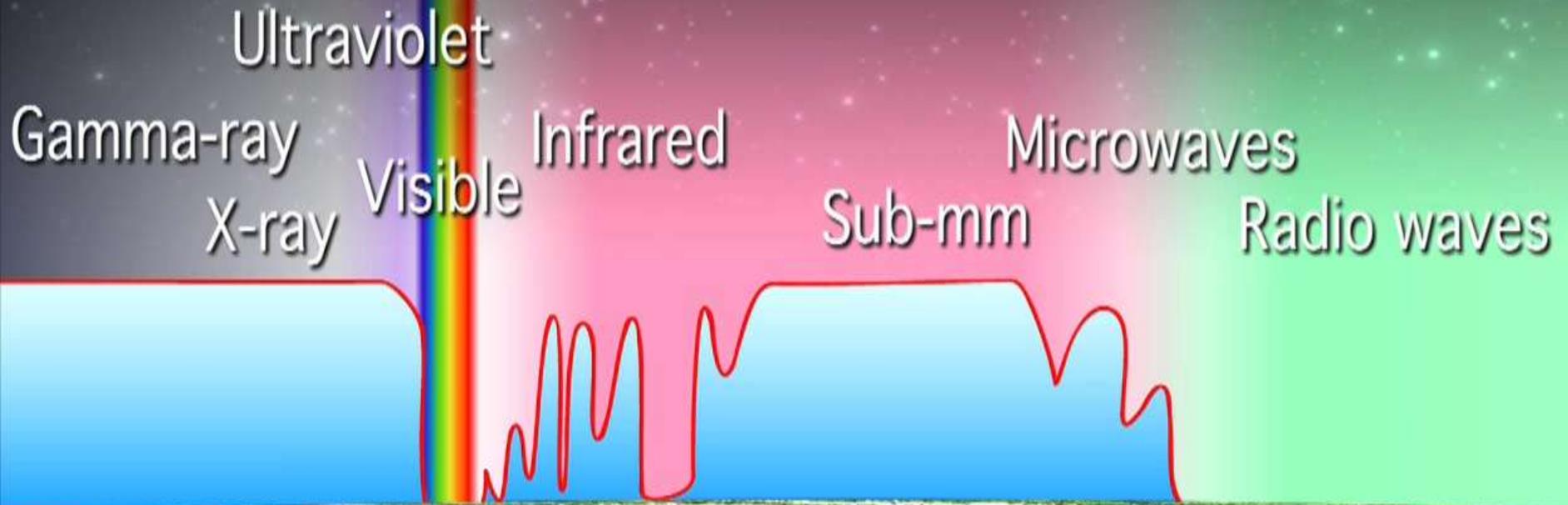


CCD & CMOS

Les photons



2 types de capteurs

- **CCD** : Charge Coupled Devices

Collection

Transfert

Conversion



de la charge

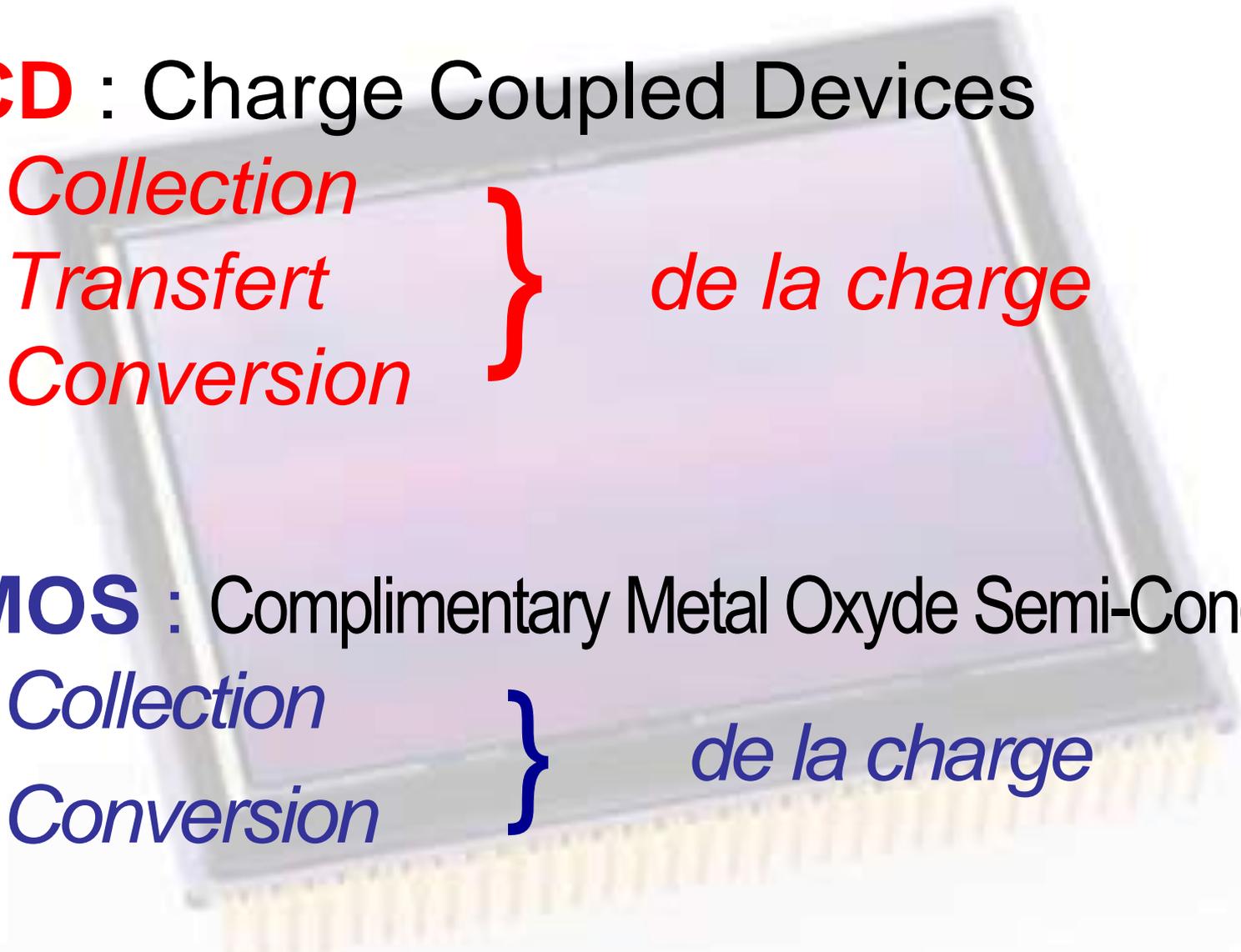
- **CMOS** : Complimentary Metal Oxyde Semi-Conductor

Collection

Conversion

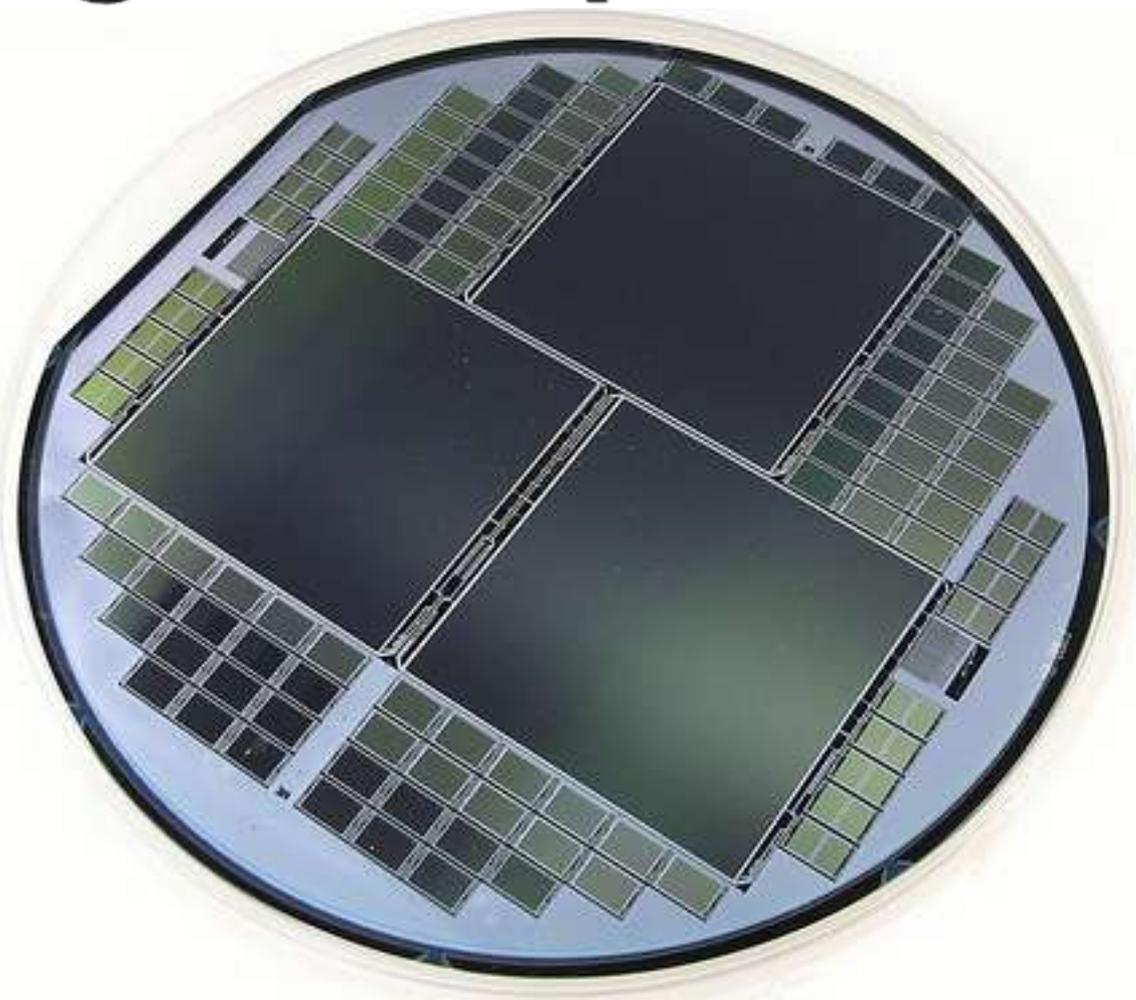


de la charge



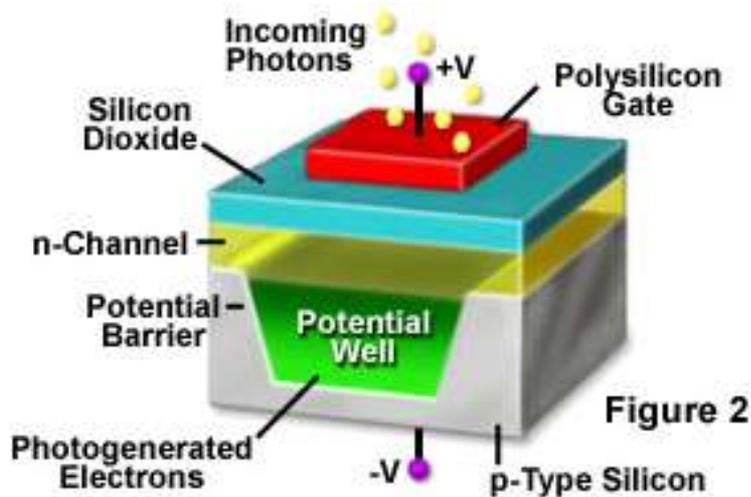
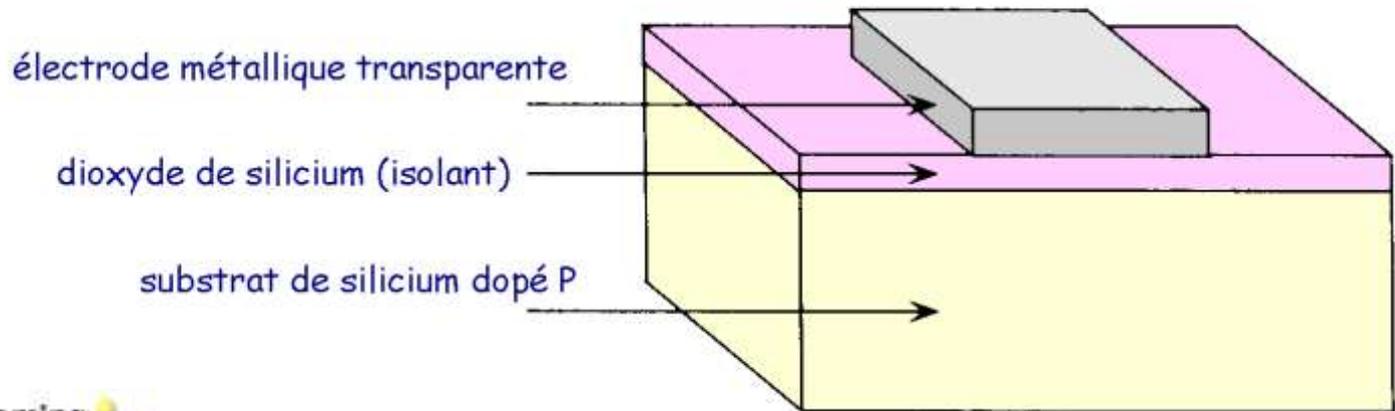
CCD

Charge Coupled Device

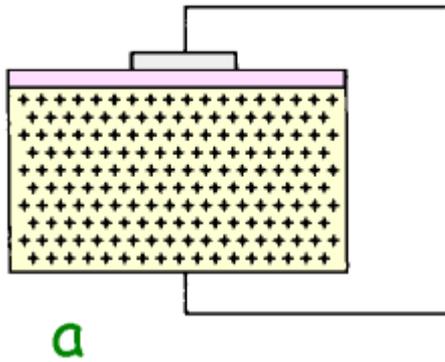


Le transistor MOS

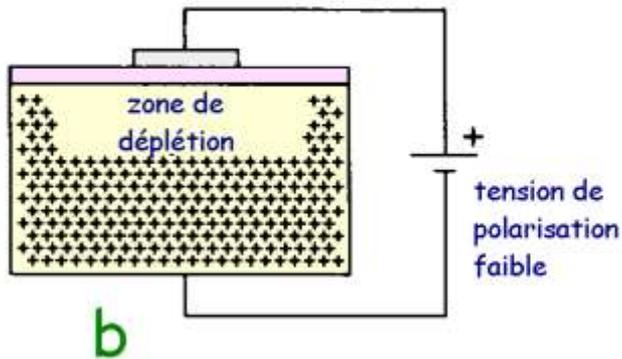
Le capteur d'image est, dans sa forme de base, construit sur un substrat de silicium dopé P et chaque photosite est délimité par une fine électrode métallique.



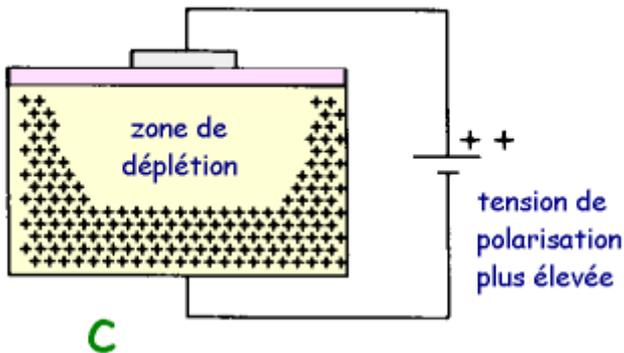
Effet photoélectrique

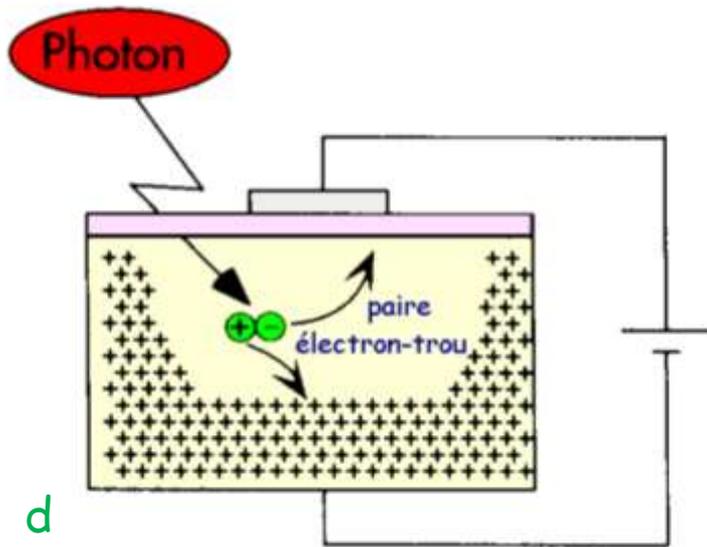


Le substrat dopé P contient des porteurs positifs (trous) majoritaires (a).



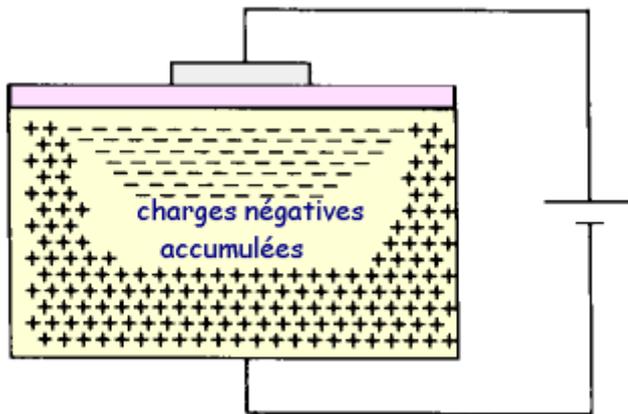
Si on applique une polarisation positive sur l'électrode métallique, ces porteurs seront repoussés et il se crée une zone de déplétion dont la hauteur dépend de la tension appliquée (b et c).





Chaque fois qu'un photon arrive dans le substrat, il y crée une paire électron-trou (d). L'électron est attiré par l'électrode et se trouve piégé dans la zone de déplétion.

d

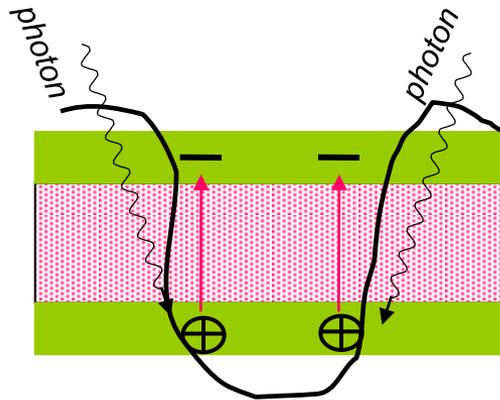
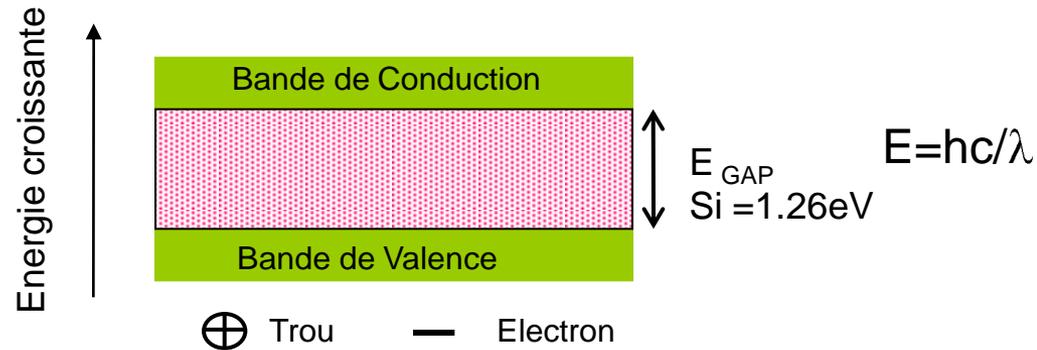


A la fin du temps d'intégration, la charge totale recueillie dans la zone de déplétion (e) est proportionnelle à l'intensité lumineuse reçue.

e

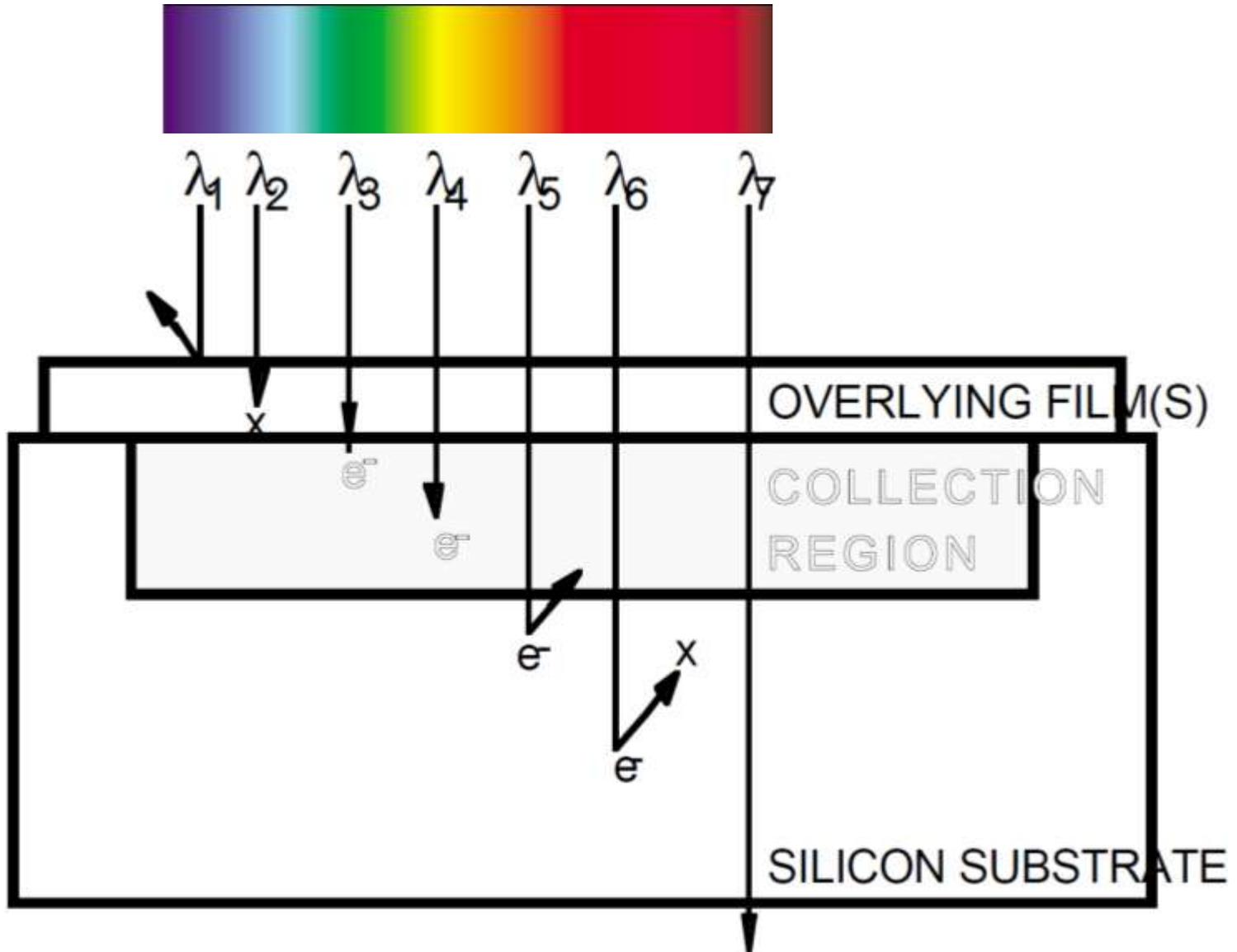
Chaque photosite se comporte donc comme un condensateur de faible valeur qui se charge au cours du temps sous l'effet de l'éclairement.

