

# Dispositivi a trasferimento di carica

CTD – Charge Transfer Devices

CCD – Charge Coupled Devices

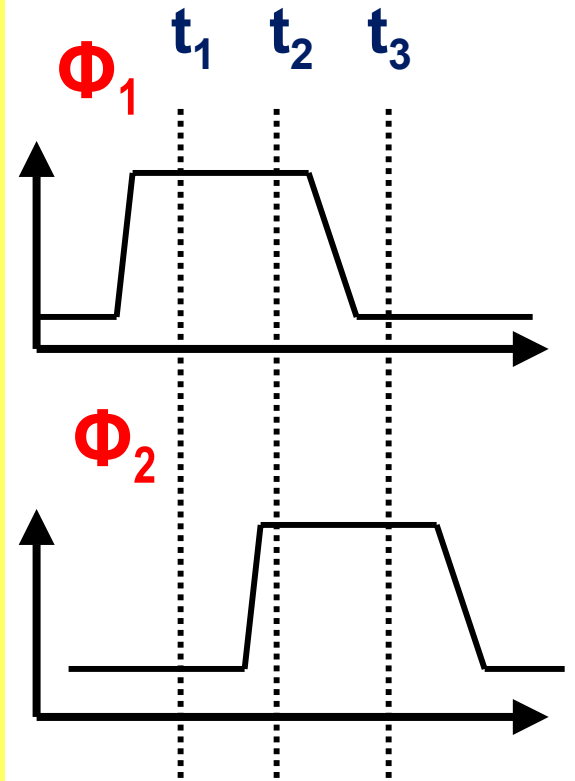
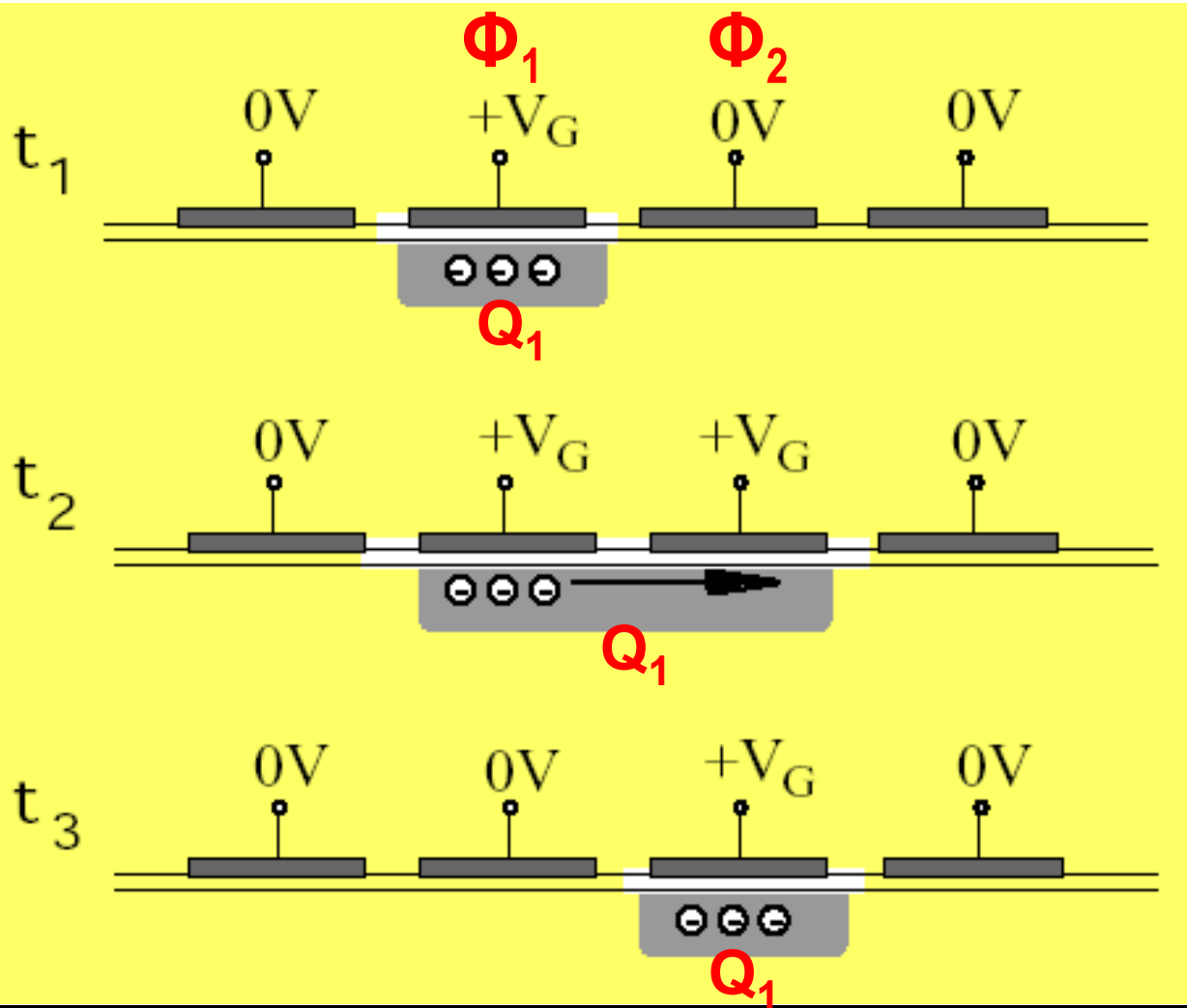
Evoluzione tecnologica:

1967: array di fotodiodi/fototransistori MOS (pixel passivi)

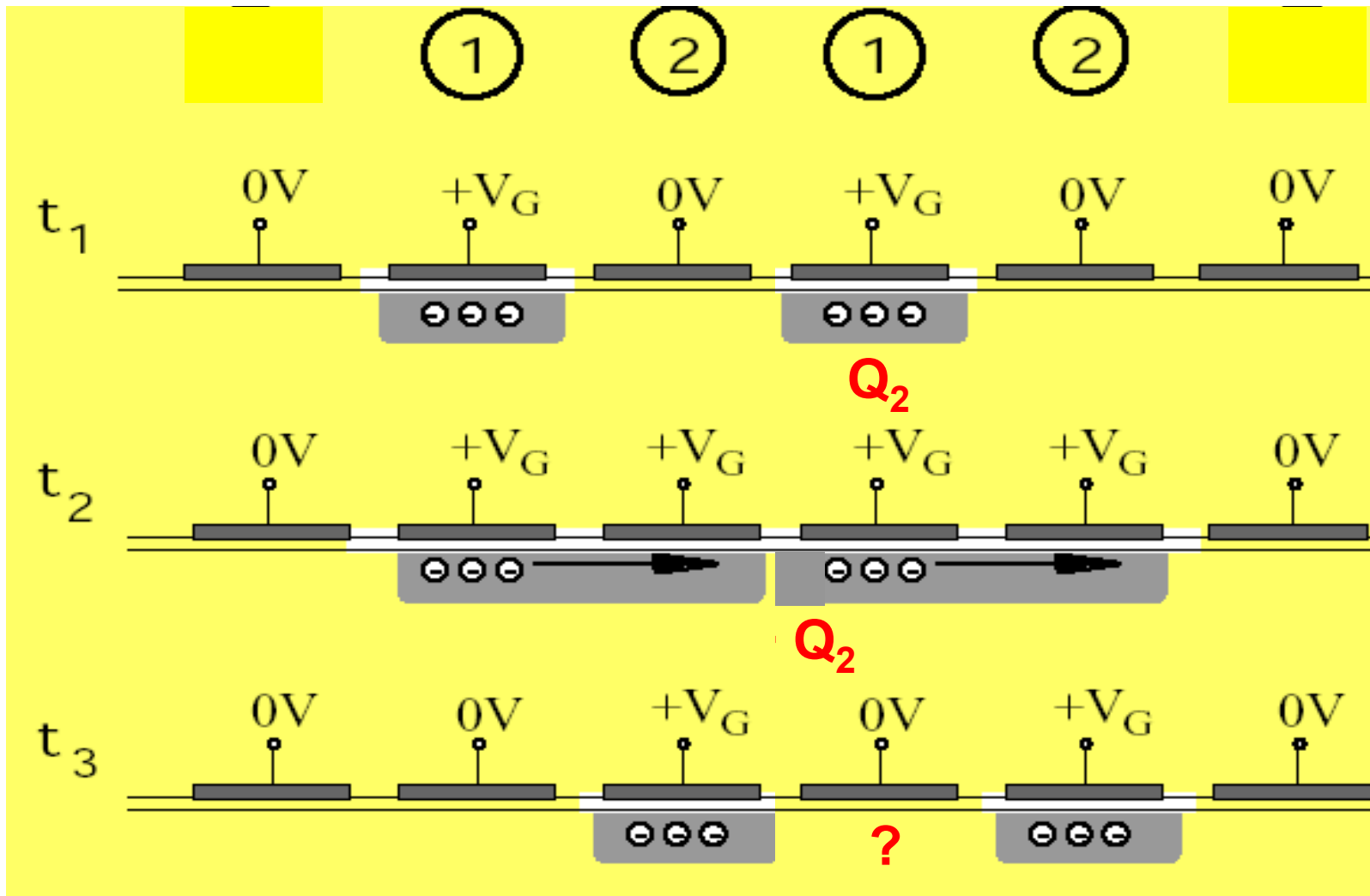
1970: sensori CCD

1980: sensori CMOS (fotodiodi + pixel attivi)

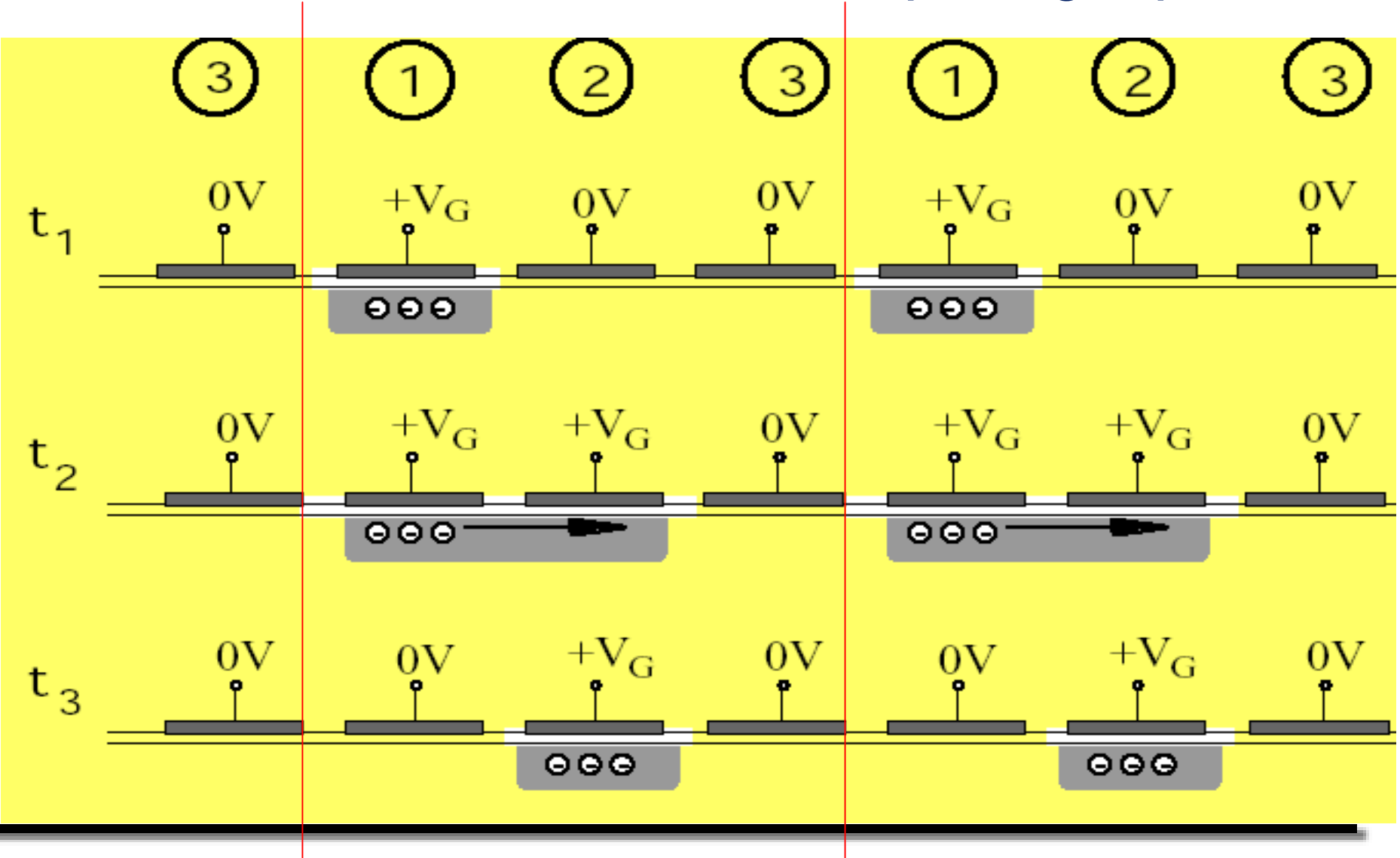
# Meccanismo di trasferimento della carica



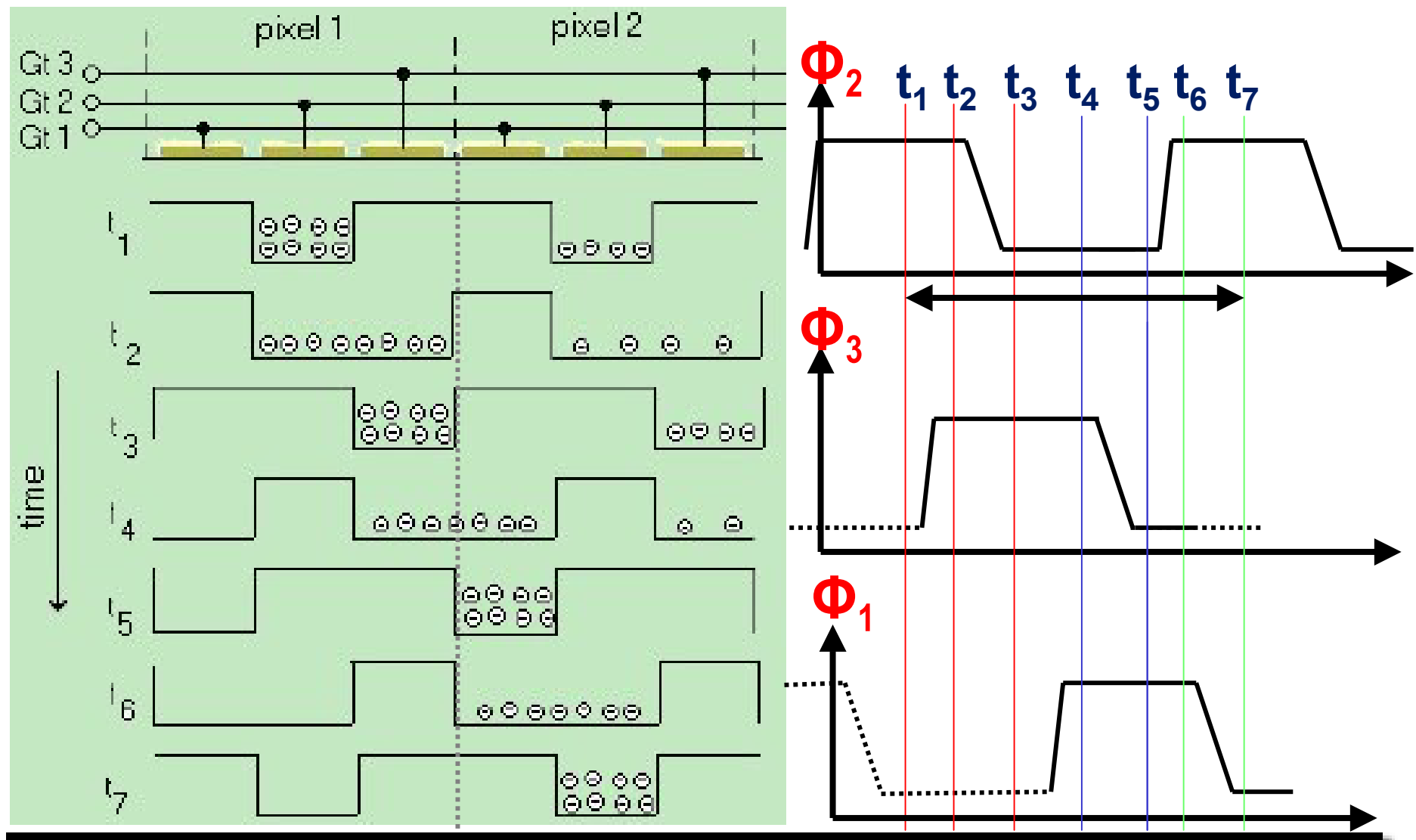
# Sistema bifase?



# Successione di tre elettrodi per ogni pixel



# Meccanismo di trasferimento a tre fasi



# Funzionamento di un CCD

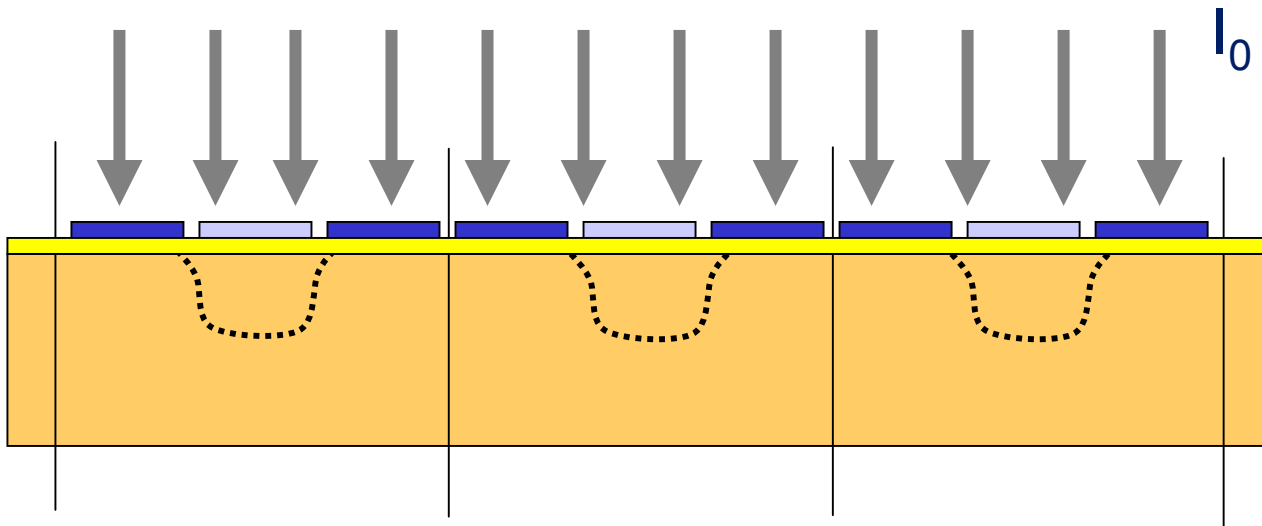
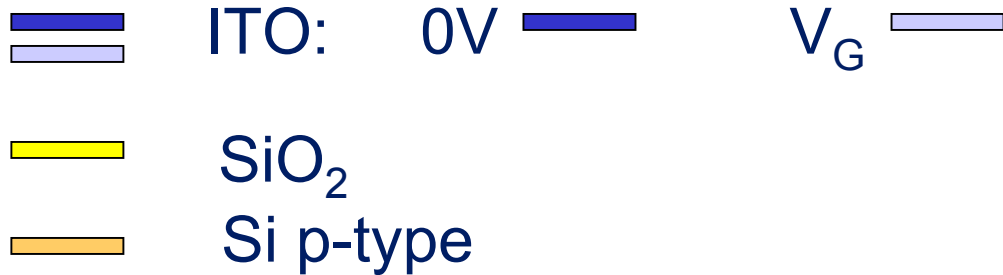
1. Campionamento del segnale (ottico o elettrico)
2. Trasferimento
3. Lettura (read-out)

Il CCD funziona come:

- un rivelatore d'immagini (sensore ottico)
- un registro a scorrimento (memoria seriale)
- una linea di ritardo analogica a valori campionati (filtro)

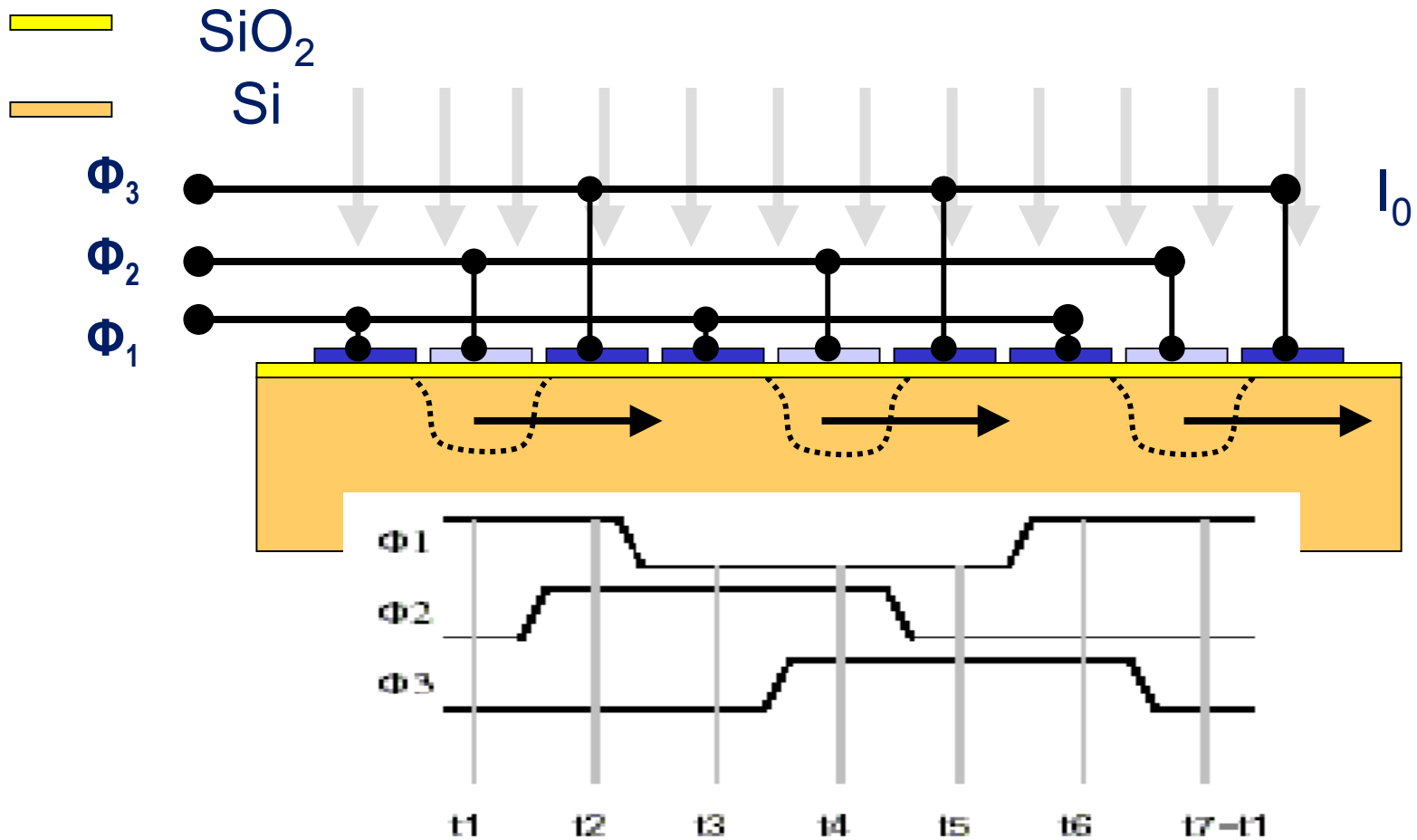
# 1. Campionamento del segnale ottico

Array di fotocondensatori MOS con gate trasparenti in ITO



## 2. Trasferimento della carica

Meccanismo di trasferimento a tre fasi





## Efficienza di trasferimento della carica

(charge transfer efficiency)

