MICRO-523: Optical Detectors

Week Six: CCD cameras (Solutions Ex6)

Claudio Bruschini
Institute of Electrical and Micro Engineering (IEM), School of Engineering (STI)
Ecole polytechnique fédérale de Lausanne (EPFL), Neuchâtel, Switzerland

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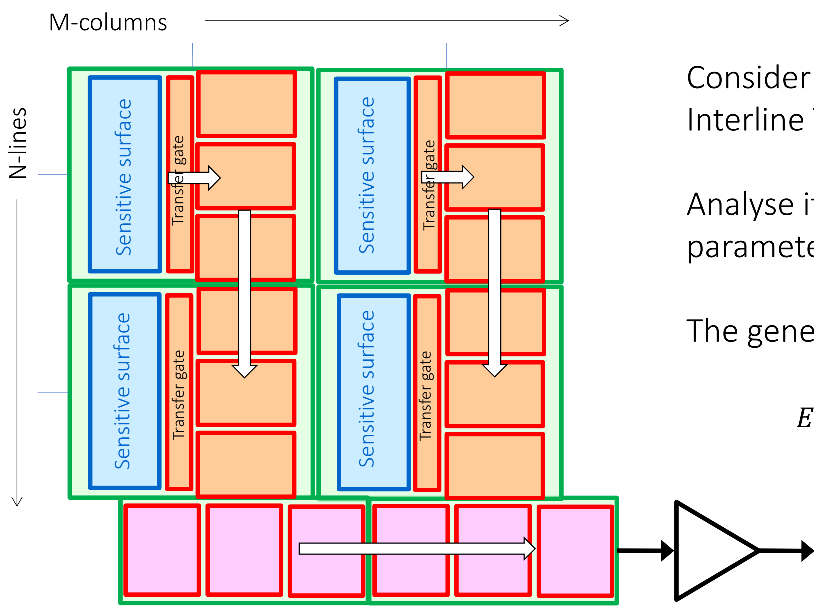
TAs: Samuele Bisi, Kodai Kaneyatsu

Outline

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:

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

<u>EN</u>:

N lines, M columns (N=1000, M = 1000, making it a 1Mpix camera)

The sensitive surface of each pixel is $C_1=3 \cdot C_0=30$ fF.

3 CCD cells per pixel for vertical registers, as well as for the horizontal output register. Each cell has a capacity of $C_0=10$fF.

A voltage of V=10V is used to create potential wells in a cell.

Calculate for an image:

a) The energy consumption in the photosensitive zone, as well as that for the transfer to the vertical registers.

b) The energy consumptoin of the vertical registers and that of the output register.

We take r = 25 images / s. Determine:

c) The power consumed by the camera as a whole.

d) The total electric current that has to be supplied.

Exercise 6.1: Data

N = 1000 lines,
M = 1000 columns (1Mpix camera)

Photosensitive capacity: C_1=30 fF

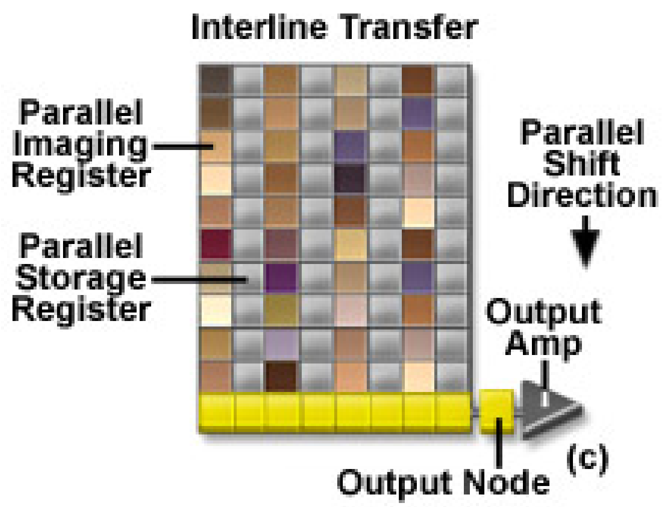
3 CCD cells per pixel for vertical registers, as well as for horizontal output register.

