$V = 10\ V$$

Energy consumption for one image:

$$E = 2\frac{(N \cdot M)}{2} \cdot (C_1 + C_0 + 3NC_0 + 3MC_0) \cdot V^2 = 6\ [\text{mJ}]$$

Power consumed for r images per second: **r=25 frames/sec.**

$$P = r \cdot E_{tot} = 2\, r \cdot \frac{(N \cdot M)}{2} \cdot (C_1 + C_0 + 3NC_0 + 3MC_0) \cdot V^2 \quad \cong \ 150\ [mW]$$

Required current:

$$I = \frac{P}{V} = 2\, r \cdot \frac{(N \cdot M)}{2} \cdot (C_1 + C_0 + 3NC_0 + 3MC_0) \cdot V \quad \cong \ 15\ [mA]$$

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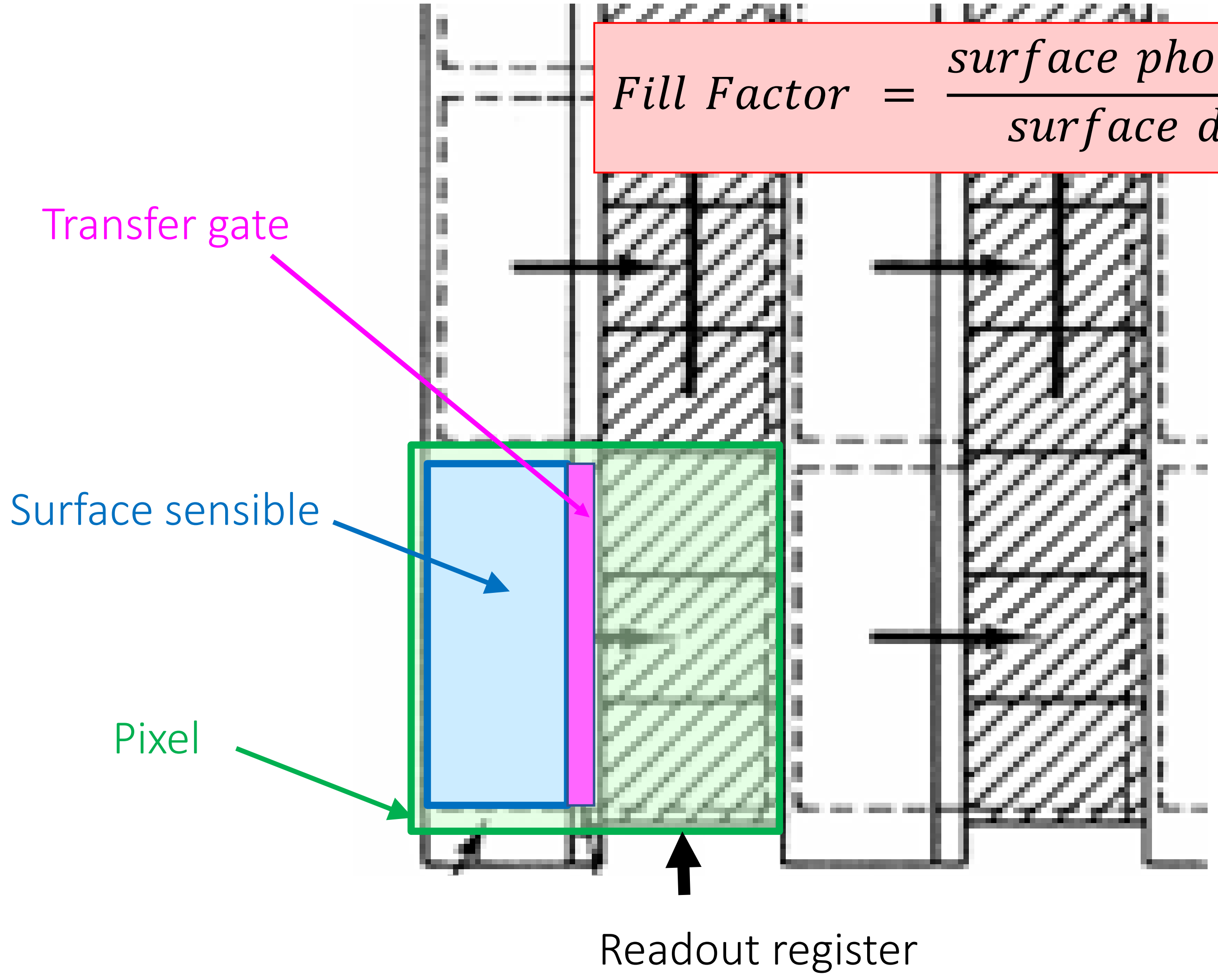
Exercise 6.2: Fill Factor