$$\eta = (1-\varepsilon),$$

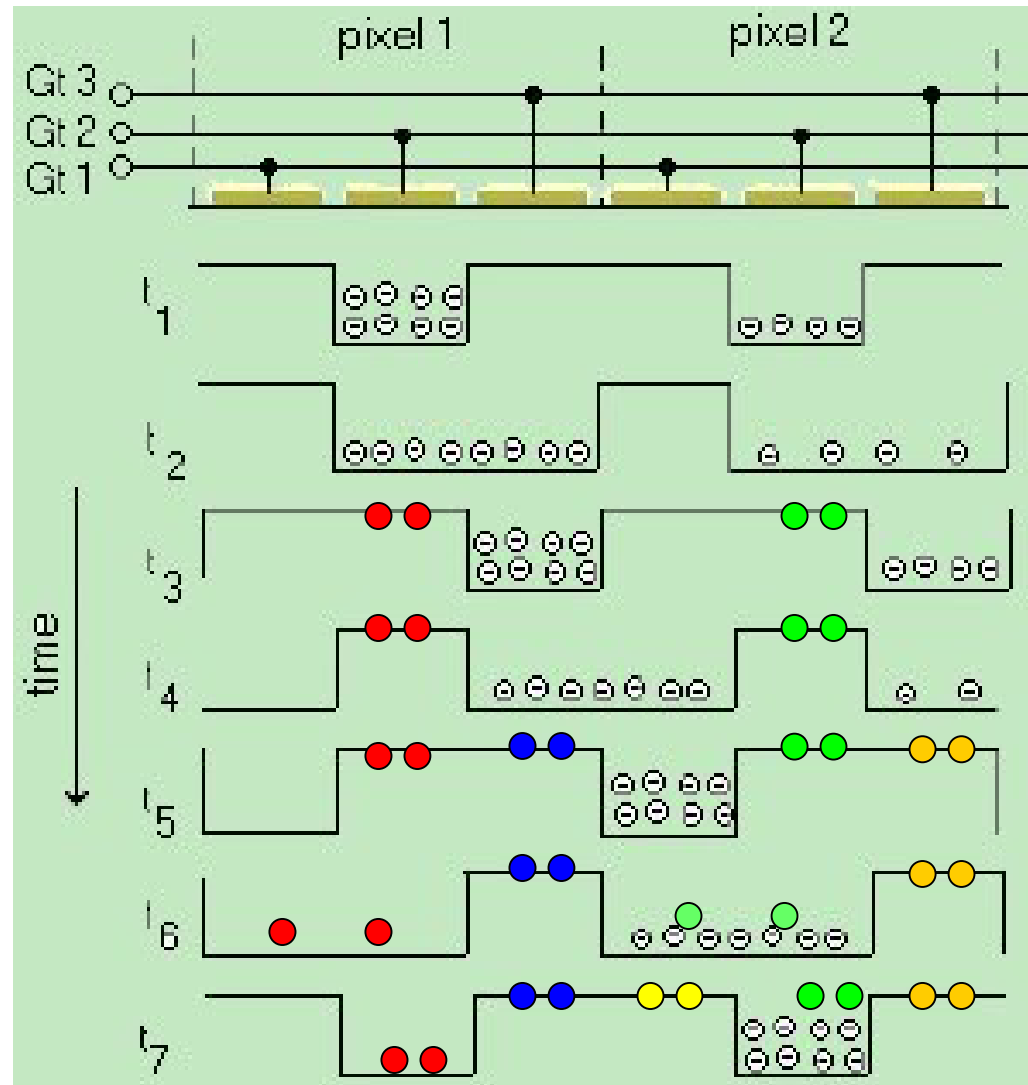
con  $\eta$  la frazione della carica trasferita da un pixel al successivo  
e  $\varepsilon$  l'inefficienza del singolo trasferimento.

Un array di N pixel con trasferimento a p fasi ha una efficienza  
totale pari a

$$\eta_{\text{tot}} = \eta^{pN} = (1-\varepsilon)^{pN}$$

Esempio:  $N = 1000$ ,  $p = 3$ ,  $\varepsilon = 10^{-4} \rightarrow \eta_{\text{tot}} = 74\%$

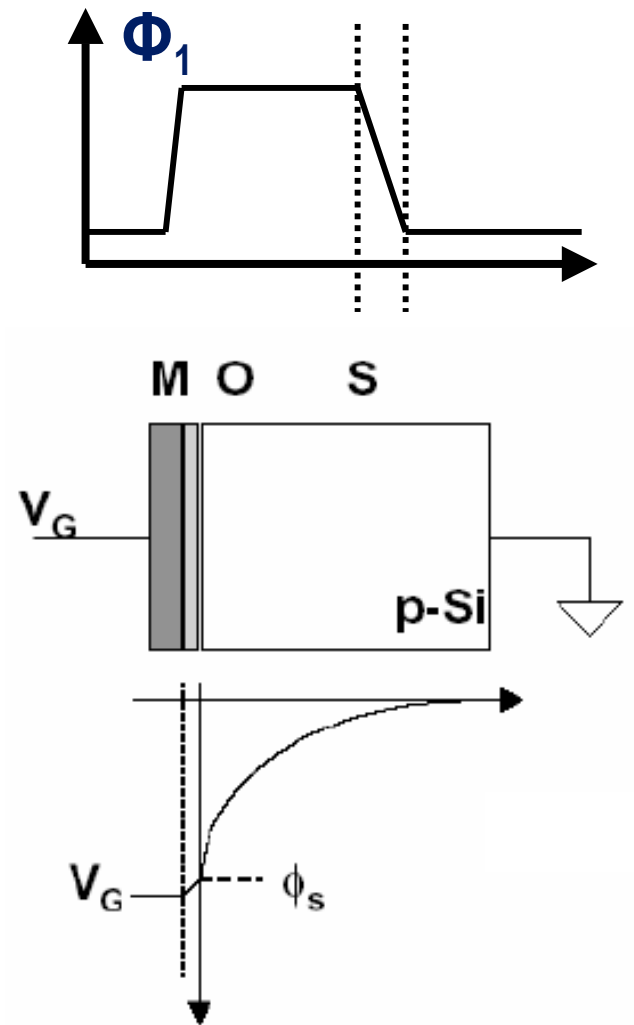
# Effetto dell'inefficienza $\epsilon$



| t     | pixel1  | pixel2              |
|-------|---|---------------------|
| $t_1$ | $q_1$   | $q_2$               |
| $t_2$ | $q_1$   | $q_2$               |
| $t_3$ | $q_1(1-\epsilon)$                               | $q_2(1-\epsilon)$   |
| $t_4$ | $q_1(1-\epsilon)$                               | $q_2(1-\epsilon)$   |
| $t_5$ | $q_1(1-\epsilon)^2$                             | $q_2(1-\epsilon)^2$ |
| $t_6$ | $q_1(1-\epsilon)^2 + q_2 \epsilon$              | $q_2(1-\epsilon)^2$ |
| $t_7$ | $q_1(1-\epsilon)^3 + q_2 \epsilon(1-\epsilon)$  | ---                 |
| $t_8$ | $q_1(1-\epsilon)^3 + 2q_2 \epsilon(1-\epsilon)$ |                     |

# Perché è $\eta \neq 1$ ?

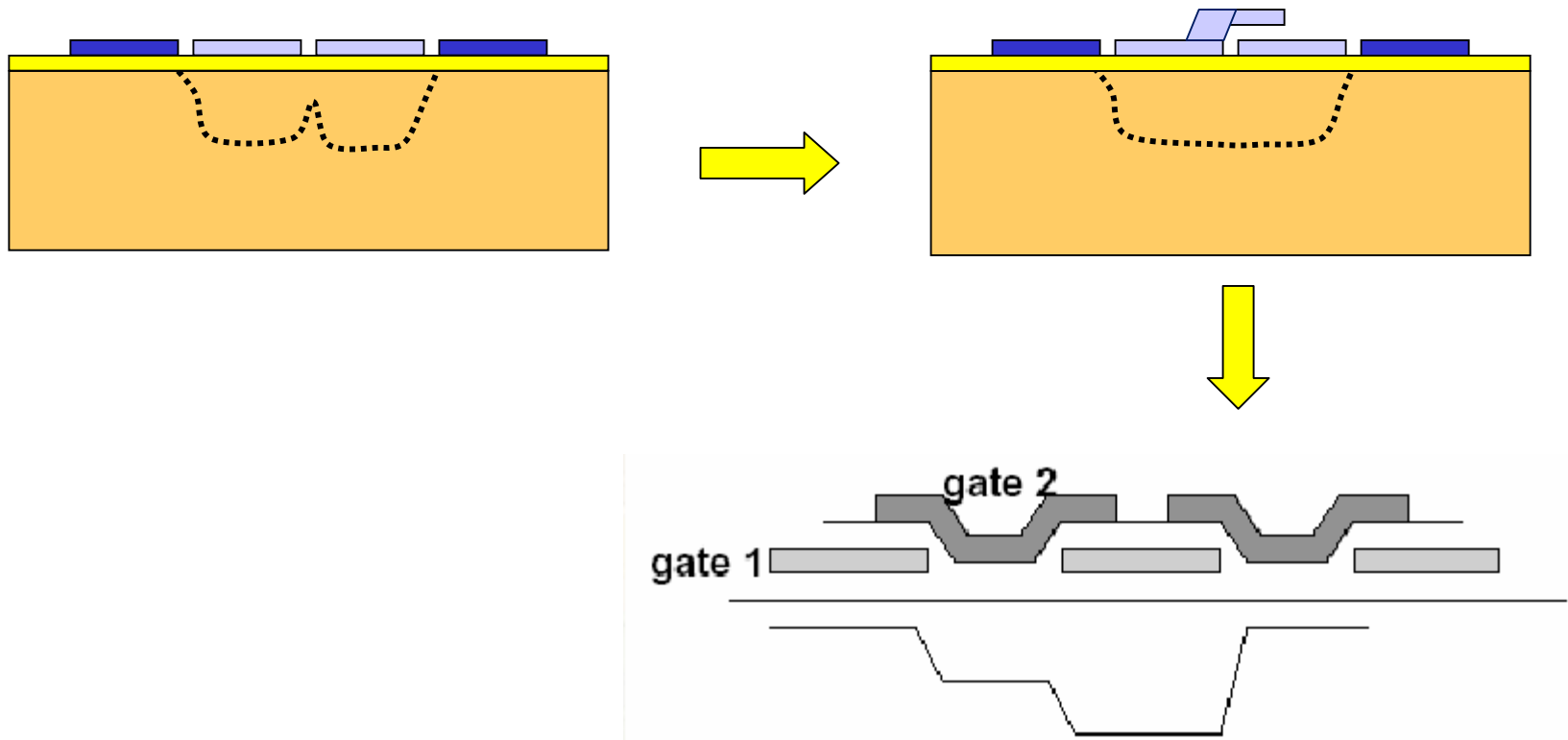
- tempo limitato di trasferimento
- carica intrappolata negli stati superficiali

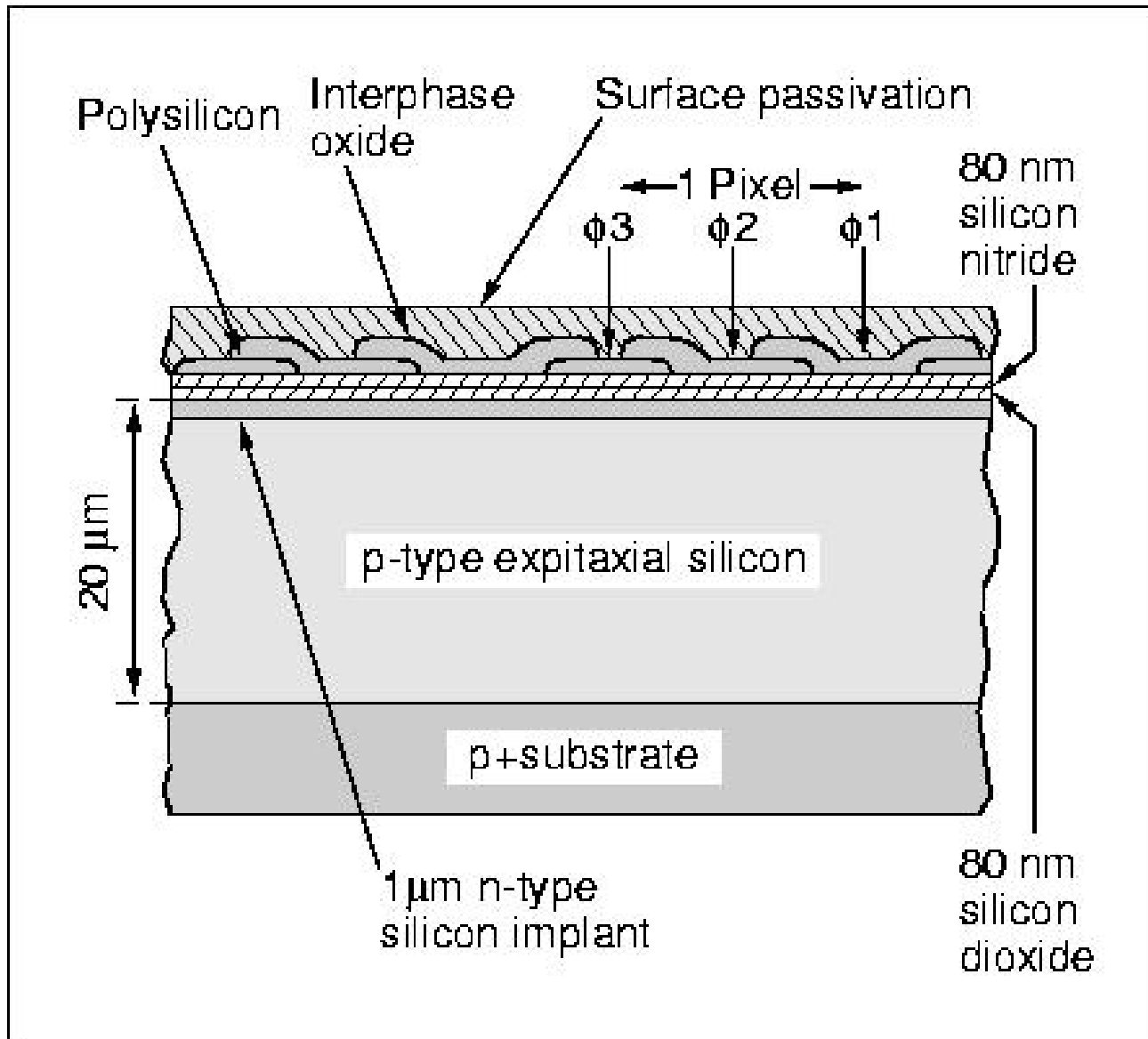


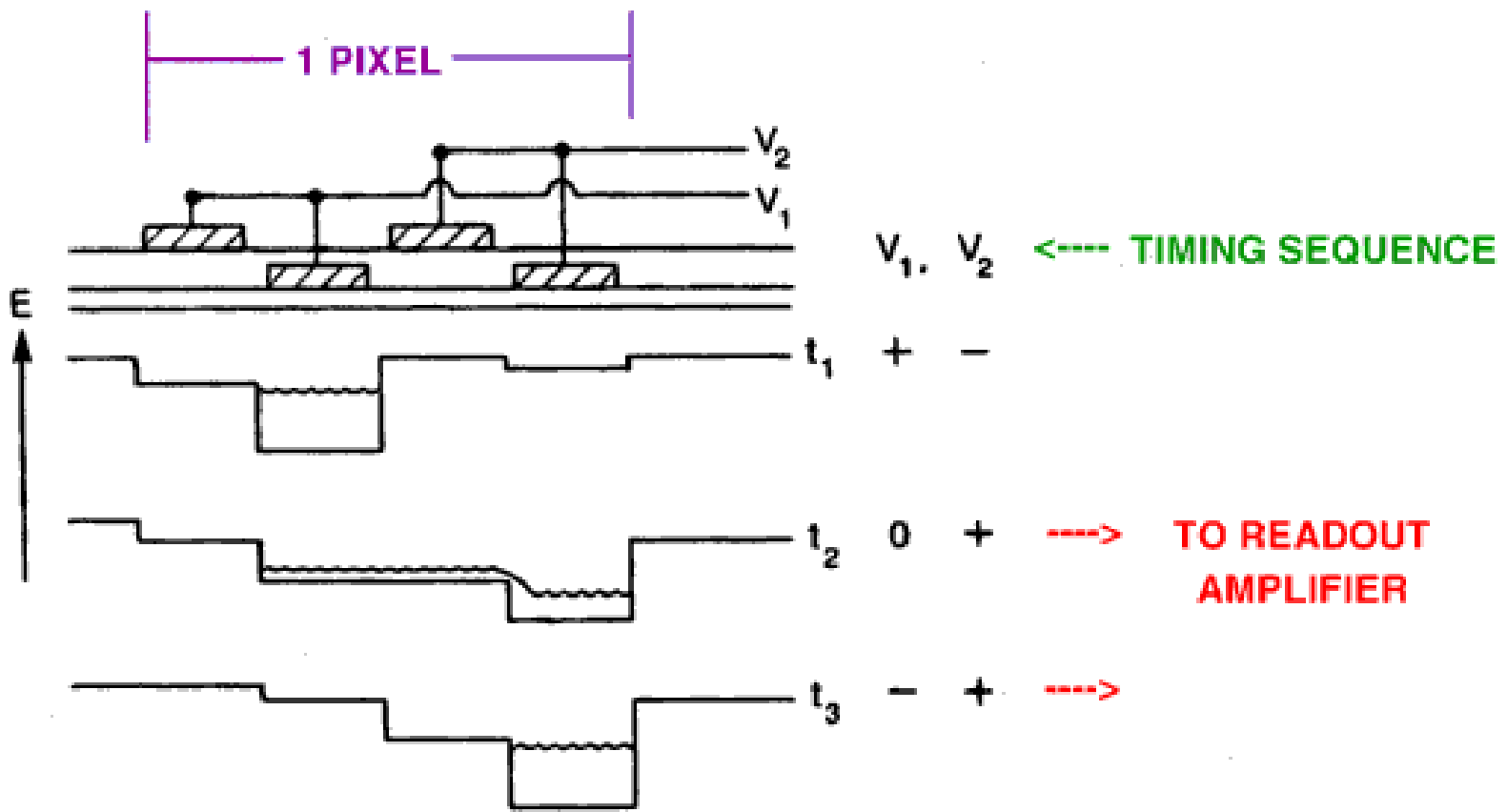
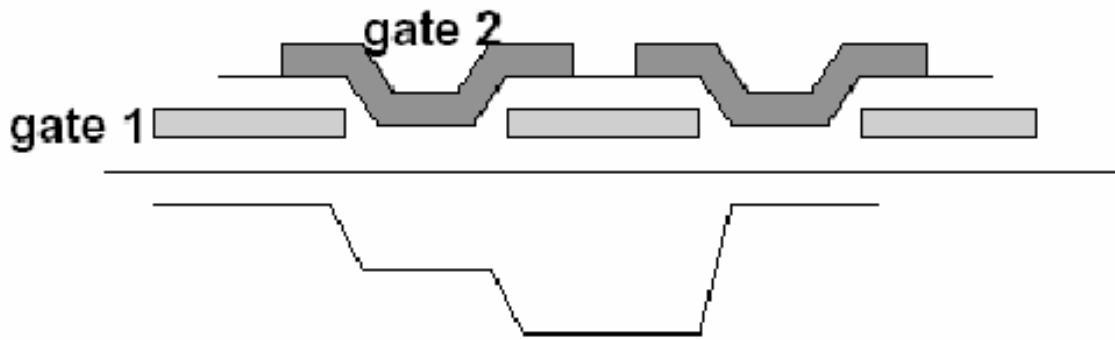
# Ottimizzazione del trasferimento di carica