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

Intéressons-nous au schéma général de transport sur toute la matrice CCD. Elle est toujours composée d'une zone photosensible, et d'une ligne de transport sériel (« serial register ») vers l'ampli de sortie.

Nous allons discuter les cas suivants:

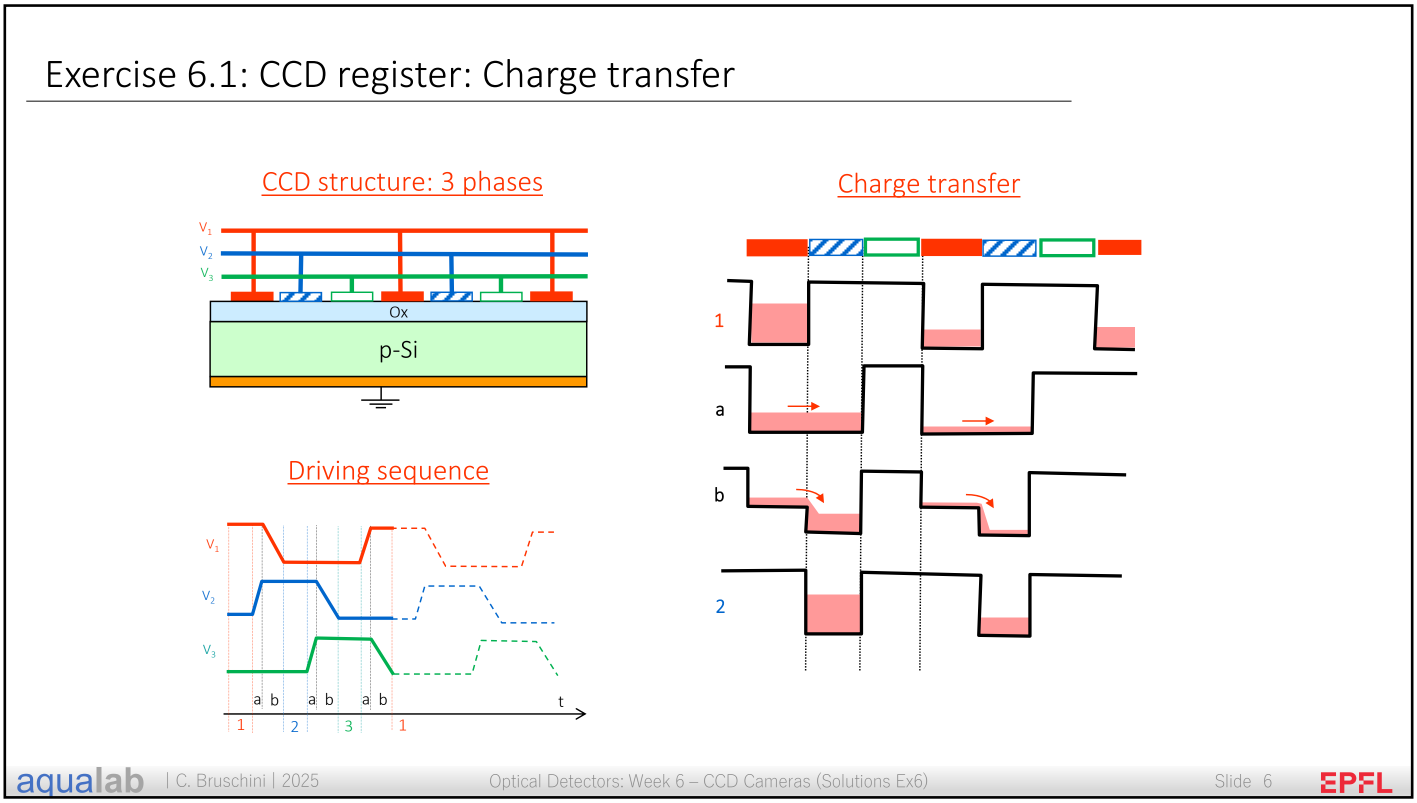
- Full-Frame
- Frame Transfer
- Interline Transfer

EN:

Let's look at the general transport scheme for the entire CCD matrix. It always consists of a photosensitive area, and a serial register line to the output amplifier.