$$Fill\ Factor = \frac{surface\ photosensible}{surface\ du\ pixel}$$

Exercise 6.2 Fill Factor: CCD Fringing Fields & Drift Current

- No fringing fields

  Only slow diffusion current

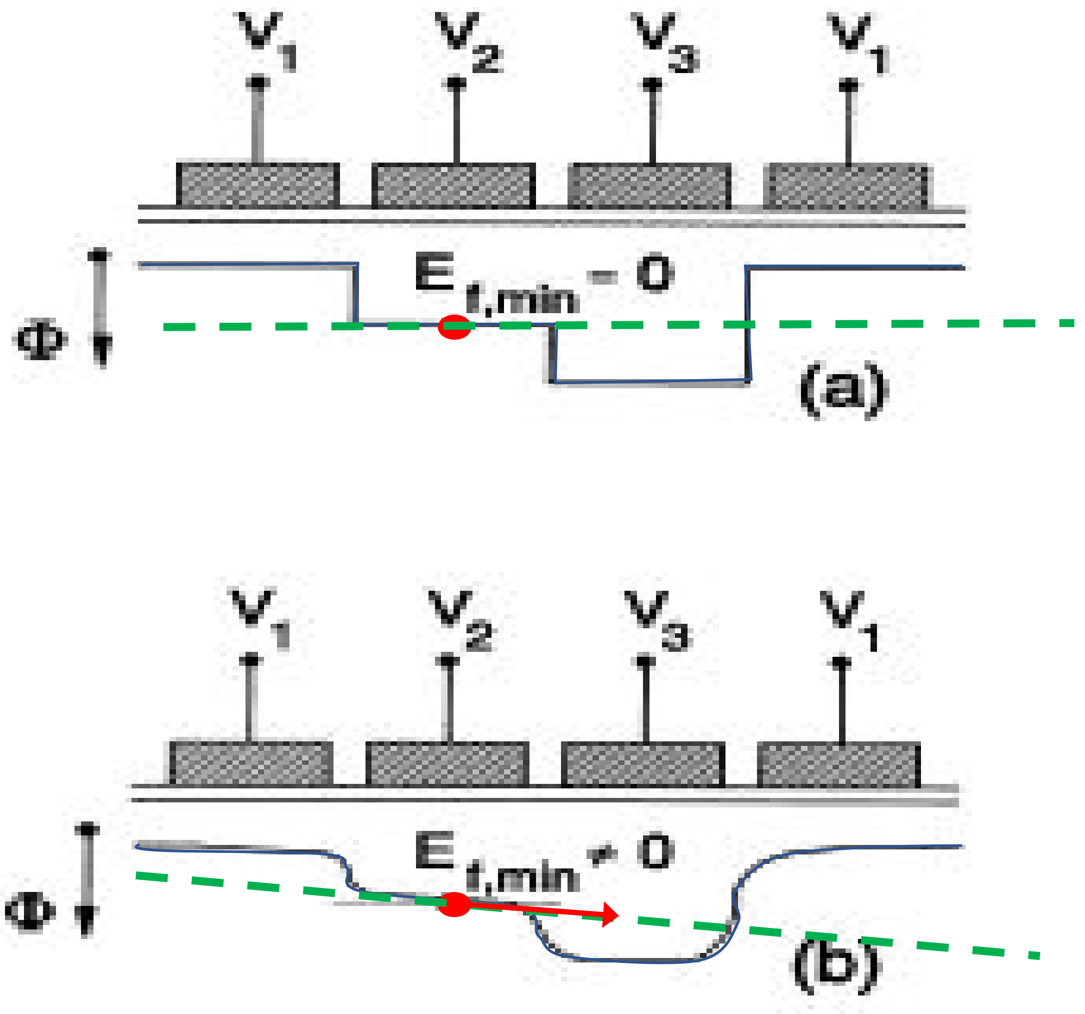
Time constant T:

- decreases with temperature (D_n increases)
- increases as L^2

- Fringing fields to support charge transport

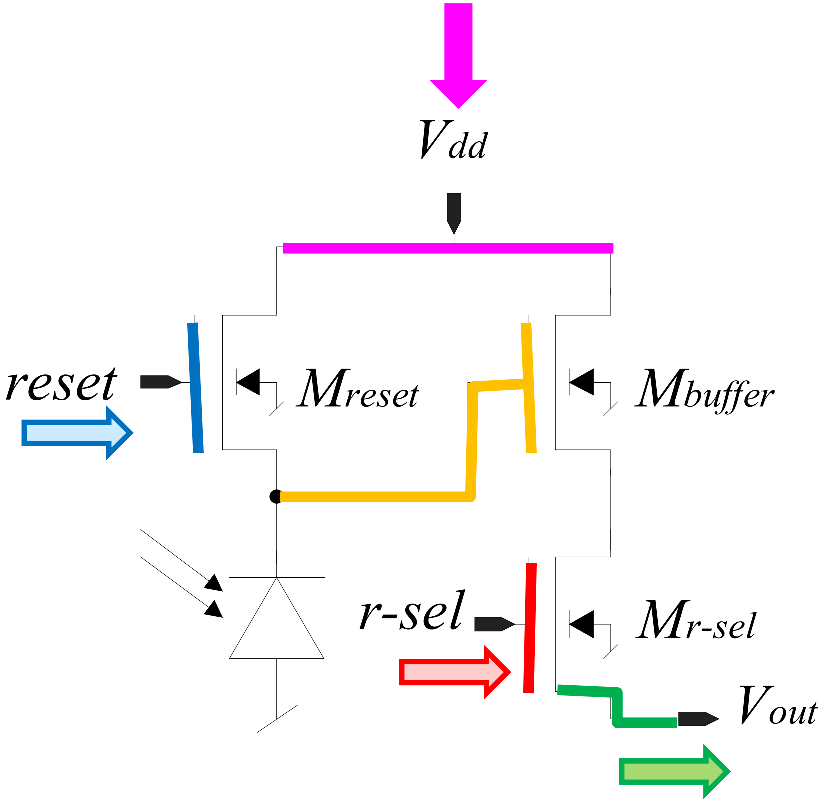
  Drift current → high speed transfer

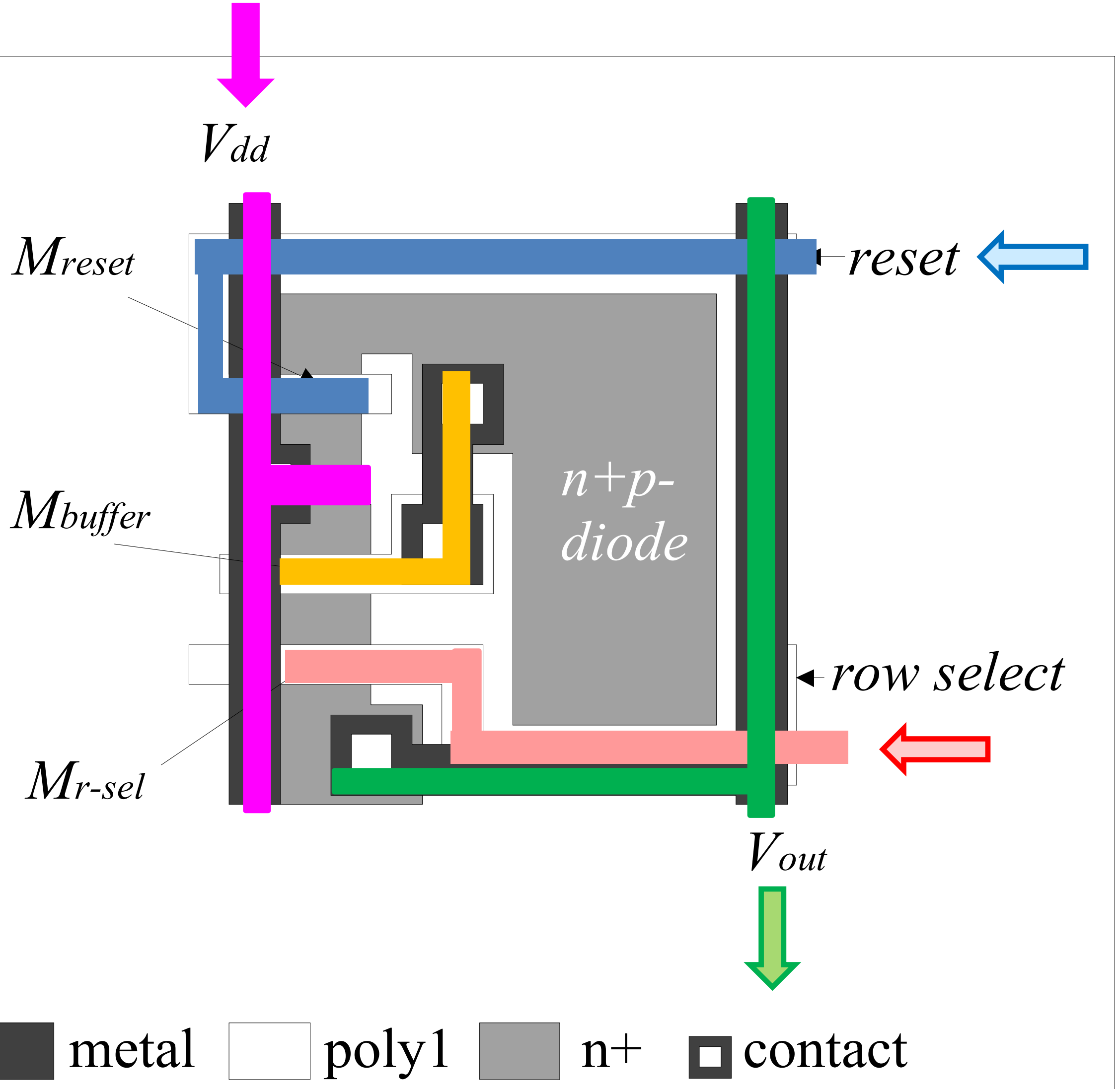
$$J_f = Q_n \cdot v_n = Q_n \cdot \mu_n \cdot E_f$$