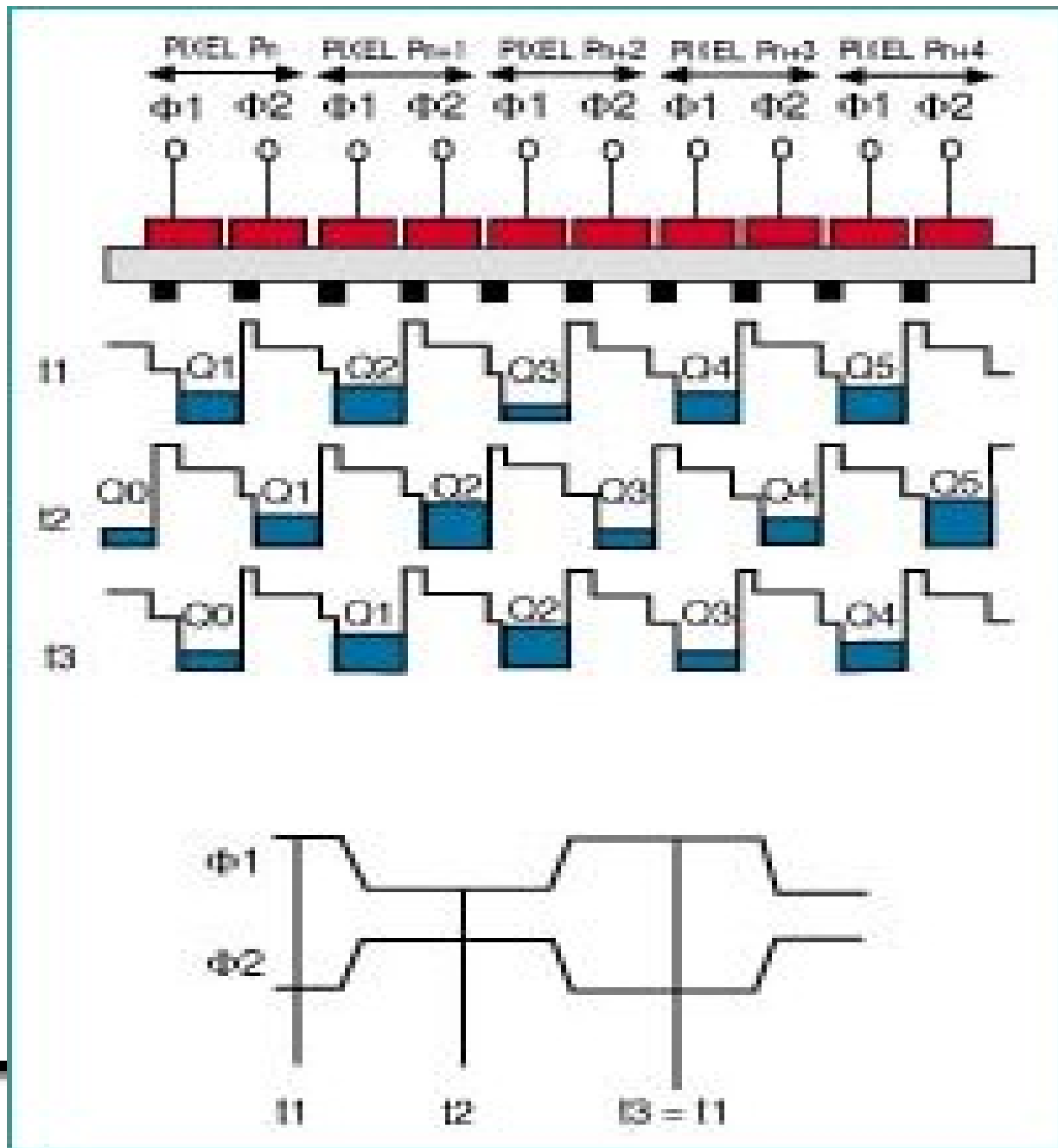
**I problema:**

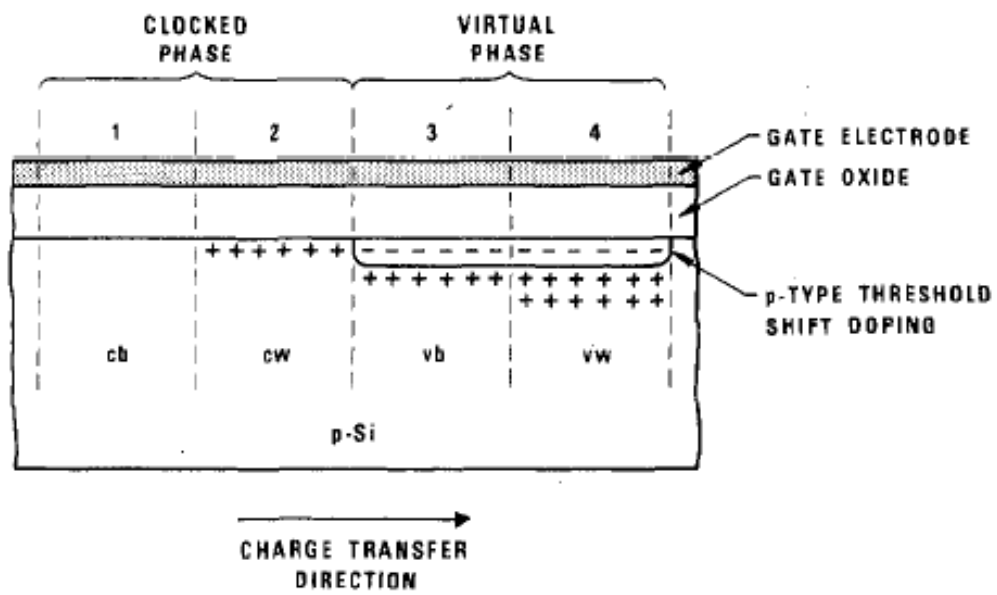
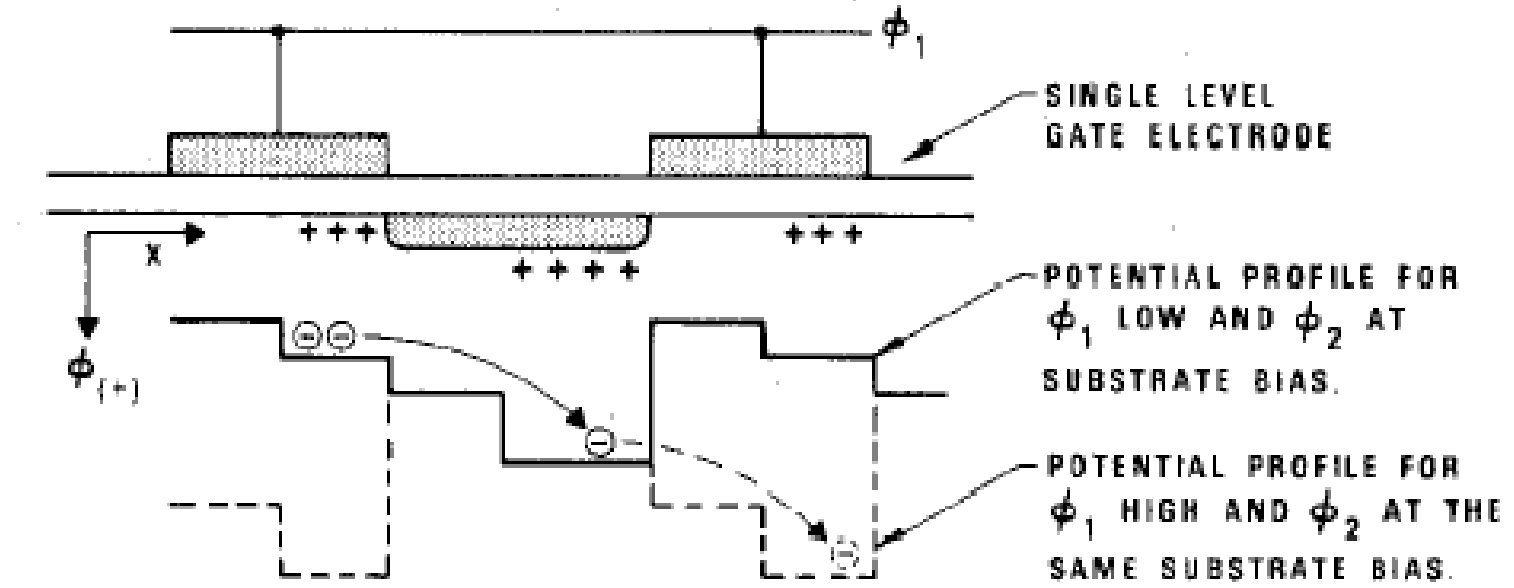
il trasferimento avviene per diffusione  $\rightarrow$  aggiunta di un campo elettrico





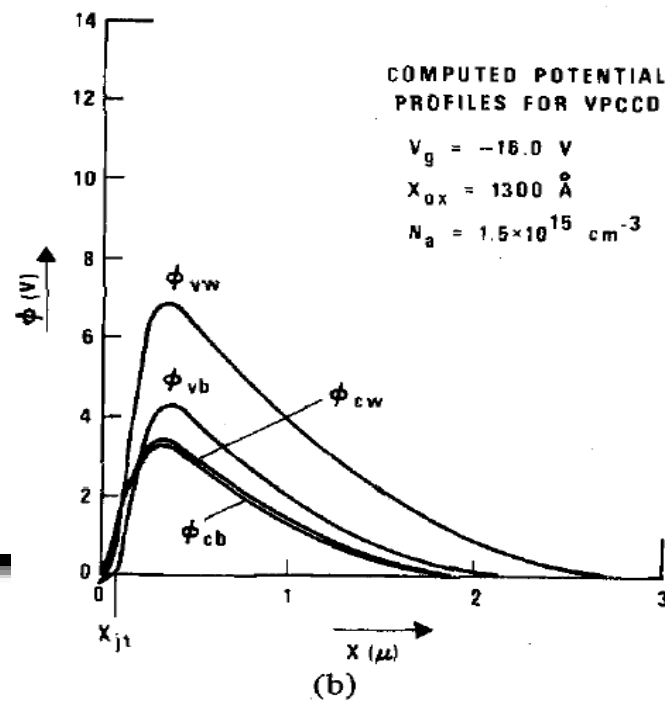
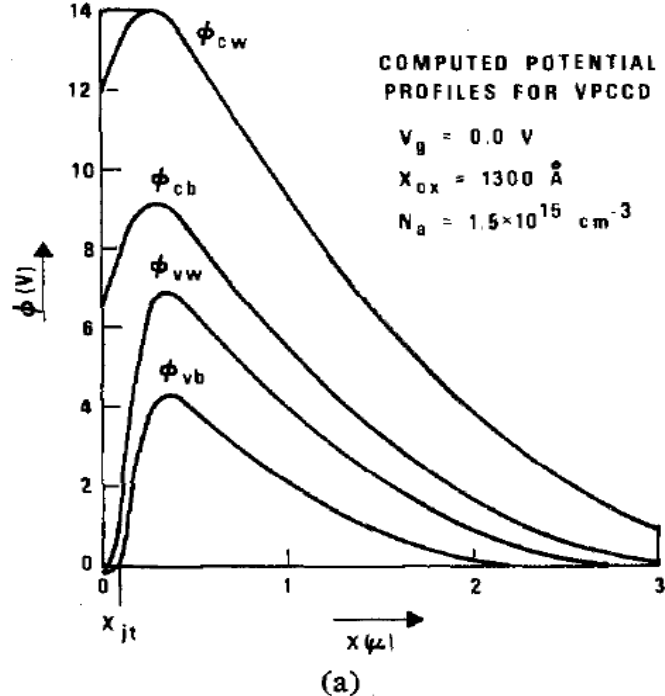
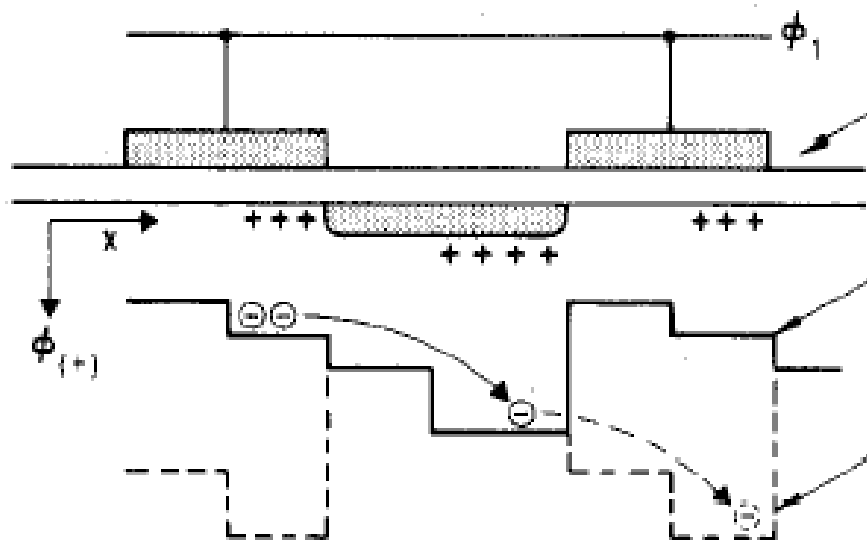
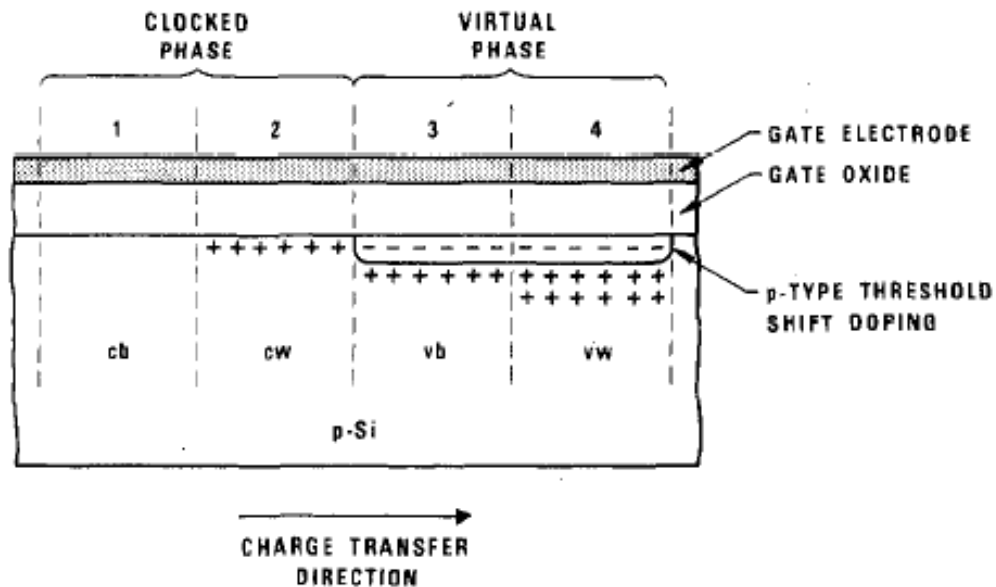






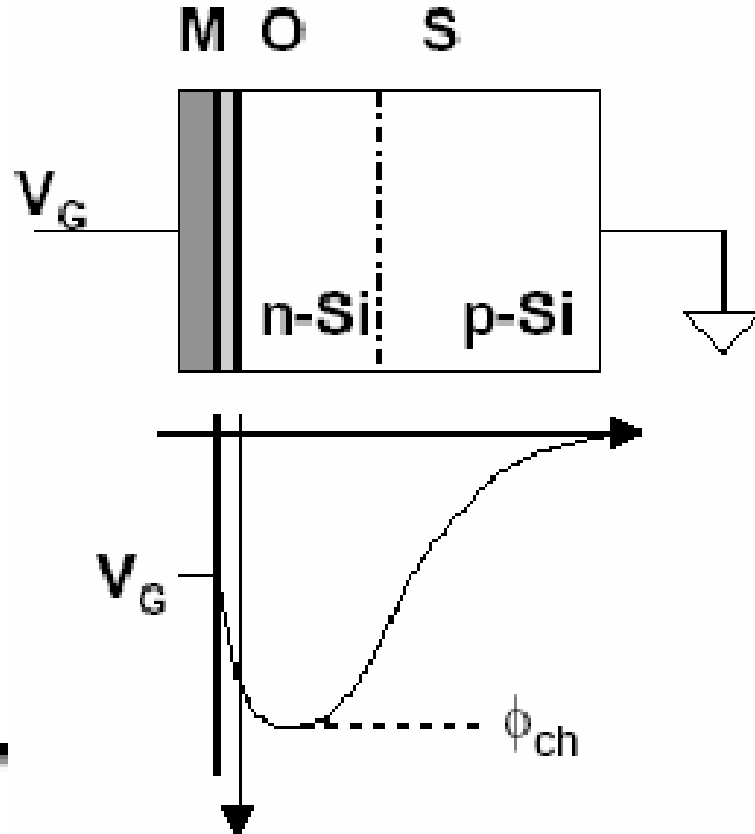
Cross section of one pixel of a **VP CCD** in the direction of charge transfer. The various regions are denoted as clocked barrier "**cb**," clocked well "**cw**," virtual barrier "**vb**," and virtual well "**vw**."





## II problema:

1. riduzione dei difetti cristallografici all'interfaccia Si-SiO<sub>2</sub>
2. aggiunta di una quantità di carica fissa in ogni buca che satura gli stati superficiali (ma riduce il range dinamico)
3. allontanamento della buca di potenziale dall'interfaccia → **BCCD**

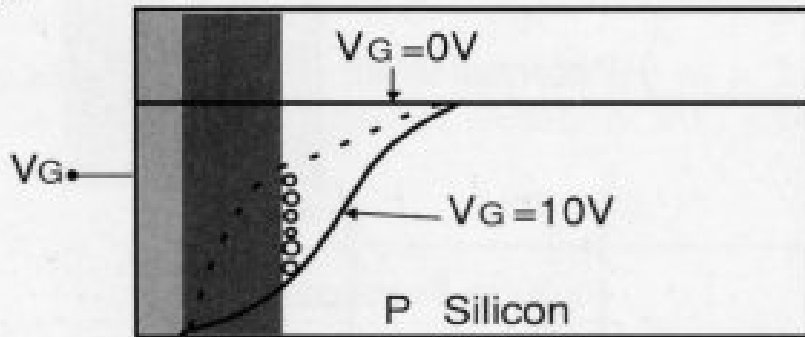


la giunzione n-p è mantenuta in inversa

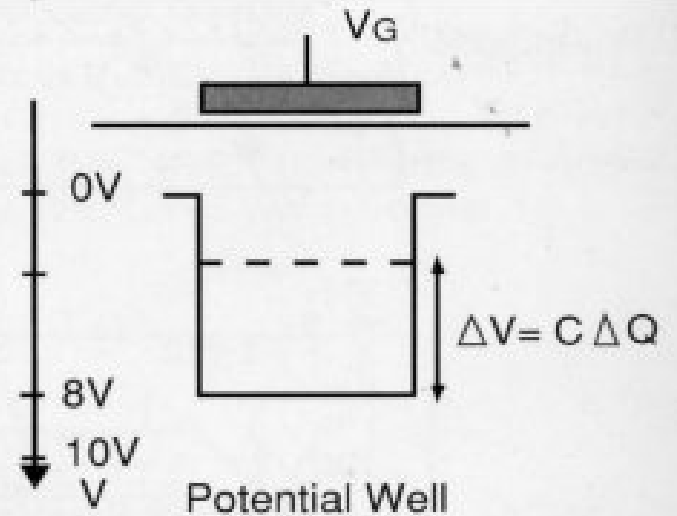
**vantaggio:**  $\varepsilon = 10^{-5}$

**svantaggio:** la capacità è ridotta

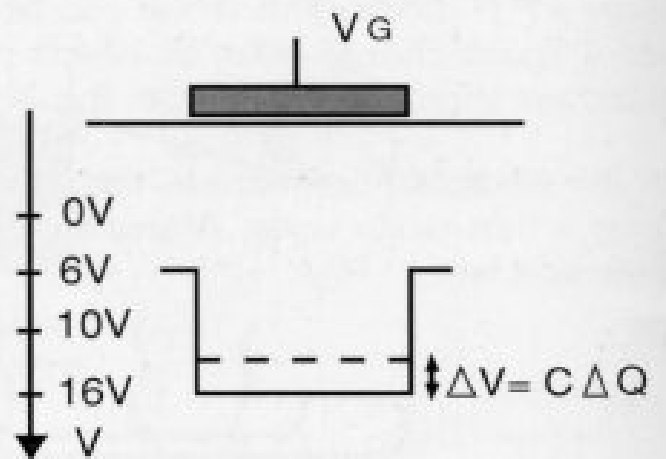
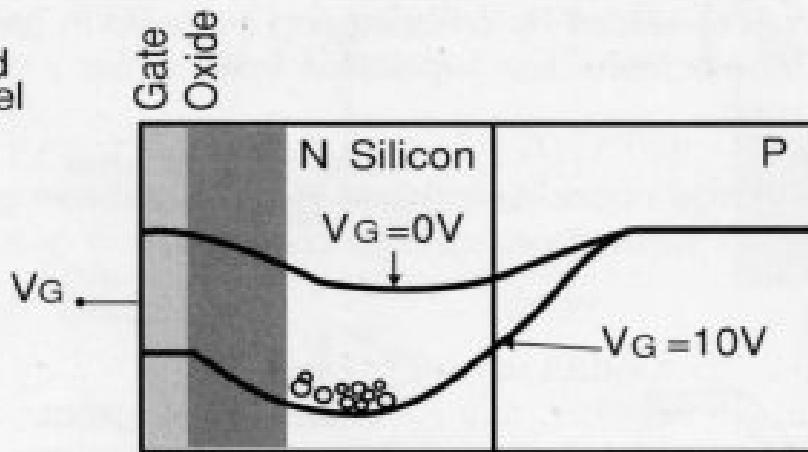
Surface Channel



Potential Profile in Silicon

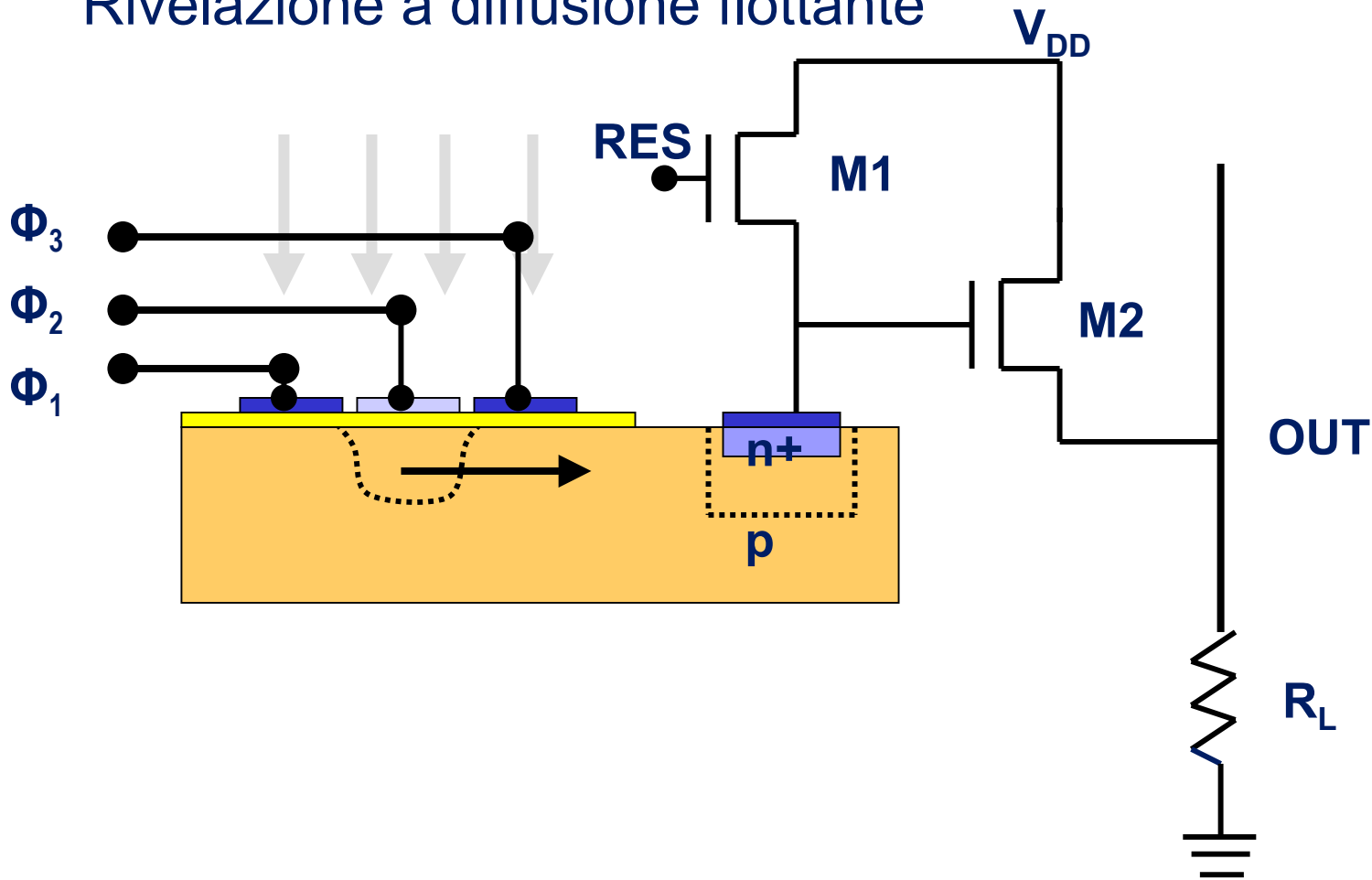


Buried Channel



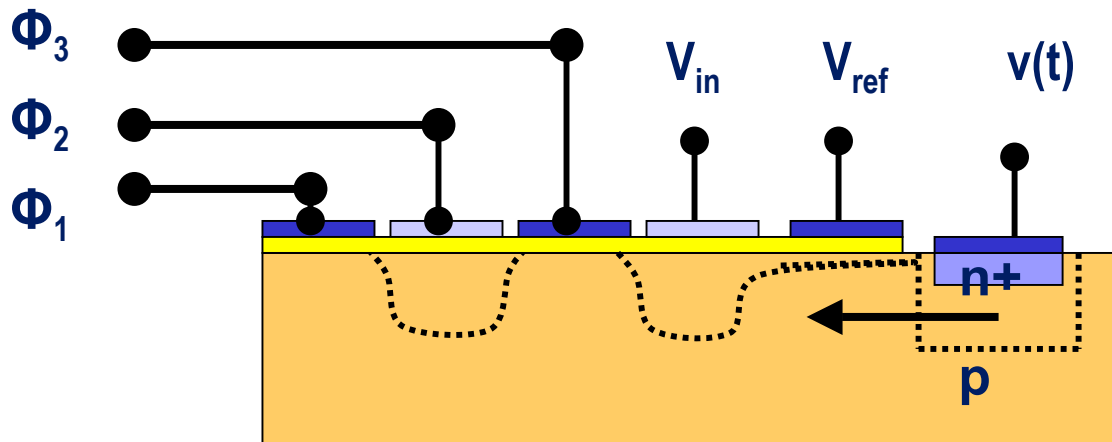
# 3. Lettura (read-out)