We will discuss the following cases:

- Full-Frame
- Frame Transfer
- Interline Transfer



En pratique les électrodes de commande sont groupées en trois groupes intercalés. Trois tensions différentes (V_1,V_2 et V_3) suffisent pour transférer toute l'information le long de la ligne CCD.

Observons la figure de droite. Supposons qu'au temps '1' , l'information soit stockée sous les électrodes « 1 » (la tension V_1 est élevée V_2 et V_3 sont faibles). La quantité de charges dans chaque puits est différente, elle constitue l'information à transporter. (Elle peut aussi être nulle!).

Au temps 'a', la tension V_2 est augmentée pour former un puits de potentiel large sous les électrodes « 1 » et « 2 ». Les charges se répartissent dans ces puits.

Au temps 'b', la tension sur les électrodes « 1 » est baissée de façon à concentrer les charges sous les électrodes « 2 ».

À la fin de cette séquence de commande, l'information est transportée d'une électrode vers la droite, et nous pouvons recommencer le processus. Les charges constituant l'information ne se dispersent pas.

Remarque: En combinant les photo-détecteurs CCD (pour générer l'information) avec des lignes CCD (pour extraire l'information) on obtient les caméras CCD.

EN:

In practice, the control electrodes are grouped into three interleaved groups. Three different voltages (V_1,V_2 and V_3) are sufficient to transfer all the information along the CCD line.

Let's take a look at the figure on the right. Let's assume that at time '1' , the information is stored under electrode '1' (voltage V_1 is high, V_2 and V_3 are low). The quantity of charges in each well is different, and constitutes the information to be transported. (It can also be zero!).

At time 'a', voltage V_2 is increased to form a large potential well under electrodes '1' and '2'. Charges are distributed in these wells.

At time 'b', the voltage on electrodes '1' is lowered to concentrate the charges under electrodes '2'.

At the end of this control sequence, the information is transported from one electrode to the right, and we can start the process again. The charges making up the information do not disperse.

Note: By combining CCD photodetectors (to generate information) with CCD lines (to extract information), we obtain CCD cameras.

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

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

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

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

$N = M = 1000$

$C_0 = 10\ fF$

$C_1 = 30\ fF$

$V = 10\ V$

The underlying idea, for this power consumption estimate, is to treat the cells of the CCD camera as a collection of capacitors that need to be charged and discharged (hence the factor 2 in the formulas) as we:

- first collect the photocharges (1st equation of this slide),
- then move them to the storage registers (2nd equation of this slide),
- then move them vertically all the way down to the output register one row after the other (next slide),
- and eventually move them horizontally in the output register for amplification and read-out (second next slide).

We assume that all operations are carried out in parallel over all cells (*reminder: we cannot address them individually due to the sensor architecture*) until the first top row reaches the output register.

Exercise 6.1: b1) Consumption of the vertical registers

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

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 $E = 2\, N \cdot (N \cdot M) \cdot \left(3 \cdot \frac{1}{2} C_0 V^2\right) = 3\ [mJ]$

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

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:

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

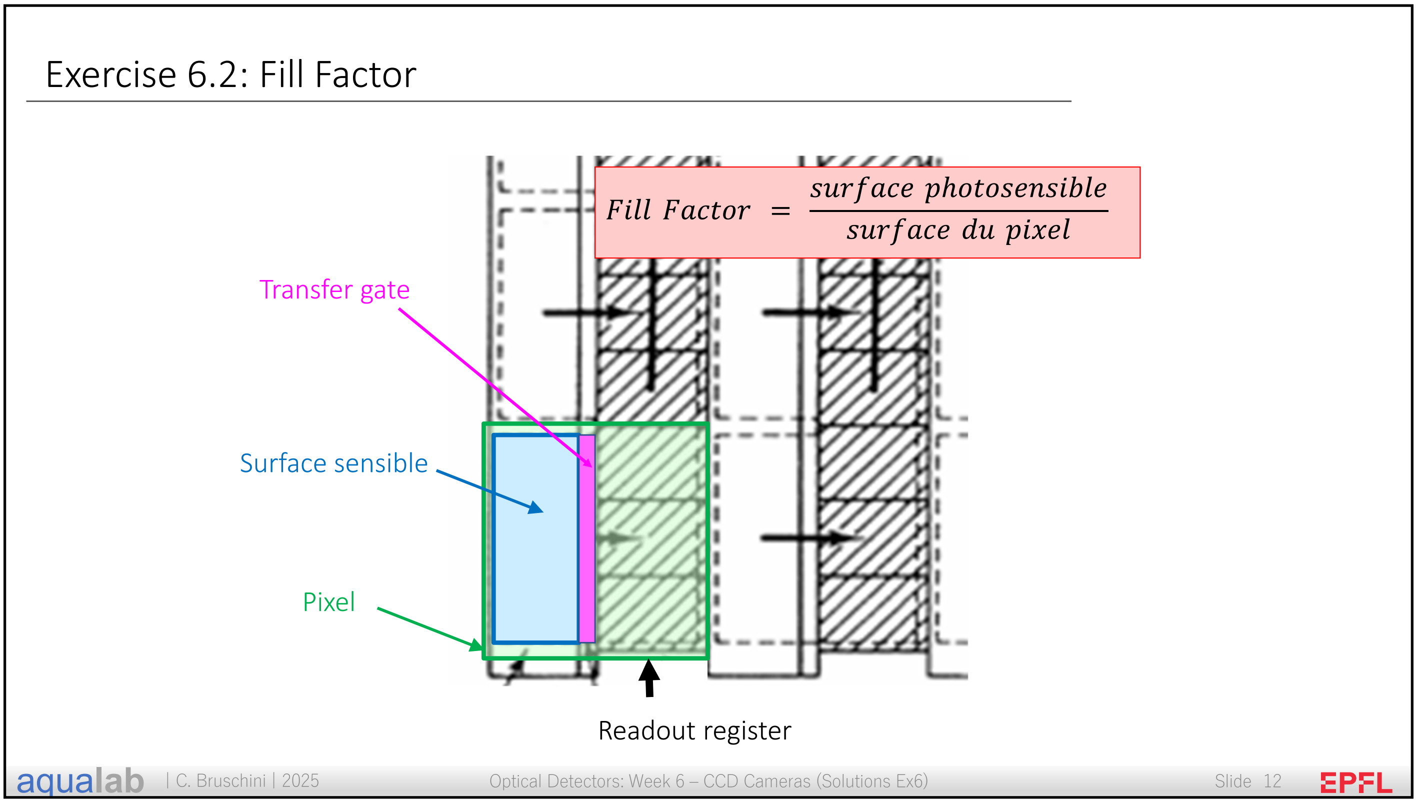
Power consumed for r images per second: **r=25 frames/sec.**

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

Required current:

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

Outline



Pour la récolte des photo-charges, le Fill Factor est un paramètre central.

Le Fill Factor (FF) décrit le rapport entre la surface photosensible et la surface totale du pixel. Il donne donc la proportion de lumière arrivant sur la zone sensible par rapport à la lumière totale sur le pixel.

Nous devrons maximiser le Fill Factor pour obtenir une grande sensitivité de la caméra.

Remarque:

La lumière qui arrive sur la zone photosensible n'est pas toute transformée en photo-charges. Il faut encore introduire l'efficience quantique η. Le produit du Fill Factor par l'efficience quantique ($FF \cdot \eta$) donne le rapport entre les photo-charges récoltées et la lumière arrivant sur tout le pixel.

EN:

The Fill Factor is a key parameter for photo-charge collection.

The Fill Factor (FF) describes the ratio between the photosensitive area and the total area of the pixel. It therefore gives the proportion of light arriving on the sensitive area in relation to the total light on the pixel.

We need to maximize the Fill Factor to achieve high camera sensitivity.

Note:

Not all the light arriving on the photosensitive area is transformed into photo-charges. We still need to introduce the quantum efficiency η. The product of the Fill Factor and the quantum efficiency ($FF \cdot \eta$) gives the ratio between the photo-charges collected and the light arriving on the entire pixel.