Effet photoélectrique

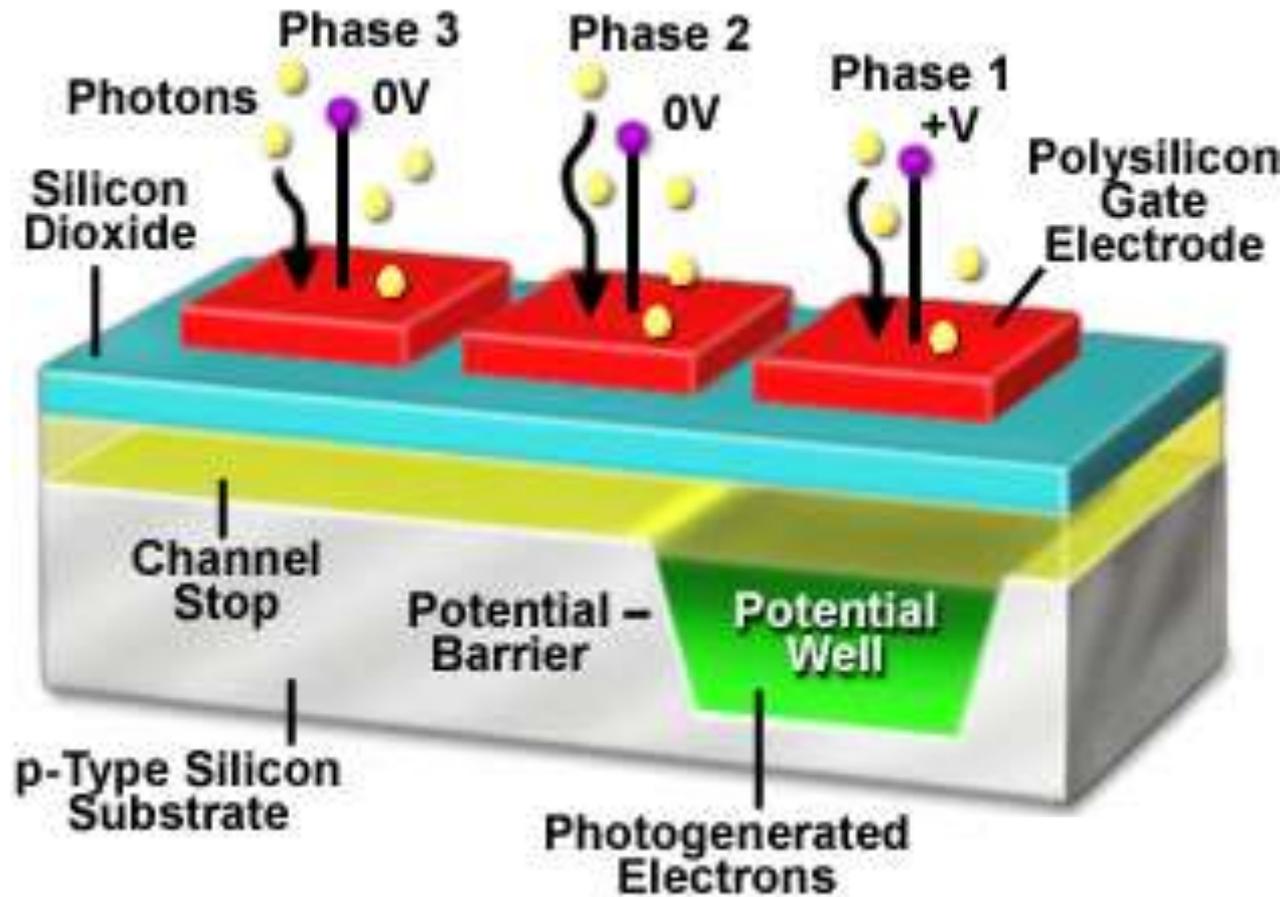


En l'absence de champ électrique
Recombinaison de la paire trou - électron

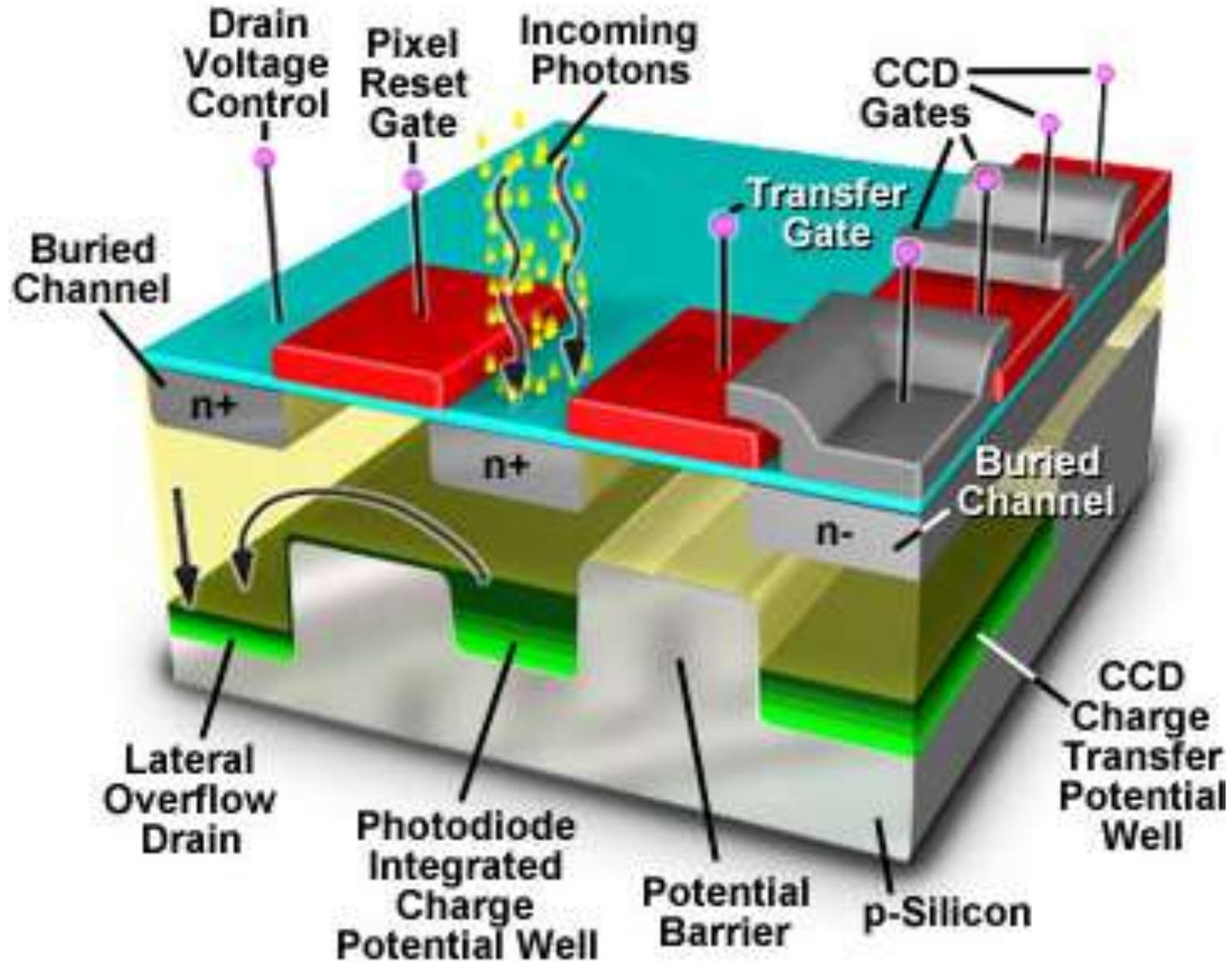
Conversion des photons



Le Pixel CCD

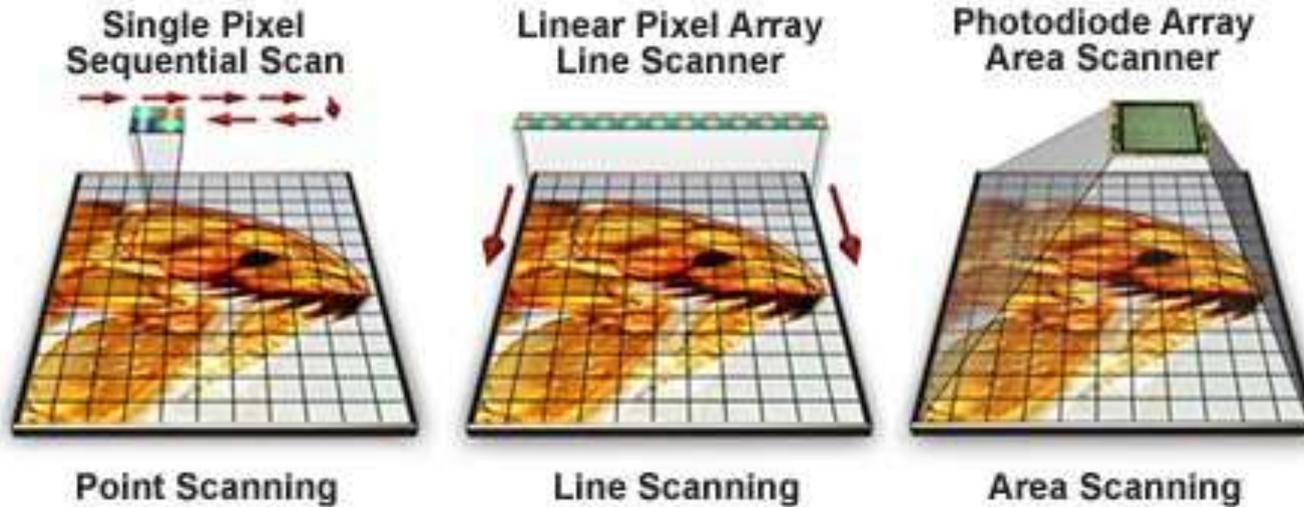


Le CCD

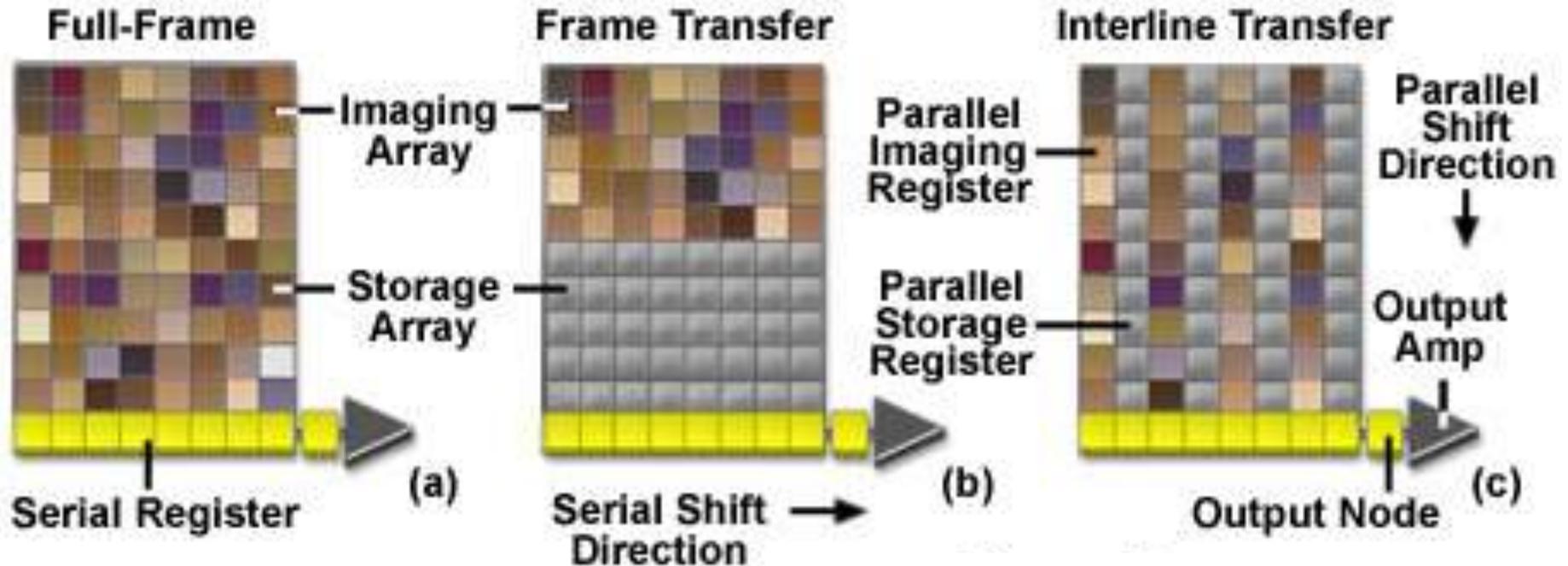


Les différentes architectures

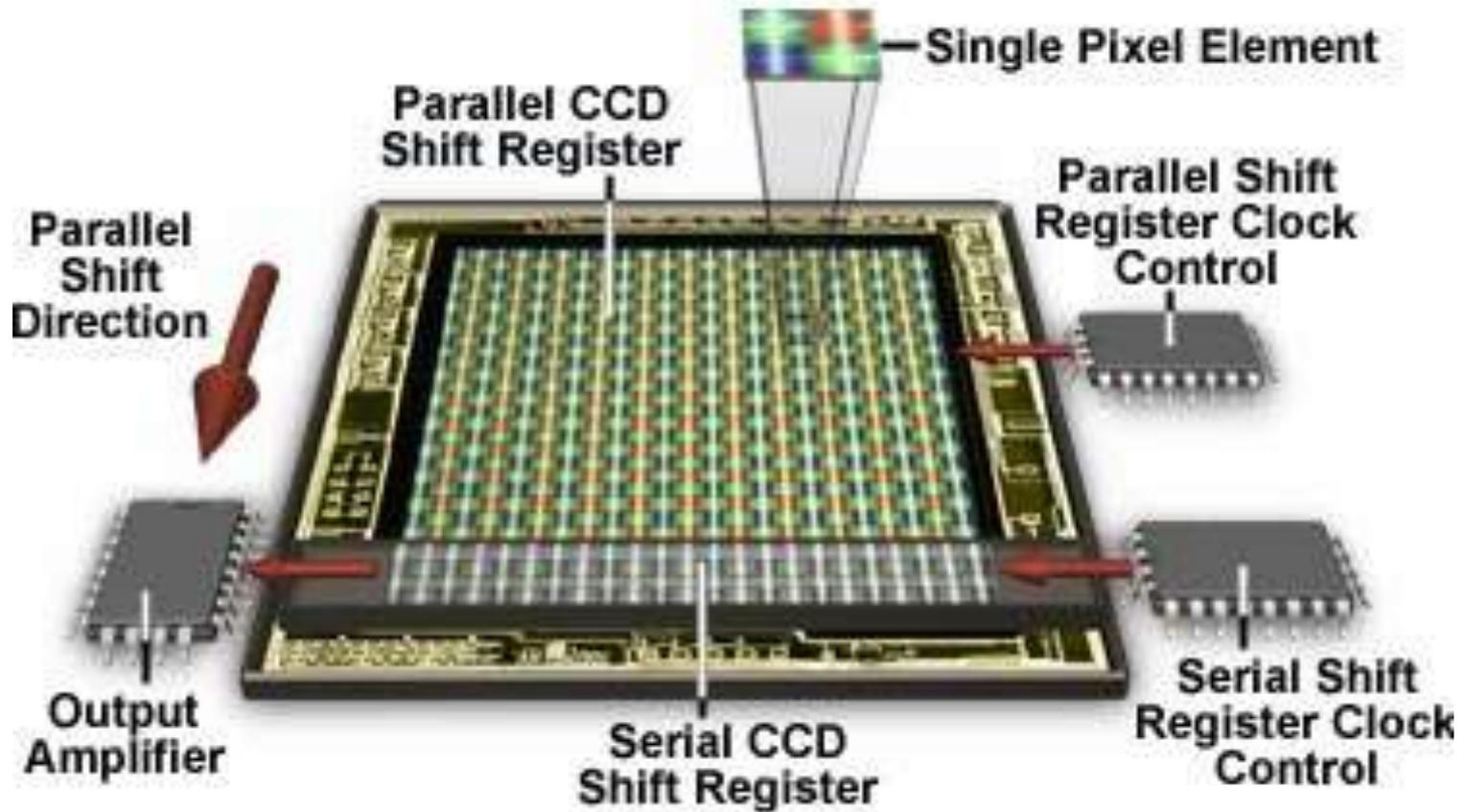
CCD Scanning Formats



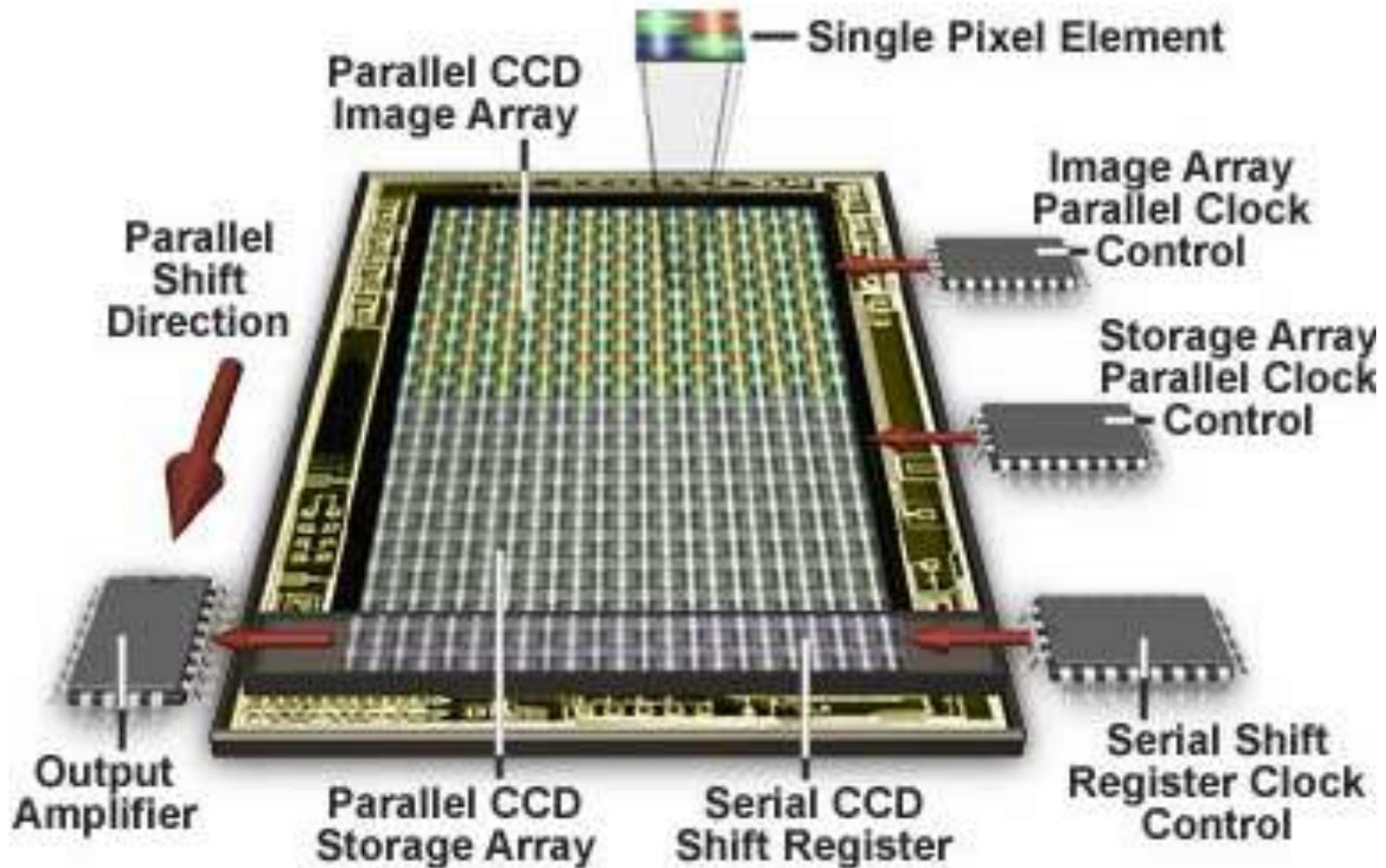
Les différentes architectures



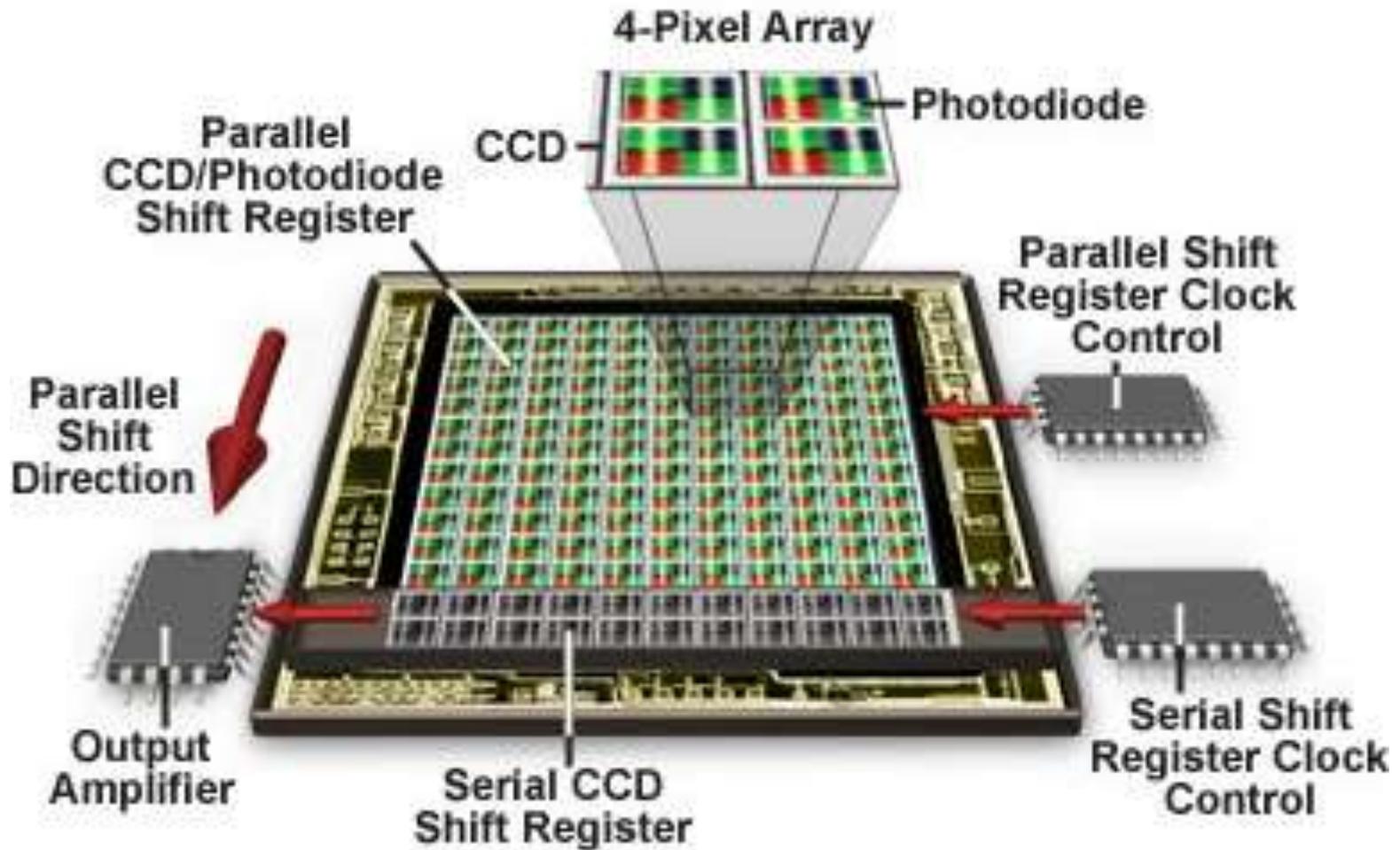
CCD plein format



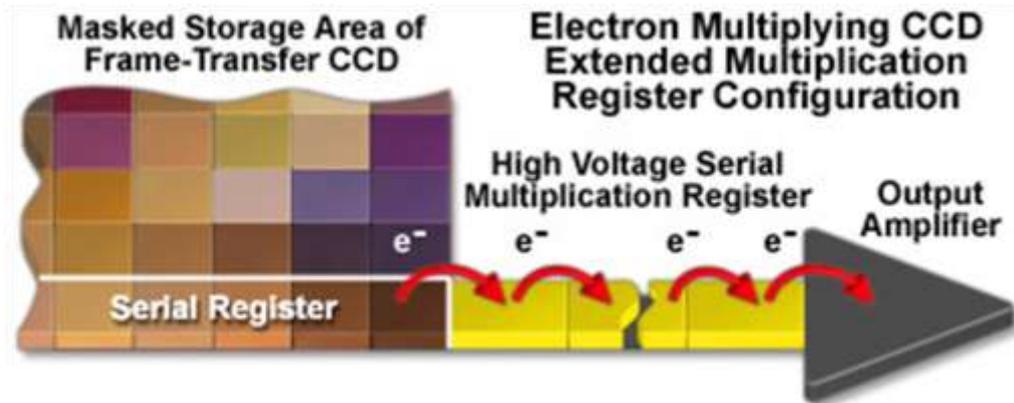
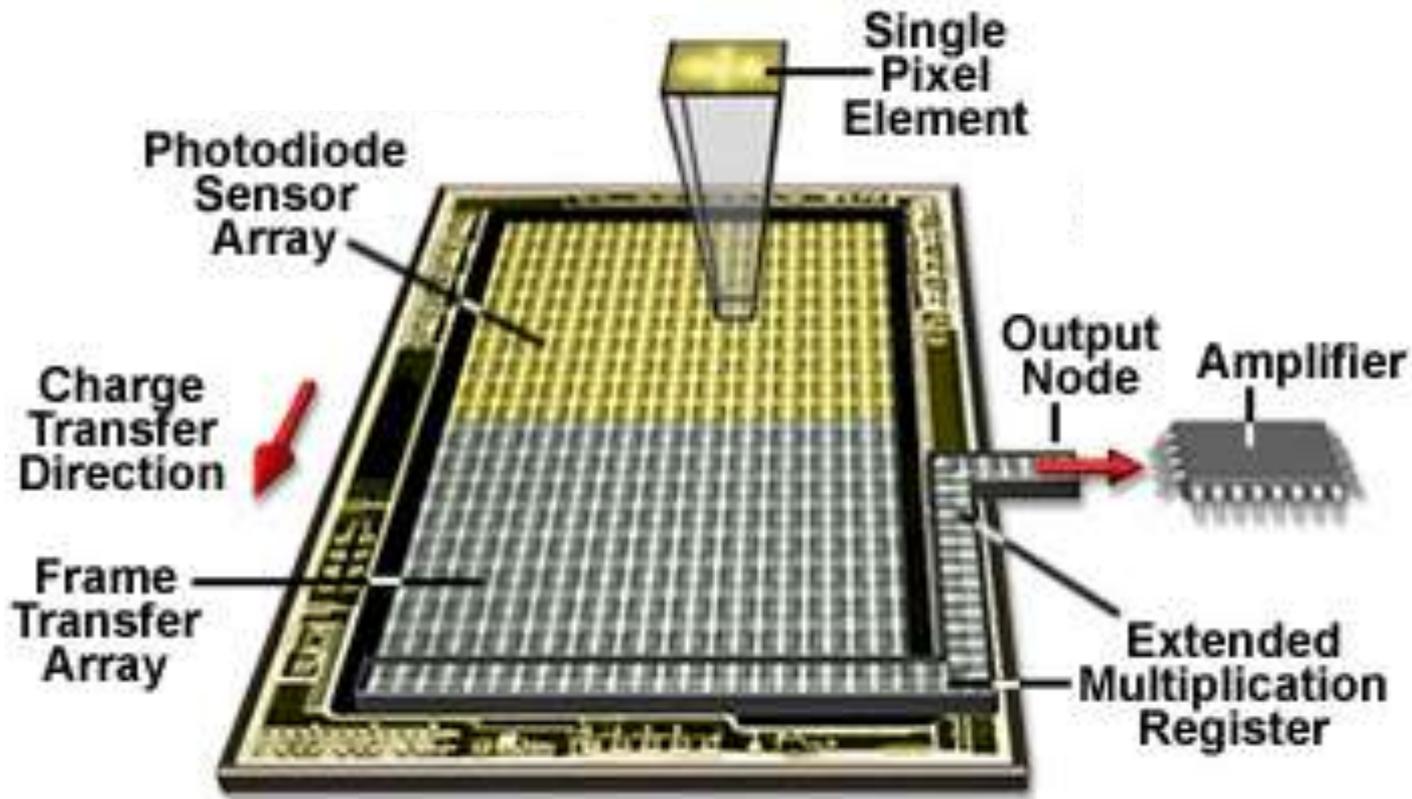
CCD à transfert de trame