Rivelazione a diffusione flottante

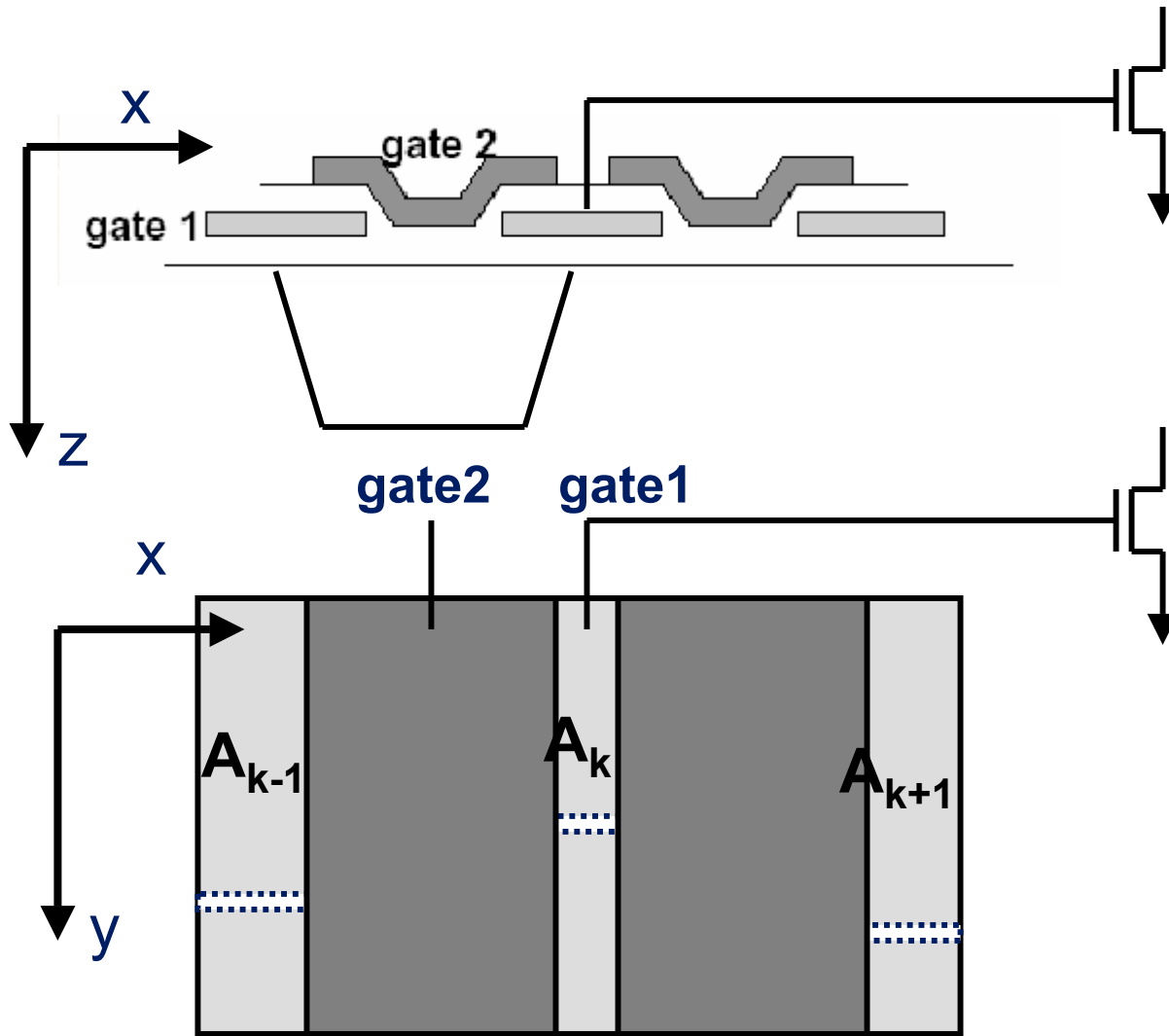


# Funzionamento del CCD come registro a scorrimento (memoria seriale) o come linea di ritardo analogica a valori campionati (filtro)

1. Campionamento del segnale elettrico
2. Trasferimento della carica



### 3. Lettura non distruttiva della carica (a gate flottante)



# Sensori ottici

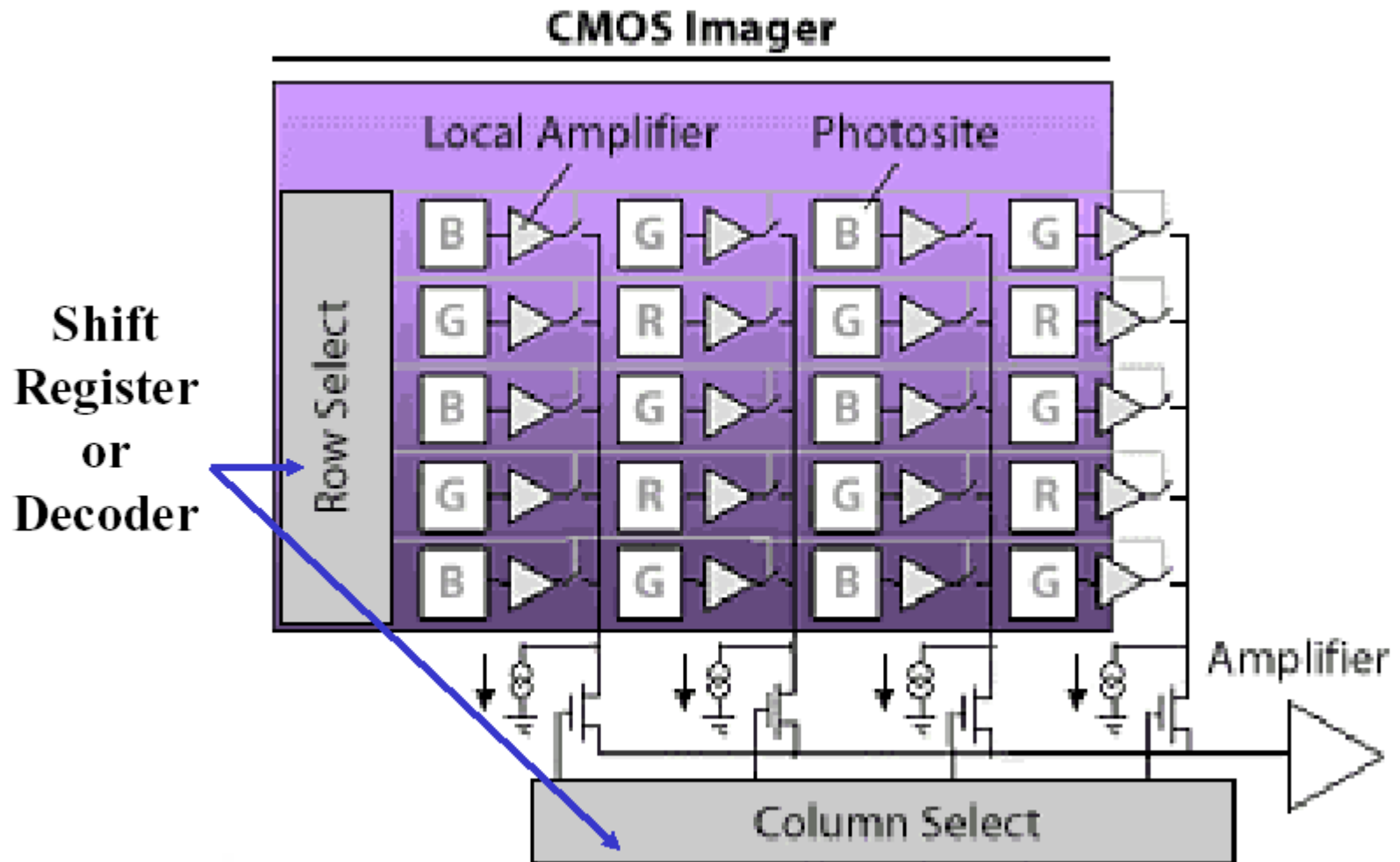
Caratterizzazione dei sensori ottici:

- architetture
  1. architettura a matrice di fotodiodi
  2. sensore CMOS
  3. sensore CID
  4. sensore CCD lineare
  5. Full Frame Transfer CCD
  6. Frame Transfer CCD
  7. Interline Transfet CCD

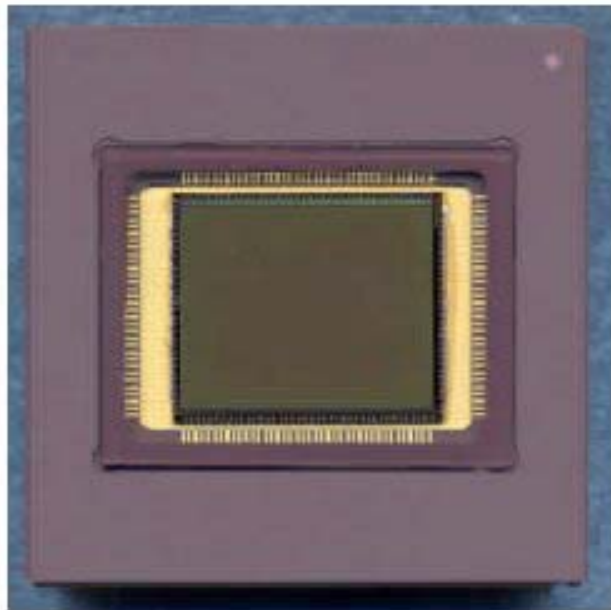
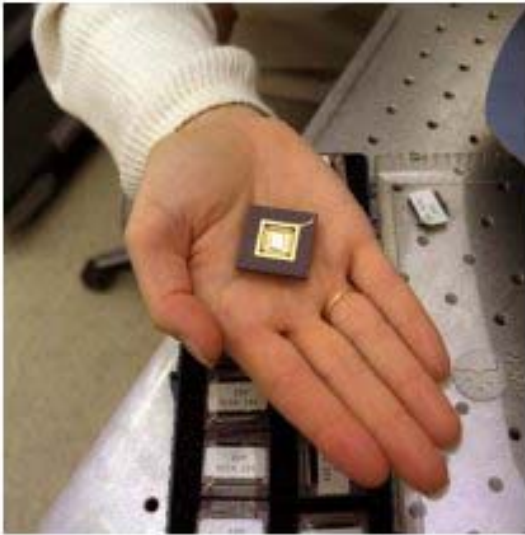




# Architettura di un sensore CMOS



# Architettura di un sensore CMOS APS

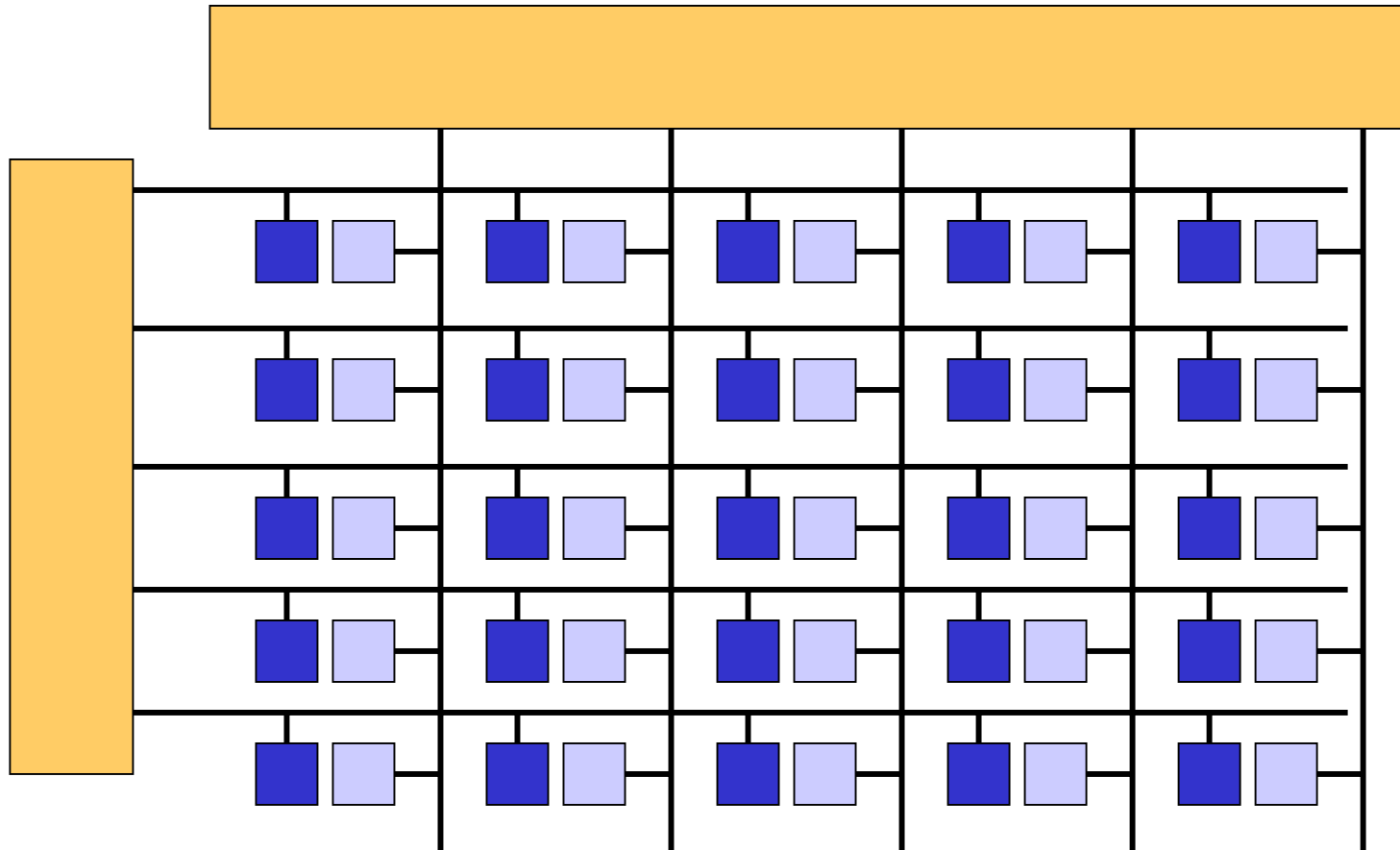


Es. Fillfactory 1.3k × 1k

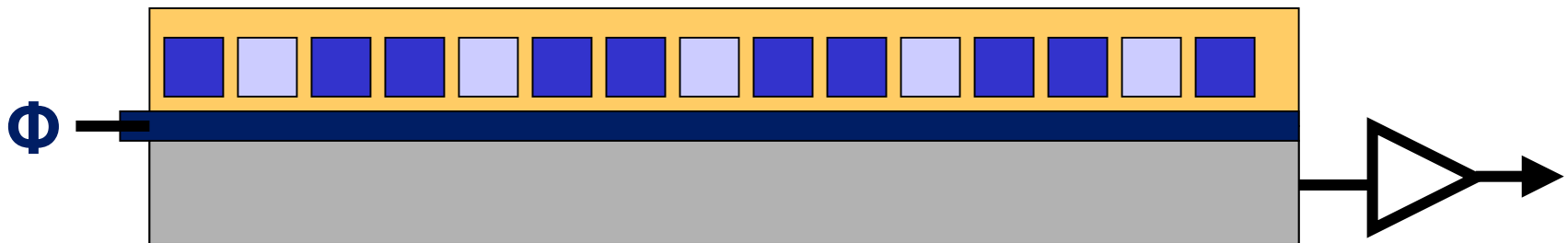
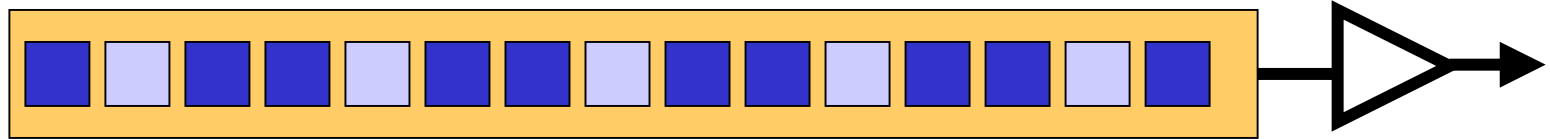
| Parameter            | Value                                      |
|----------------------|--|
| Pixel pitch          | 14 * 14 $\mu\text{m}^2$                    |
| Resolution           | 1280 * 1024                                |
| Frame rate           | 450 fr/sec@ 40MHz                          |
| die size             | 19.2 * 16.2 $\text{mm}^2$                  |
| Readout sequence     | Progressive scan                           |
| Shutter type         | Synchronous with variable integration time |
| Windowing            | Programmable via SPI                       |
| Number of outputs    | 16   |
| Color filter pattern | Bayer (first pixel = red)                  |
| Package              | Pin grid array 145 pins                    |

Table 1 : general specifications of the LUPA sensor

# Architettura di un sensore CID (Charge Injection Device)



# Architettura di un sensore CCD lineare



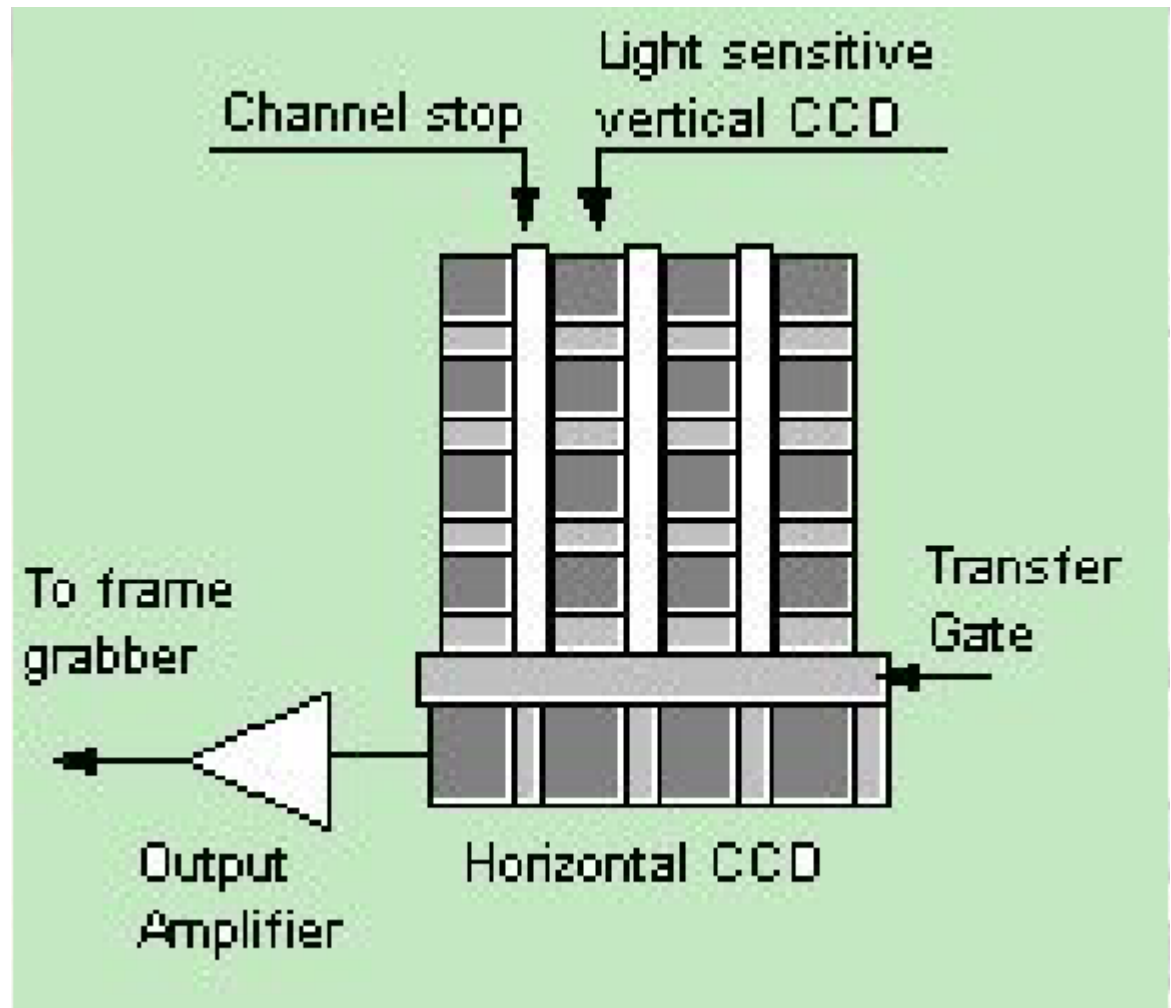
# Architetture per sensori CCD a matrice

## Full Frame Transfer CCD

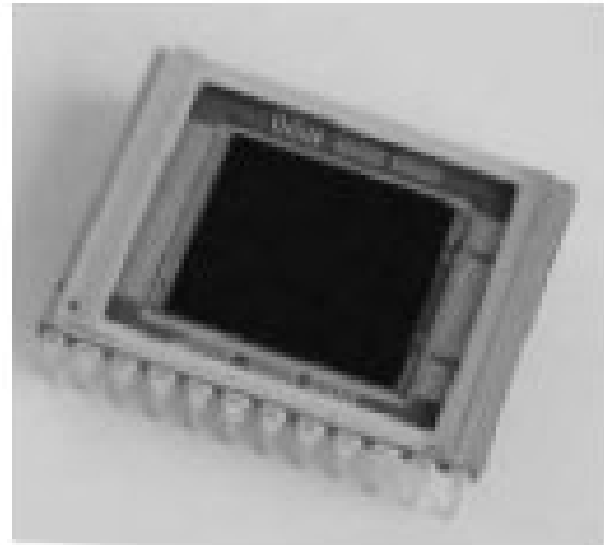
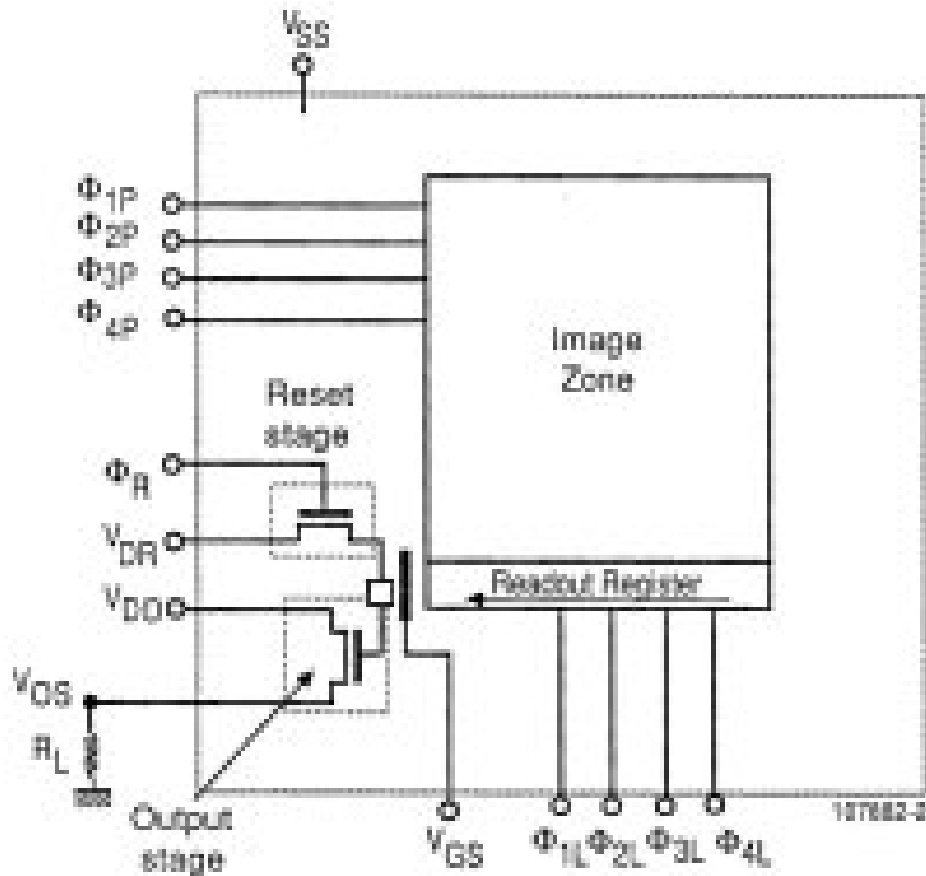
→max risoluzione

→occorre l'otturatore  
meccanico

(KODAK KAF0400)