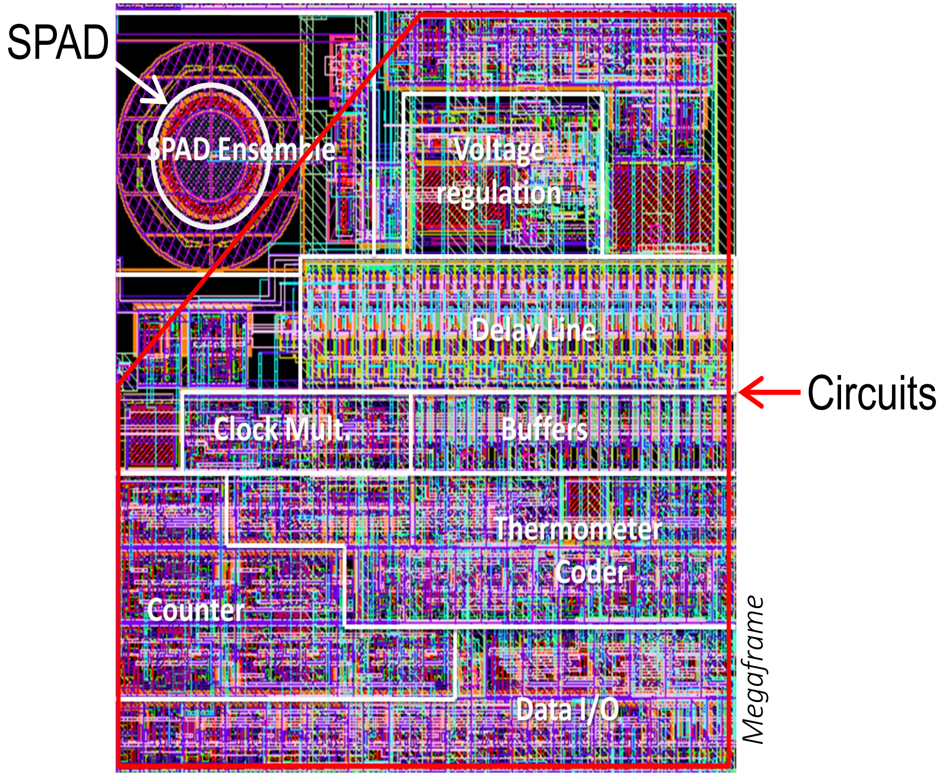
A. J. P. Theuwissen, Solid-State Imaging with Charge-Coupled Devices