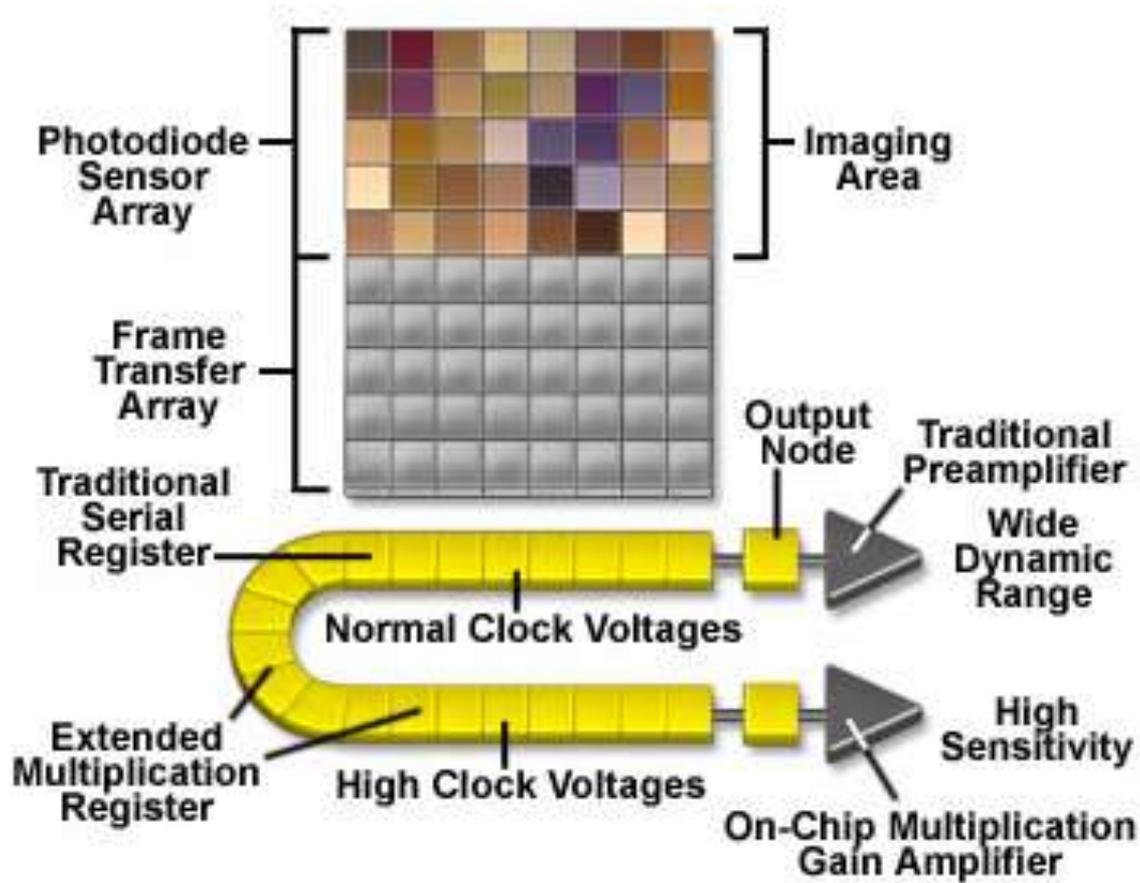
CCD interligne



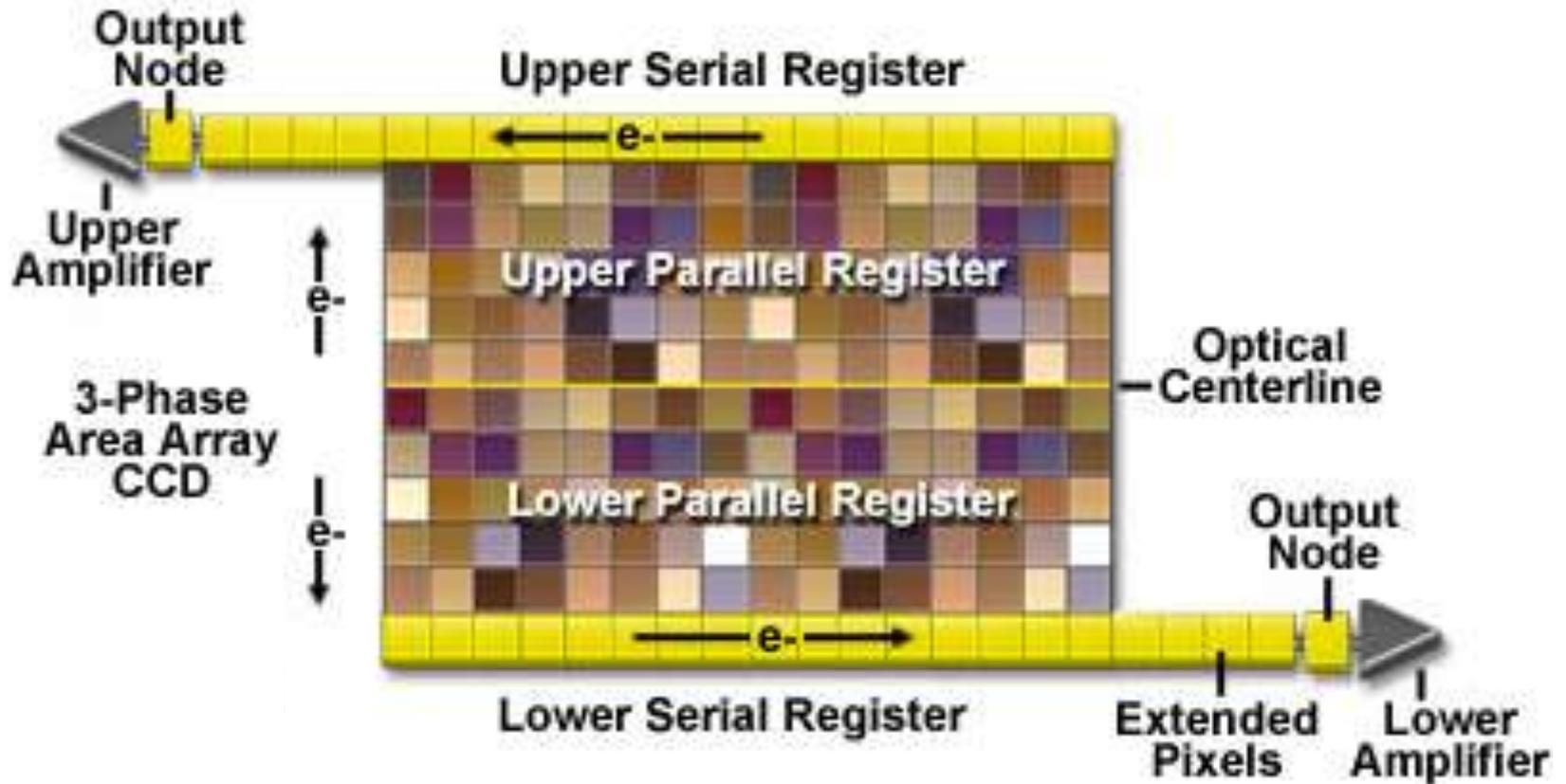
EMCCD



EMCCD double amplificateur



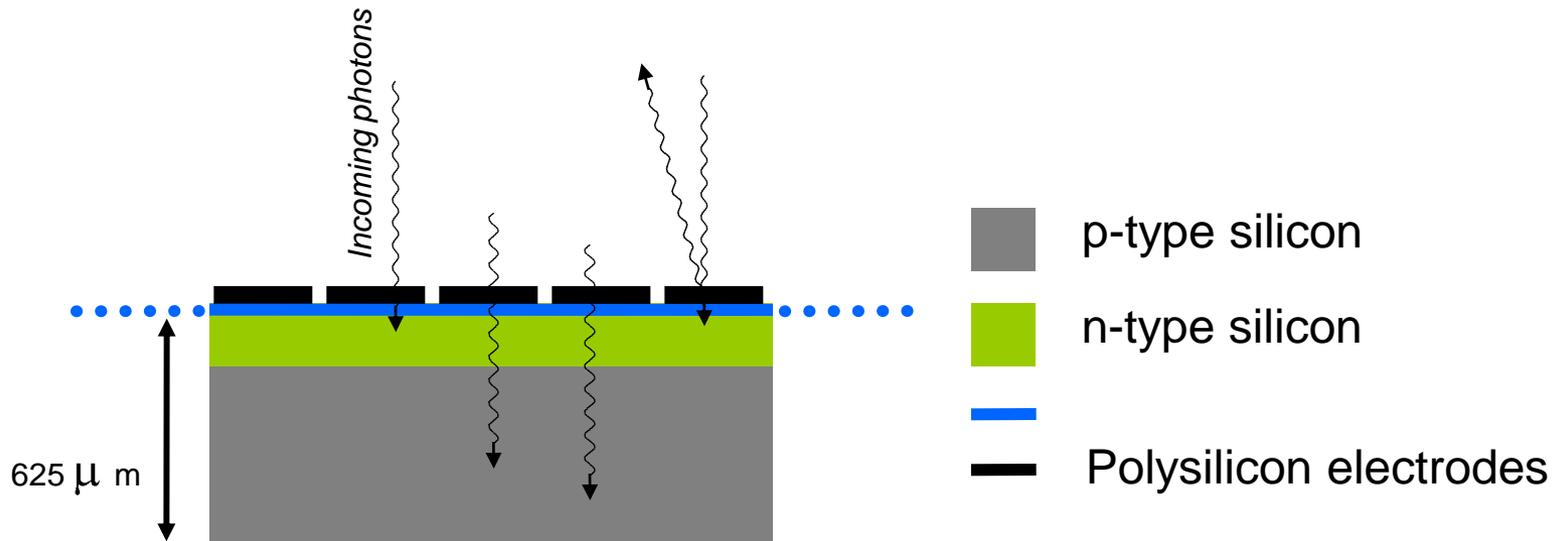
CCD multi-sorties



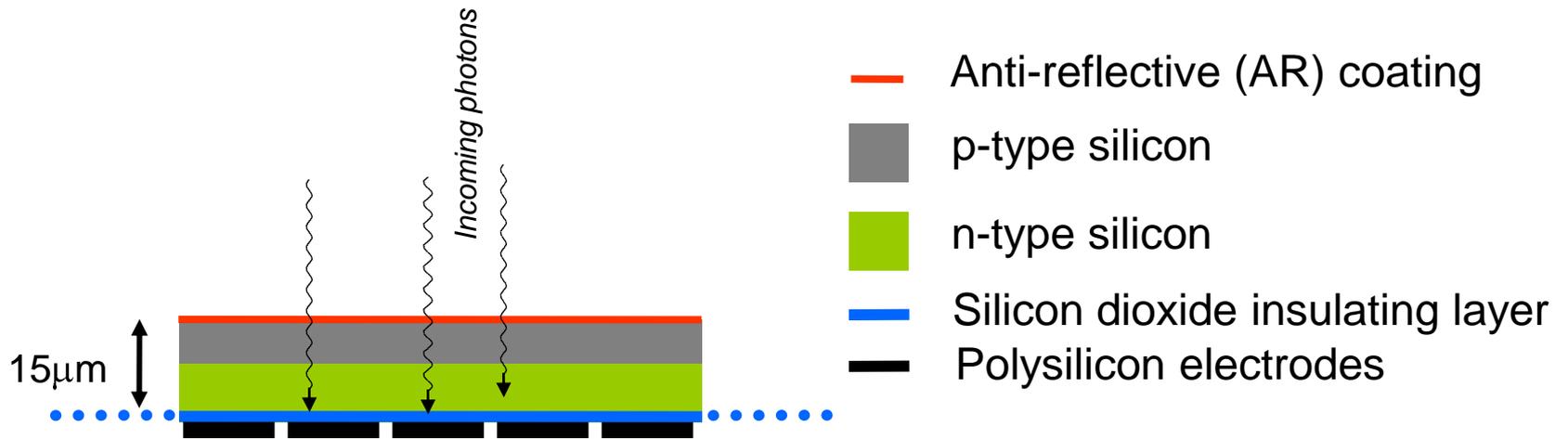
Les différentes technologies CCD

- **Front illuminated**
 - **Back illuminated / back thinned**
 - **Deep depletion**
 - **Deep depletion back-illuminated**
 - **Fully depleted**
- 
- The background of the slide features a collage of images related to CCD technology. At the top center is a circular inset showing a detailed cross-section of a CCD sensor, illustrating the internal layers and structure. Below this, there are several rectangular images showing different types of CCD sensors and their packaging. Some are shown as bare silicon wafers with various colored regions, while others are mounted on printed circuit boards (PCBs) with gold wire bonds. The overall image is semi-transparent, allowing the text to be clearly visible over it.

(Thick) front-side illuminated CCD

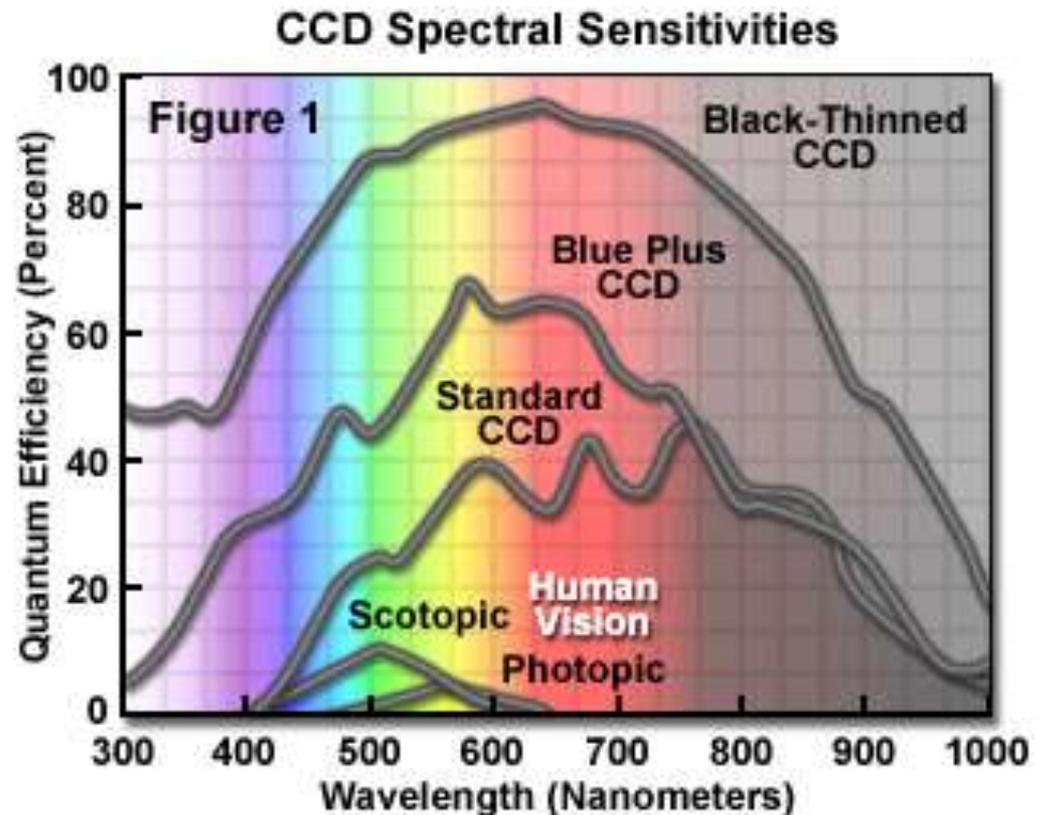
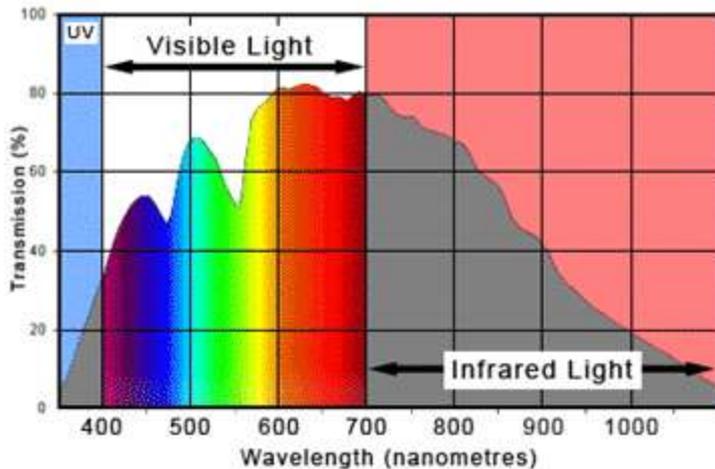


(Thin) back-side illuminated CCDs

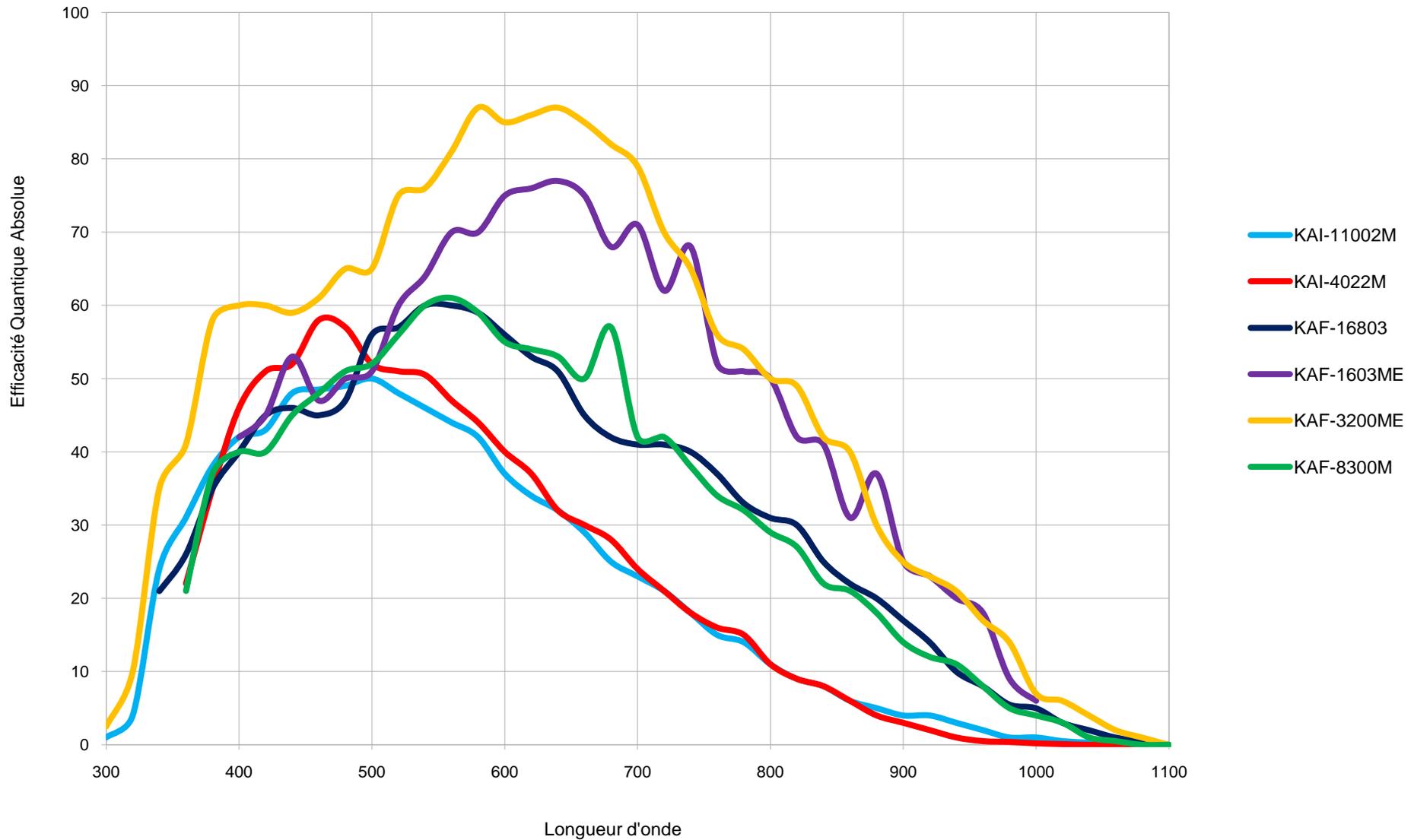


Rendement Quantique

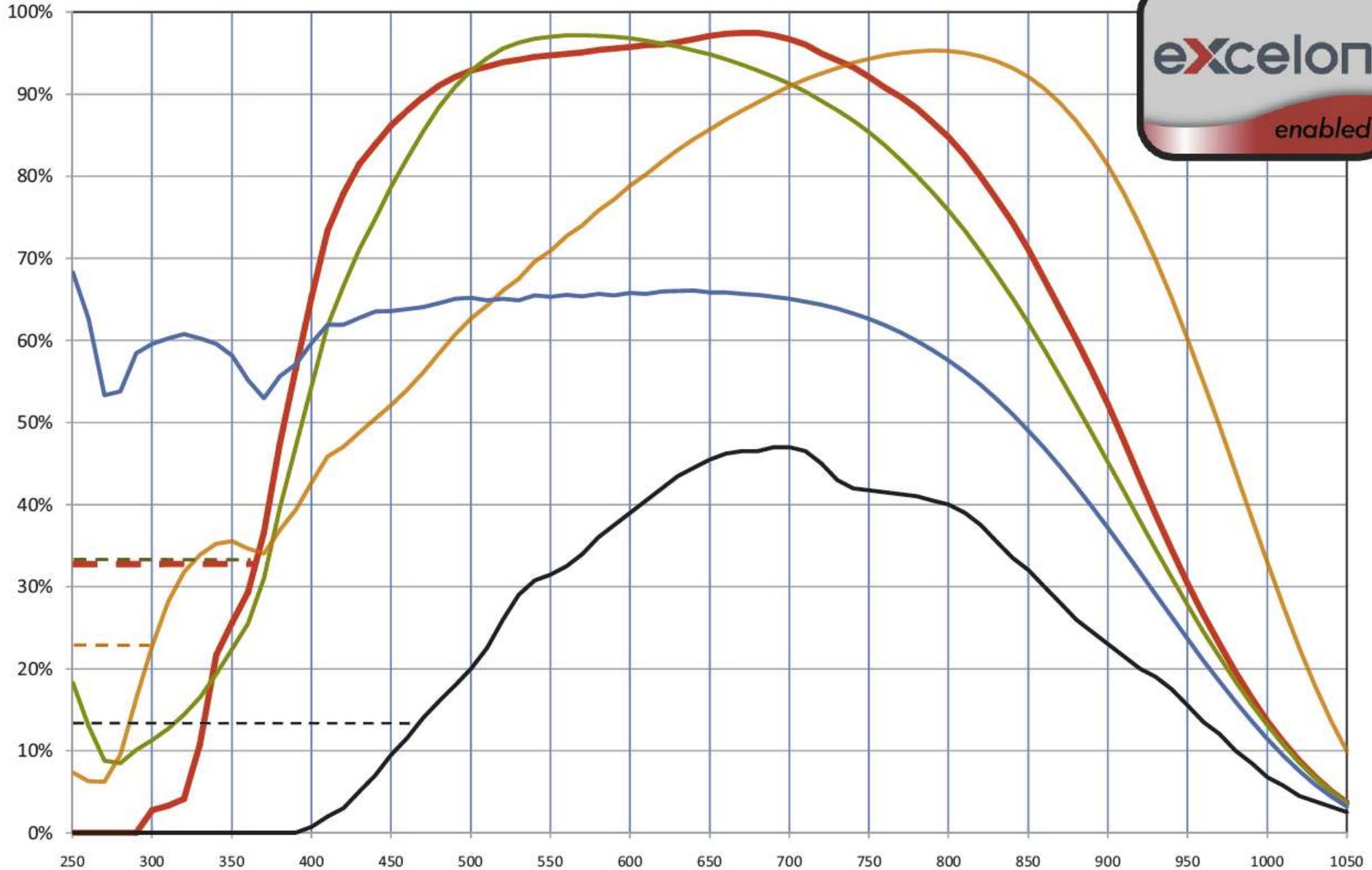
$$QE = \frac{\text{Nbre photon détectés}}{\text{Nbre photons incidents}}$$



CCD Kodak



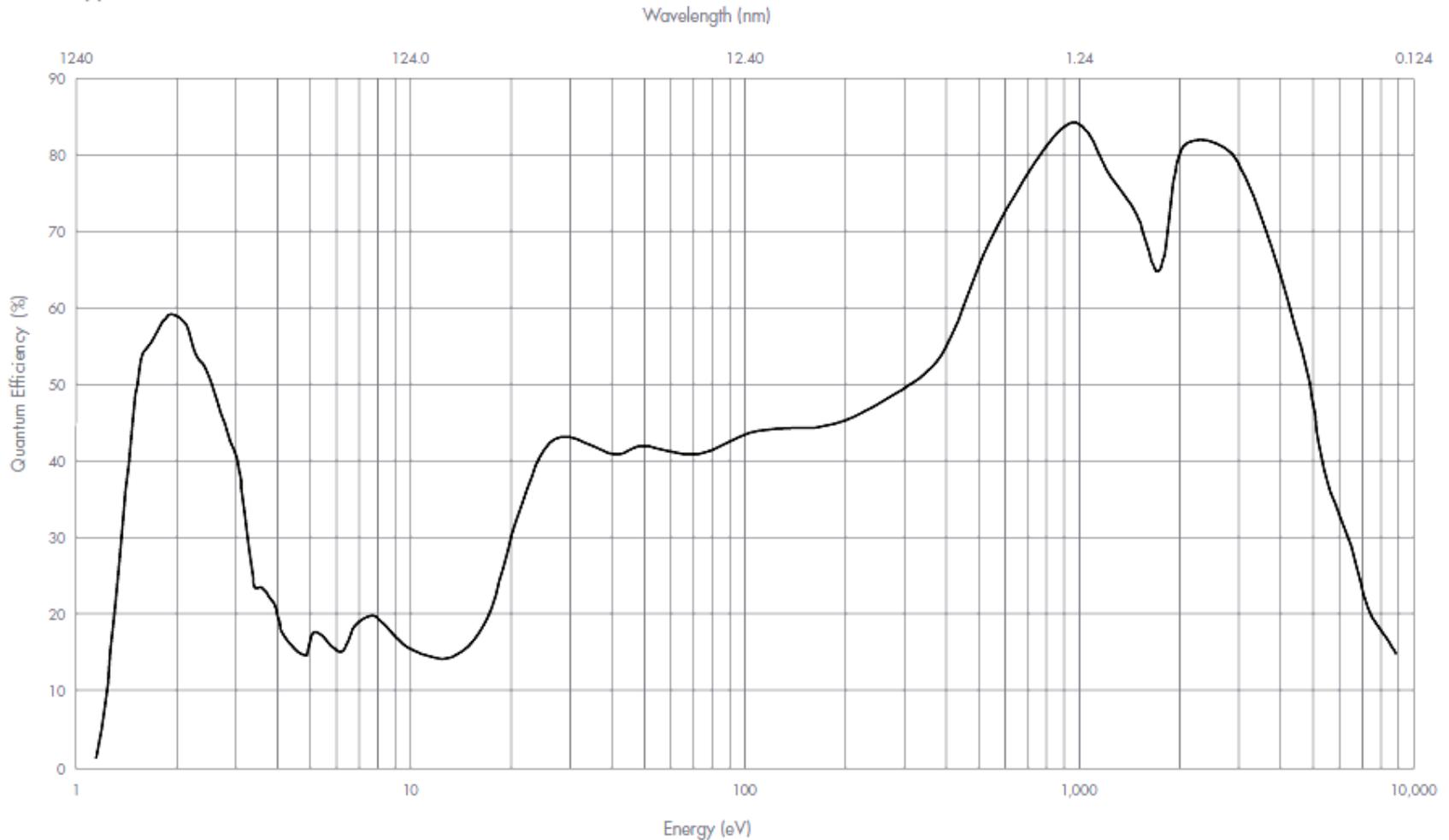
CCD E2V 42-40



Back-ill. eXcelon back-ill. Deep depletion back-ill. Back-ill. UV front ill. ---- coating UV

Rendement étendu CCD back-illuminated no AR

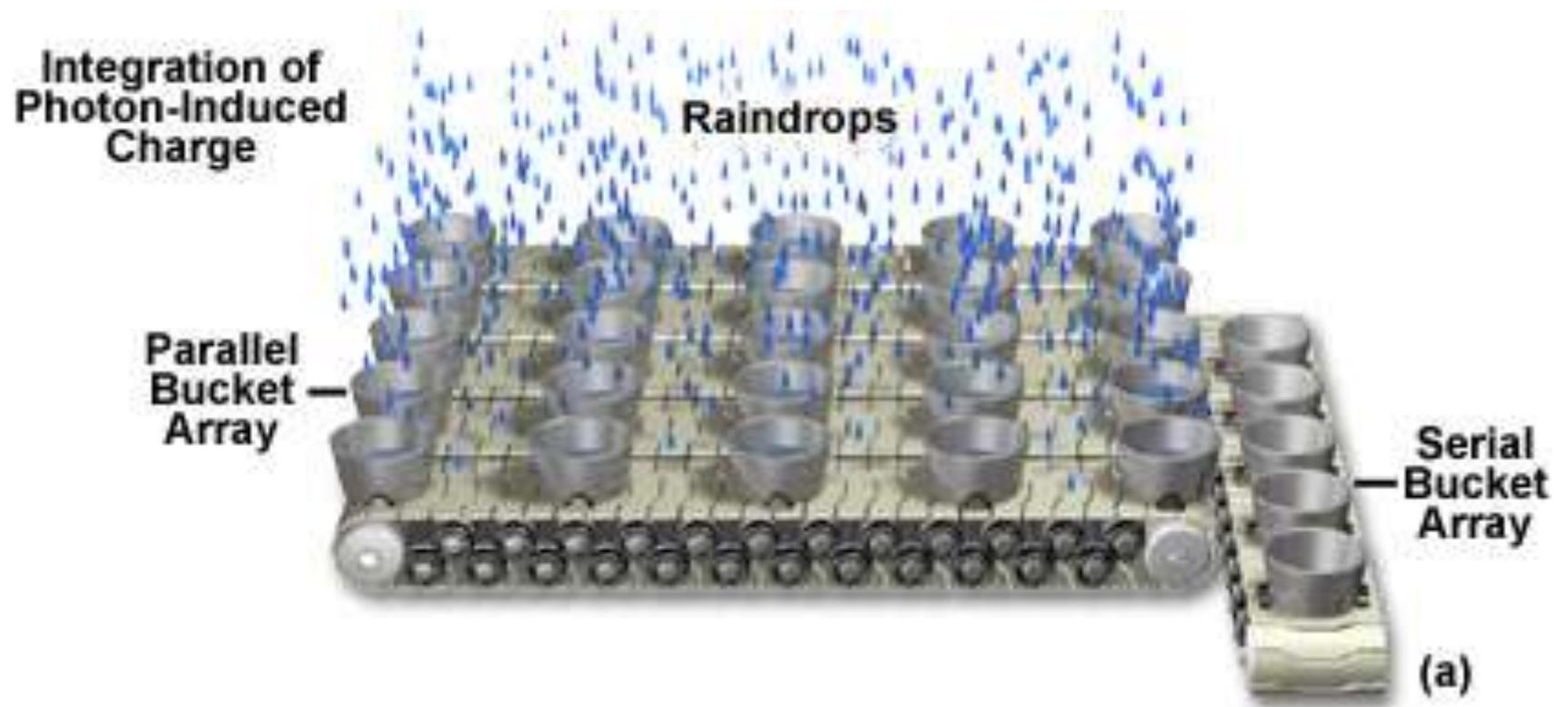
Typical QE from 1 eV to 10 keV



La lecture du CCD



Transfert de charge

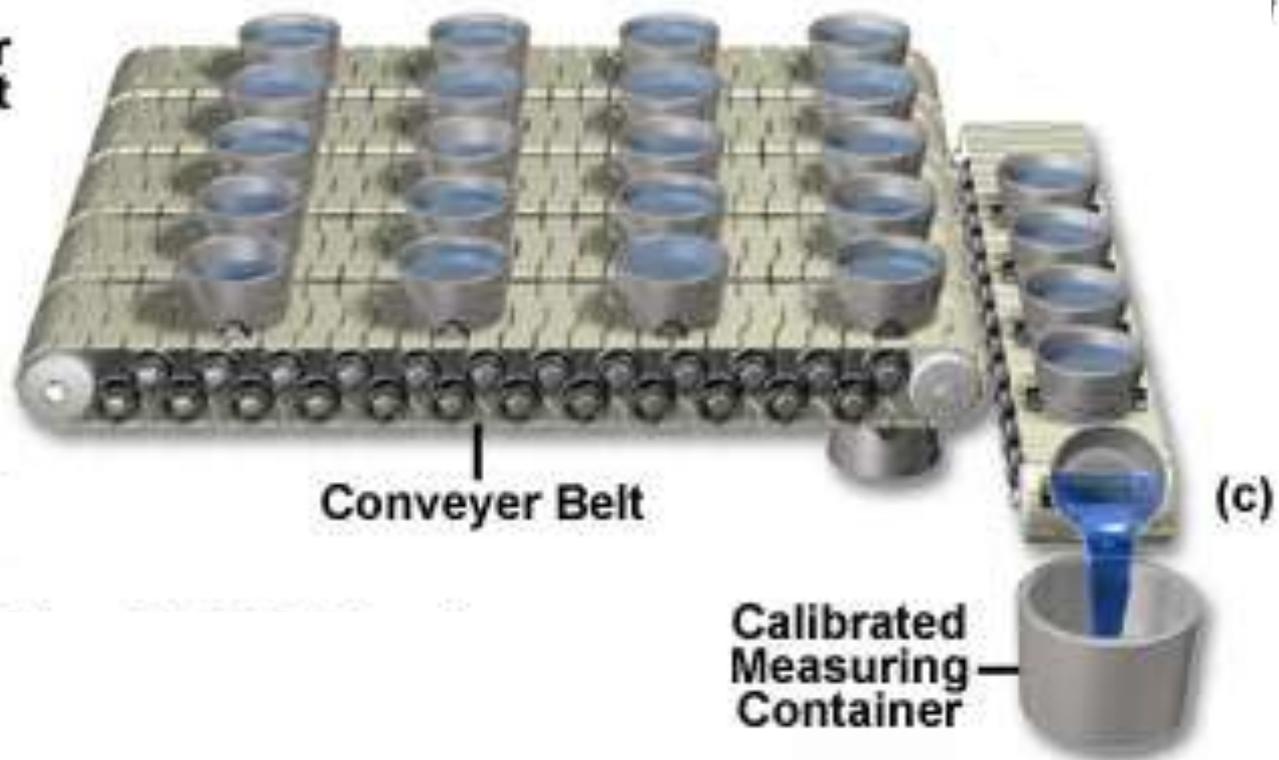


**Parallel Register
Shift (1 Row)**



(b)