# Architetture per sensori CCD a matrice



**Figure 21b** - Full-frame FT sensor organization

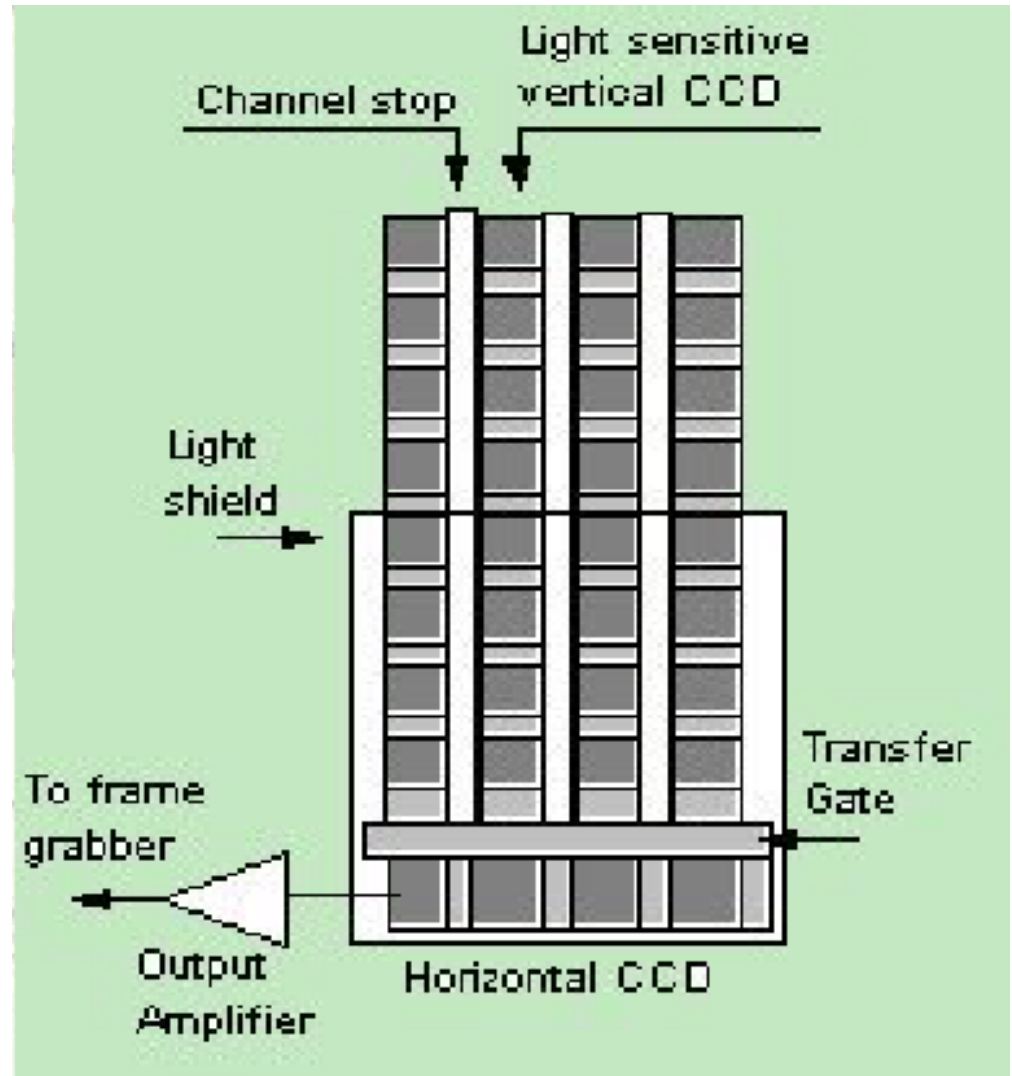
# Architetture per sensori CCD a matrice

## Frame Transfer CCD

→ max risoluzione

→ non occorre  
l'otturatore meccanico

(PHILIPS FT12)



# Architetture per sensori CCD a matrice

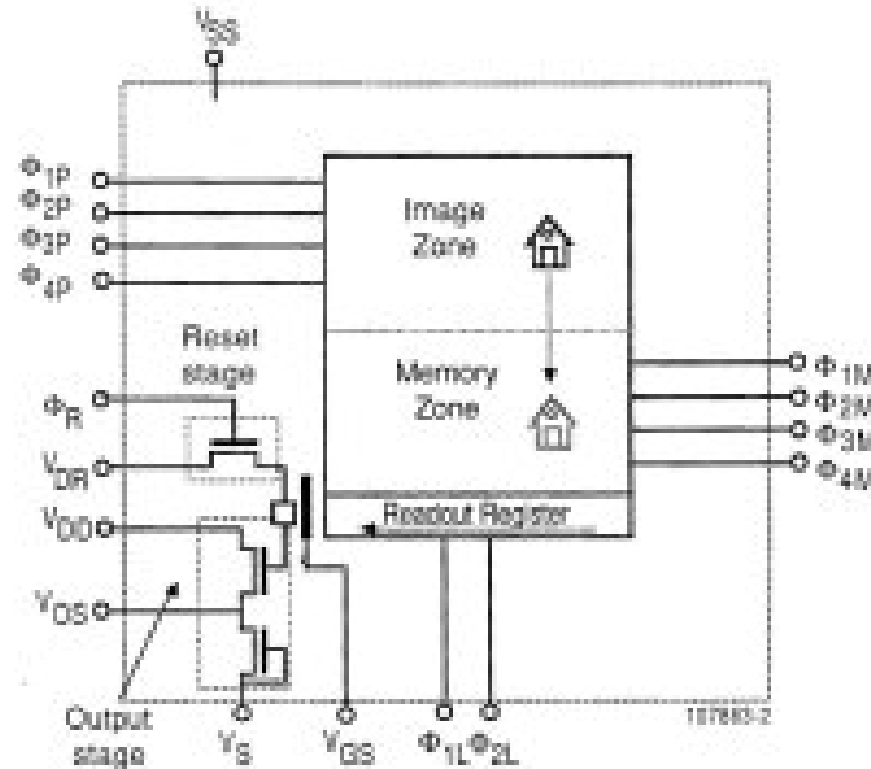
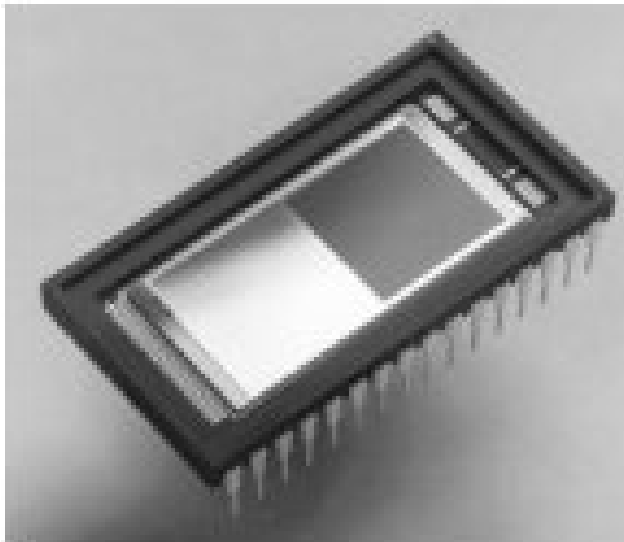


Figure 21a - TV mode FT sensor organization



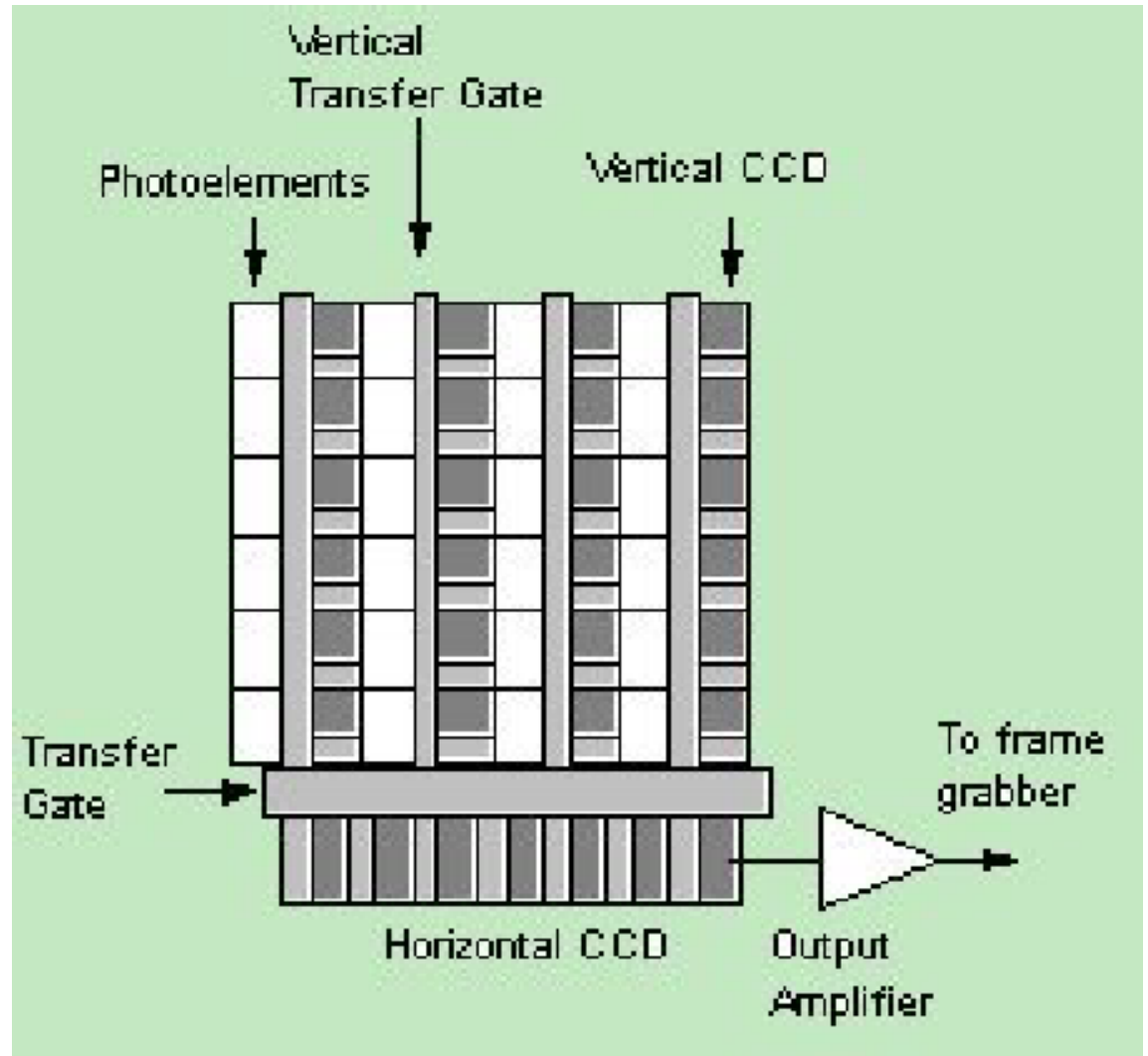
# Architetture per sensori CCD a matrice

## Interline Transfer CCD

→ si riduce il tempo tra due immagini

→ ridotta risoluzione (30% di zona buia)

(SONY)



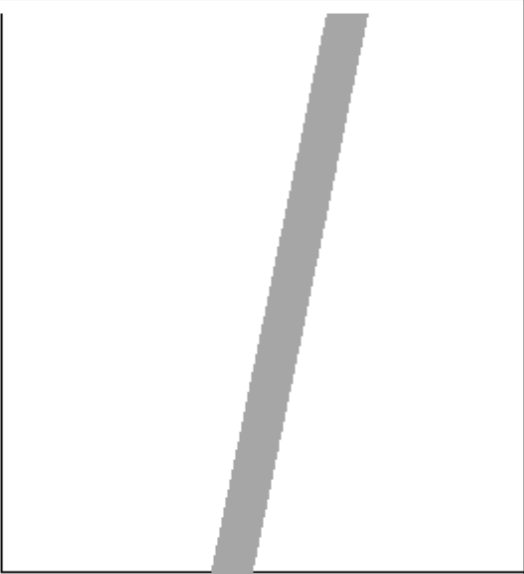
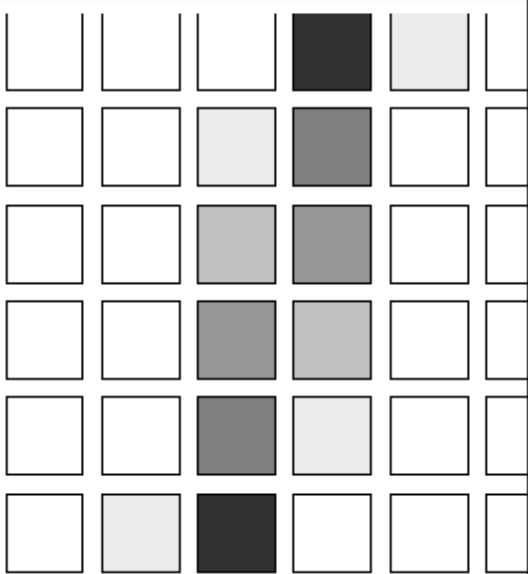
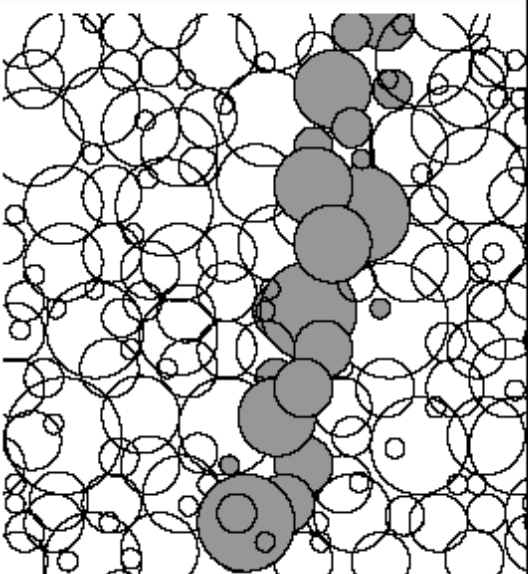
# Sensori ottici

Caratterizzazione dei sensori ottici:

- condizioni operative e prestazioni
  1. risoluzione spaziale dell'immagine
  2. gestione dei colori
  3. riflessione superficiale e rifrazione degli strati interposti di dielettrico
  4. blooming
  5. fill-factor

# Risoluzione spaziale dell'immagine

**The image of a thin line is not a thin line**

|   |  |   |
|---|--|---|
|  |  |  |
| <b>Image of a thin line</b>   | <b>Pixel array</b>   | <b>Film grains</b>  |

## Risoluzione spaziale dell'immagine

| Camera                   | sensor type | n. pixel | sensor size                 | pixel size |
|--------------------------|-------------|----------|-----------------------------|------------|
| Konica-Minolta DiMAGE Xg | CCD         | 3.3M     | 5.3 x 4.0 mm <sup>2</sup>   | 2.6 um     |
| PowerShot S500           | CCD         | 5.0M     | 7.2 x 5.3 mm <sup>2</sup>   | 2.7 um     |
| Nikon Coolpix 8700       | CCD         | 8.0M     | 8.8 x 6.6 mm <sup>2</sup>   | 2.7 um     |
| Olympus C-8080 Wide Zoom | CCD         | 8.0M     | 8.8 x 6.6 mm <sup>2</sup>   | 2.7 um     |
| Sony DSC-828             | CCD         | 8.0M     | 8.8 x 6.6 mm <sup>2</sup>   | 2.7 um     |
| Konica Minolta Dimage A2 | CCD         | 8.0M     | 8.8 x 6.6 mm <sup>2</sup>   | 2.7 um     |
| Nikon D70                | CCD         | 6.1M     | 23.7 x 15.6 mm <sup>2</sup> | 7.8 um     |
| Canon EOS-1Ds            | CMOS        | 11.4M    | 36 x 24 mm <sup>2</sup>     | 8.8 um     |
| Kodak DCS-14n            | CMOS        | 13.8M    | 36 x 24 mm <sup>2</sup>     | 8.0 um     |

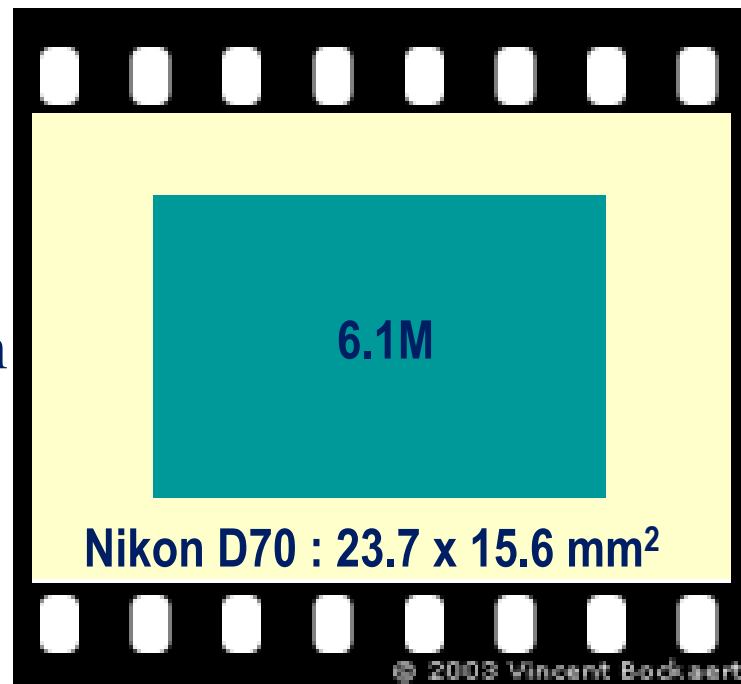
**rapporto di forma 4:3**

**rapporto di forma 3:2**

# Risoluzione spaziale dell'immagine



24 mm



36 mm

Dimensione dei pixel:

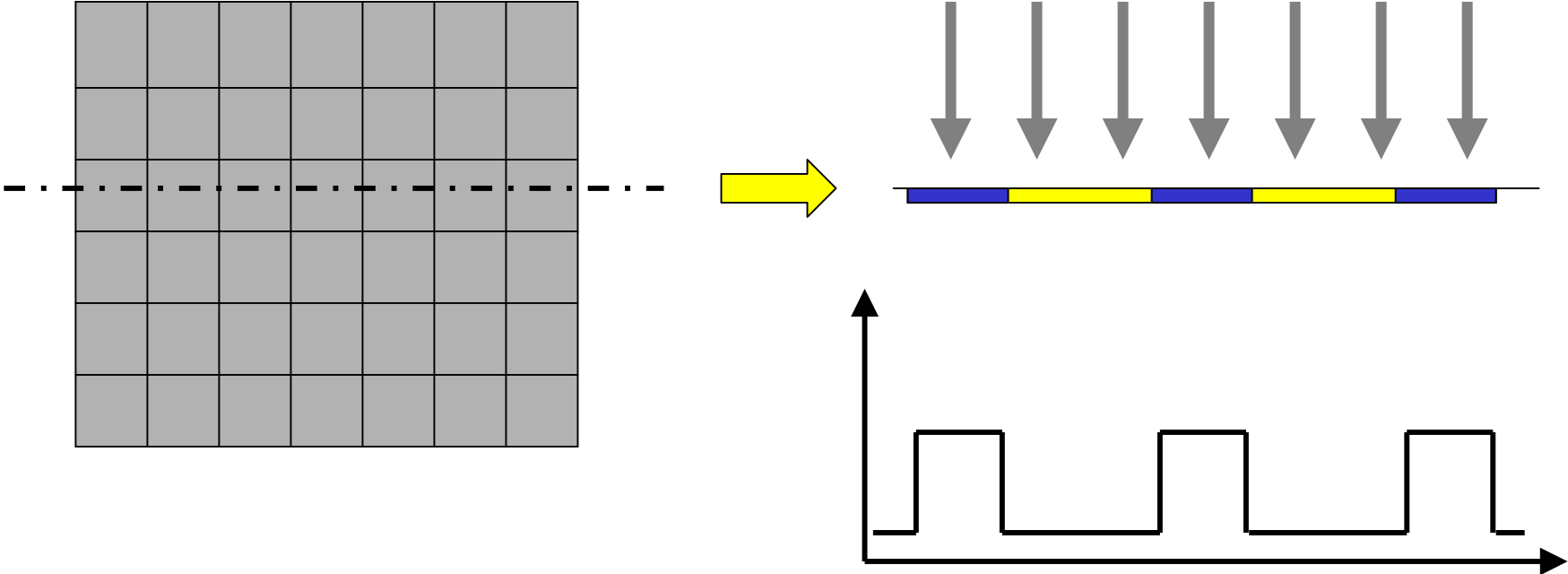


2.6um

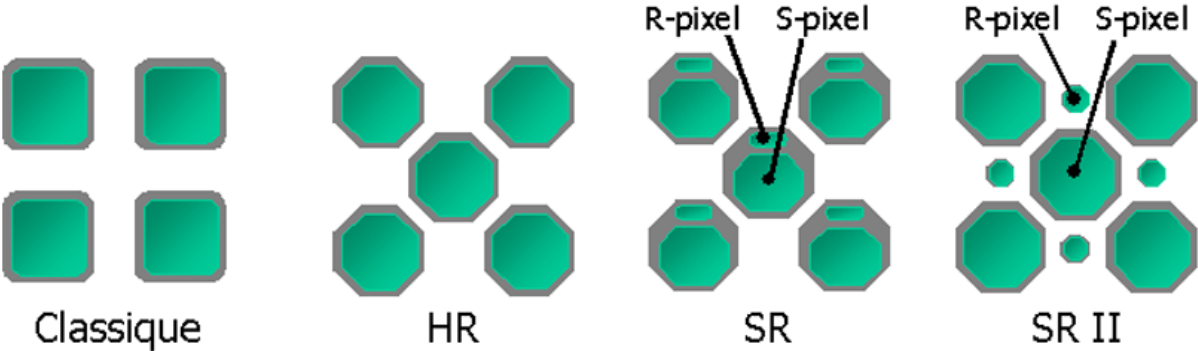


7.8um

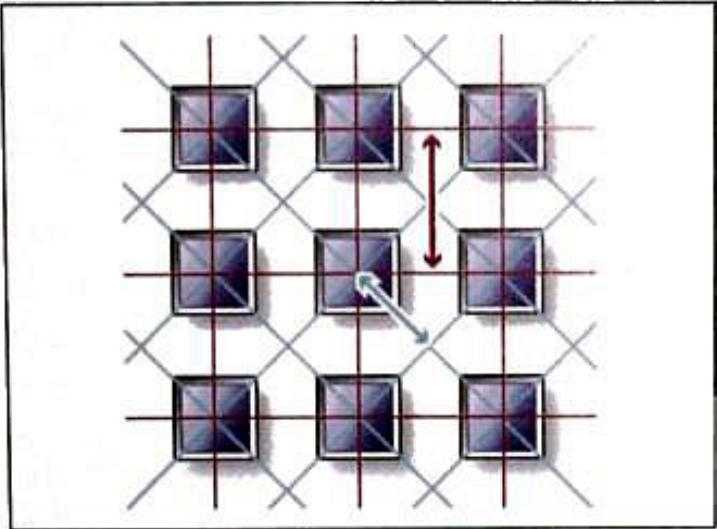
# Problemi relativi al campionamento dell'immagine



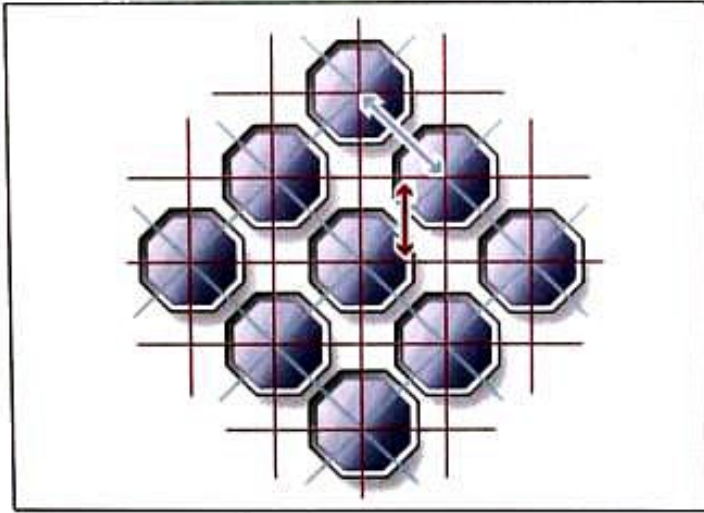
# Problemi relativi al campionamento dell'immagine



**HR** stands for "High Resolution" and **SR** stands for "Super dynamic Range"



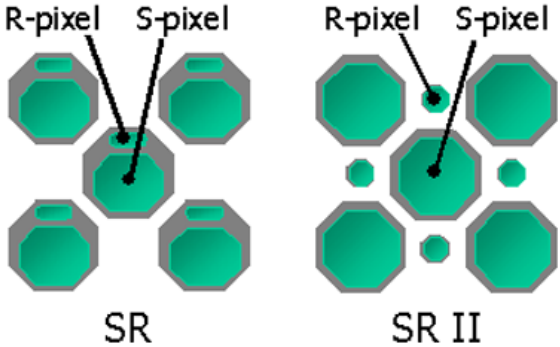
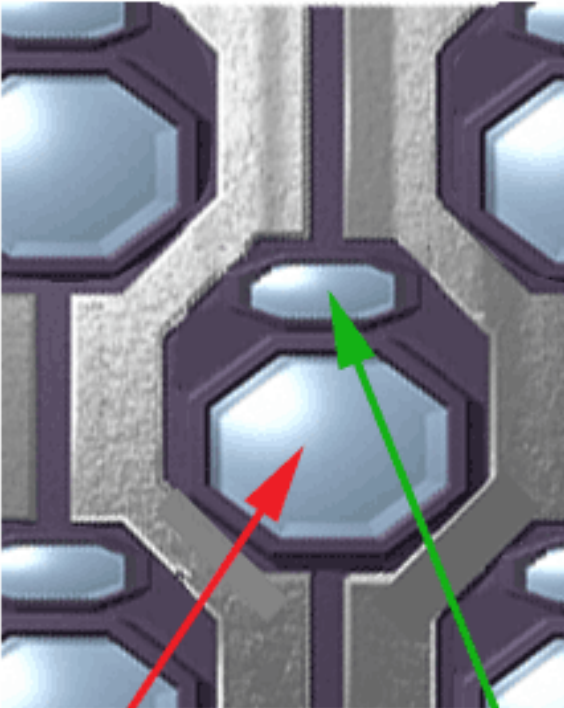
Since gaps are wider on the perpendicular axes, a conventional CCD suffers from horizontal/vertical resolution that is lower than the resolution on the diagonals.