Exercise 6.2 Fill Factor: CMOS Pixel Layout with a 3T design



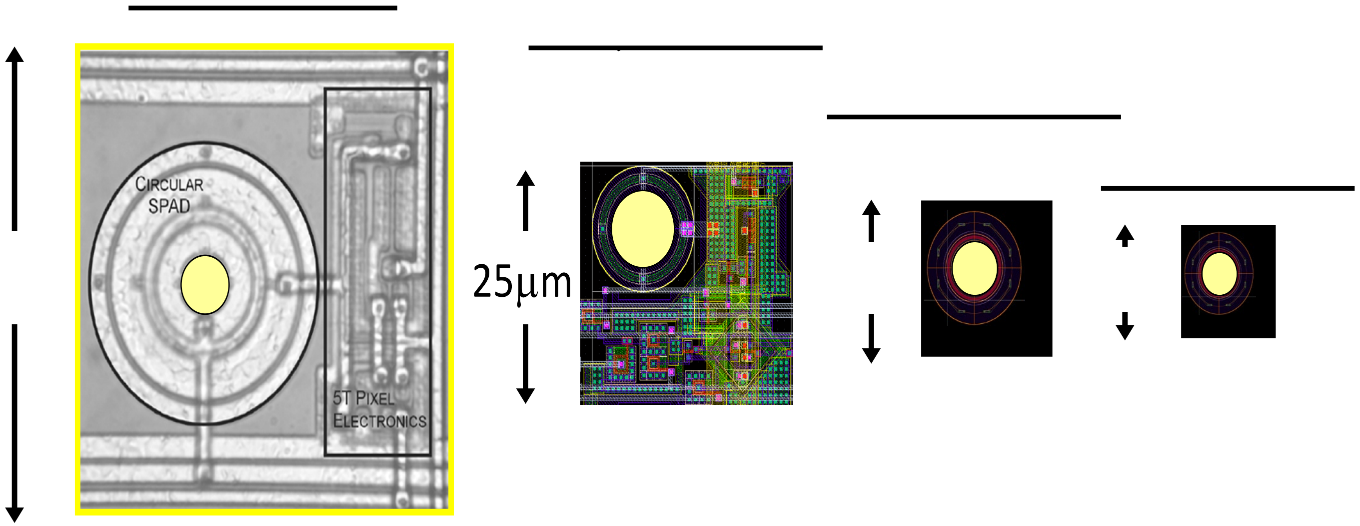


Exercise 6.2 Fill Factor: Trends in SPADs



Monolithic Integration of a SPAD and electronic circuits in standard CMOS technology

Limitation: low fill factor (FF)



- Higher fill factor, higher resolution
- Lower power consumption, more cost-effective

- Higher doping concentration → narrow depletion
  - → higher dark count rate (DCR) (higher tunneling)
  - → lower photon detection probability (PDP)

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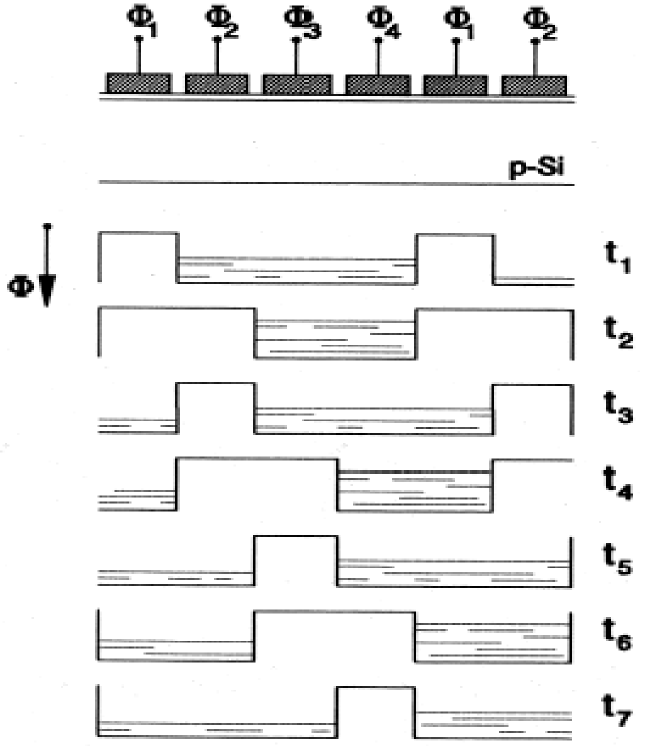
Exercise 6.3: Charge Transfer Efficiency CTE