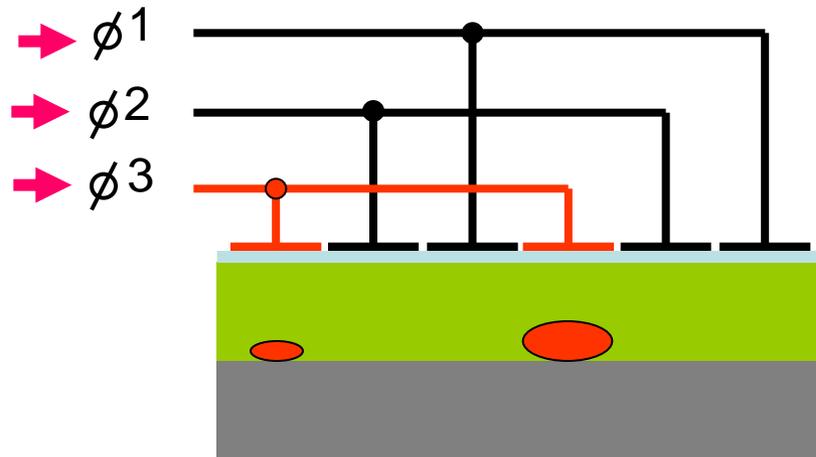
**Serial Register
Shift to Output**



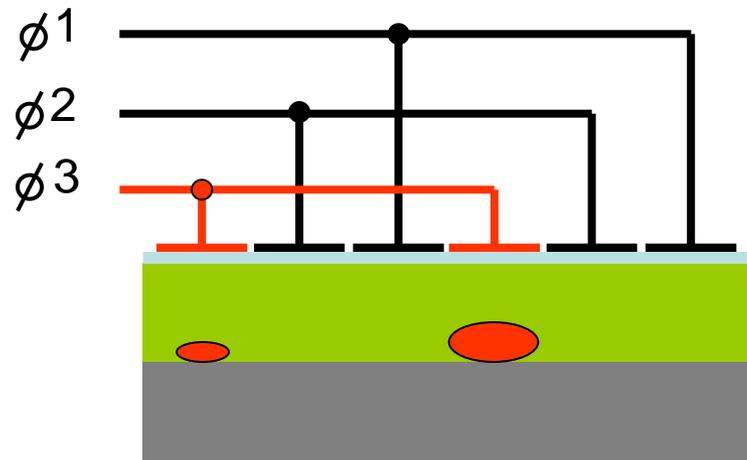
Charges

“Buckets” are Moved by Changing Voltage Pattern

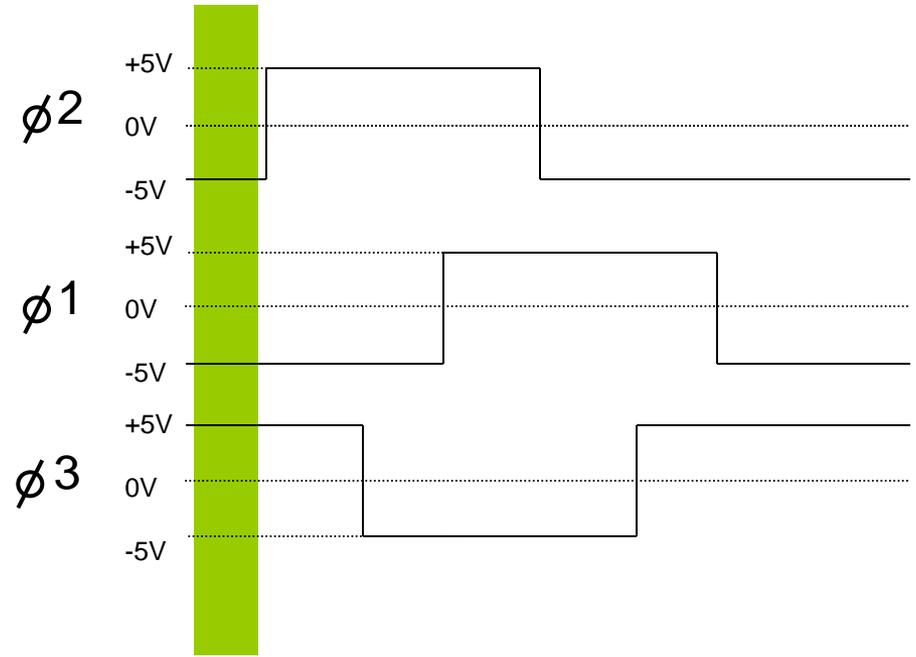
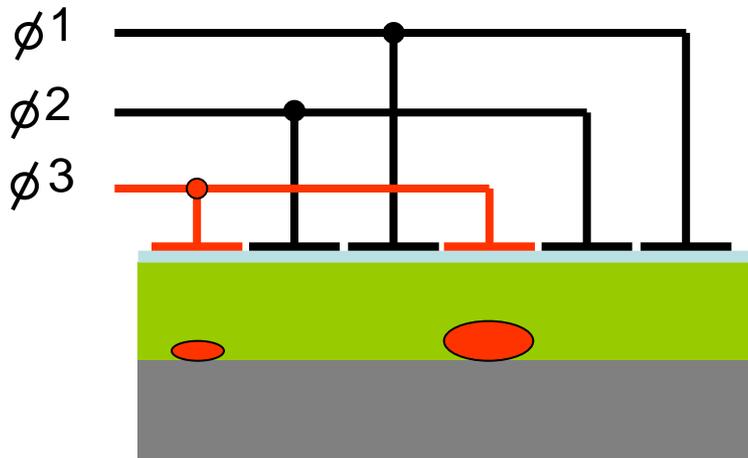
Apply Voltages
Here



Charge Transfer

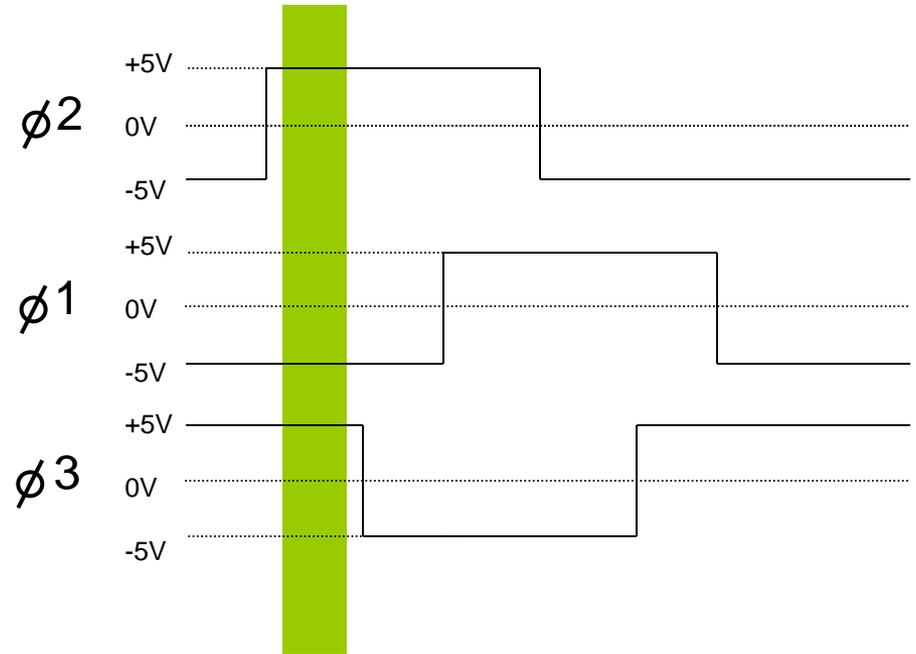
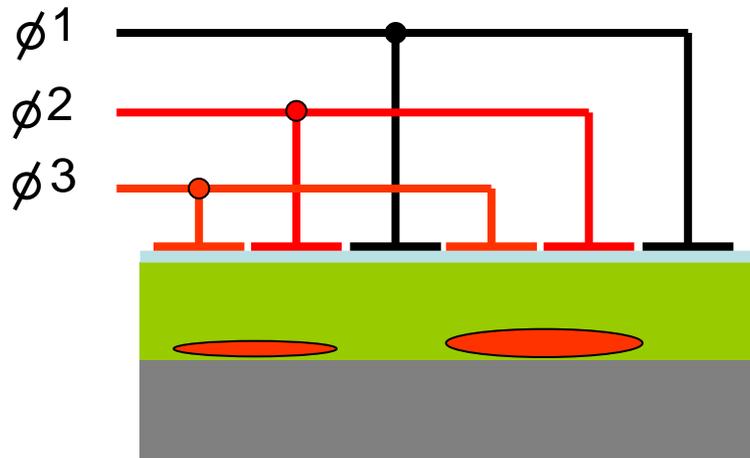


Charge Transfer - 1

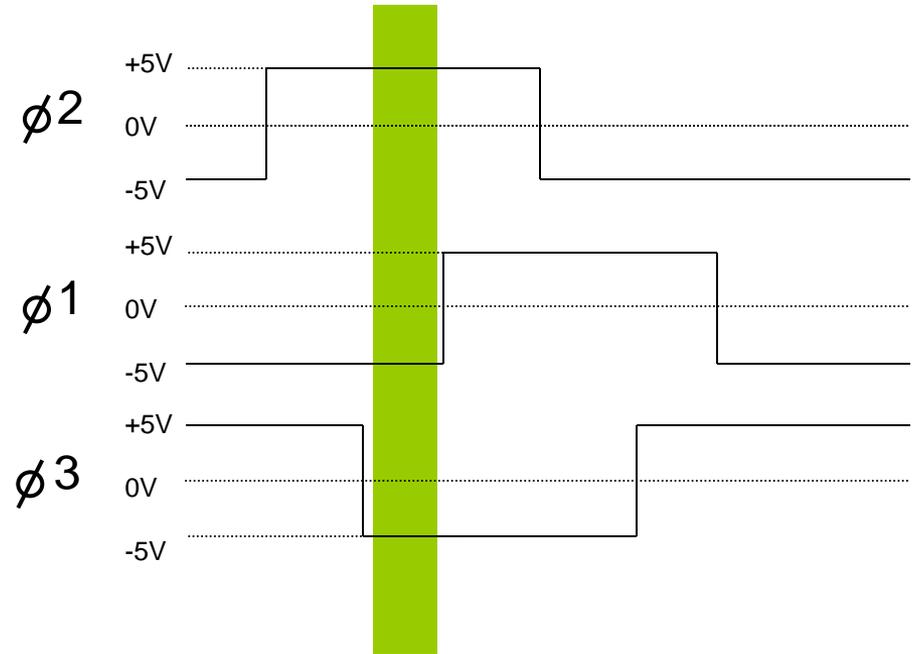
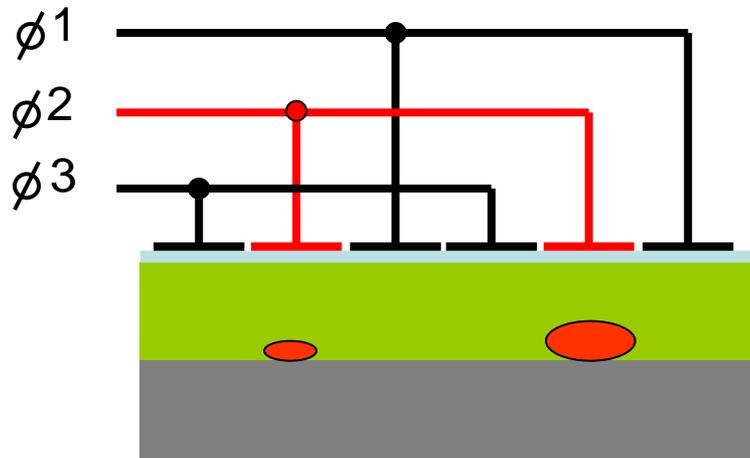


Time-slice shown in diagram

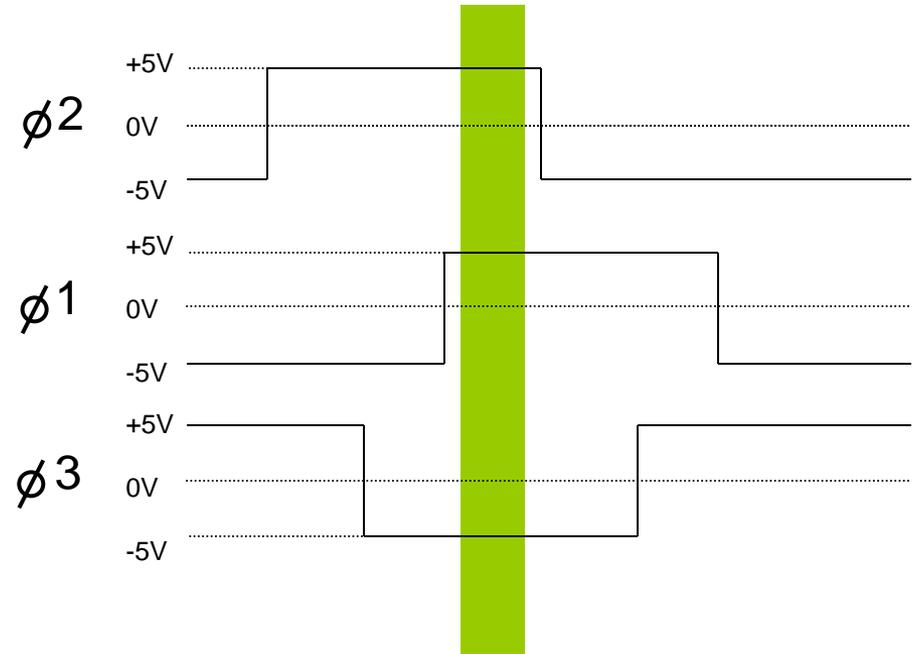
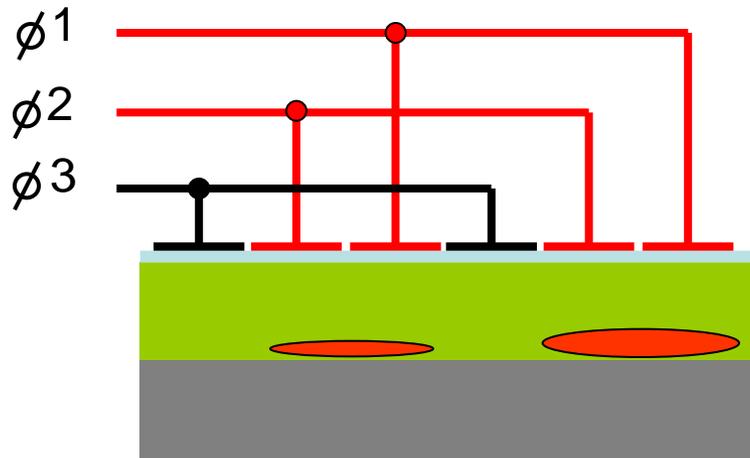
Charge Transfer - 2



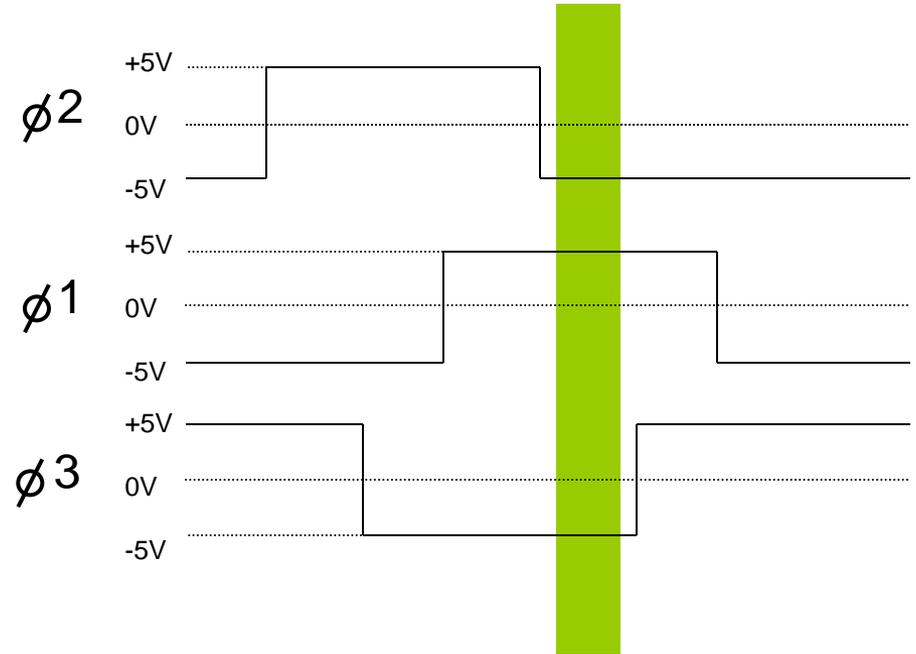
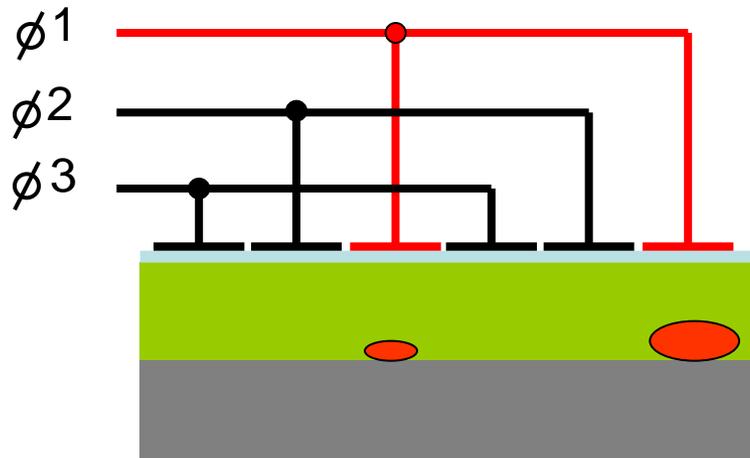
Charge Transfer - 3