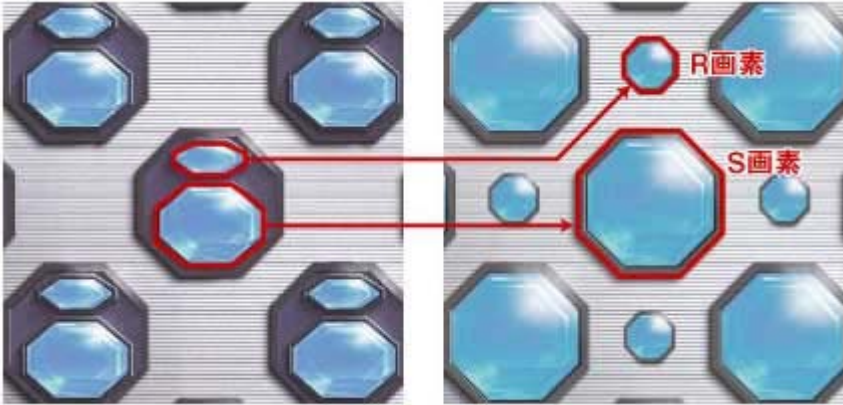
The Super CCD has narrower intervals on the perpendicular axes, so vertical/horizontal resolution is higher than diagonal resolution.

# Problemi relativi al campionamento dell'immagine

Super CCD SR



SR stands for "Super dynamic Range"



**S (Sensitivity) Pixel**  
**High sensitivity**  
 Captures bright dark areas,  
 but over-exposes light areas

**R (Range) Pixel**  
**Low sensitivity**  
 Captures bright light area,  
 but under-exposes dark areas



# Gestione del colore

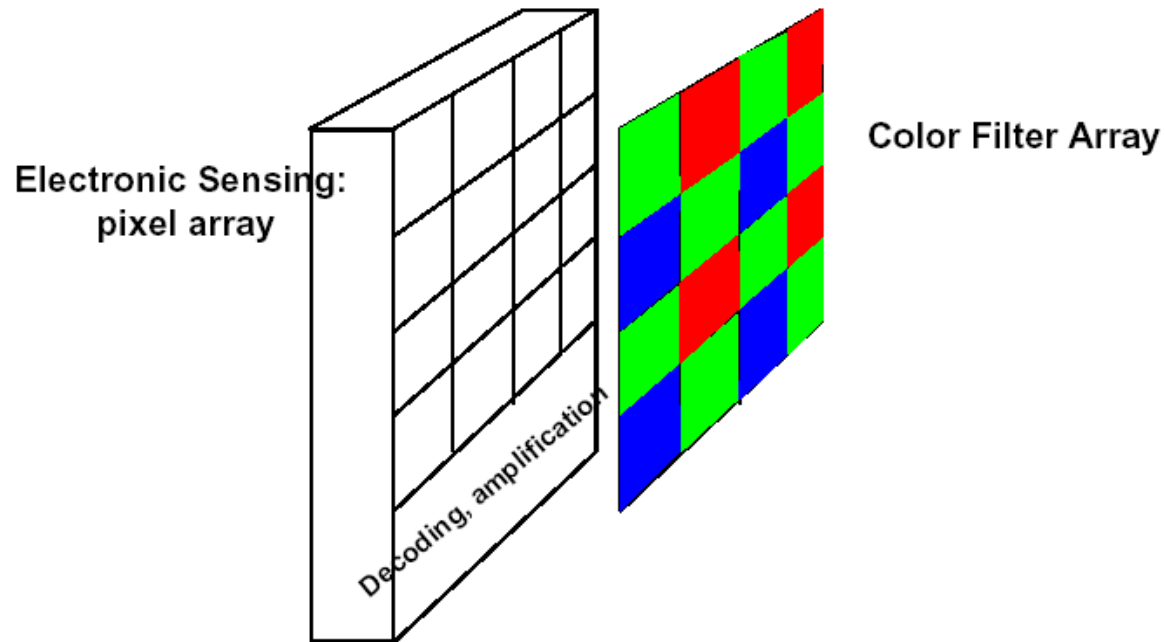
## Metodi:

1. illuminazione sequenziale con 3 filtri di colore RGB
  - sensore standard bianco/nero
  - lento, solo per immagini fisse
2. tre sensori “coperti” dai tre filtri di colore RGB
  - massima velocità, massima risoluzione
  - costoso, gestione parallela complessa

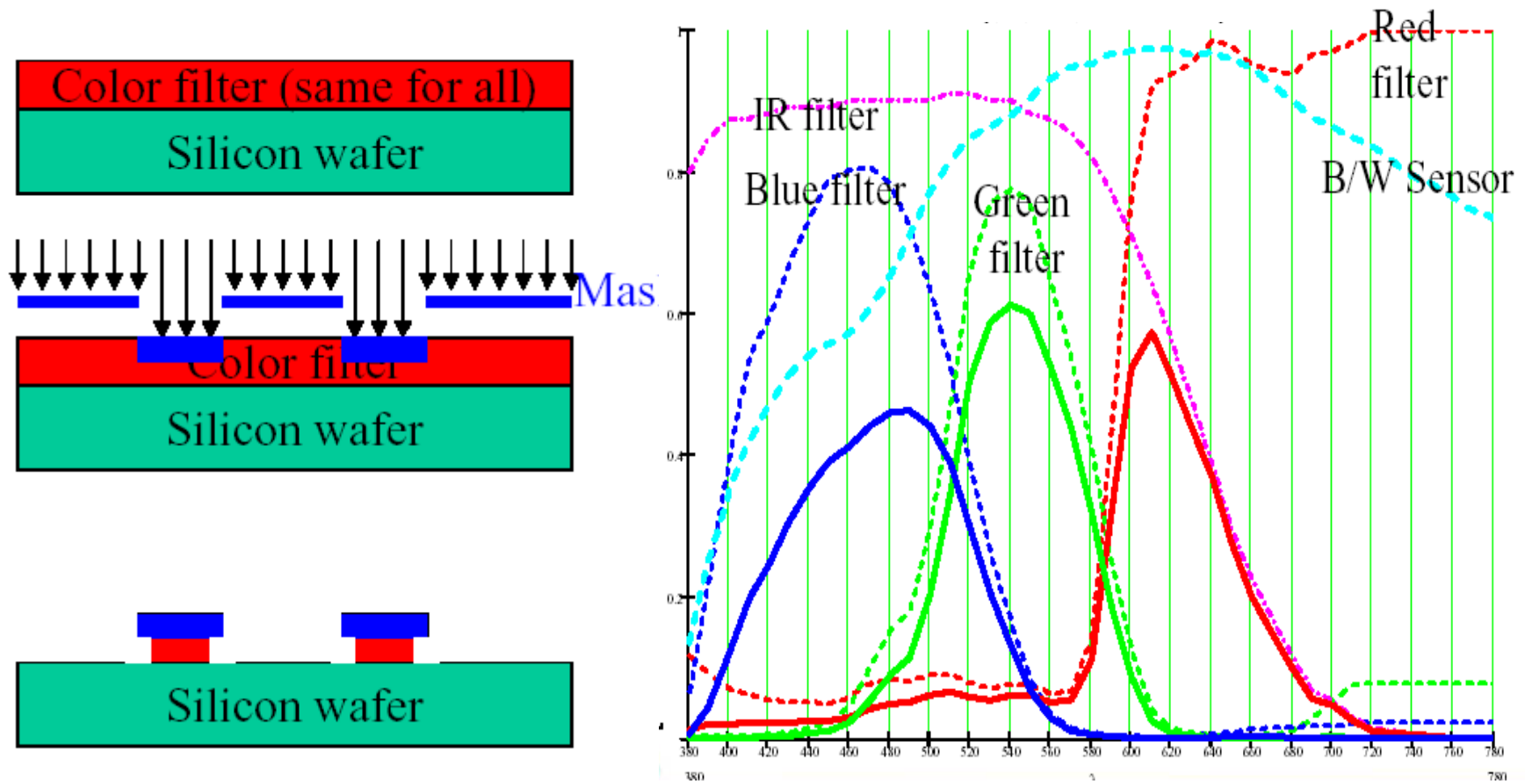
## Gestione del colore

### 3. pattern di filtri RGB realizzati con polimeri depositi sul sensore

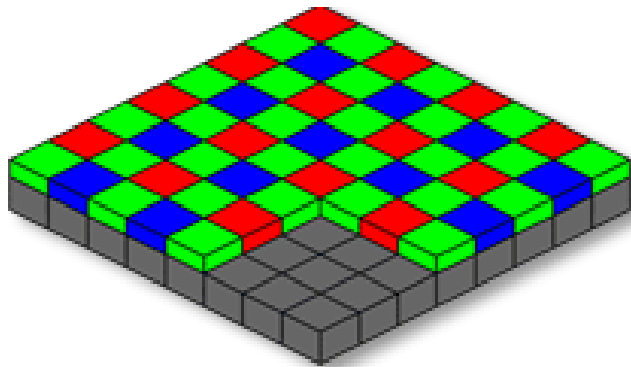
- sensore bianco/nero con uno strato superficiale in più
- ogni pixel ha un solo colore, distribuzione non uniforme dei colori



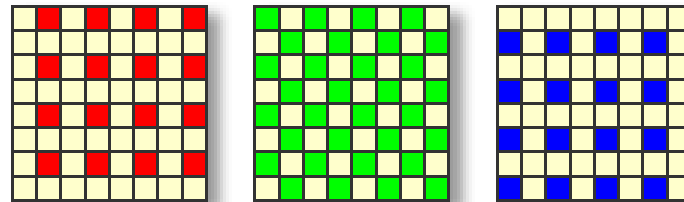
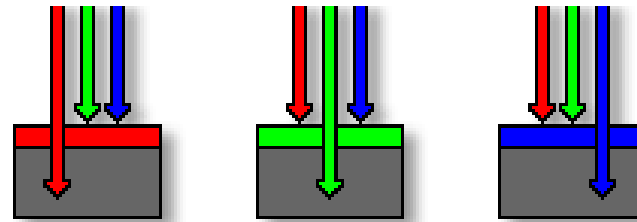
# Processo di deposizione degli array di filtri di colore



# pattern di Bayer GRGB



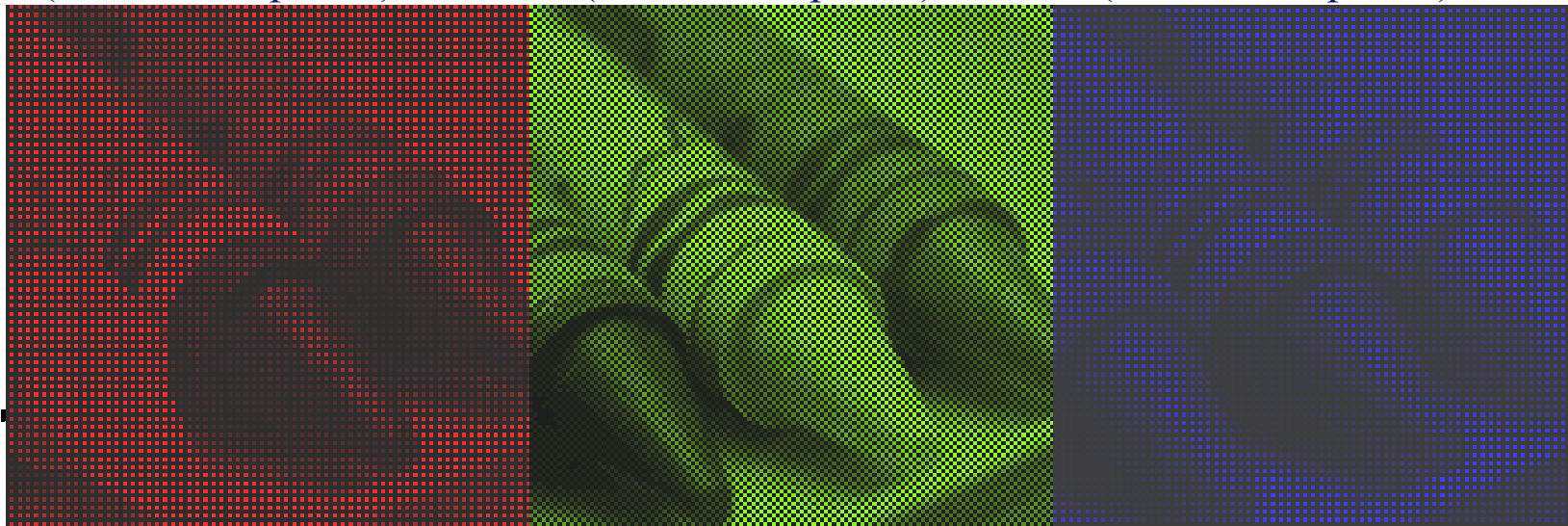
Color Filter Array Sensor



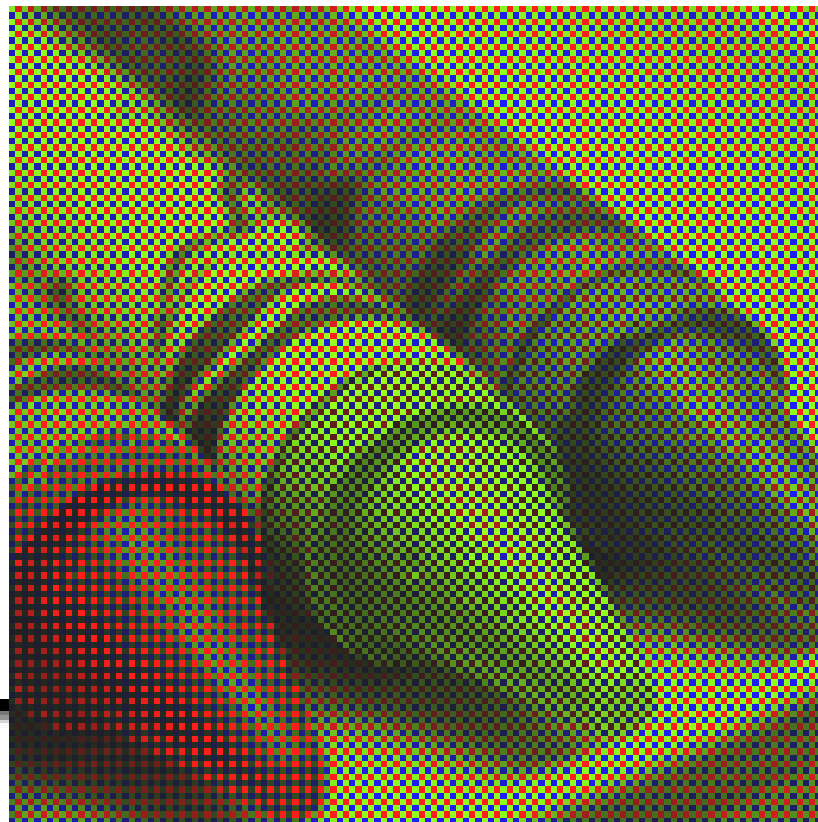
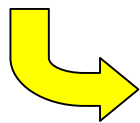
Red channel pixels  
(25% of the pixels)

Green channel pixels  
(50% of the pixels)

Blue channel pixels  
(25% of the pixels)



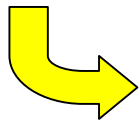
somma delle  
tre immagini  
campionate





immagini ricostruite  
con le medie dei  
primi vicini

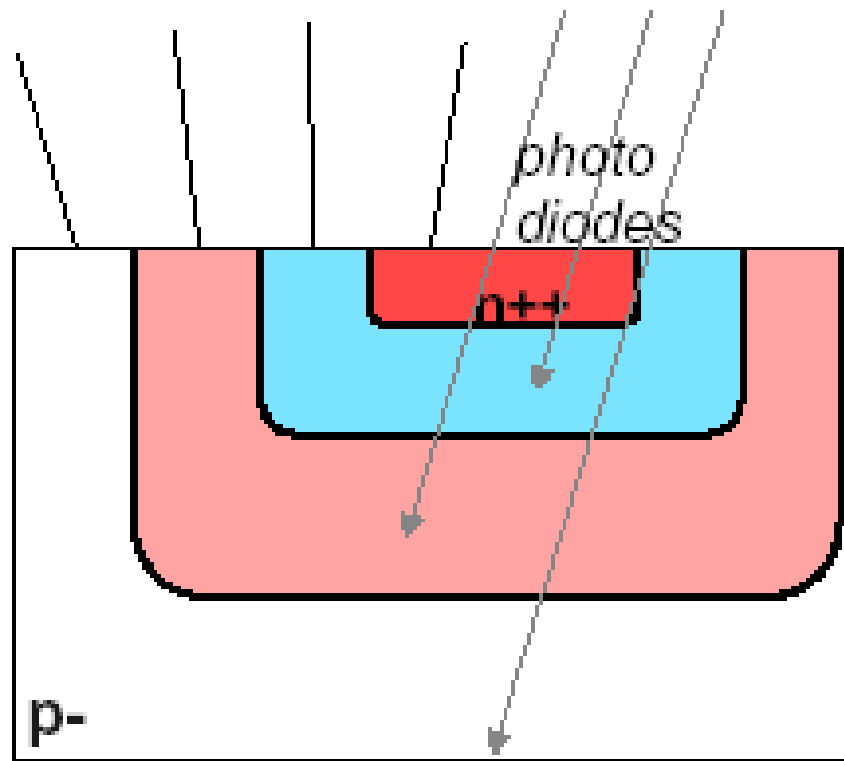
→ algoritmi di  
demosaicizzazione



## Gestione del colore

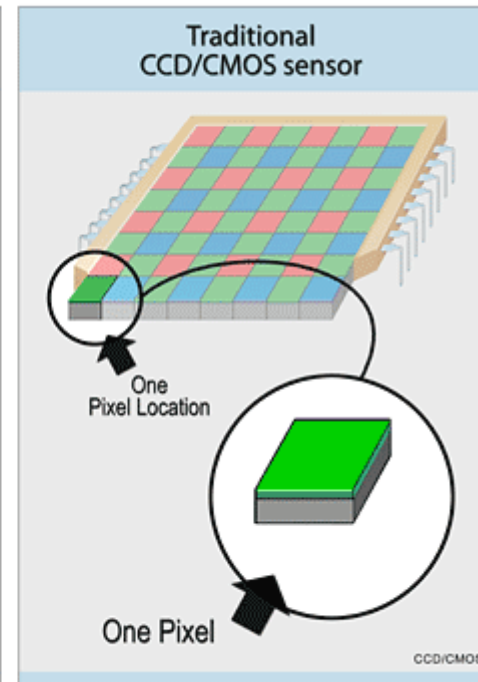
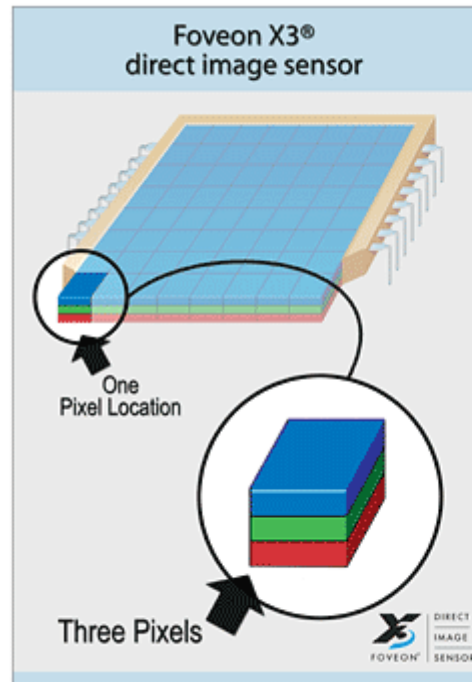
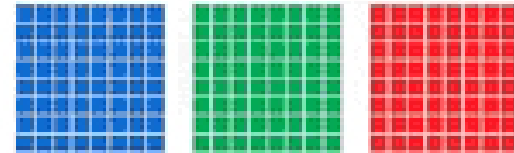
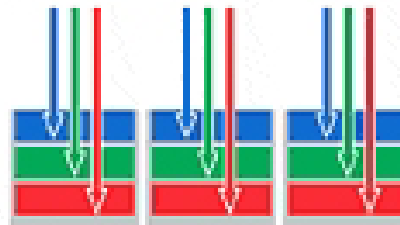
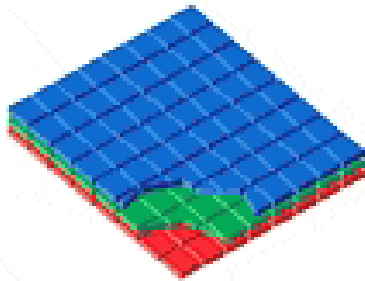
### 4. tre fotodiodi realizzati in verticale