Exercise 6.2 Fill Factor: CCD Fringing Fields & Drift Current

- No fringing fields

Only slow diffusion current

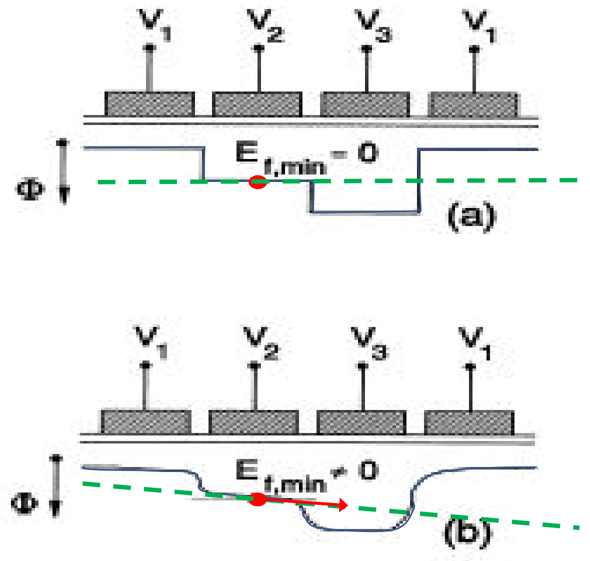
Time constant T:

- 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

Considérons maintenant deux cellules avec des potentiels différents sut le gate.

a) Idéalement le potentiel suit un profil en escalier parfait. Au centre de chaque cellule le potentiel est plat, il n'y a donc pas de champ électrique (pas de pente du potentiel). Les électrons au centre d'une cellule ne sont pas poussés à bouger par un courant de drift.

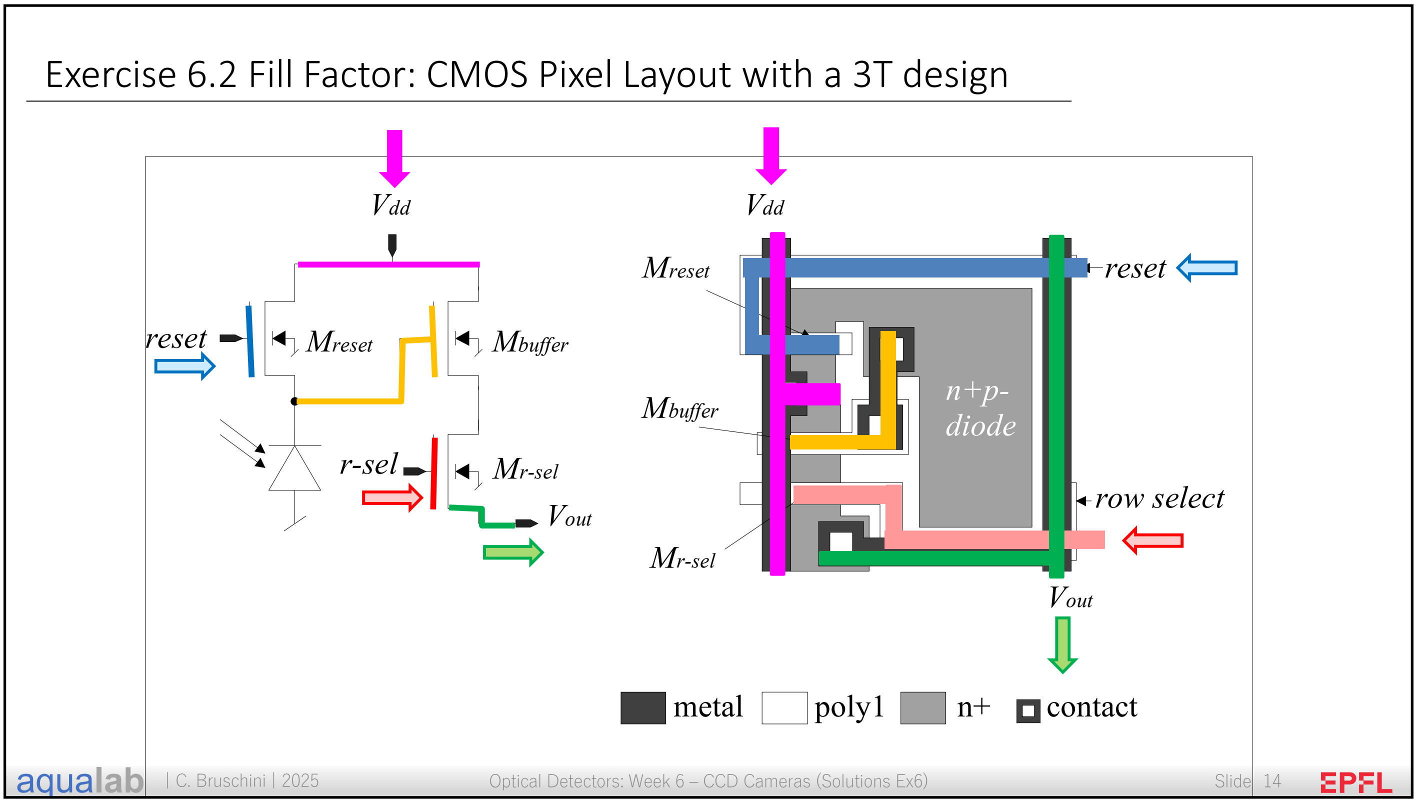
b) En réalité, la structure 3D induit un lissage du potentiel électrique. Le vrai potentiel est une sorte d'escalier arrondi. Un champ électrique (une pente du potentiel) subsiste même au centre d'une cellule. C'est le « fringing field ». Il pousse les électrons vers la cellule au potentiel le plus bas et permet donc de diminuer considérablement le temps de transfert. Pour une fois, un effet « parasite » nous donne un coup de main !!