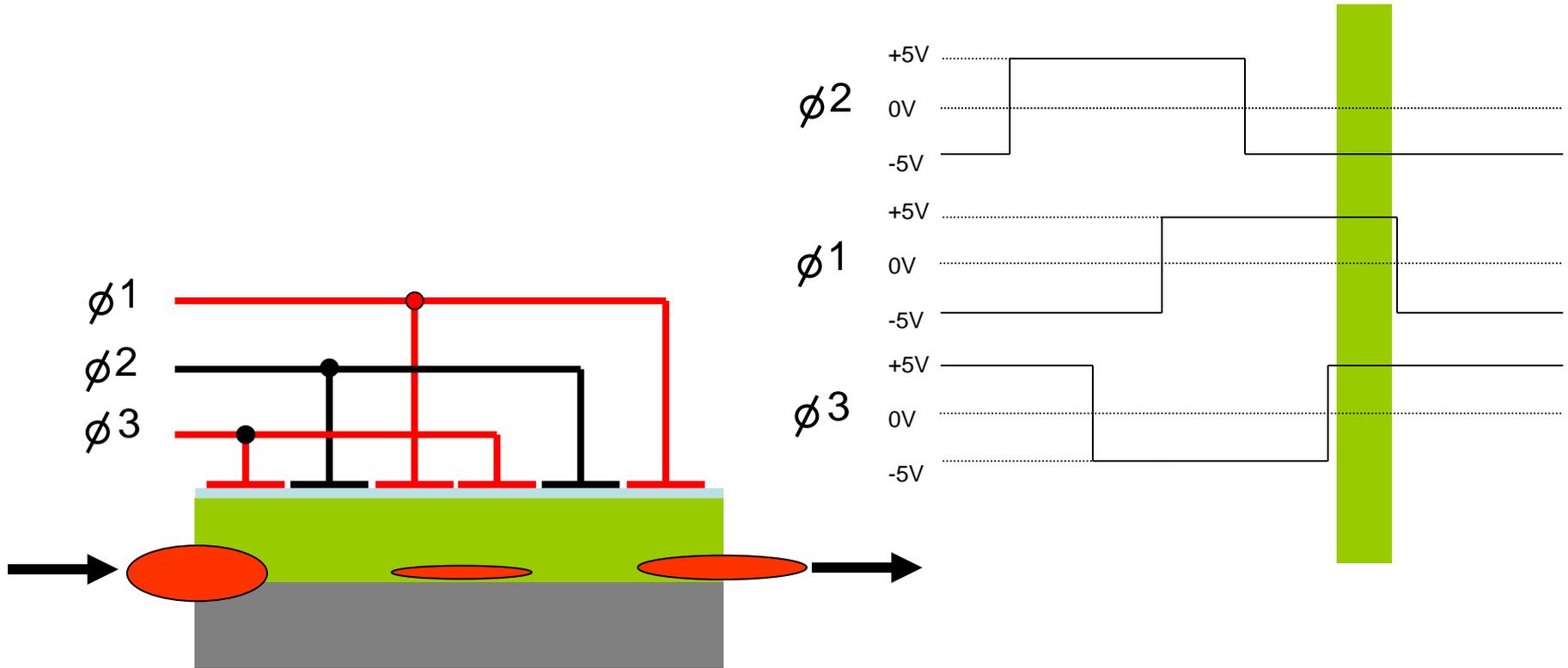
Charge Transfer - 4



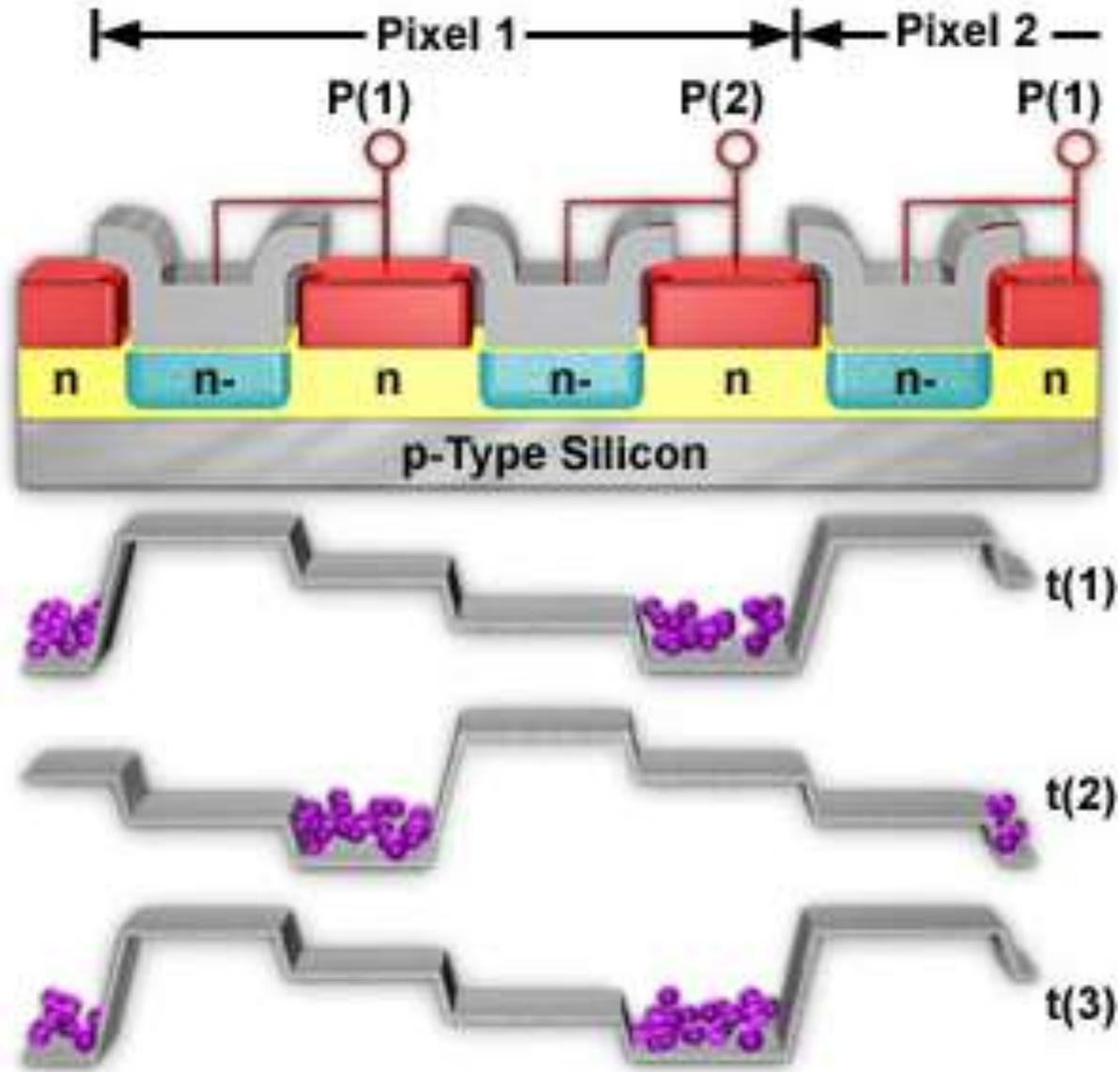
Charge Transfer - 5



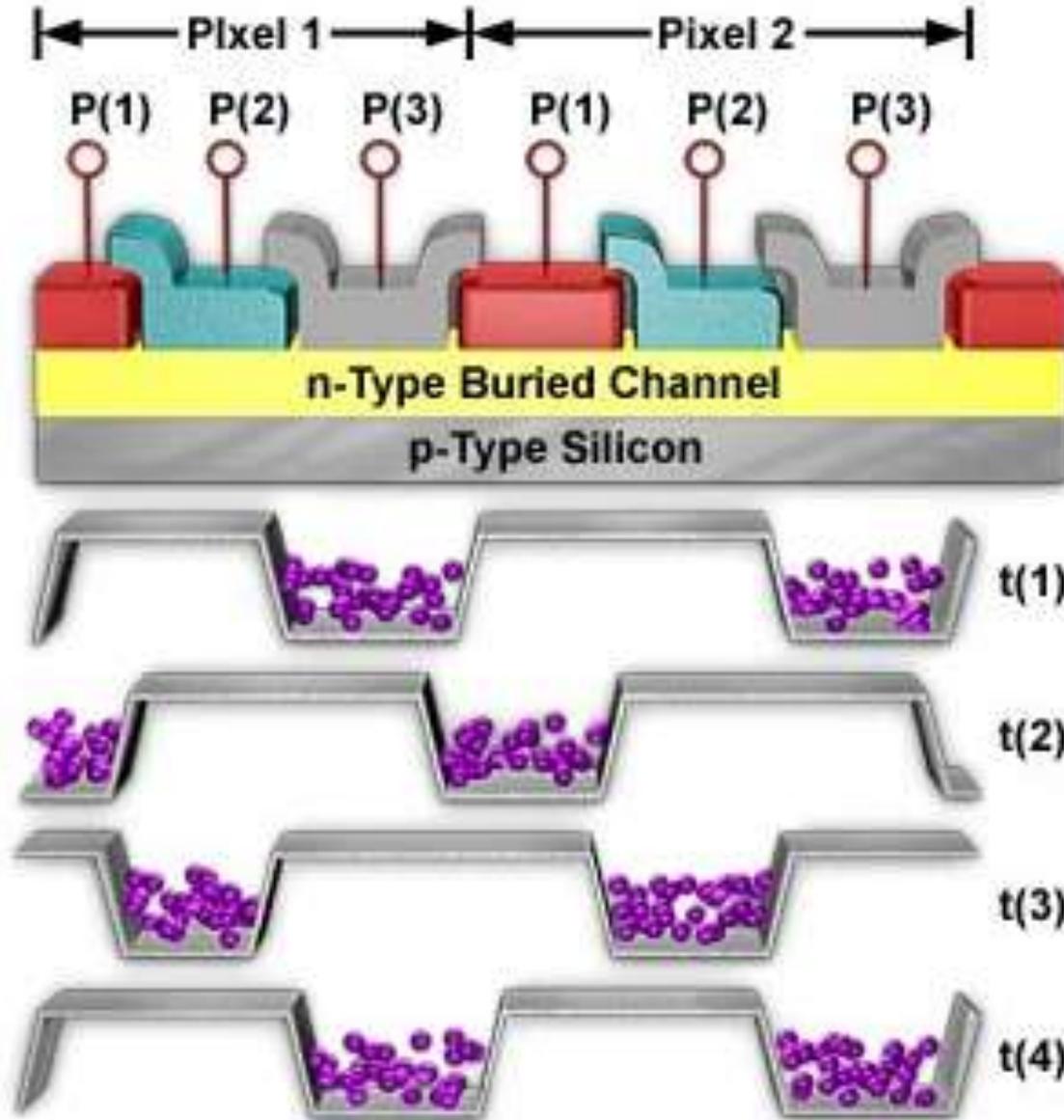
Charge Transfer - 6



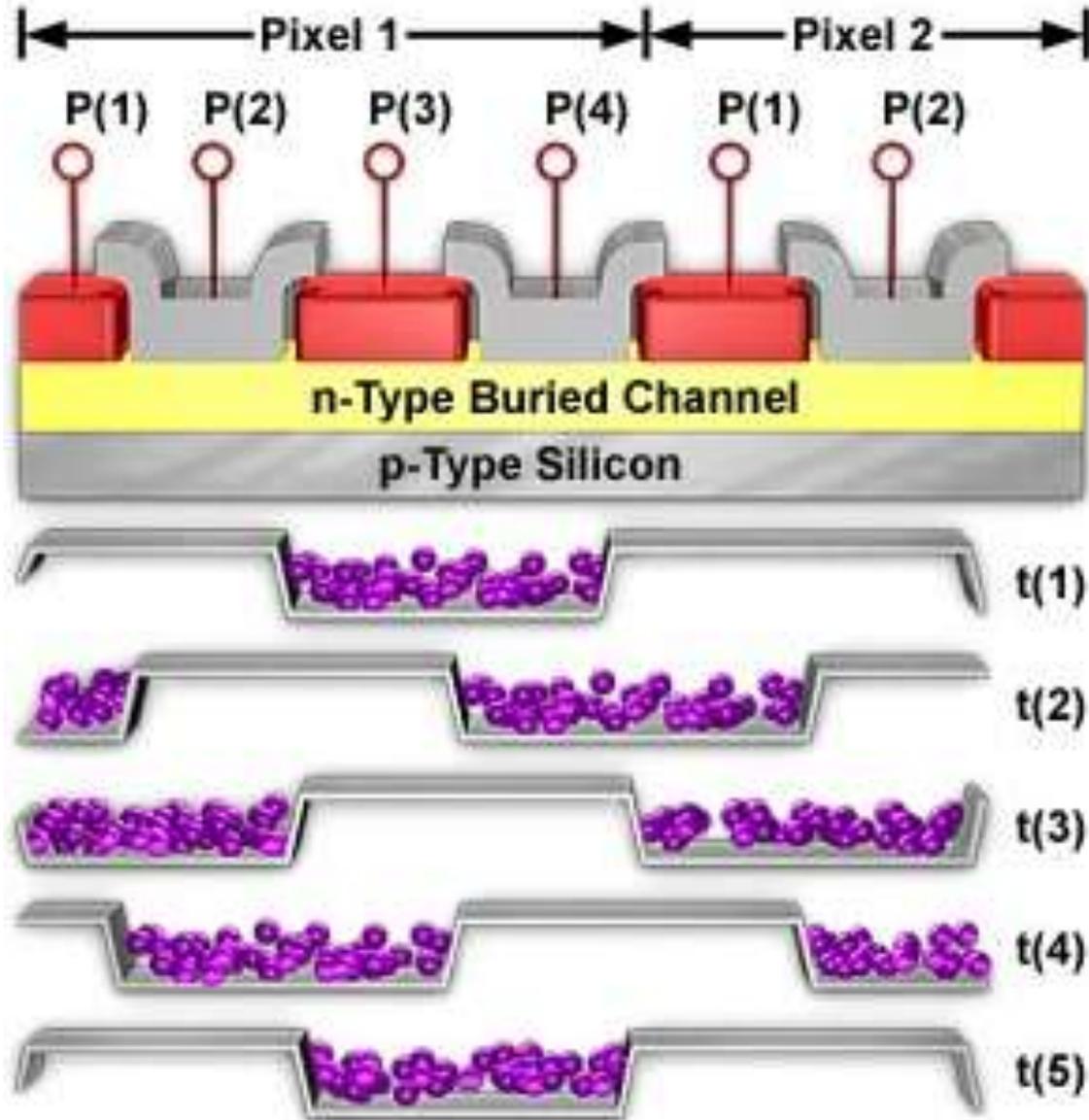
Transfert à 2 phases



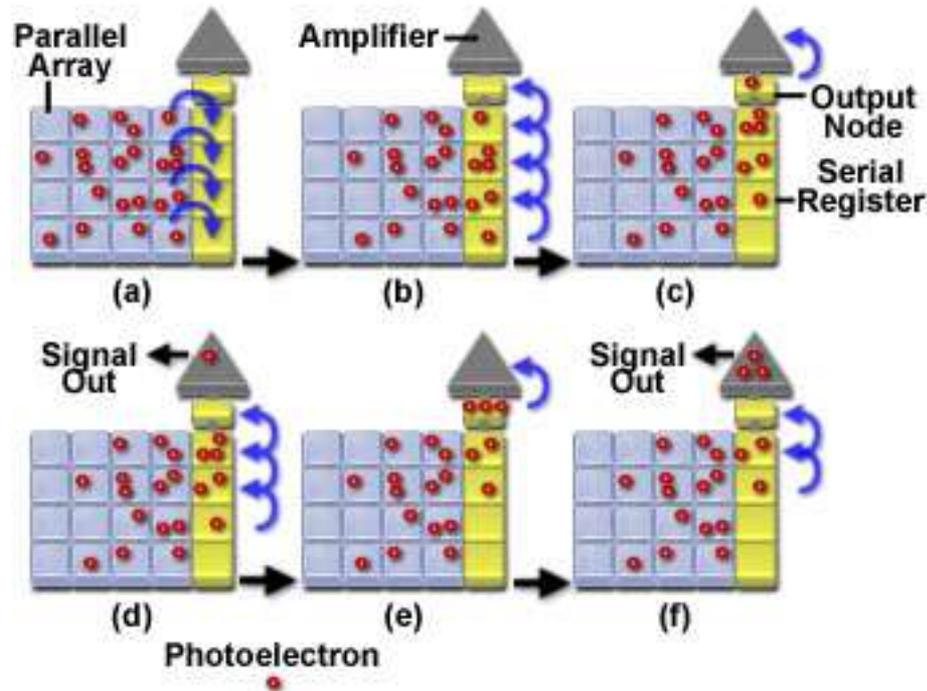
Transfert à 3 phases



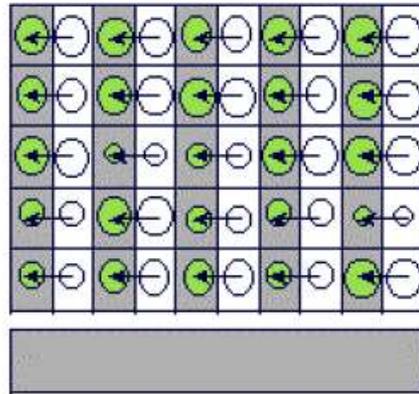
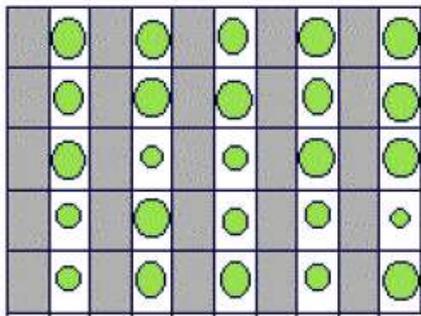
Transfert à 4 phases



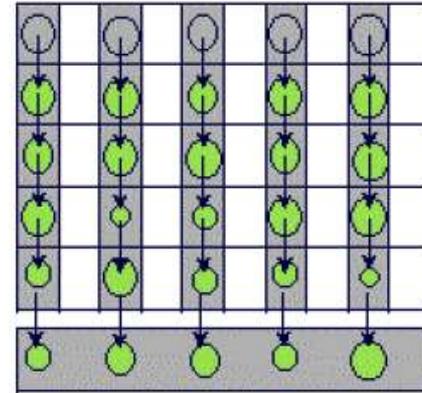
La lecture du CCD



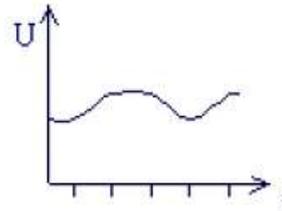
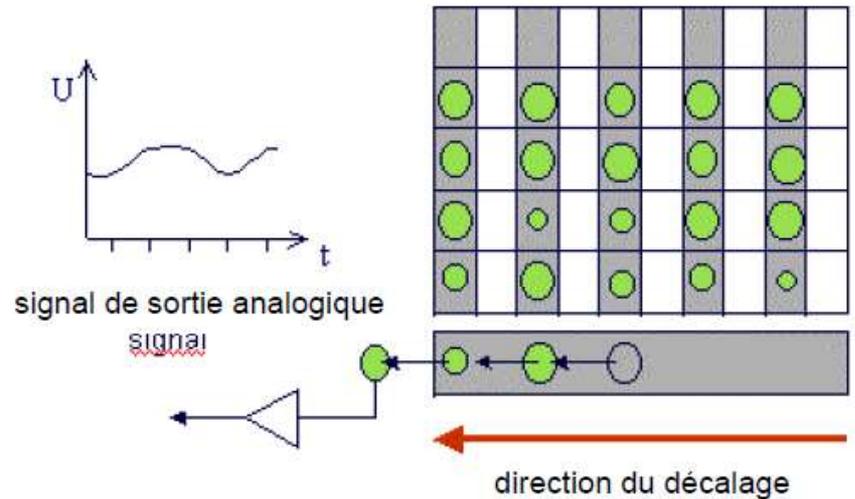
La lecture du CCD interligne



direction du décalage



direction du décalage

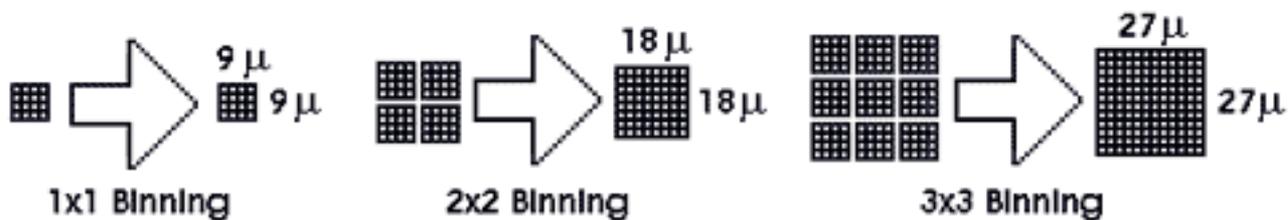
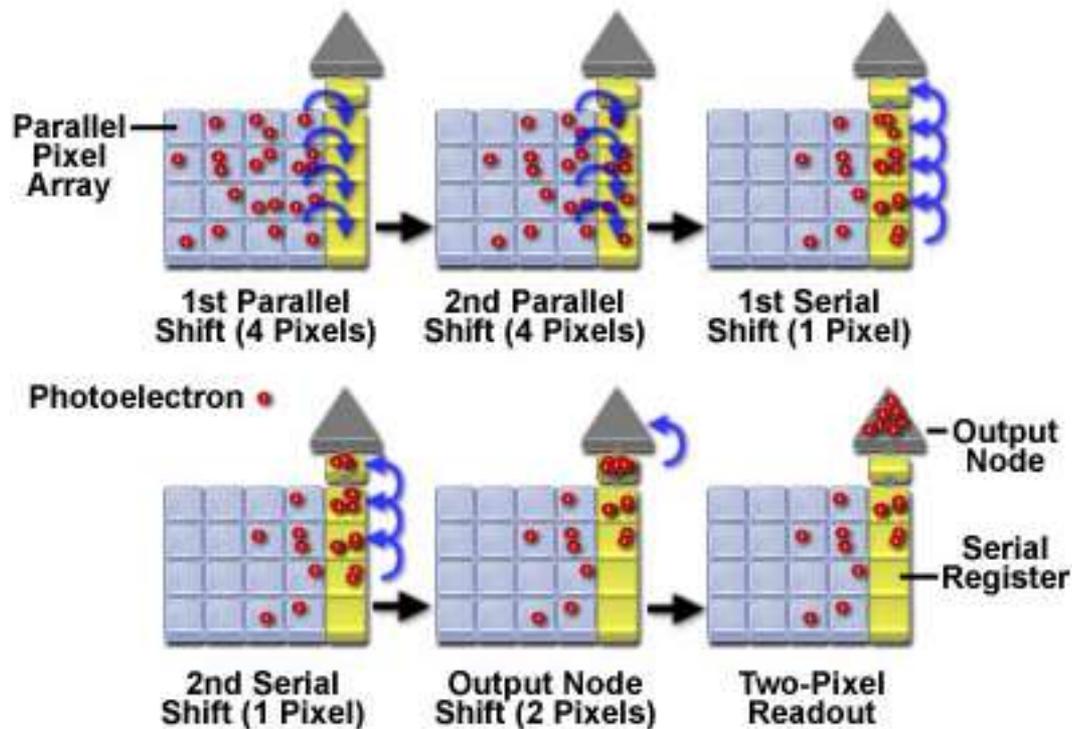


signal de sortie analogique

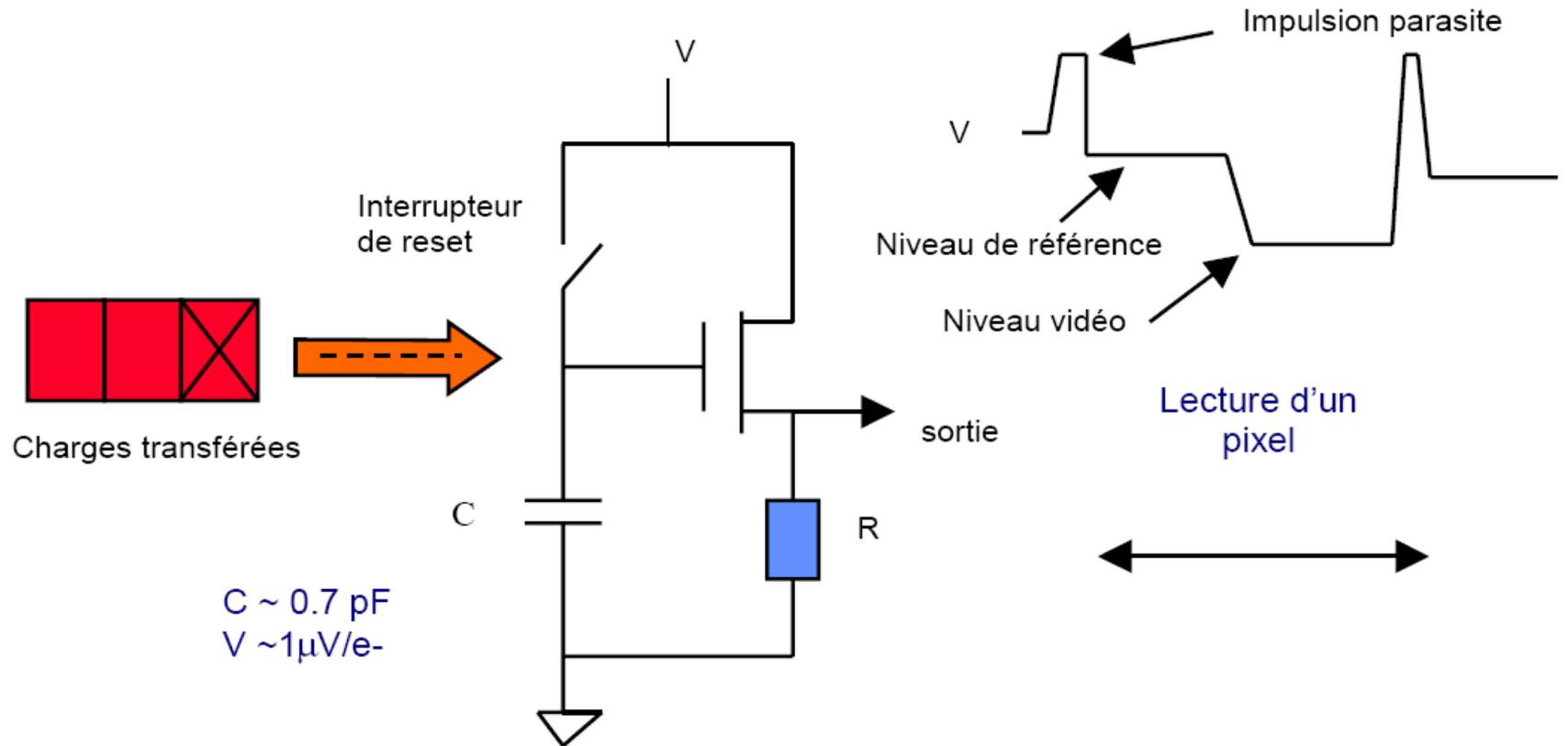
signal

direction du décalage

Le binning

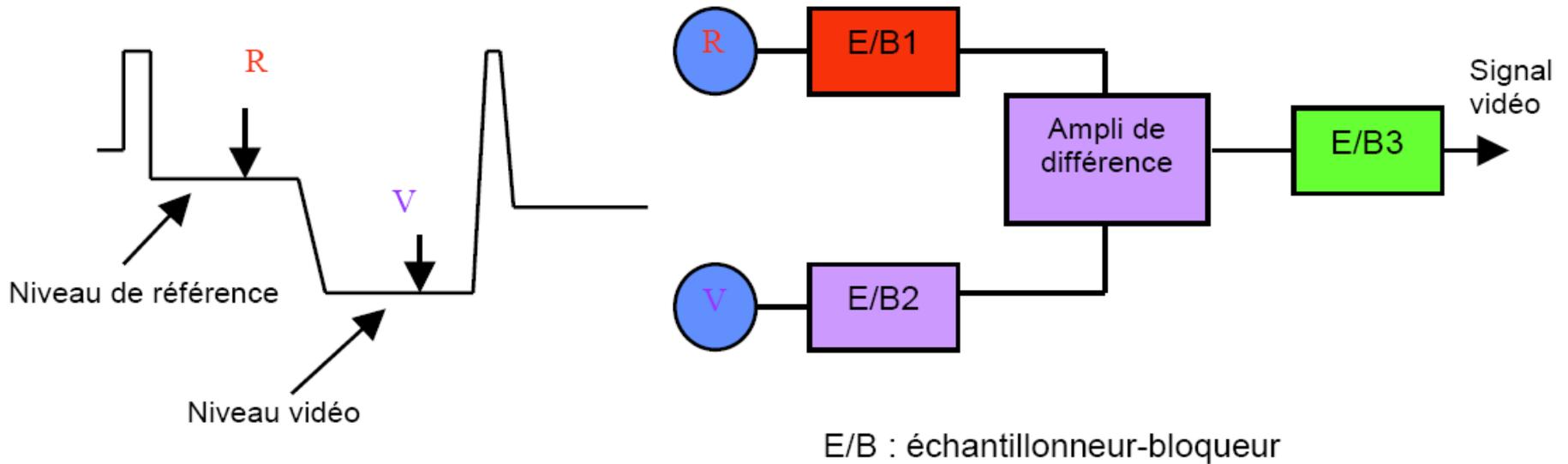


La lecture du CCD



A la lecture d'une ligne après l'autre, le registre horizontal est vidé et les paquets de charges sont transférés sur la grille d'un transistor MOS servant de convertisseur charge-tension.

La lecture du CCD



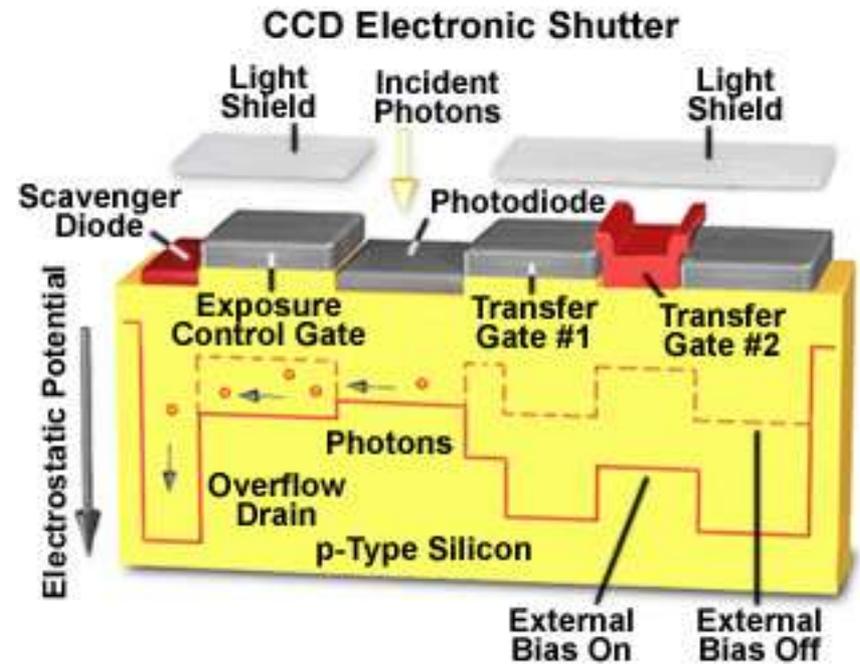
L'information « niveau vidéo » n'est pas disponible en permanence sur la source du transistor, il faut donc prévoir un dispositif d'échantillonnage, qui va s'affranchir également des dérives possibles du niveau de référence.

Obturbateur

Mécanique

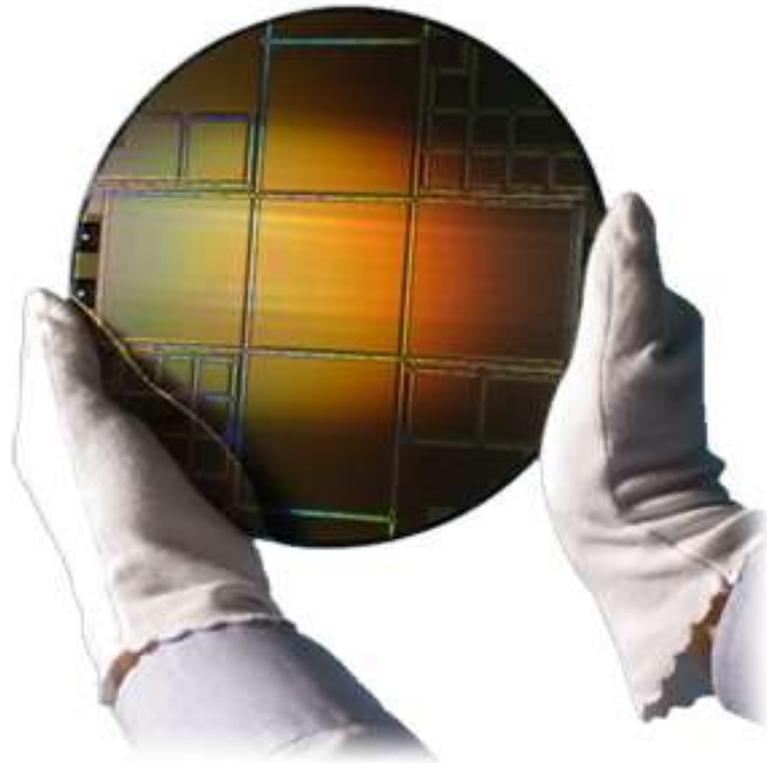


Electronique

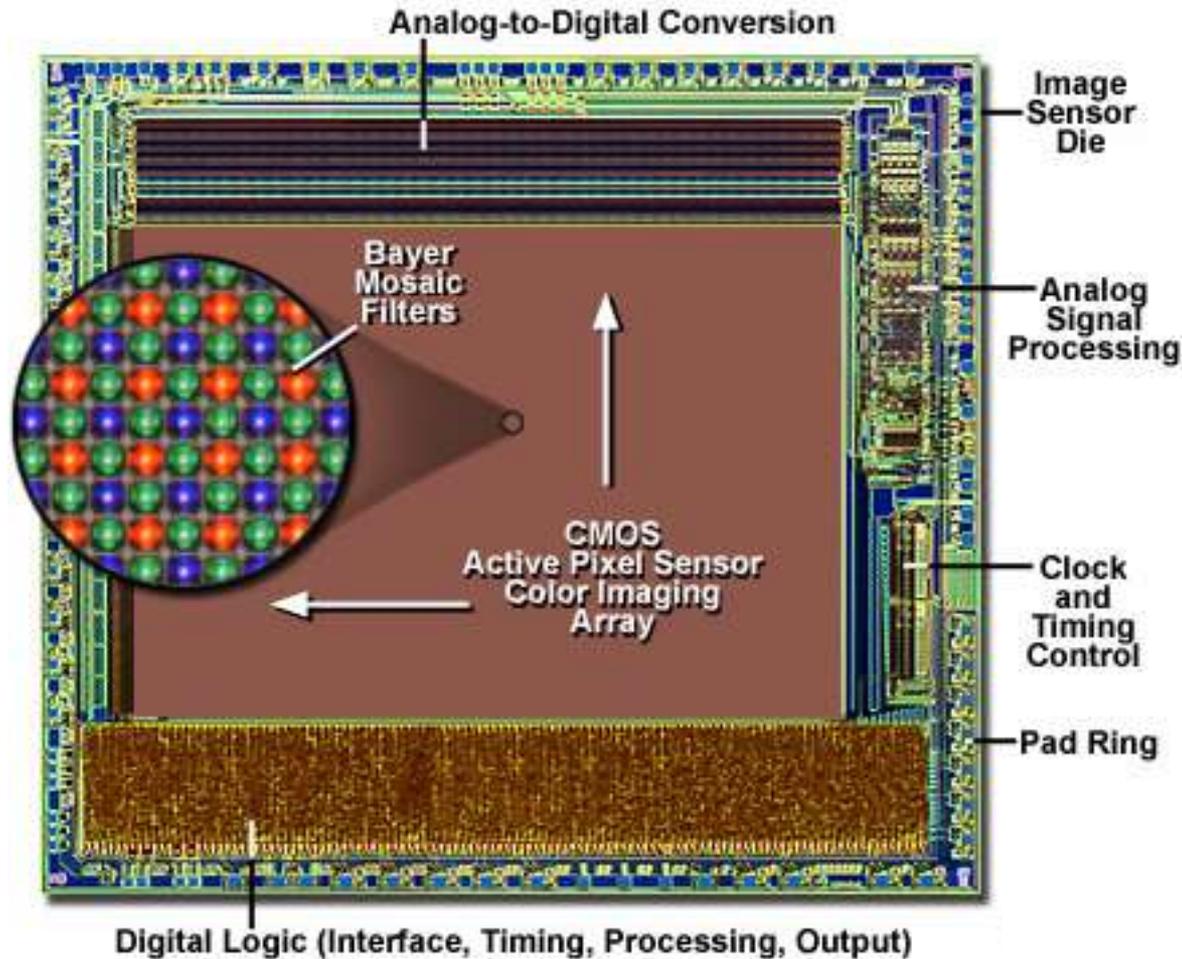


CMOS

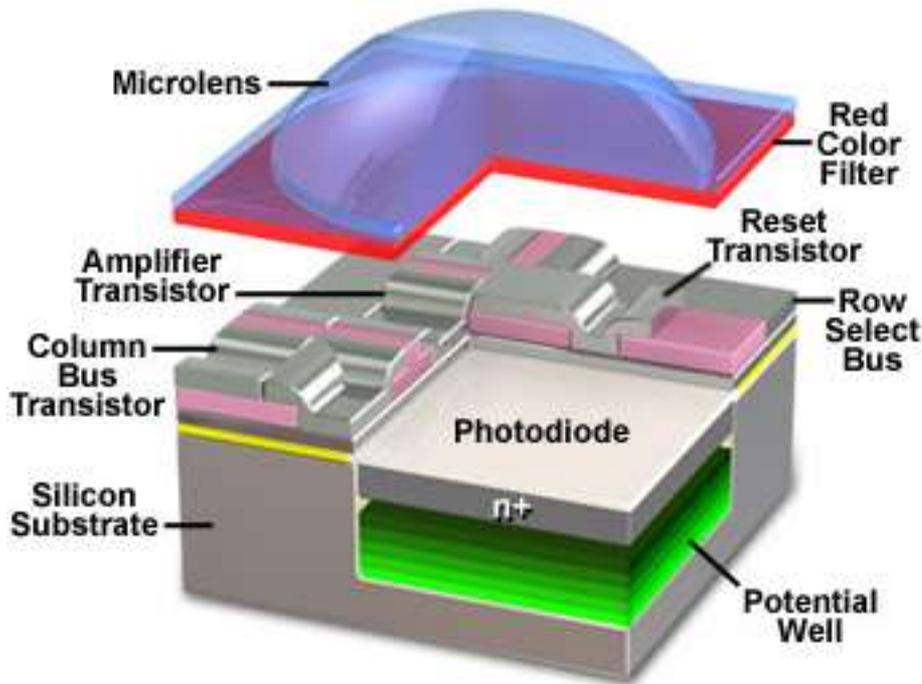
**Complementary Metal
Oxide Semiconductor**