- l'informazione completa sul colore in ogni pixel
- CMOS non standard



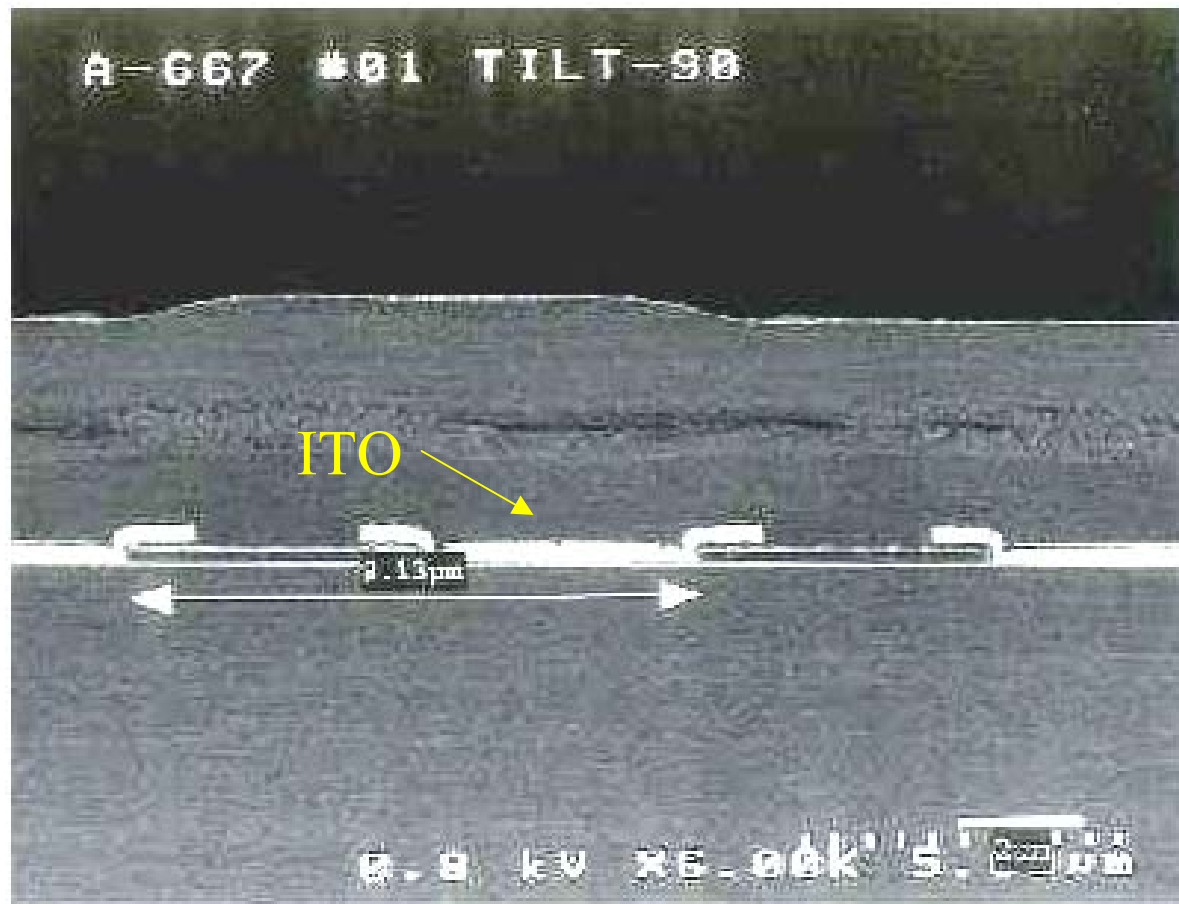
# La tecnica Foveon (SIGMA, Polaroid)

Foveon® X3™ Capture

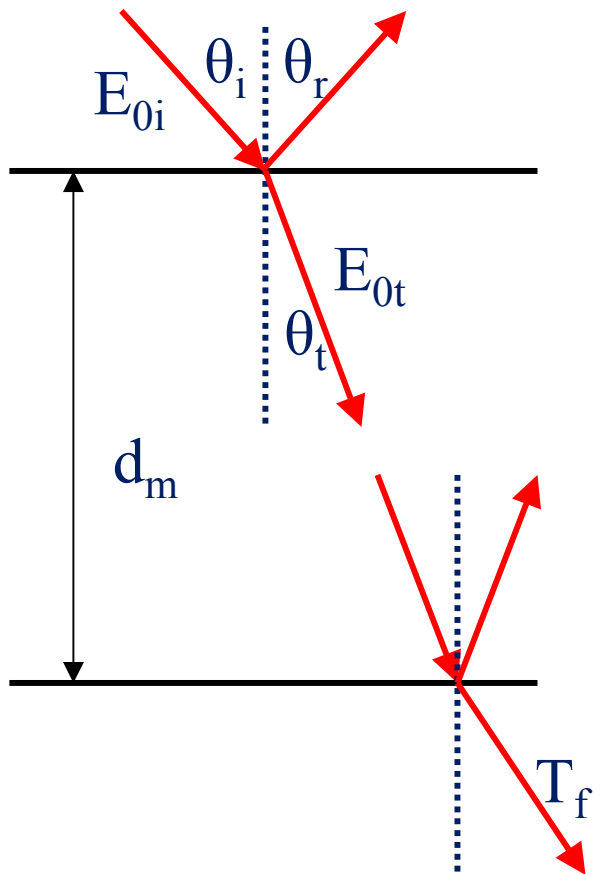




# Riflessione superficiale e rifrazione degli strati interposti di dielettrico



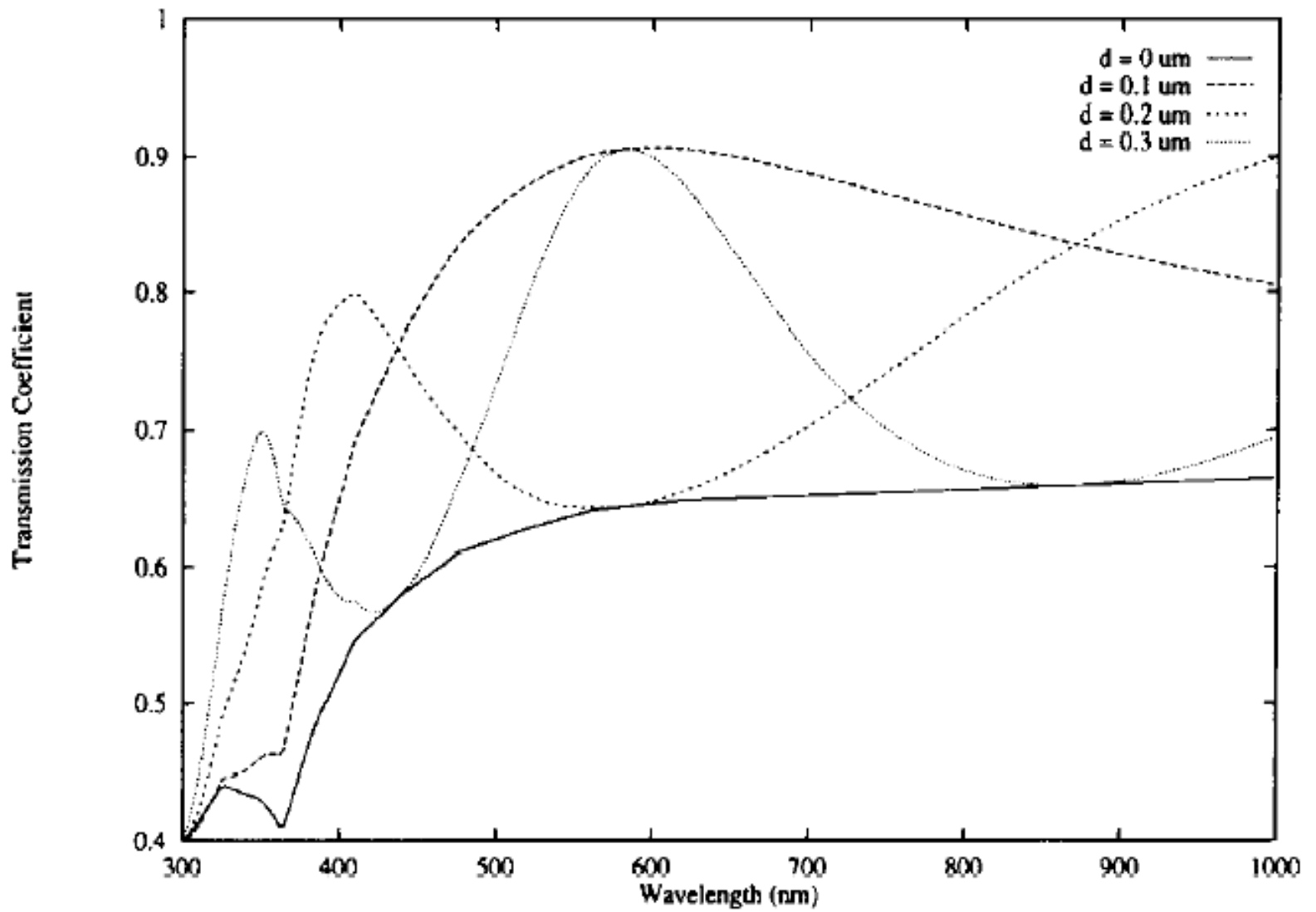
## Radiazione incidente su una superficie

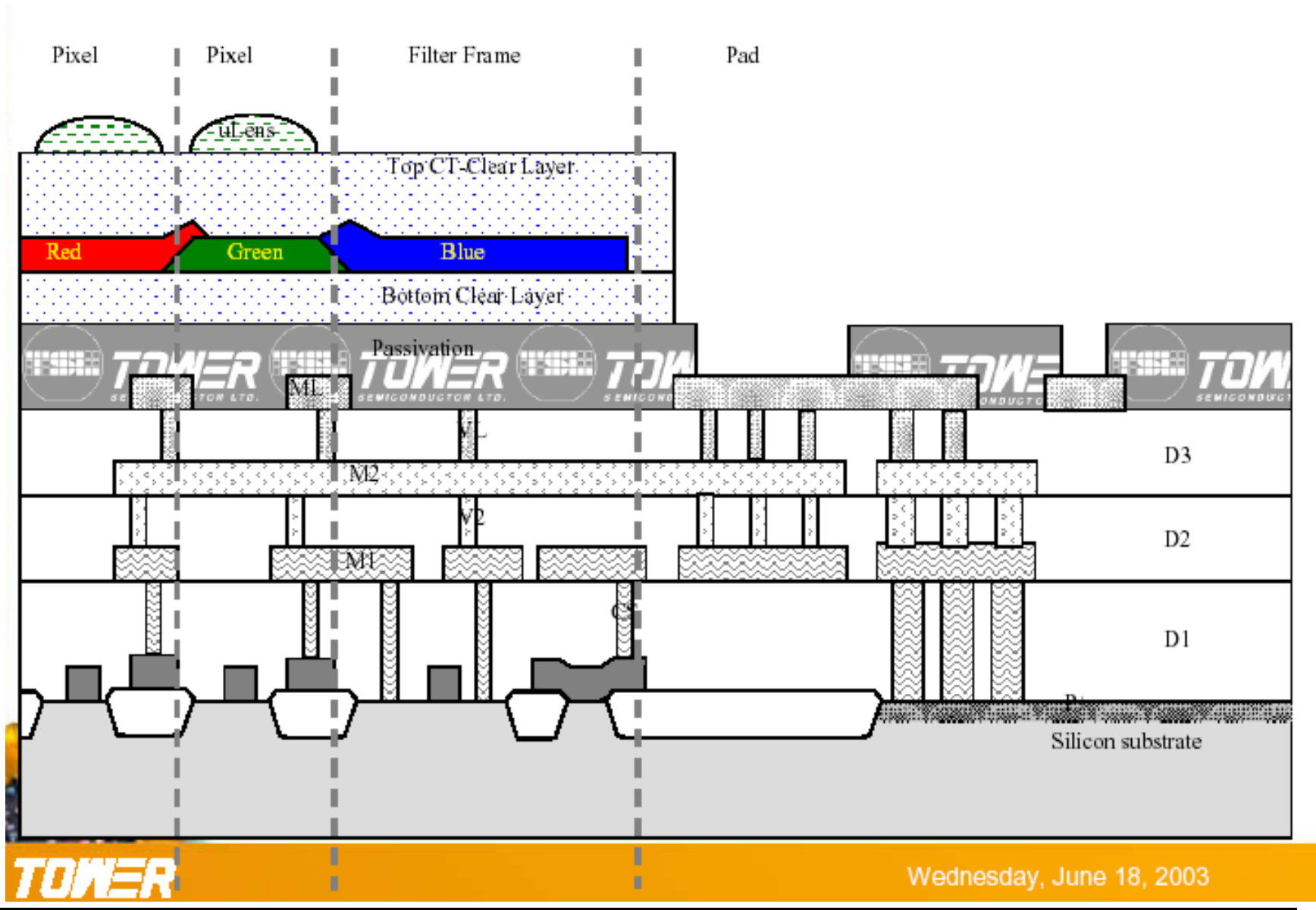


1. i raggi giacciono tutti sul piano di incidenza
2. gli angoli di incidenza e di riflessione sono uguali
3. Legge di Snell:  $n_i \sin\theta_i = n_t \sin\theta_t$
4. Equazioni di Fresnel:

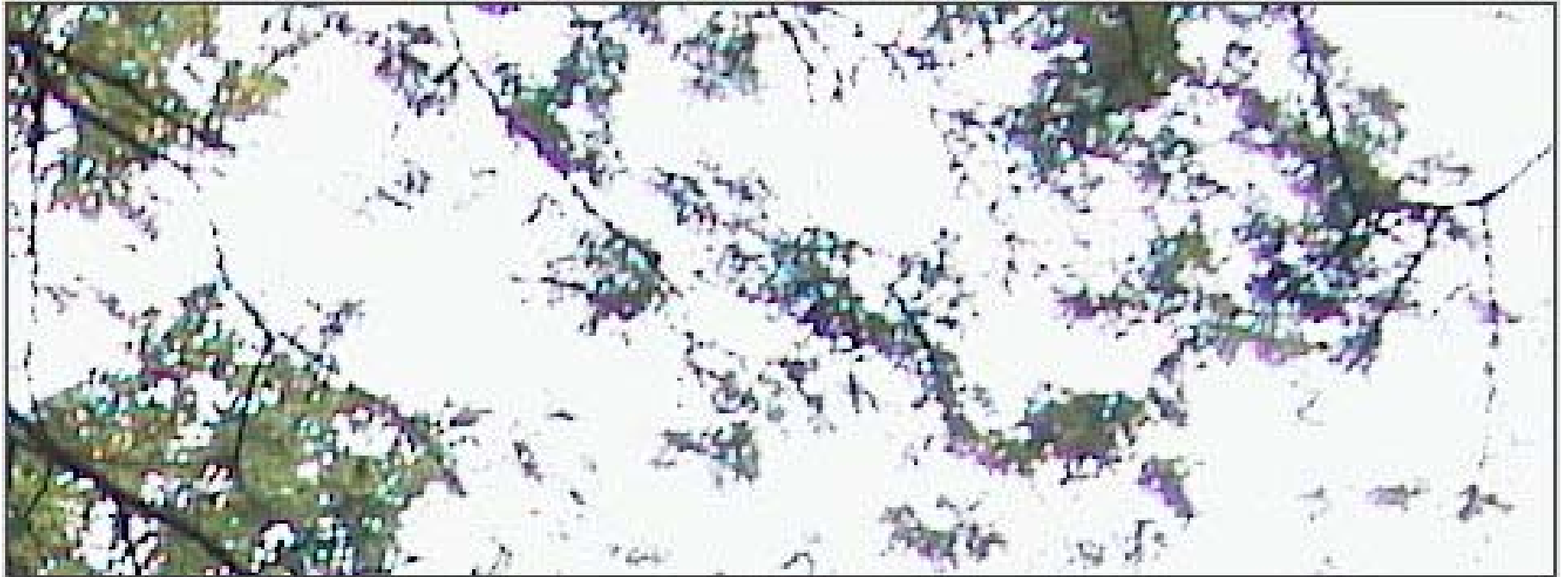
$$T = \left( \frac{n_t \cos\theta_t}{n_i \cos\theta_i} \right) \left( \frac{E_{0t}}{E_{0i}} \right)^2$$

5.  $T_f = T_f(d_m, \lambda, n_i, n_f, n_m)$

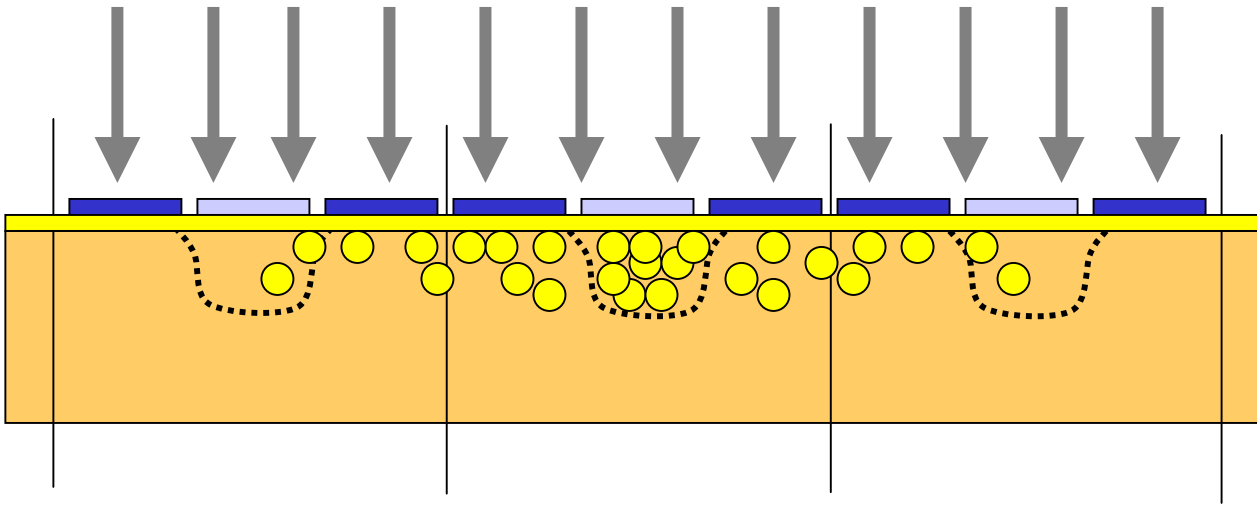




# Blooming



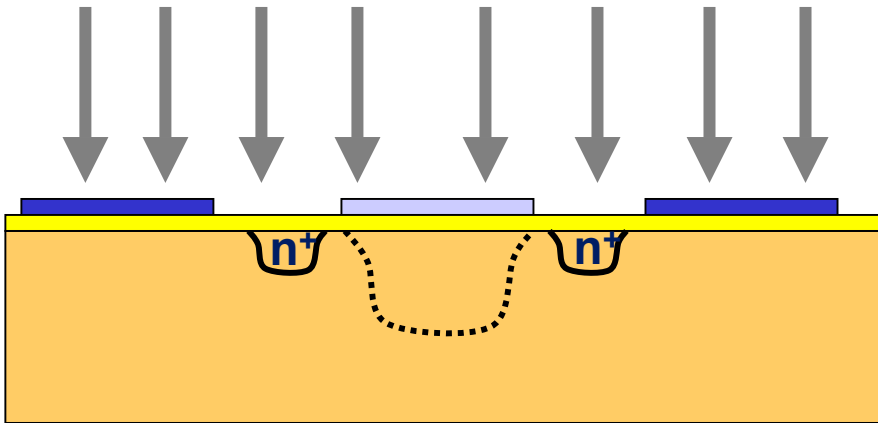
# Blooming



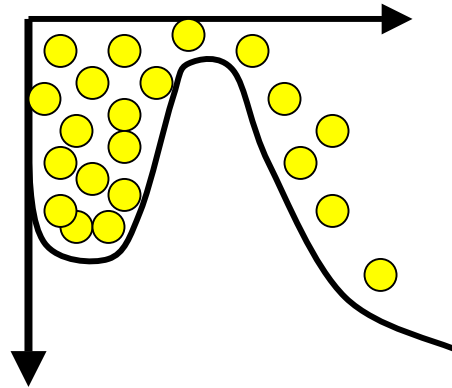
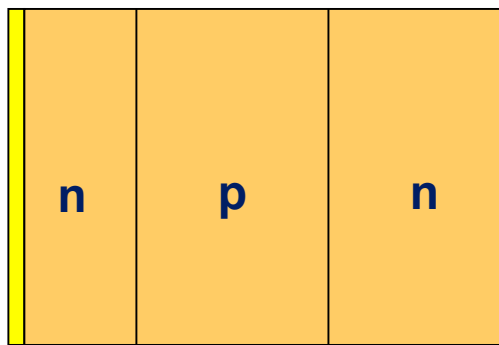
Carica di saturazione:  $Q_{iMAX} = -C_{ox} (V_{DD} - V_{FB})$

$Q_{iMAX} \sim -q \times 10^6 \text{ C}$

## Tecniche anti-blooming

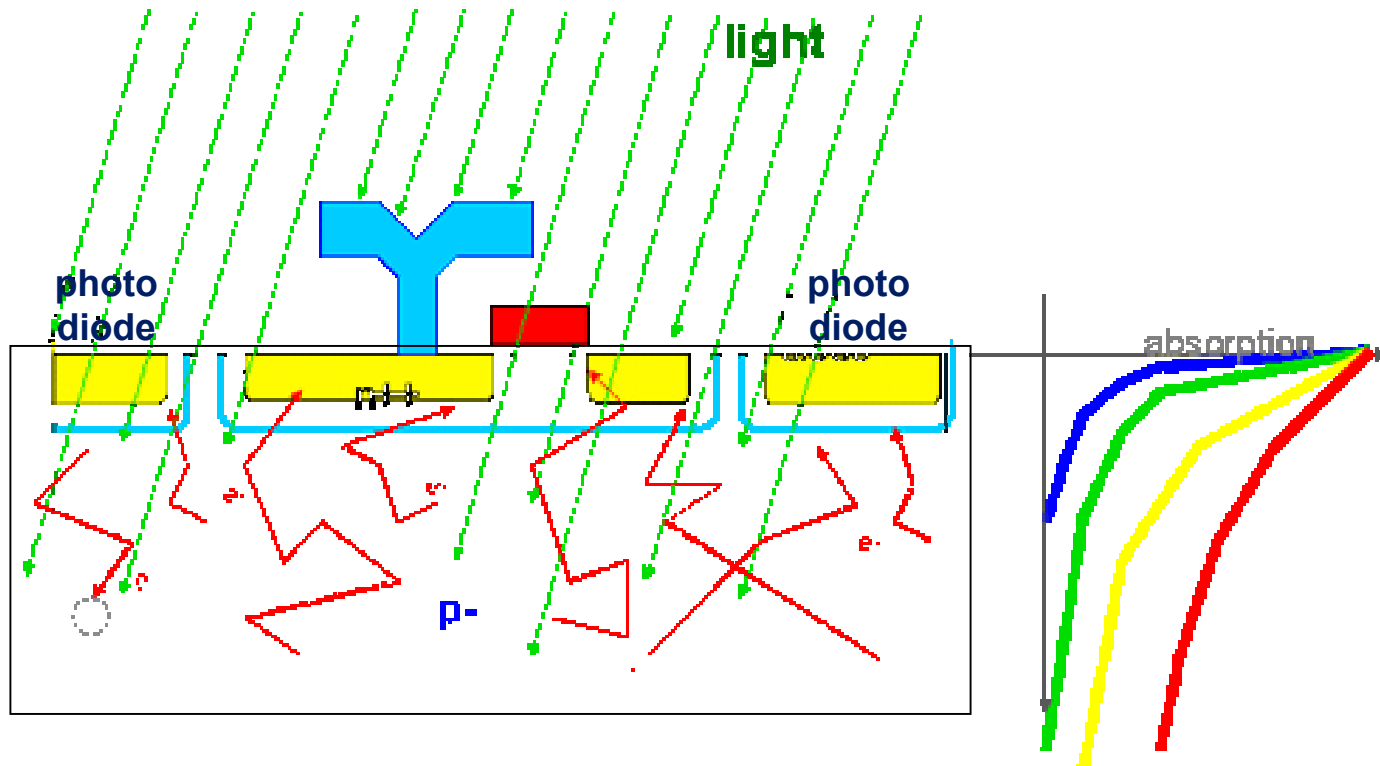


Anti-blooming orizzontale  
(area esposta ridotta del 70%)



Anti-blooming verticale

# Fill-factor



1. oscuramento delle metallizzazioni
2. cariche raccolte da giunzioni inattive
3. dimensioni ridotte del fotodiode
4. ricombinazione di cariche fotogenerate con i maggioritari