- CTE: Charge Transfer Efficiency = ability to transfer all the charge from storage site to storage site
- (1-CTE) Charge Transfer Inefficiency

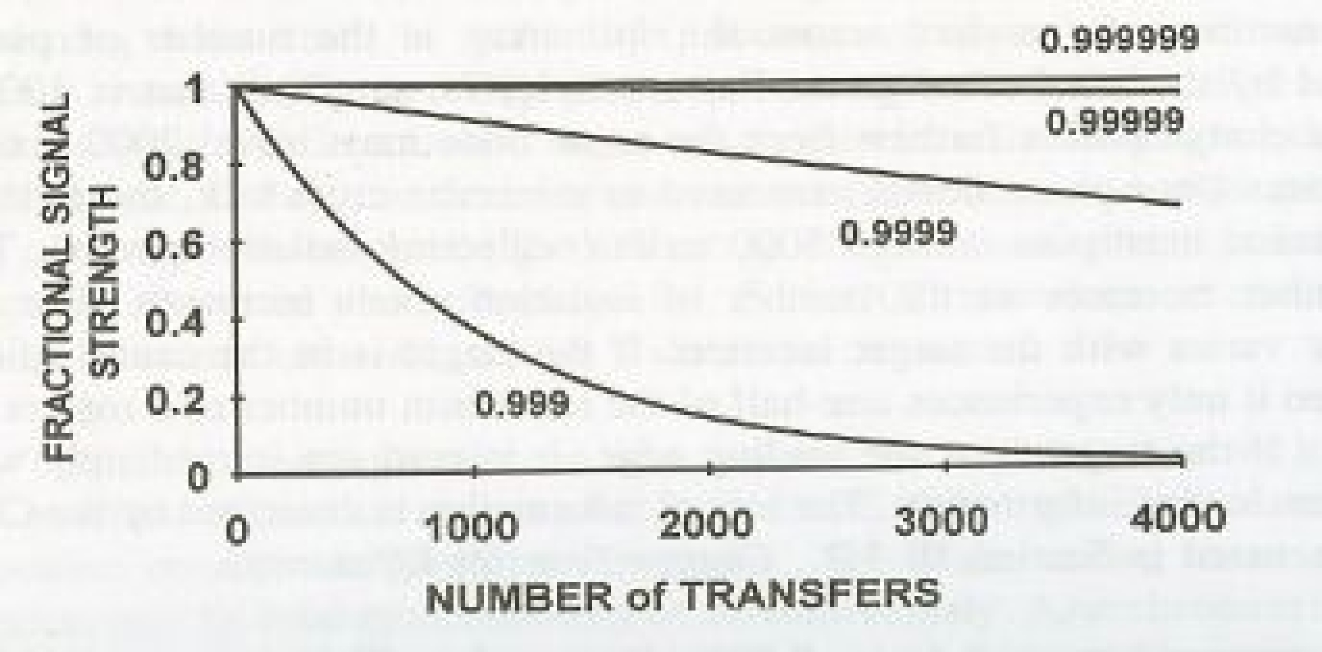


The net efficiency varies with the pixel position in the array. The farthest pixel from the sense node suffers higher loss: For a 1,000x1,000 pixels sensor with 4 phases, the charge packet farthest from the output has to travel 2,000 pixels or pass through 8,000 wells.

→ Which CTE is needed to keep the information in the right cell after several thousand transfers?

6.3 Charge Transfer Efficiency (CTE)

The fractional signal strength X_N after N transfers: $(CTE)^N$



Fractional output X_N as a function of CTE and number of transfers

CCD Arrays cameras and displays,
G.C. Holst

Q: How to measure it?

Exercise 6.3: Charge Transfer Efficiency

- Basic limitation of the performance of CCD related to efficiency with which charges can be transported from one well to the next

- The fraction of the charge that is transferred from one potential to the adjacent one is called Charge Transfer Efficiency (CTE)

- CTE (SCCD) = 99.99%
- **CTE (BCDD) = 99.99995%** ✓