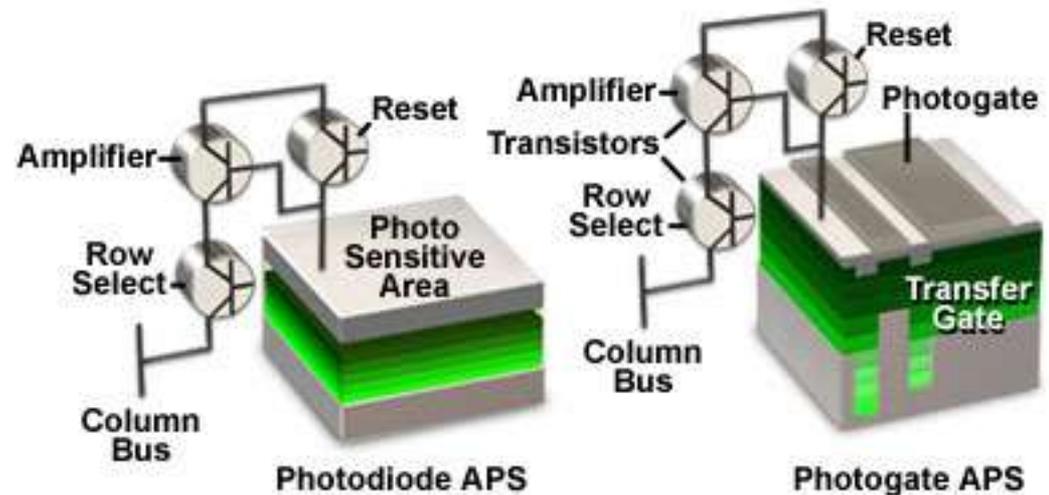
Architecture d'un capteur CMOS



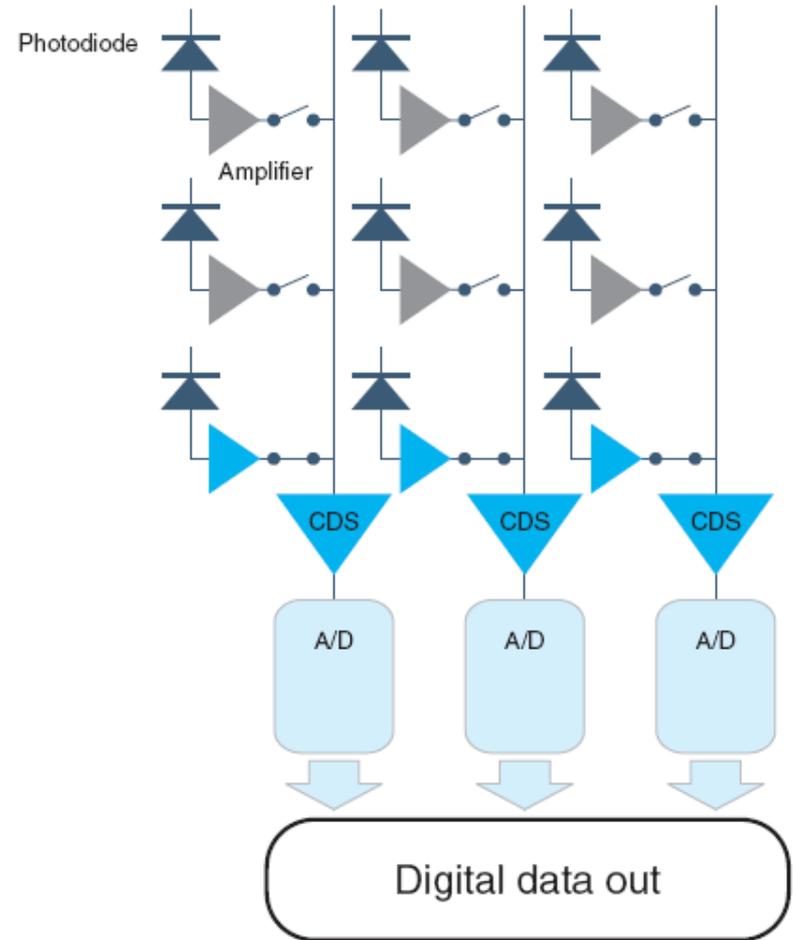
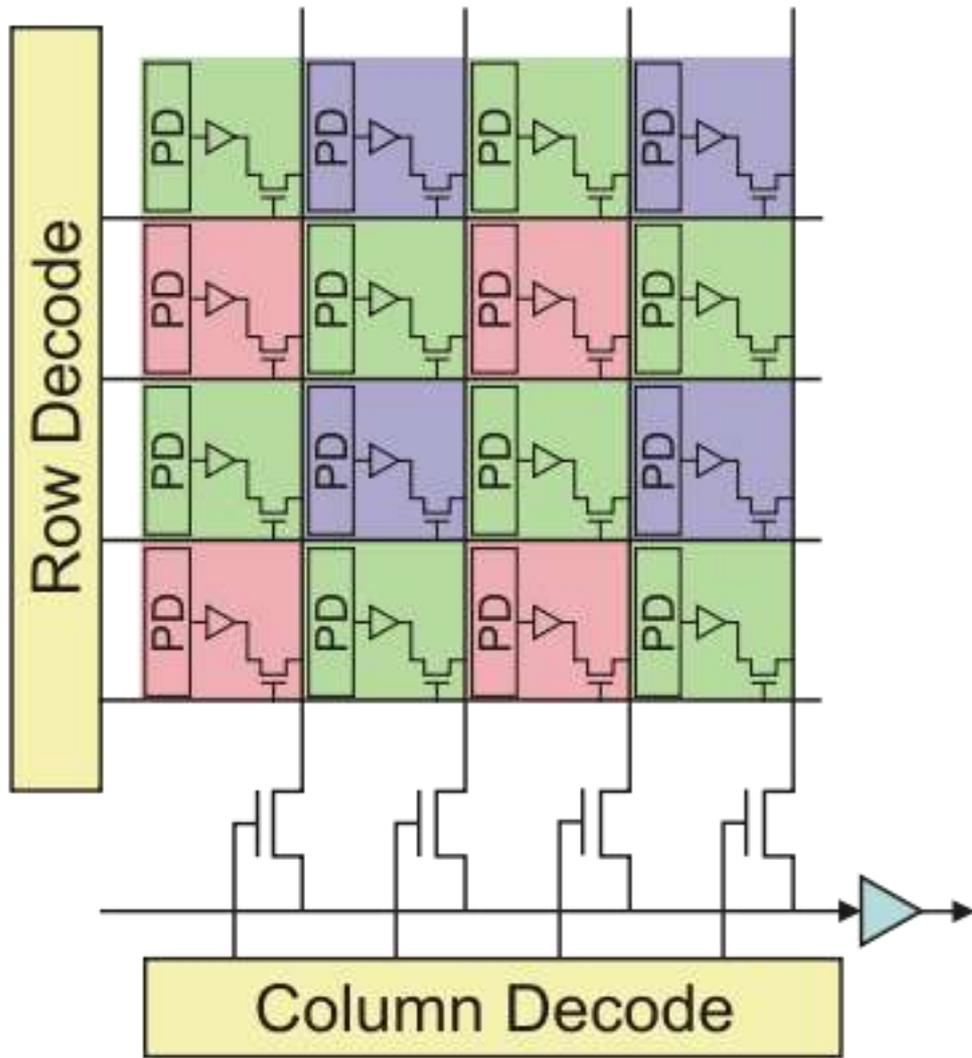
Le pixel du capteur CMOS



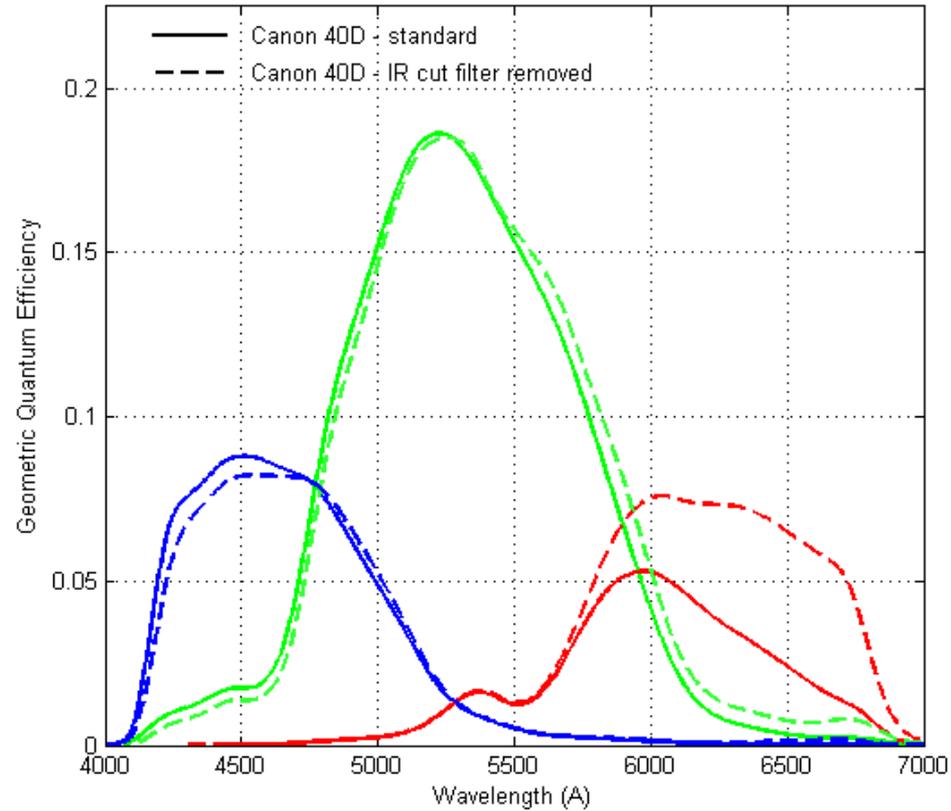
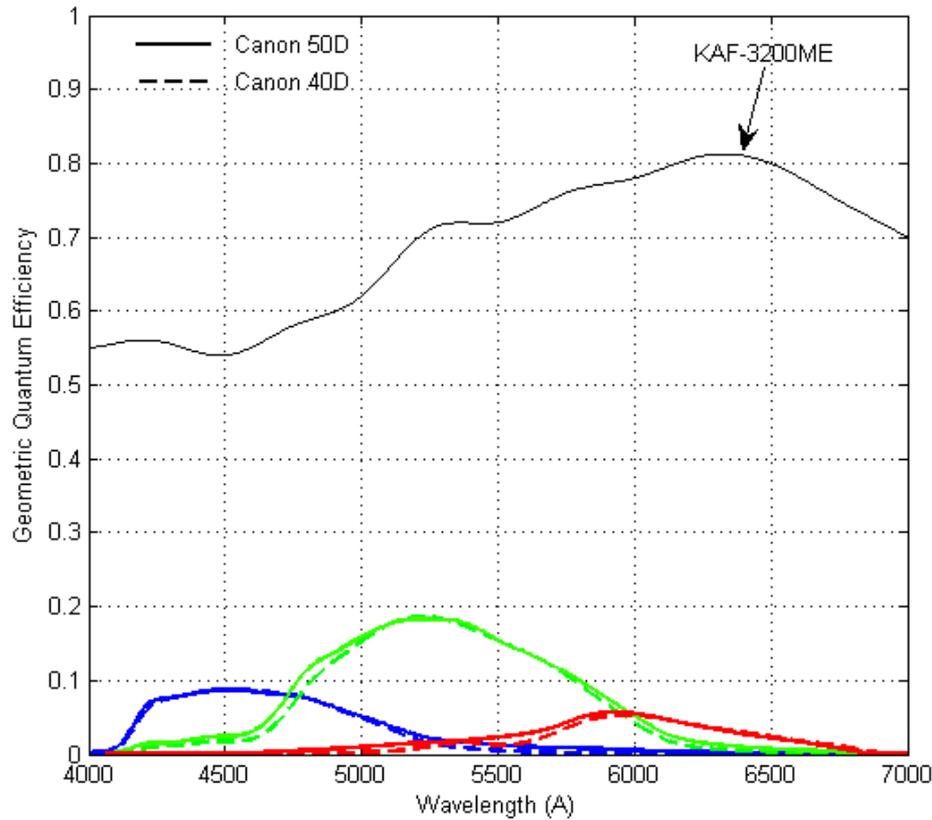
Photodiode and Photogate Structural Features



Structure(s) du capteur CMOS



Rendement Quantique



Canon EOS 350D with original IR cut

Canon EOS 350D with Baader IR cut

Canon EOS 350D without IR cut

Ca H
3968 A

Hbeta
4861 A

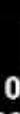
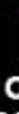
Na
5893 A

Halpha
6563 A

O2
6869 A

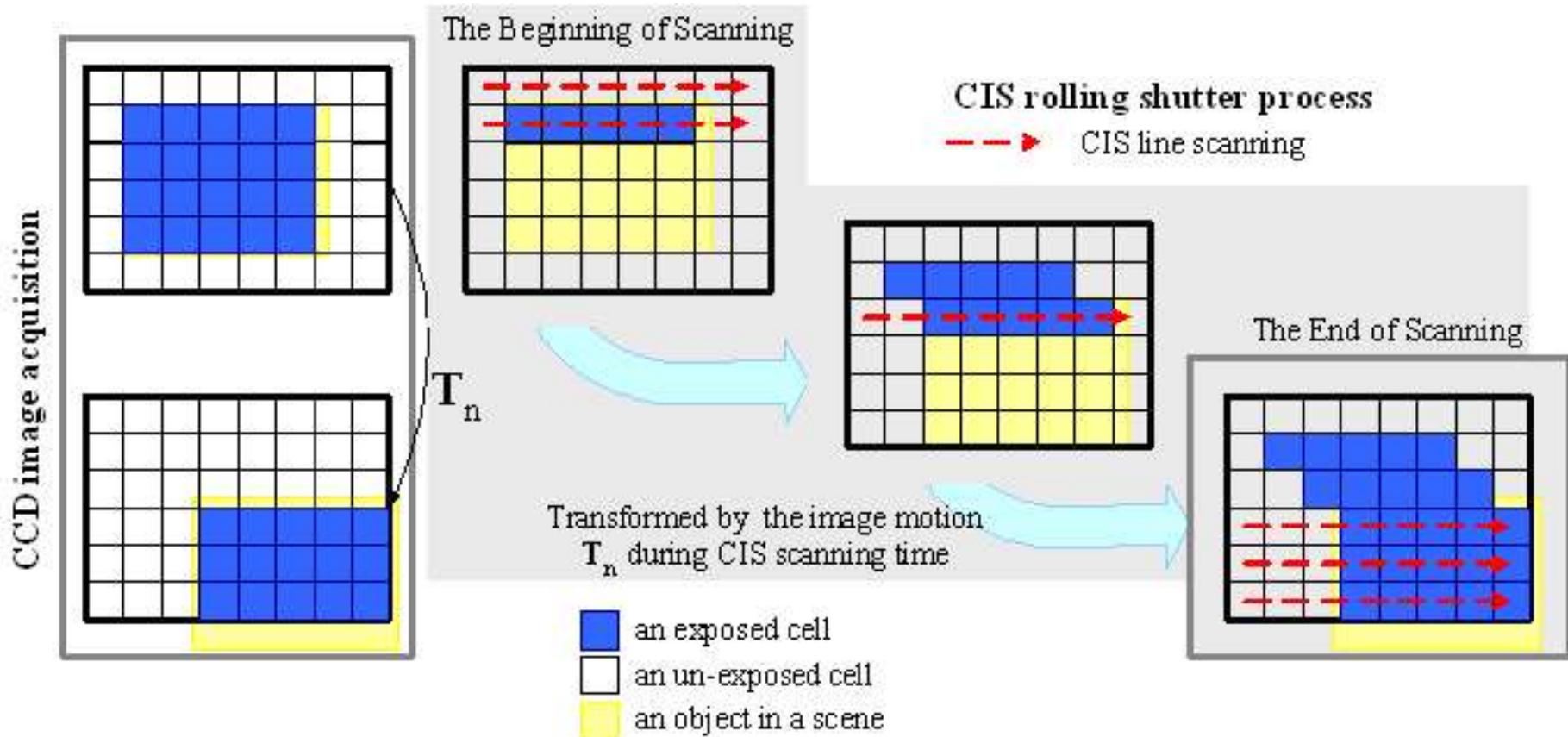
H2O
7186 A

O2
7605 A

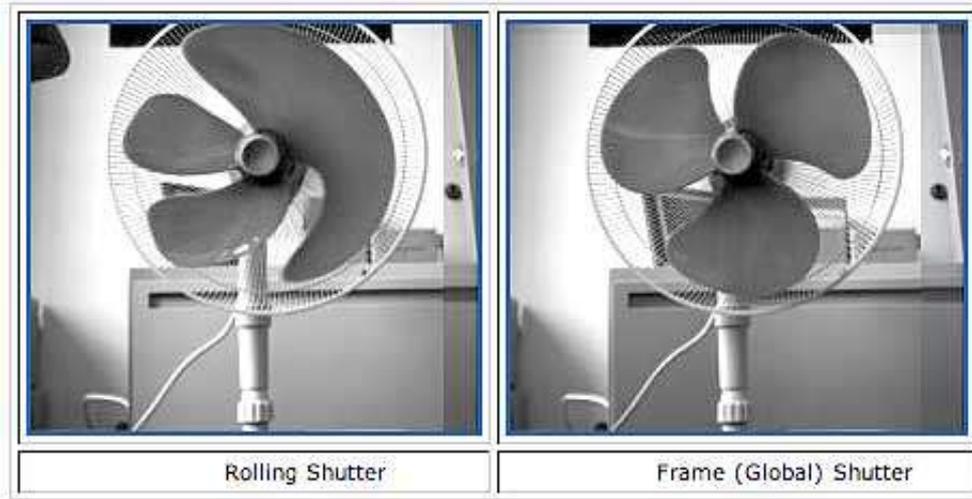


Obturateur : électronique

Problème : « rolling shutter »



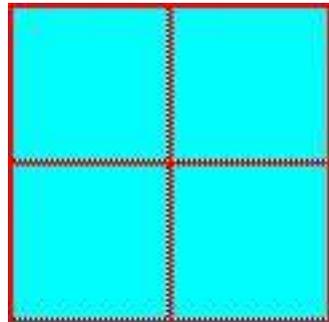
Problème : « rolling shutter »



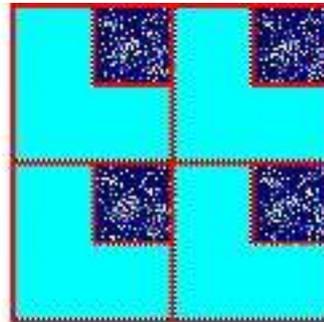


Les défauts des capteurs

Le « fill factor »