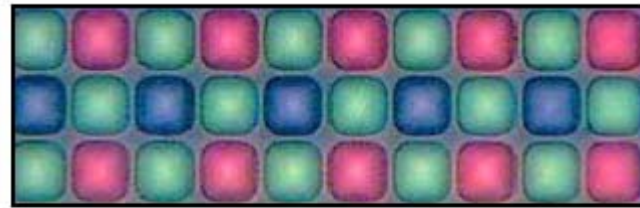
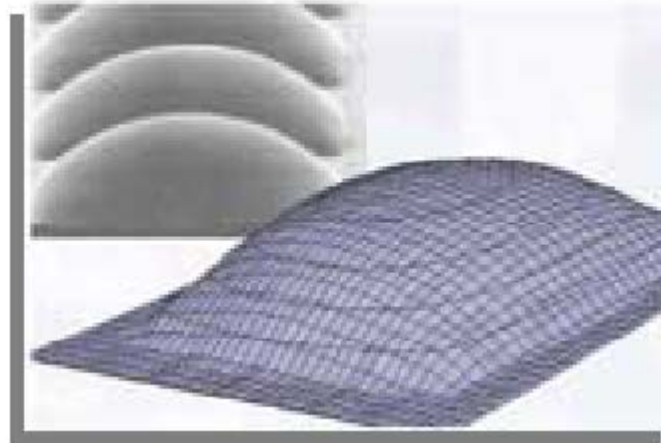
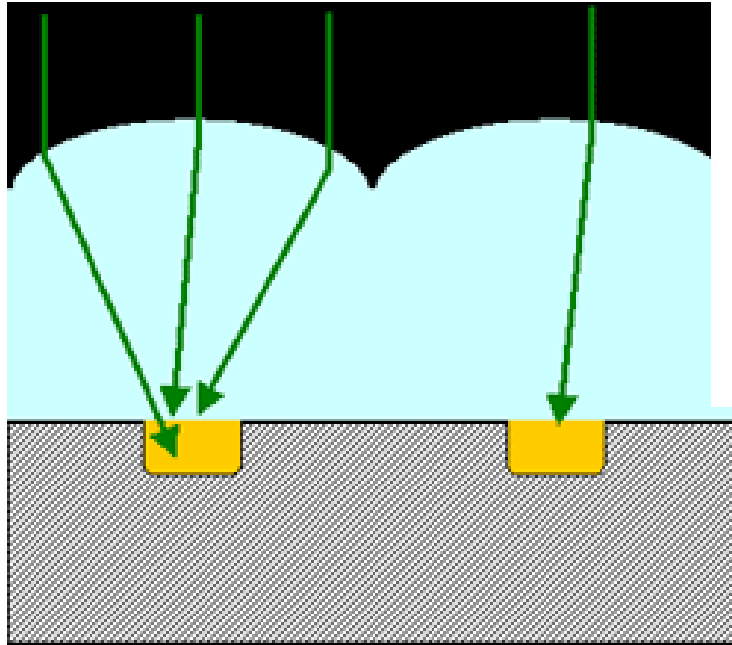
## Metodi per aumentare il fill factor

1. pixel più larghi (con dispositivi attivi di area maggiore)
2. uso delle architetture a massima area utilizzata (Frame Transfer CCD e fotodiodi a pixel passivo)
3. realizzazione delle micro-lenti superficiali (Kodak)
4. tecnologia high-FF per sensori CMOS a pixel attivi (brevetto della FillFactory)



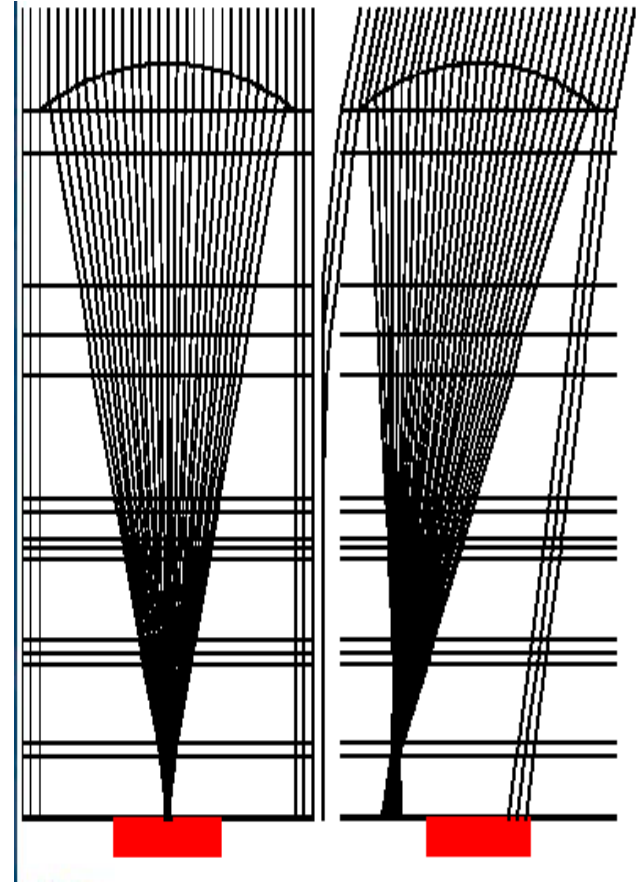
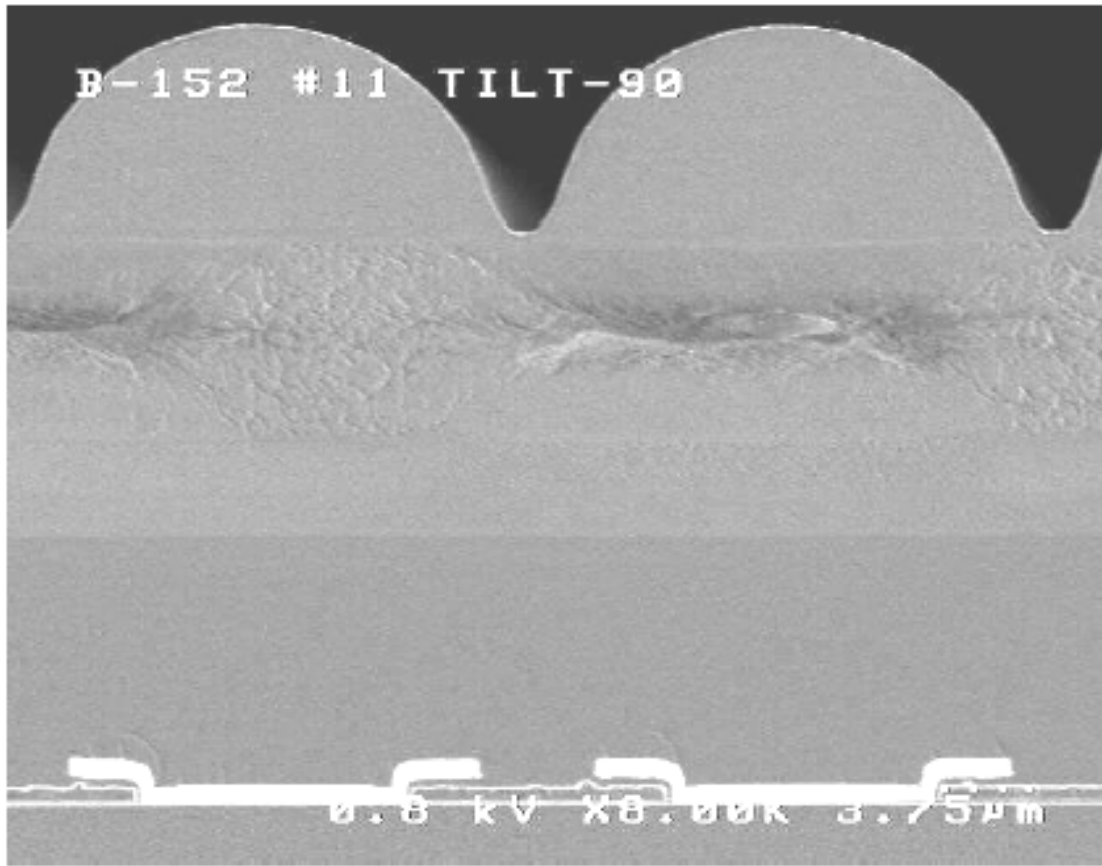
<http://www.fillfactory.com>

## Micro-lenti superficiali

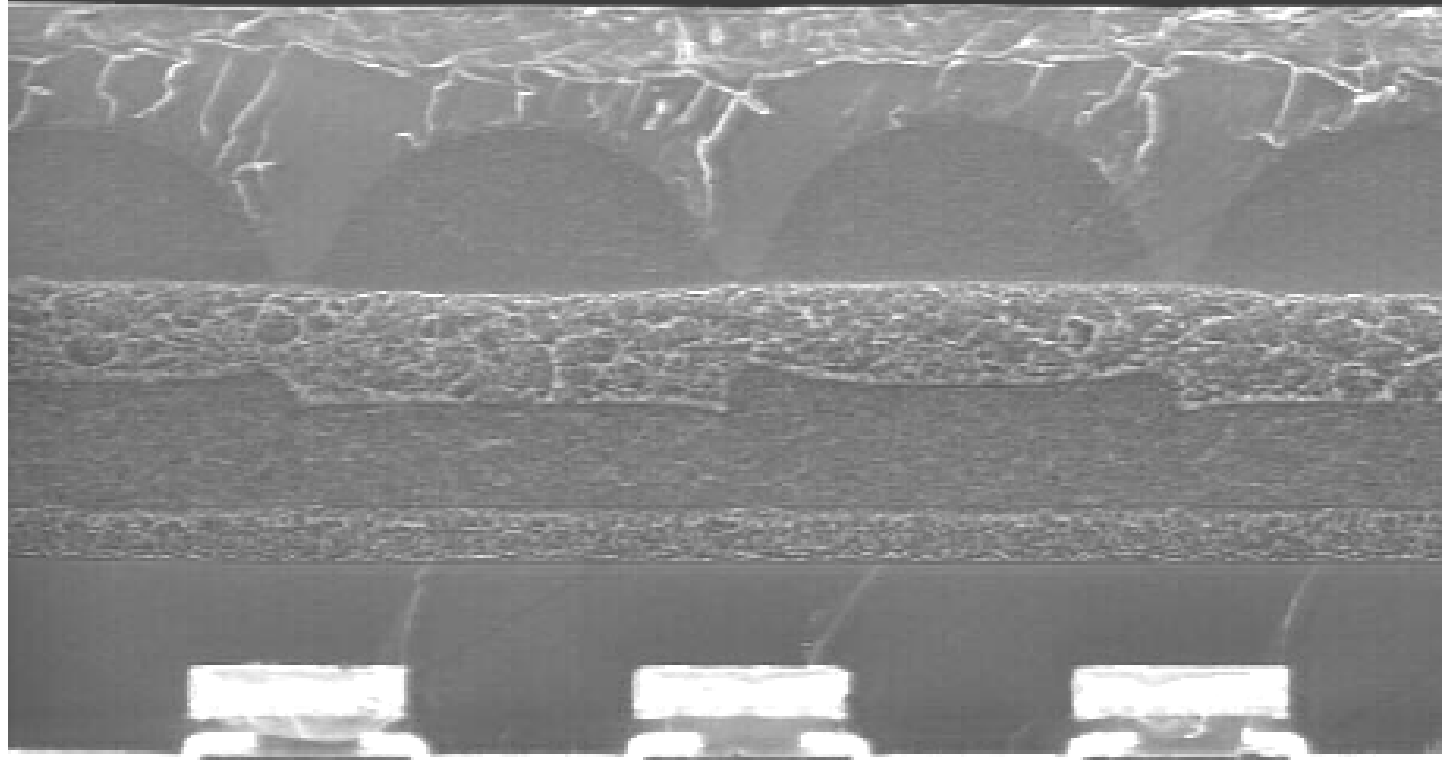


Micro-lenses over Color Filter Array  
(CFA)

- collimano la luce sull'area attiva del fotodiode (si raggiunge il 90% di FF per luce ortogonale)
- post-processing non standard, strato antiriflessione non efficiente per luce con angolo incidente grande

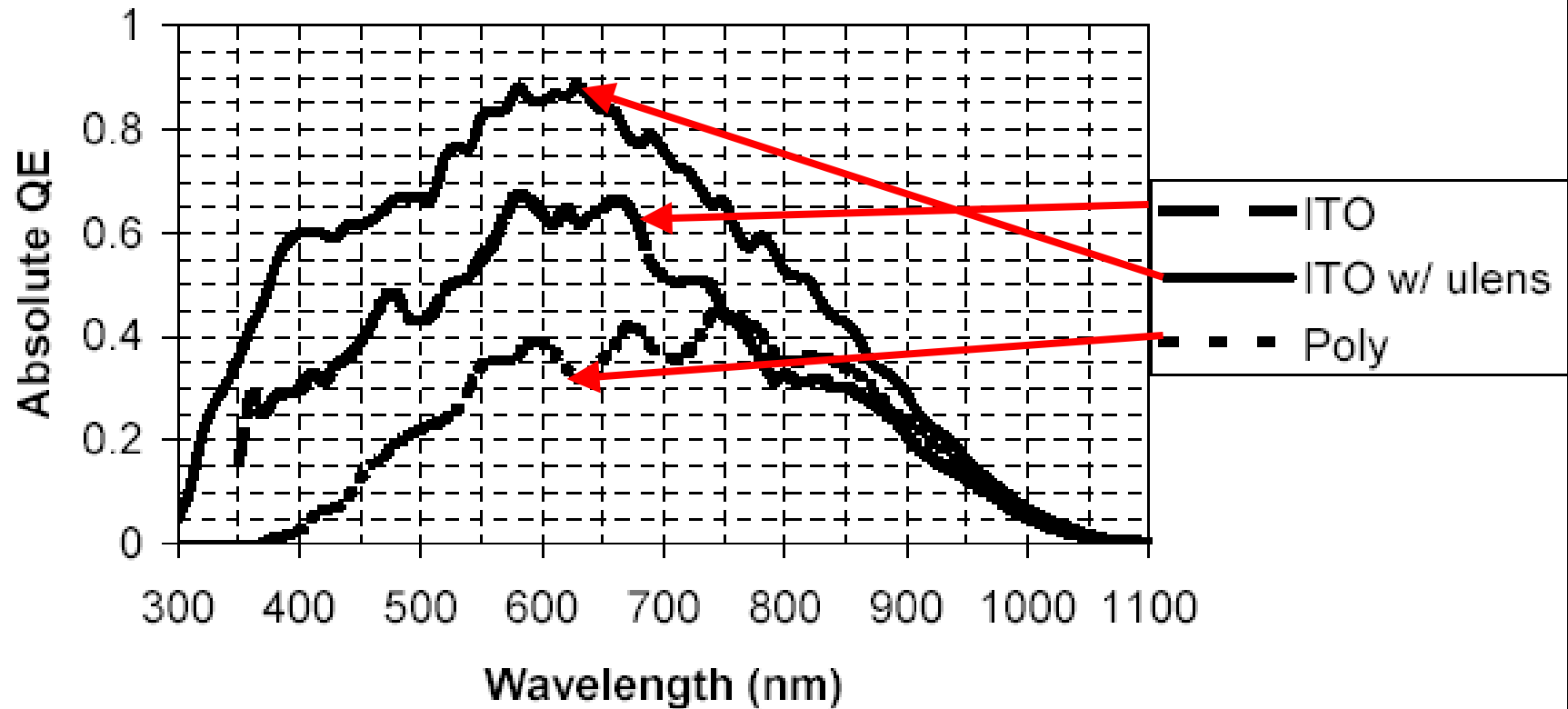


B-273 #01 TILT-90

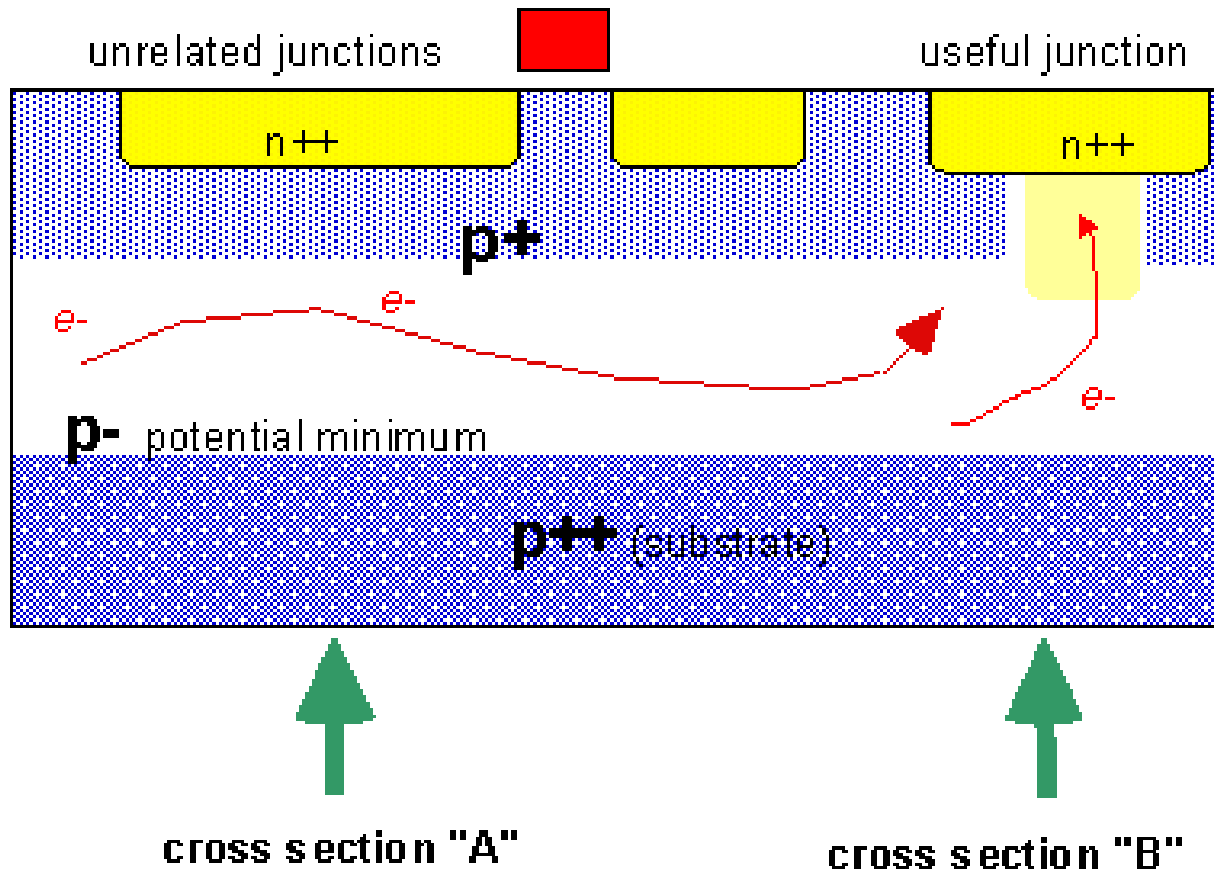


0.8 kV X5.00K 6.00µm

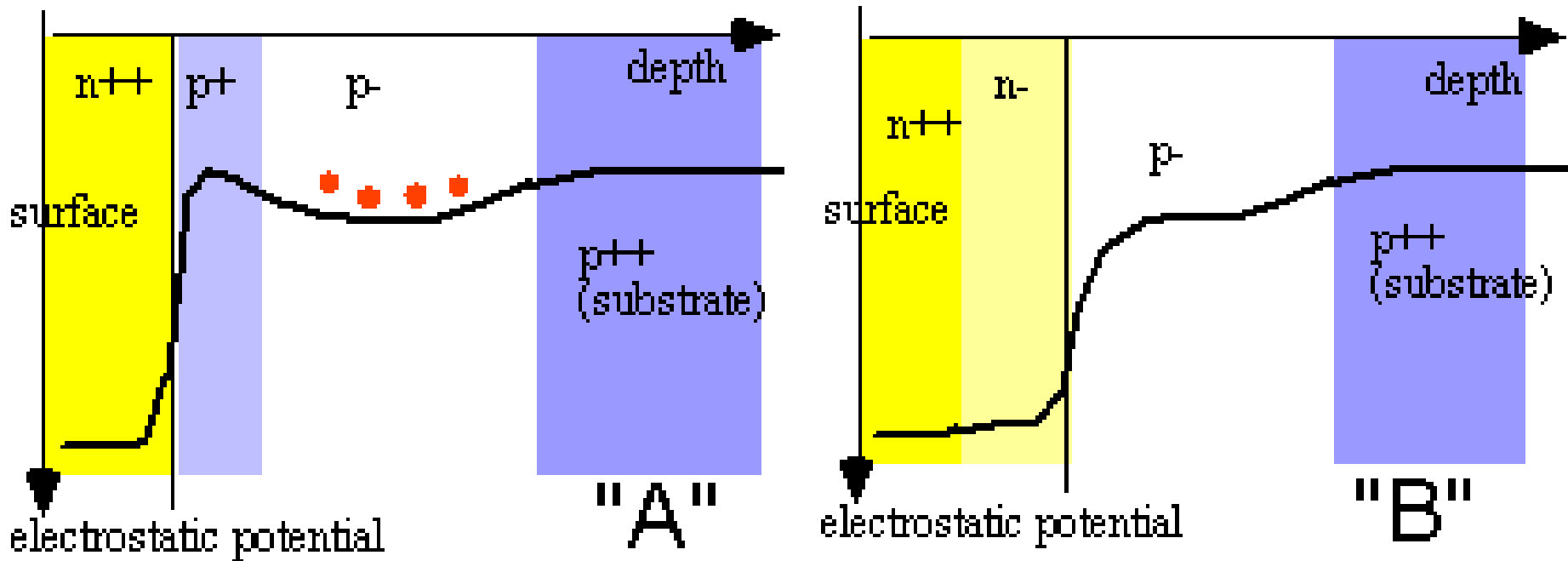
## 6.8- $\mu\text{m}$ full frame CCD pixel



# High Fill-Factor technology

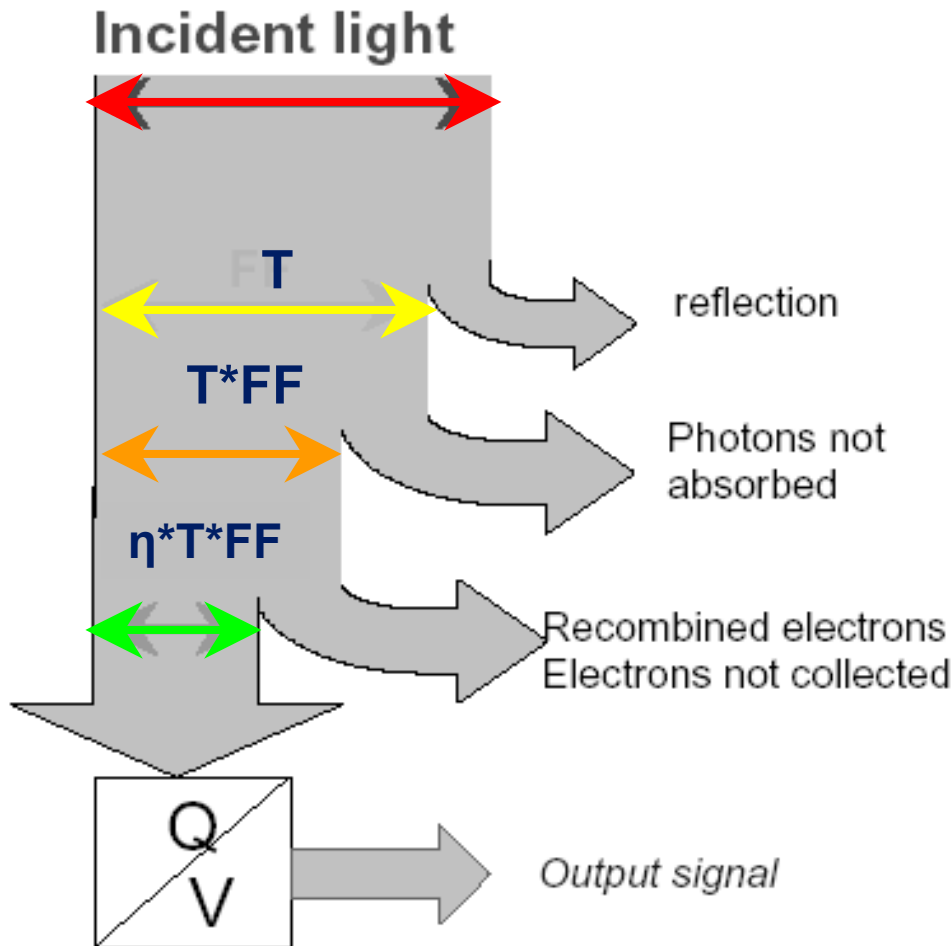


## High Fill-Factor technology



- si ottiene un FF del 100%, eccetto per la luce che non raggiunge la superficie del silicio
- si ottiene un rapporto segnale/rumore più alto
- si ottiene una sensibilità più alta

# Sensibilità del sensore ottico



**ottimizzazione degli strati antiriflesso**

**ottimizzazione del fill-factor**

**ottimizzazione dell'efficienza quantica**

**ottimizzazione delle aree attive e del read-out**