EN:

Now consider two cells with different potentials on the gate.

a) Ideally, the potential follows a perfect staircase profile. At the center of each cell, the potential is flat, so there is no electric field (no potential slope). Electrons at the center of a cell are not driven to move by a drift current.

b) In reality, the 3D structure induces a smoothing of the electric potential. The true potential is a kind of rounded staircase. An electric field (a potential slope) remains even at the center of a cell. This is the "fringing field". It pushes the electrons towards the cell with the lowest potential, thus considerably reducing the transfer time. For once, a "parasitic" effect gives us a helping hand!



Le pixel 3T peut être très compact, ce qui permet de maintenir un Fill Factor élevé. Dans ce design, il y a 4 lignes de connexion par pixel :

•la tension VDD,

•le signal digital de reset,

•le signal digital de sélection de ligne (r-sel),

•la tension de sortie.

À vous d’estimer le Fill Factor !

<u>EN :</u>

The 3T pixel can be very compact, which allows for maintaining a high Fill Factor. In this design, there are 4 connection lines per pixel:

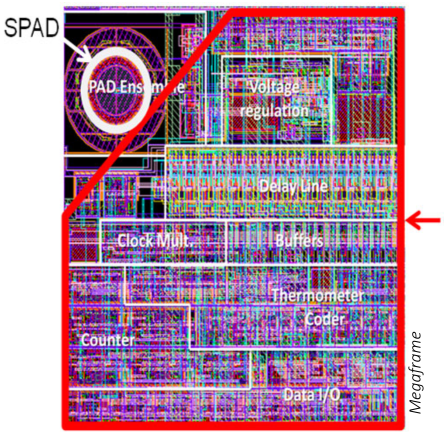
•VDD voltage,

•digital reset signal,

•digital row selection signal (r-sel),

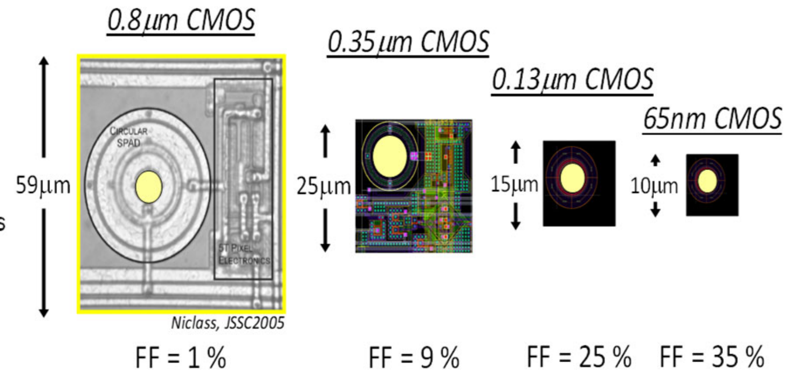
•output voltage.