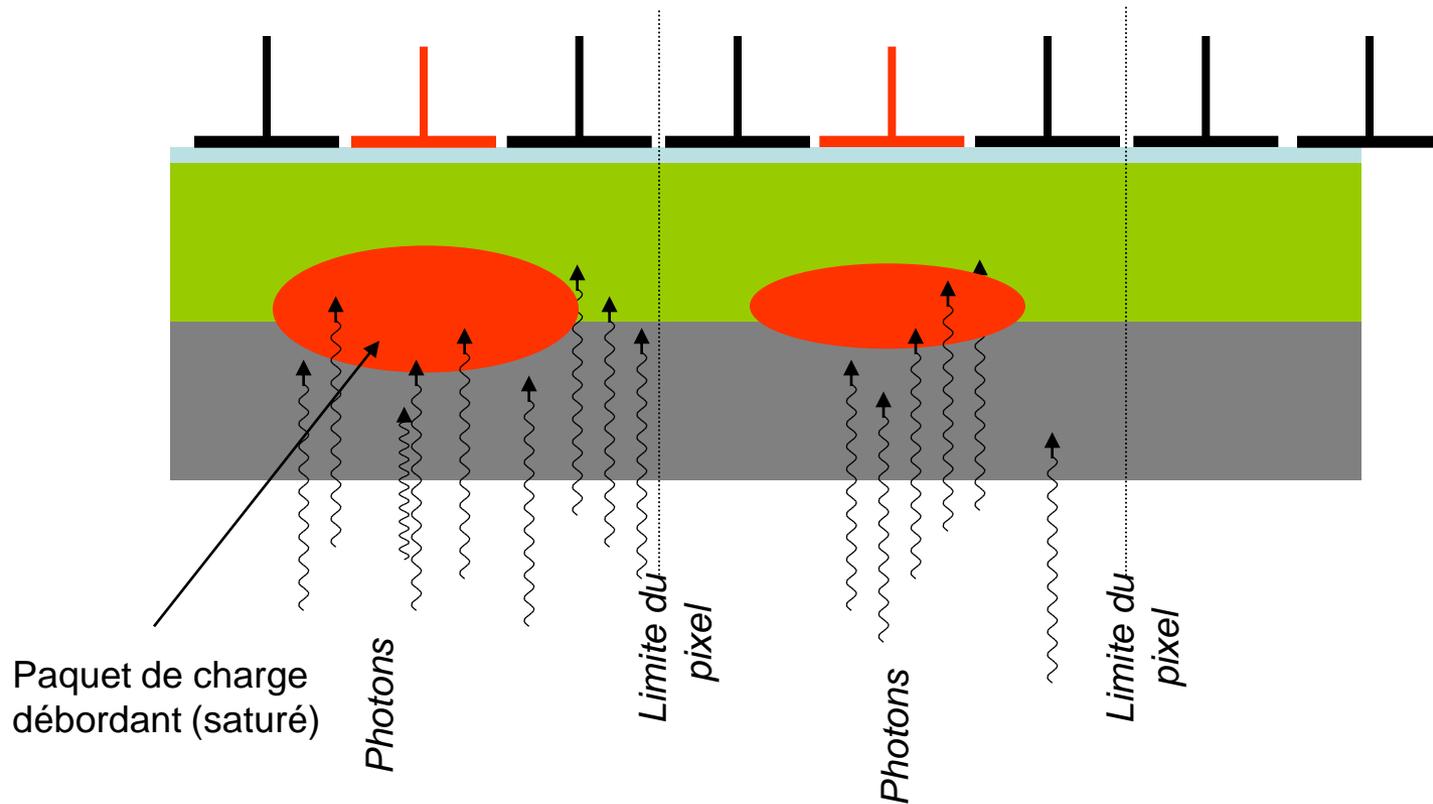


100% Fill factor

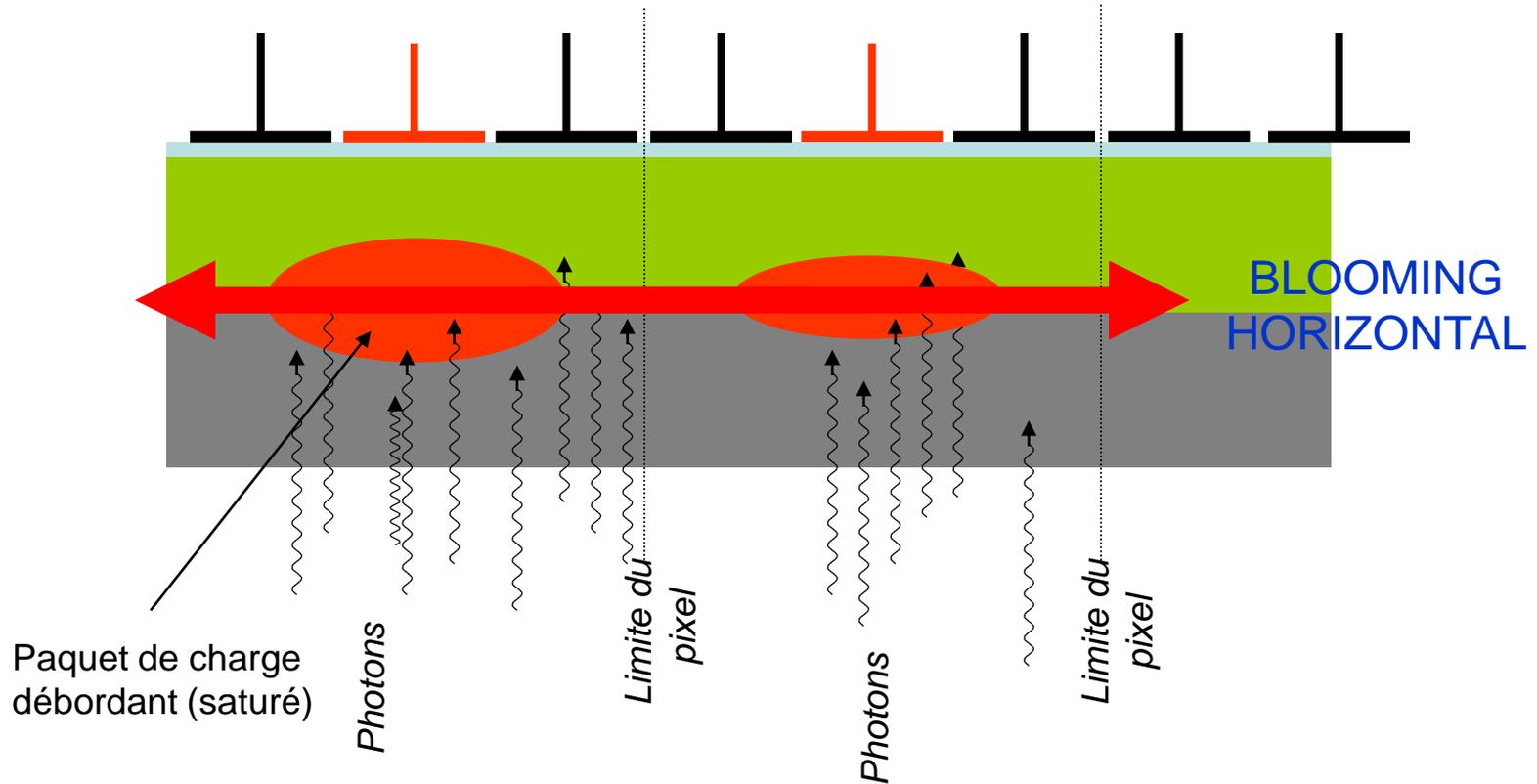


75% Fill factor

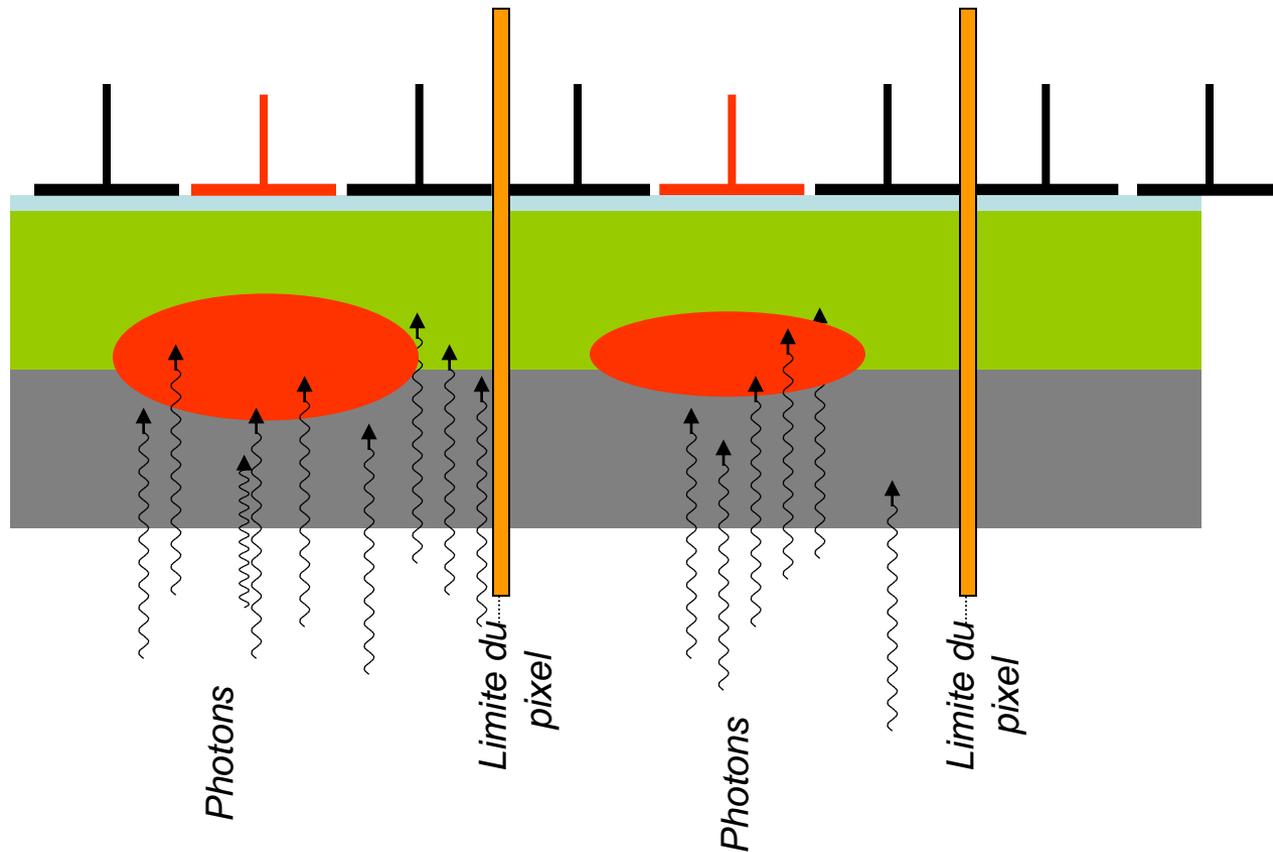
Le blooming



Le blooming



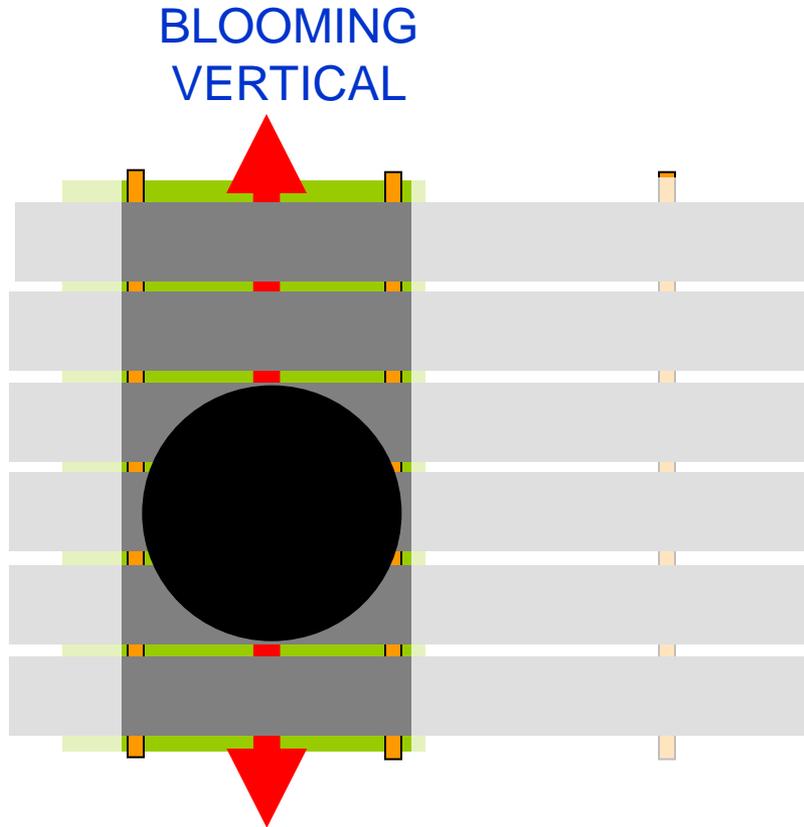
Le blooming



Réduction: **Installation de drains d'évacuation**

Vertical overflow drain \Leftrightarrow Résolution

Le blooming

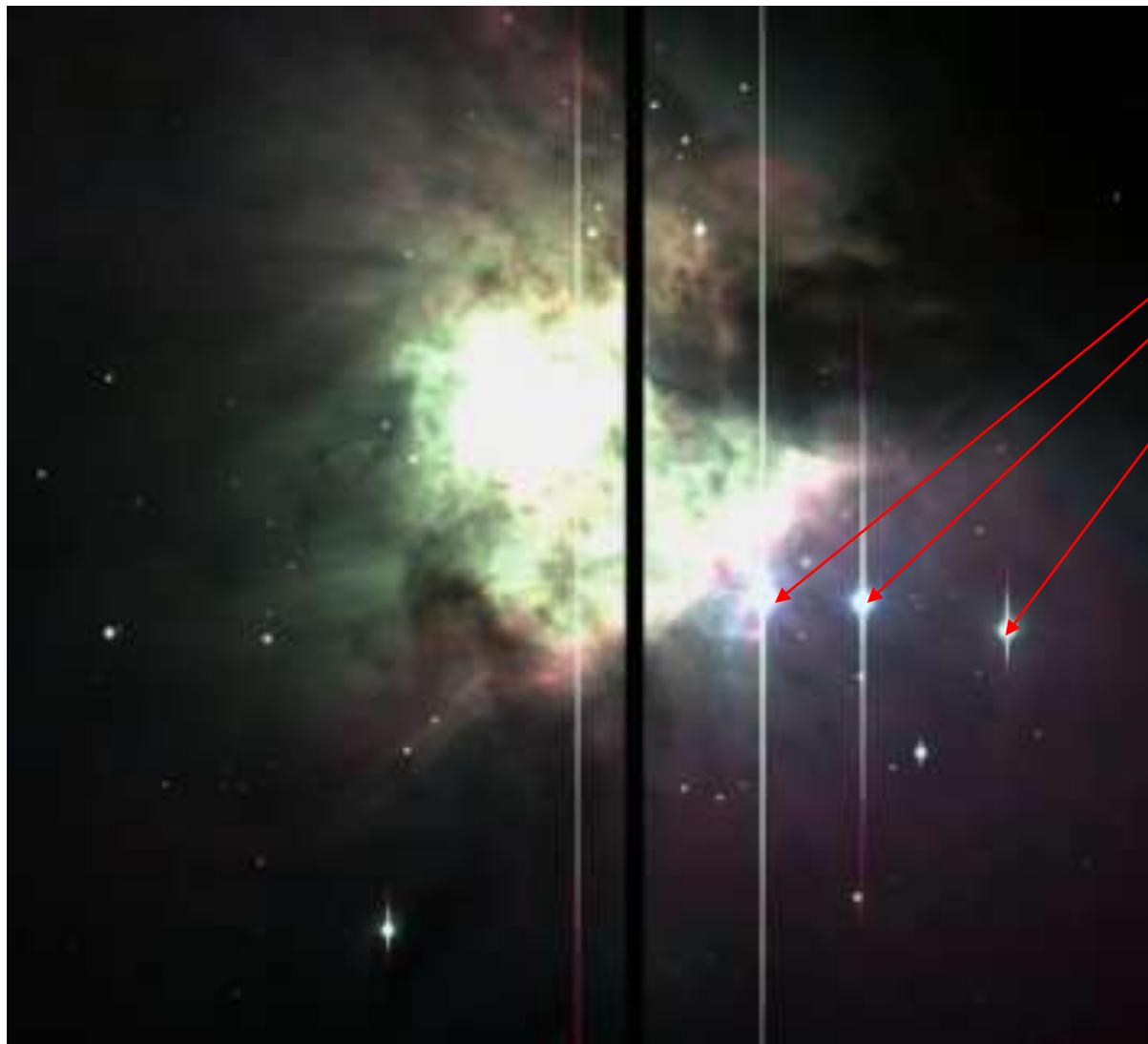


Les drains ne suffisent plus
La charge se répand dans la
colonne.

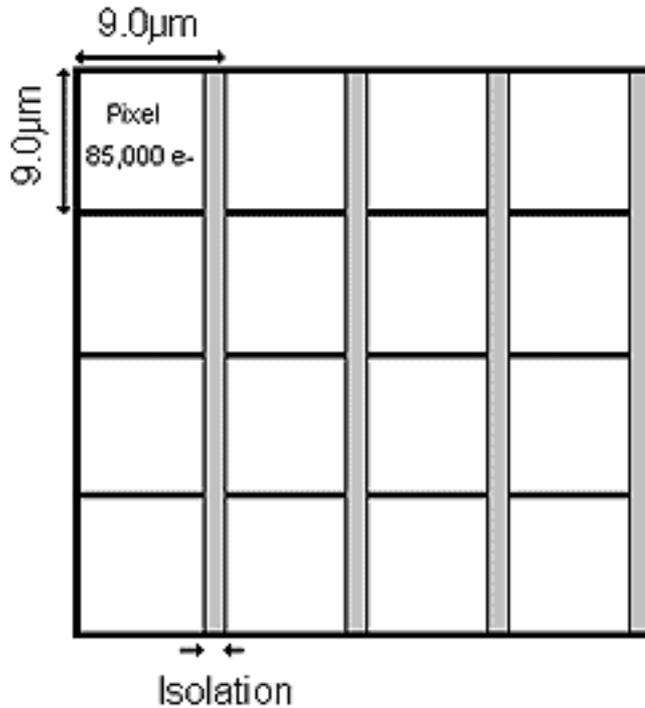
Pixel saturé
Nbre électrons \gg FWC

Réduction: [Eviter la saturation](#)

EXEMPLE
DE BLOOMING

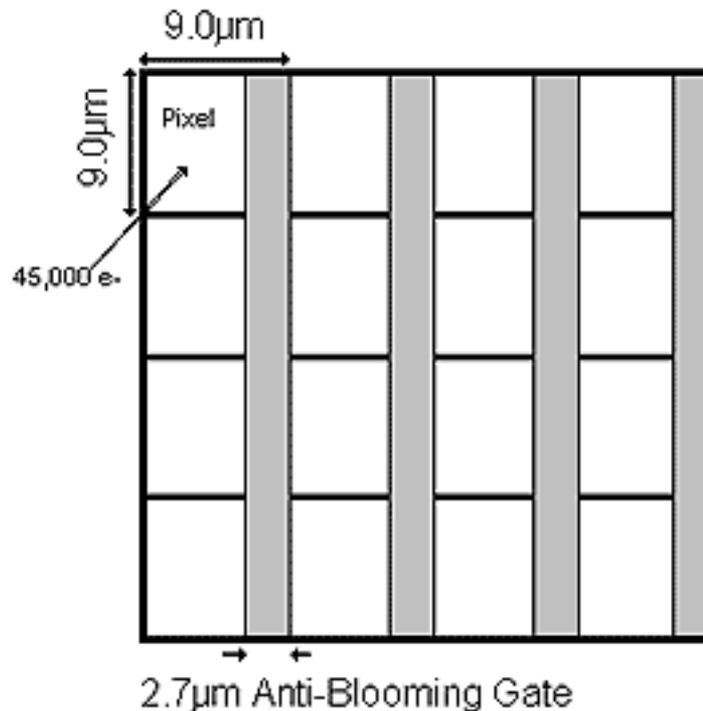


Anti-blooming



No Anti-Blooming Gate

100% Fill Factor
85,000 electron well depth
Higher Quantum Efficiency
Blooming (Streaking) possible



Anti-Blooming Gate

70% Fill Factor
45,000 electron well depth
Lower Quantum Efficiency

Anti-blooming

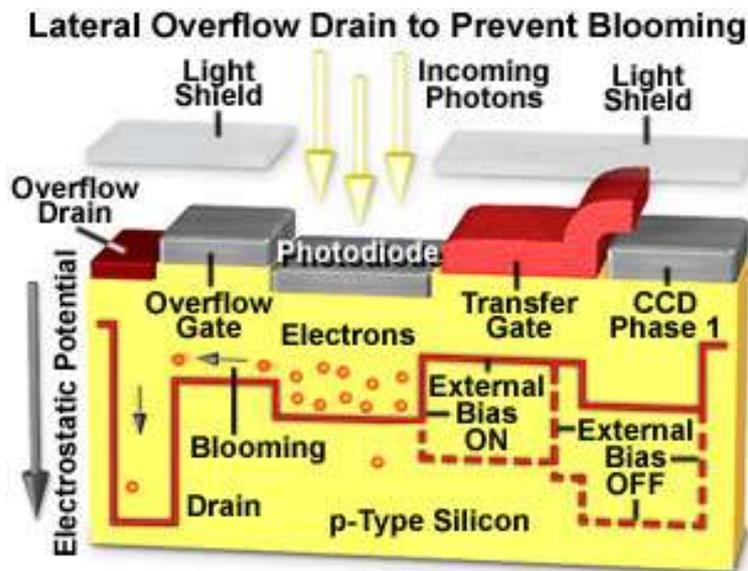
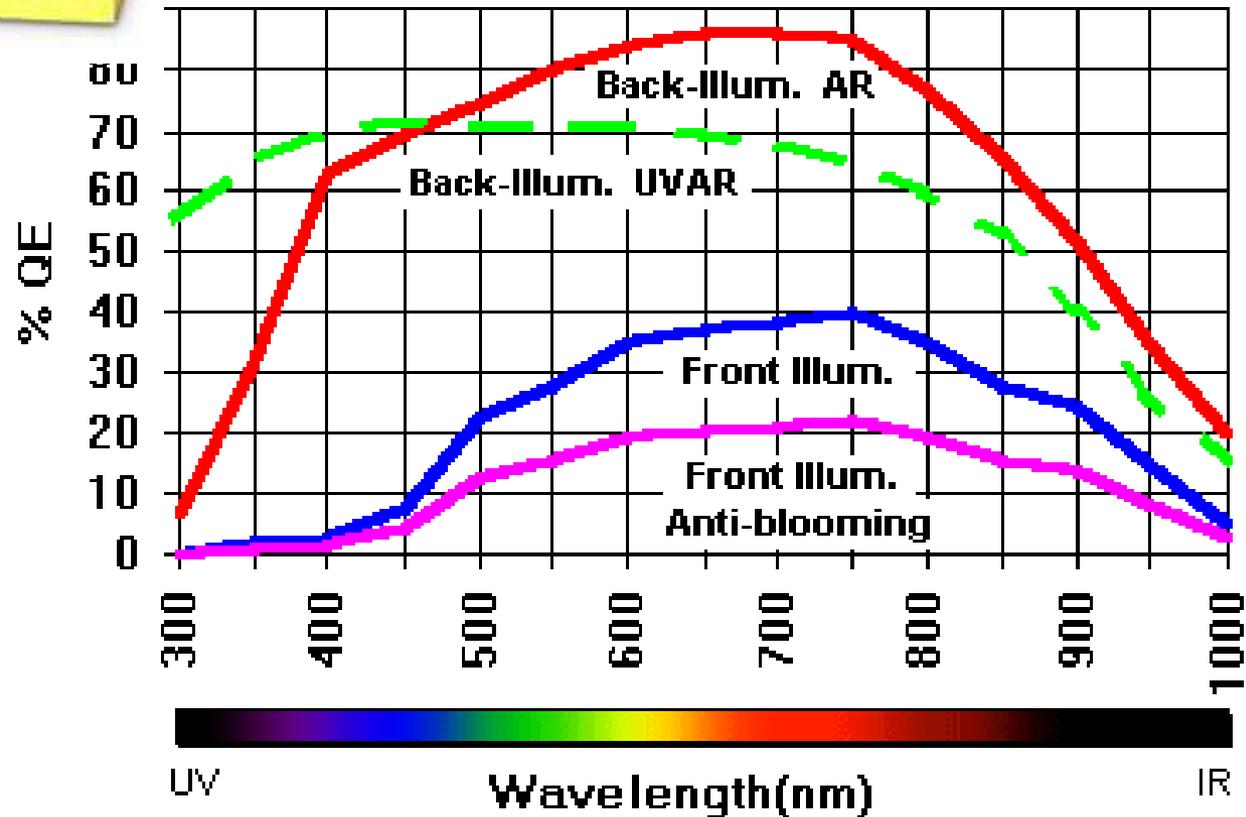


Figure 3



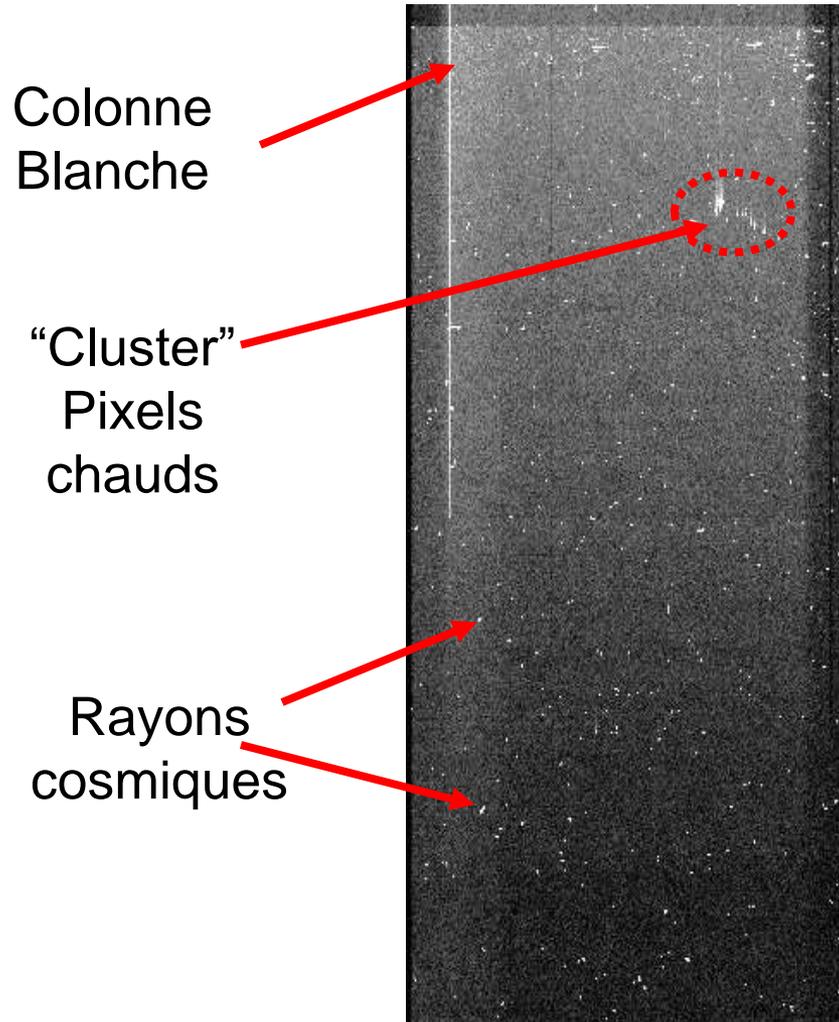
Défauts cosmétiques

Colonne noire



- Colonnes mortes
 - 1 pixel mort piège les charges de toute la colonne (ou partie)
- Pixels noirs

Défauts cosmétiques



Colonne blanche

“Traps” = piège

Pixels chauds

Pixels avec un courant d’obscurité élevé

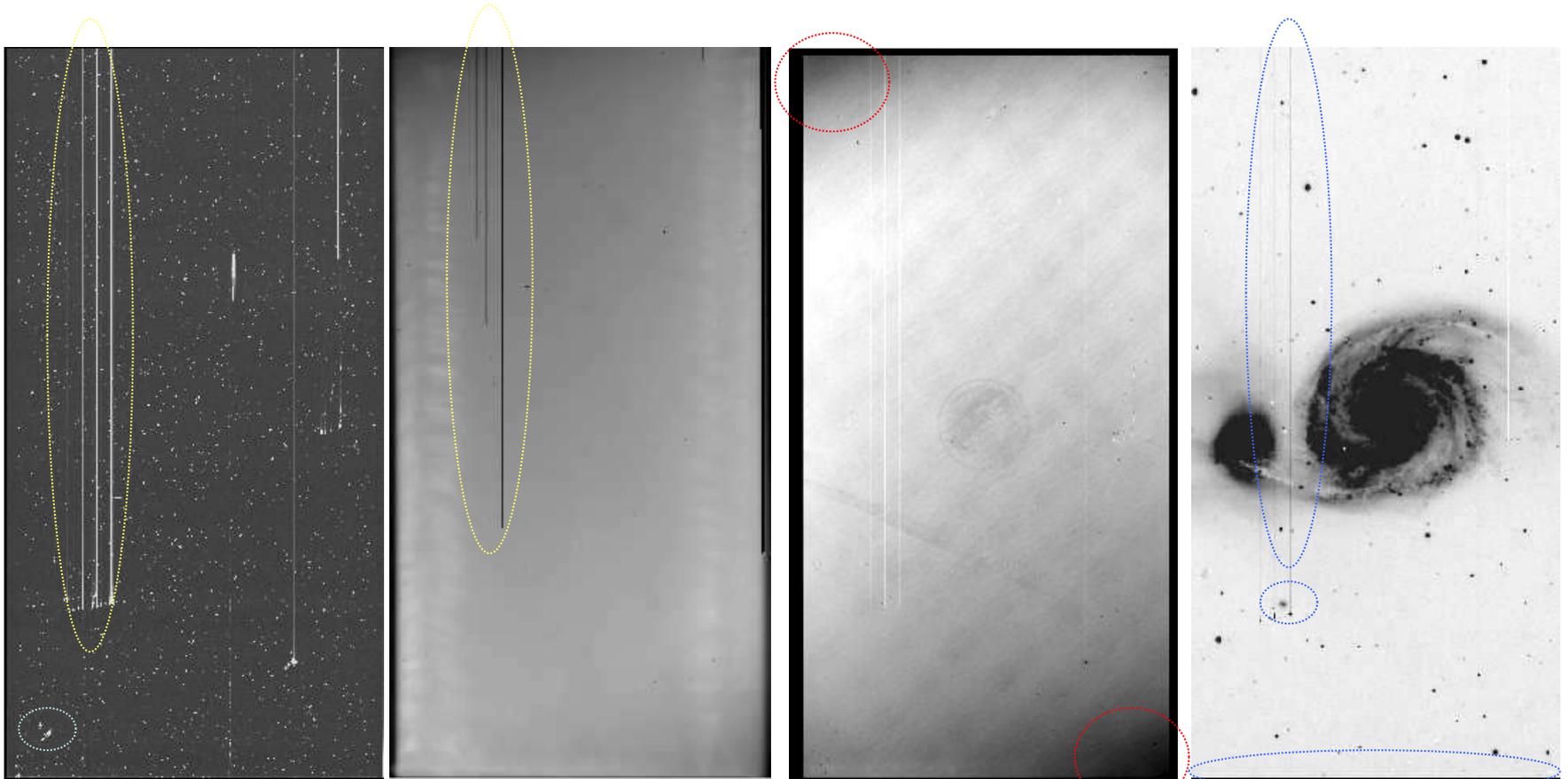
Origine : fabrication

Rayons cosmiques(γ)

Imprévisible

Ionisation d’e⁻ dans le Si

Mise en évidence des défauts



Dark Frame
Vue noire

Flat Field
Eclaircissement uniforme

Négatif

Défauts

Pixel défectueux	Un pixel dont la sortie dévie de plus de 6% comparativement aux pixels adjacents lorsqu'ils sont illuminés à 70% de la saturation.
Pixel chaud (Hot pixel)	Pixels avec des tensions de sortie extrêmement élevées. Typiquement, un pixel dont le courant de noir est 10 fois plus élevé que le courant de noir moyen.
Pixel noir (Dark pixel)	Pixels avec une tension de sortie basse et/ou une faible réponse. Typiquement un pixel dont la sortie est la moitié des autres alors que le fond continu remplit quasiment les puits.
Piège à pixel (Trap)	Un piège interfère avec le processus de transfert de charge et il en résulte soit une partielle soit une complète mauvaise colonne (soit tout blanc, soit tout noir).
Colonne	Plusieurs (typiquement 10 voire plus) défauts points dans la même colonne. Peut être provoqué par des pièges à pixels.
Cluster	Un cluster (groupe) de pixels présentant des défauts points



GRADE

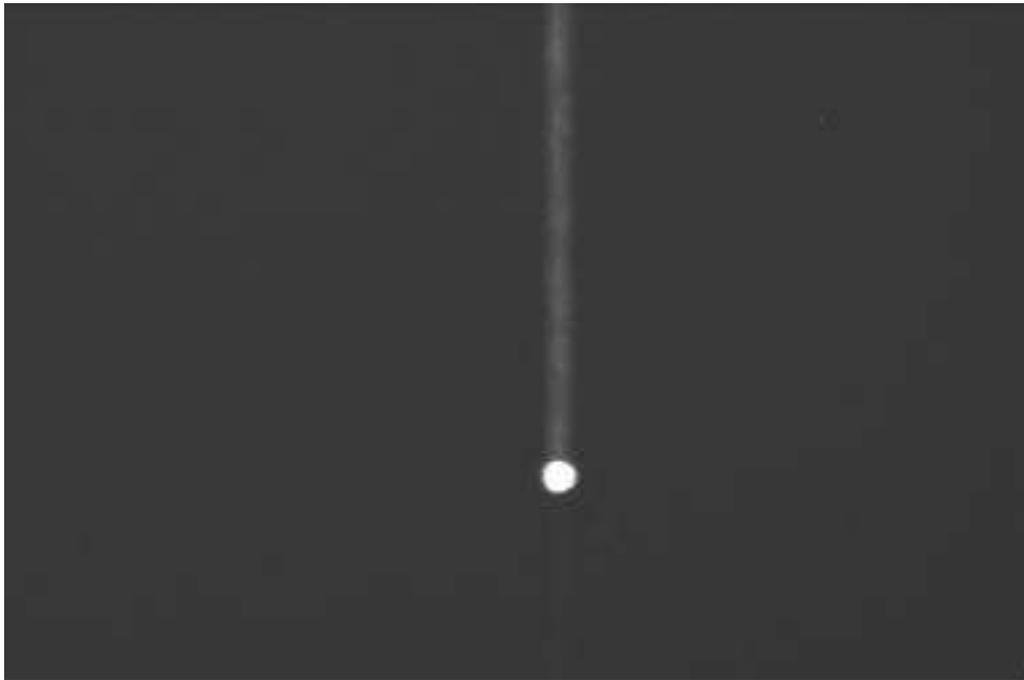
Definitions for KAF-3200E (Non-ABG only)

- Point Defect: DARK: A pixel which deviates by more than 6% from neighboring pixels when illuminated to 70% of saturation, OR BRIGHT: A Pixel with dark current > 5000 e/pixel/sec at 25°C.
- Cluster Defect: A grouping of not more than 5 adjacent point defects
- Column Defect: (1) A grouping of >5 contiguous point defects along a single column, (2) A column containing a pixel with dark current >12,000 e/pixel/sec (bright column), (3) A column that does not meet the minimum vertical CCD charge capacity (low charge capacity column), (4) A column which loses more than 250e under 2Ke illumination. (trap defect).
- Neighboring pixels: The surrounding 128 x 128 pixels or ±64 columns/rows.
- Defect Separation: Column and cluster defects are separated by no less than two (2) pixels in any direction (excluding single pixel defects).

KAF-3200E	Point Defects Central 1544x1040	Point Defects Total	Cluster Defects Central 1544x1040	Total Cluster Defects	Column Defects Central 1544x1040	Column Defects Total
Class 0*	0	0	0	0	0	0
Class 1	Up to 2	Up to 5	0	0	0	0
Class 2	Up to 5	Up to 10	Up to 2	Up to 4	0	0
Class 3	Up to 10	Up to 20	Up to 4	Up to 8	0	Up to 4

* Note: Kodak does not yet offer this detector in a Class 0

“smearing”

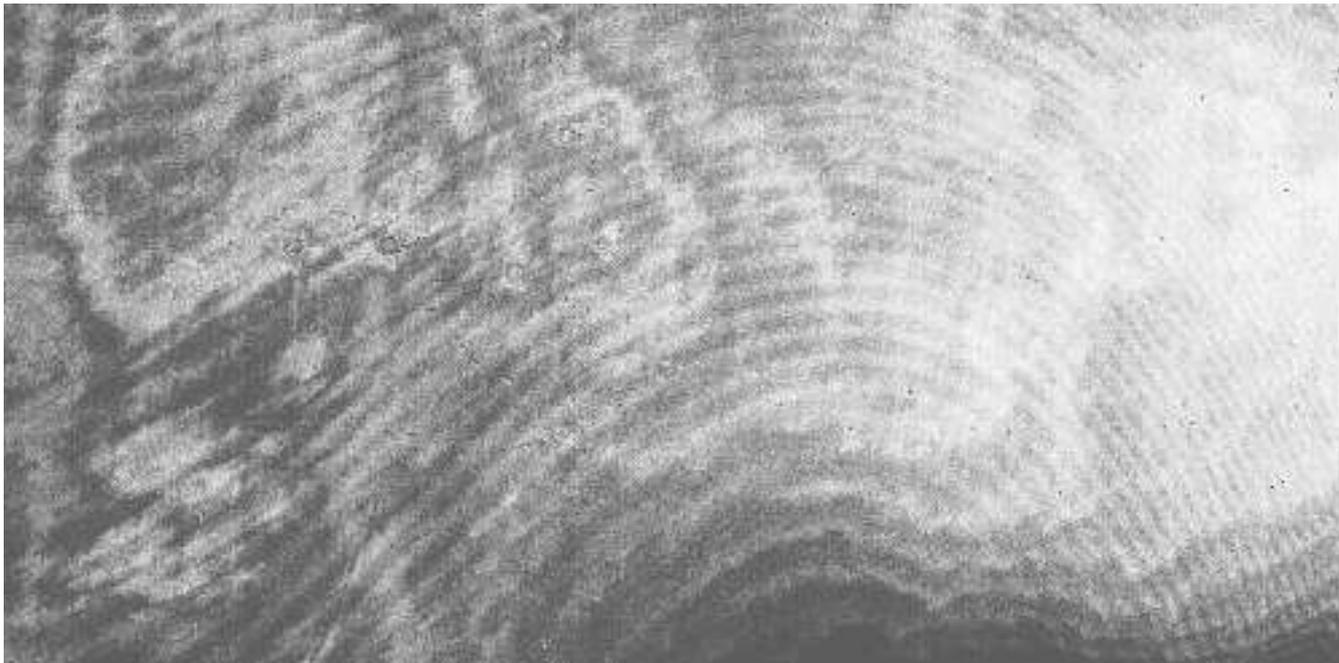


phénomène de traînée

La lecture de l'image a lieu sans obturateur, par translation le long d'une colonne (ici, vers le haut). Au passage d'un pixel fortement illuminé, l'information des pixels en amont, dont la lecture passe par ce pixel illuminé, est altérée par la superposition de photo-électrons supplémentaires.