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)



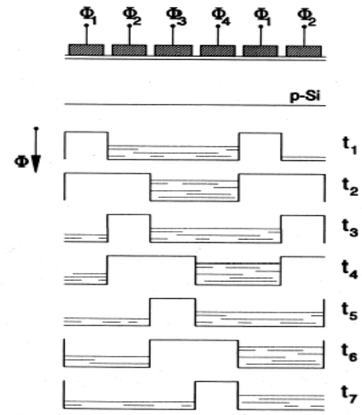
- Higher fill factor, higher resolution
- Lower power consumption, more cost-effective

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

Outline

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?

Pour le transport des photo-charges, le paramètre central est le « Charge Transfer Efficiency » (CTE).

Il décrit, **pour une étape** de transfert, la proportion (en %) de charges transférées d'un puits à l'autre. Le terme (1-CTE) correspond aux charges non-transférées.

Il est capital d'obtenir un excellent CTE. En effet, les caméras modernes ont un grand nombre de pixels. Considérons un système de transfert à 4 phases avec une matrice de 1000x1000 pixels. Chaque pixel est composé de 4 cellules CCD, il faut donc 4 transferts pour passer l'information d'un pixel au suivant. Pour amener l'information des pixels les plus éloignés vers la sortie, il faudra traverser 1000 pixels en vertical et 1000 pixels dans le registre horizontal de lecture (total 2000 pixels). Au final, il faut effectuer 8000 transferts de charges.

EN:

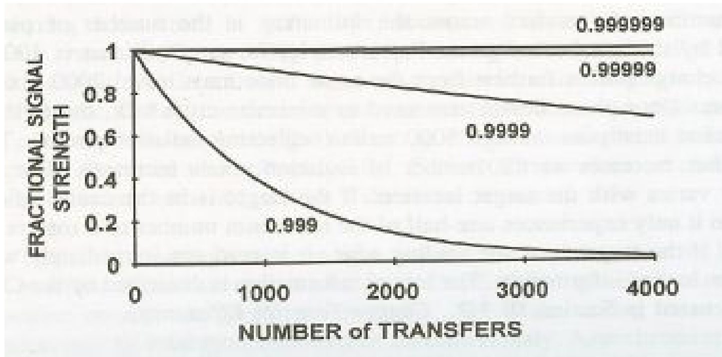
For photo-charge transport, the central parameter is Charge Transfer Efficiency (CTE).

For a given transfer step, it describes the proportion (in %) of charges transferred from one well to another. The term (1-CTE) corresponds to non-transferred charges.

It's vital to achieve an excellent CTE. Modern cameras have a large number of pixels. Consider a 4-phase transfer system with a matrix of 1000x1000 pixels. Each pixel is made up of 4 CCD cells, so 4 transfers are needed to pass information from one pixel to the next. To bring the information from the furthest pixels to the output, 1000 pixels must be traversed vertically and 1000 pixels in the horizontal readout register (total 2000 pixels). All in all, 8,000 charge transfers are required.

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?

Transfert sur un grand nombre d'étapes en fonction du CTE.

(Il faut une CTE avec six 9 après la virgule pour maintenir l'information dans la bonne cellule après plusieurs milliers de transferts !!).

EN:

Transfer over a large number of steps depending on the CTE.

(You need a CTE with six 9s after the decimal point to keep the information in the right cell after several thousand transfers!)

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%

Au final, l'optimisation de la Charge Transfer Efficiency (CTE) est obtenue par:

- Une miniaturisation de la taille de chaque pixel, cela rend efficace le courant de diffusion.
- Une structure BCCD pour:
  - Choisir la profondeur des photo-charges sous l'oxyde et maximiser les fringing fields.
  - Éviter les pièges en surface.

EN:

Ultimately, Charge Transfer Efficiency (CTE) is optimized by:

- A miniaturization of the size of each pixel, making the diffusion current efficient.
- A BCCD structure to:
  - Choose the depth of photo-charges under the oxide and maximize fringing fields.
  - Avoid surface traps.