“franges”

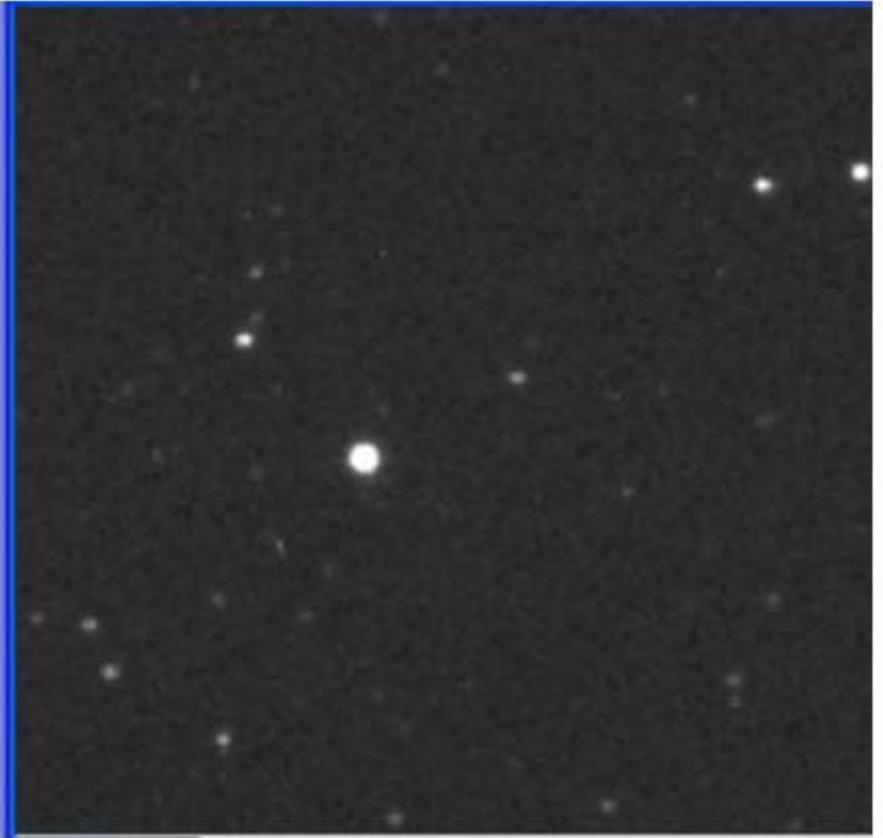
Franges d'interférence de la caméra : les photons, surtout dans le rouge, peuvent être réfléchis dans la zone sensible du CCD avant d'être absorbés. Ceci conduit à des franges d'interférences, gênantes car elles modulent le champ de réponse de la caméra.



“la rémanence”



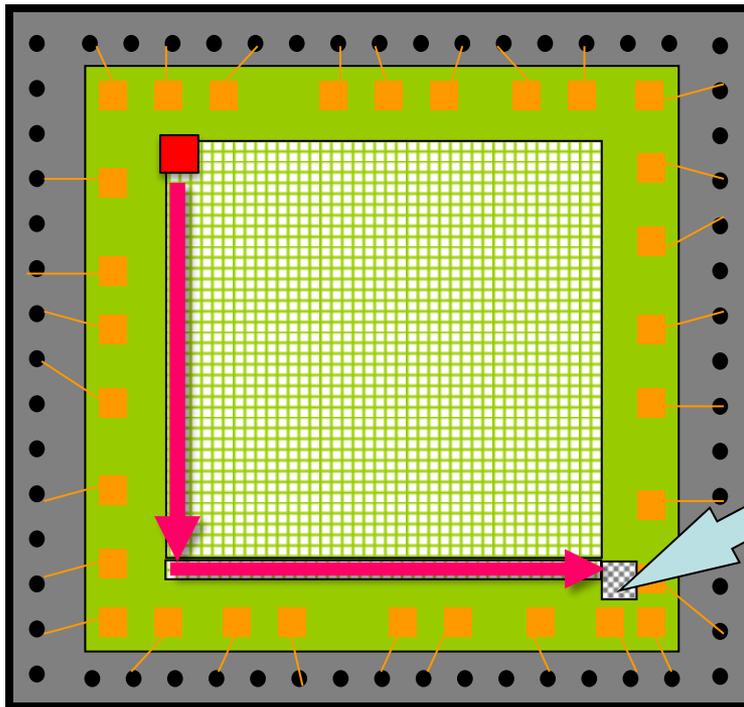
Image with RBI



Actual starfield
(the “nebula” was RBI)

Efficacité du transfert de charge

- CTE : Efficacité du transfert de charge > 0.999995
Ex: Capteur 1000×1000 pixels



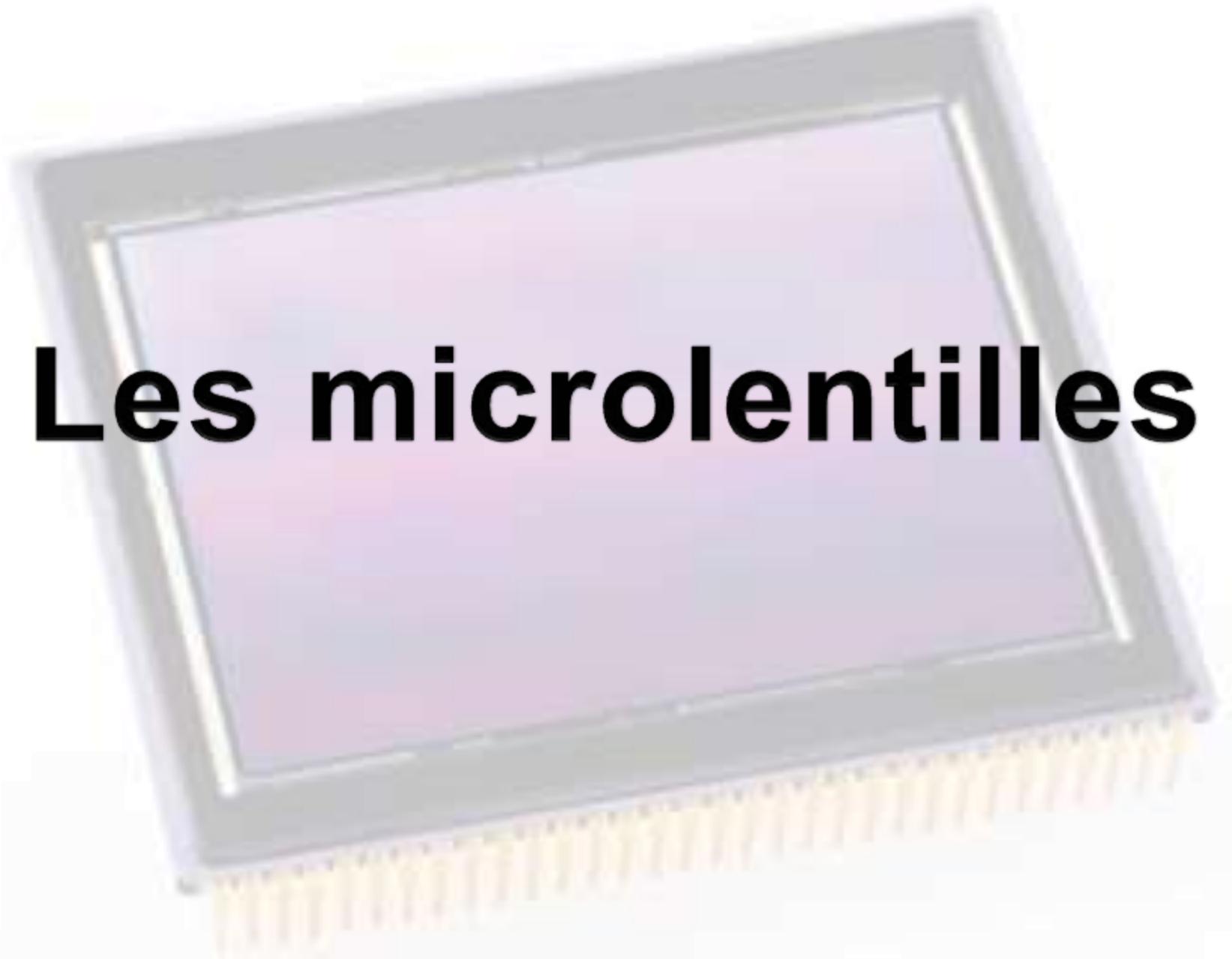
Systeme à 4 phases => 8000 puits

Pour 8000 transferts:

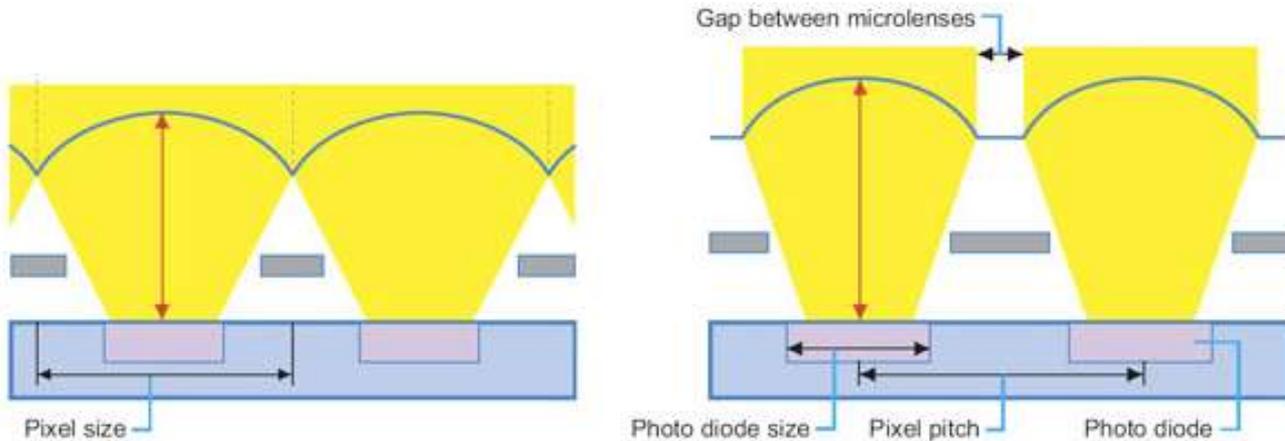
$$0,999995^{8000} = 0,96$$

- Conversion de la charge en tension
- Smear : Insolation des capteurs en cours de transfert

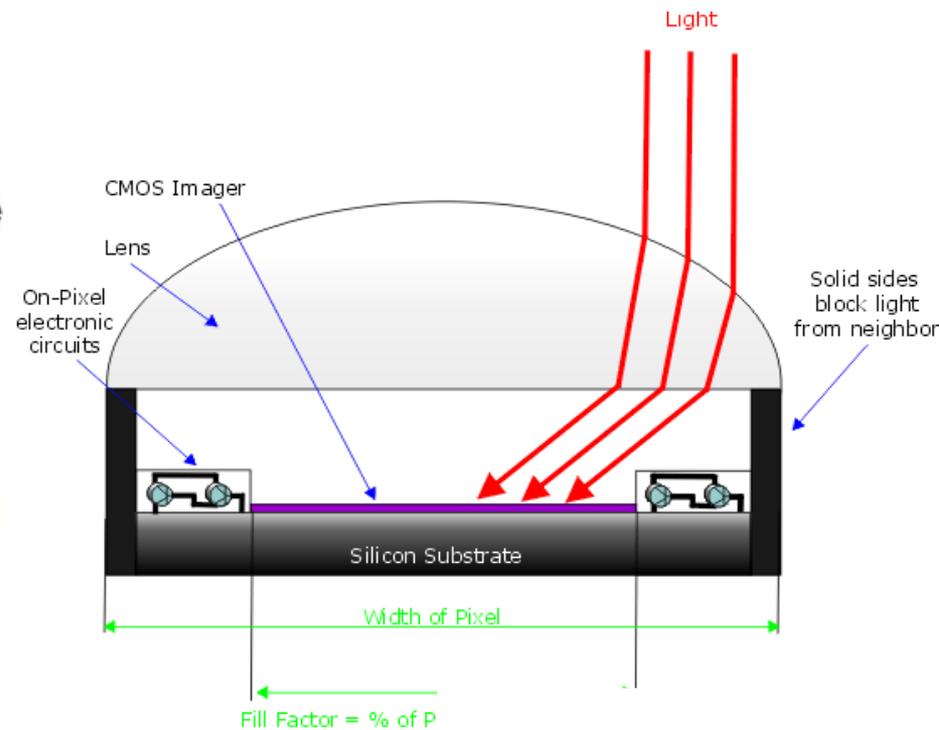
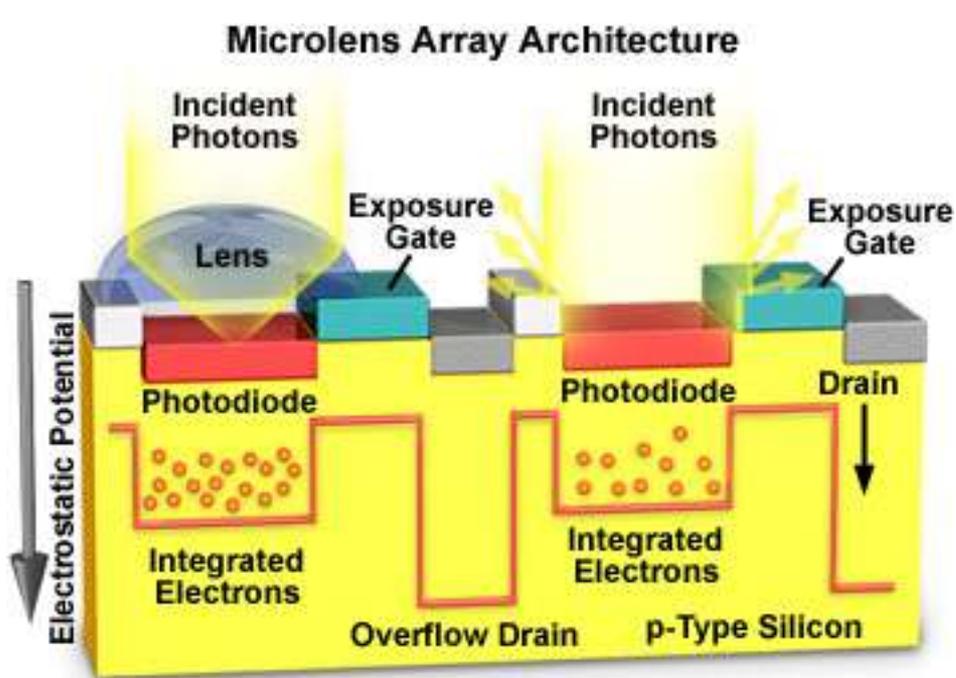
Les microlentilles



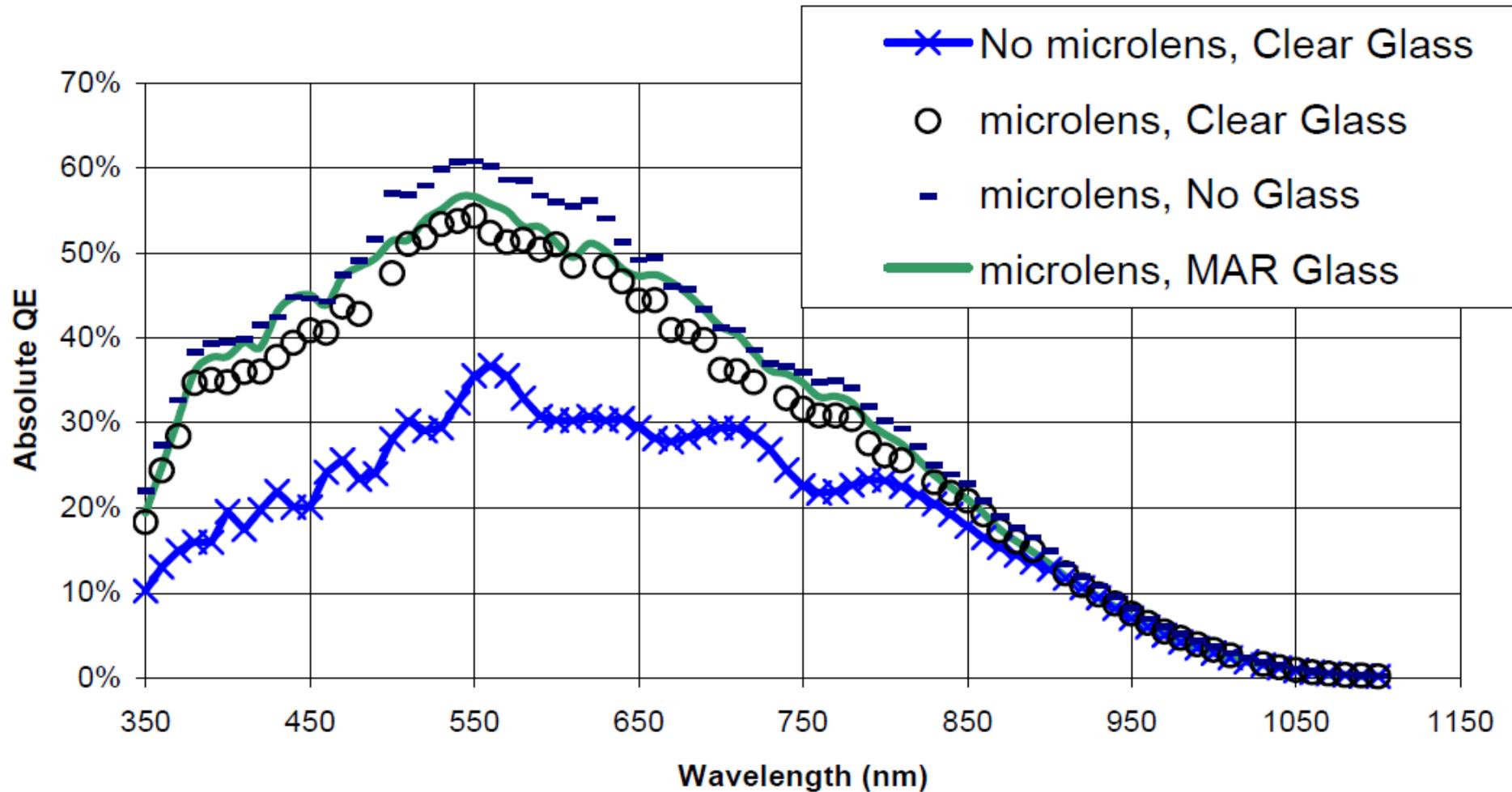
Les microlentilles



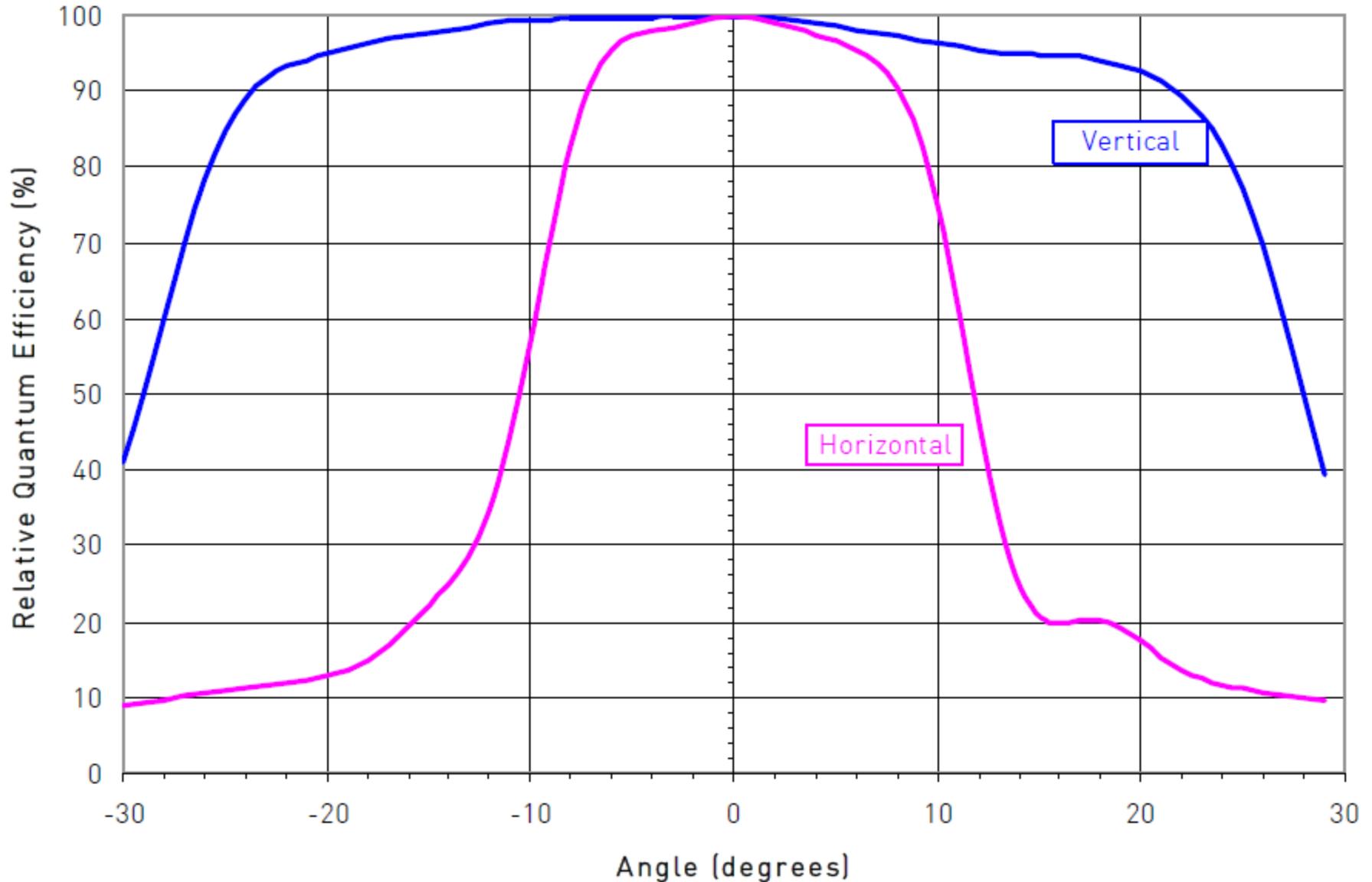
Microlens Array Architecture



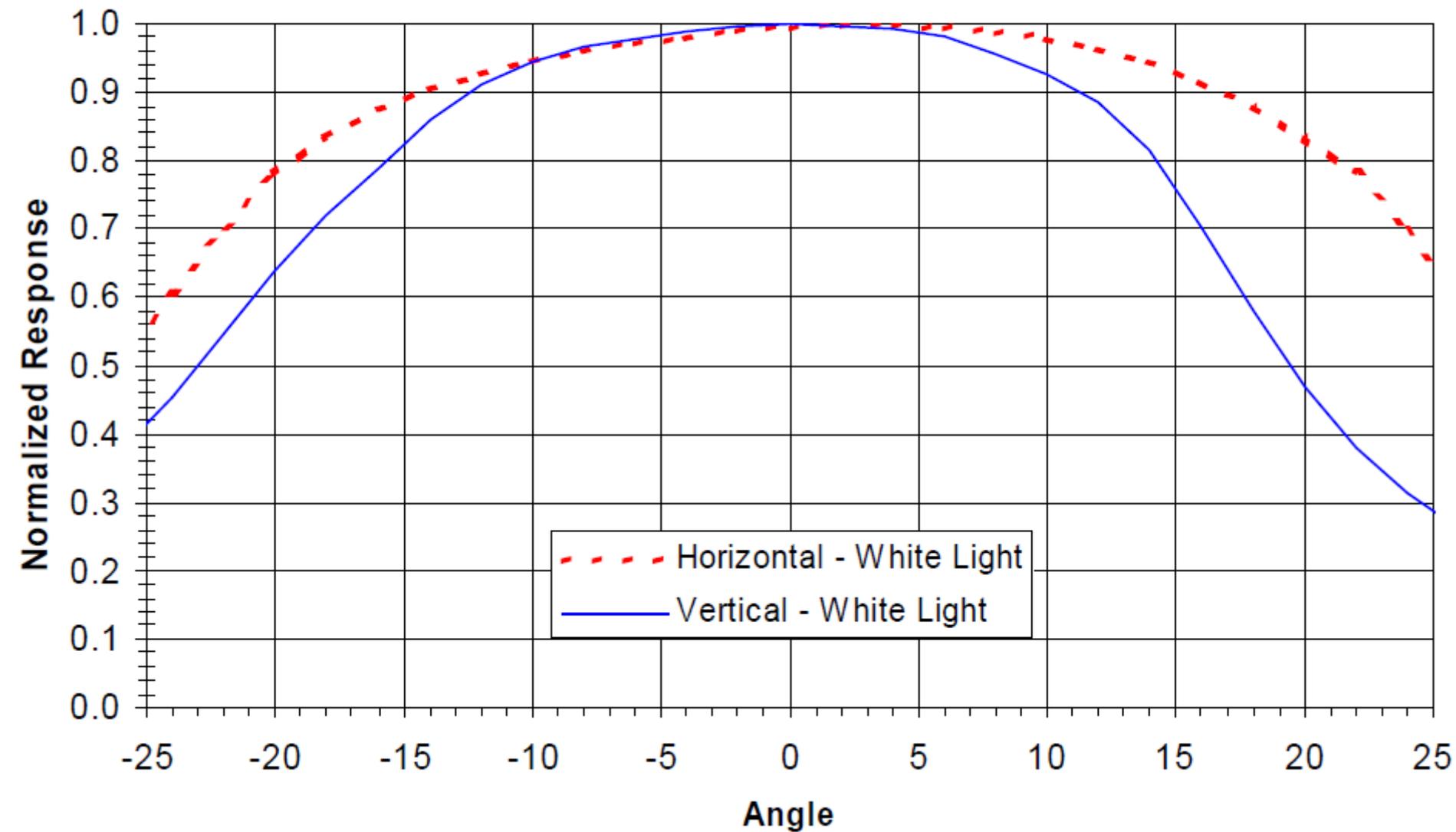
KAF-8300 Quantum Efficiency



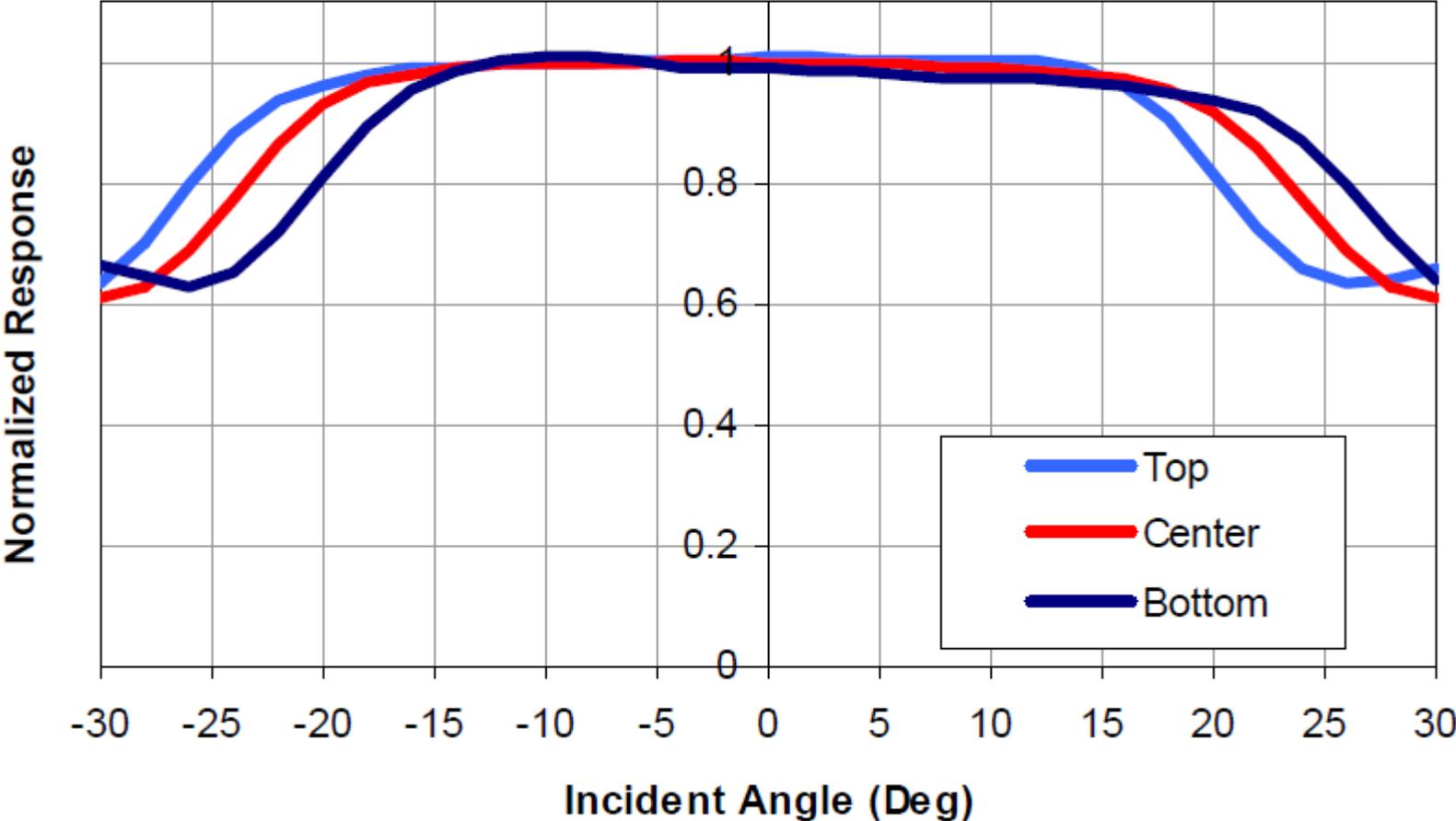
KAI4022 avec microlentilles



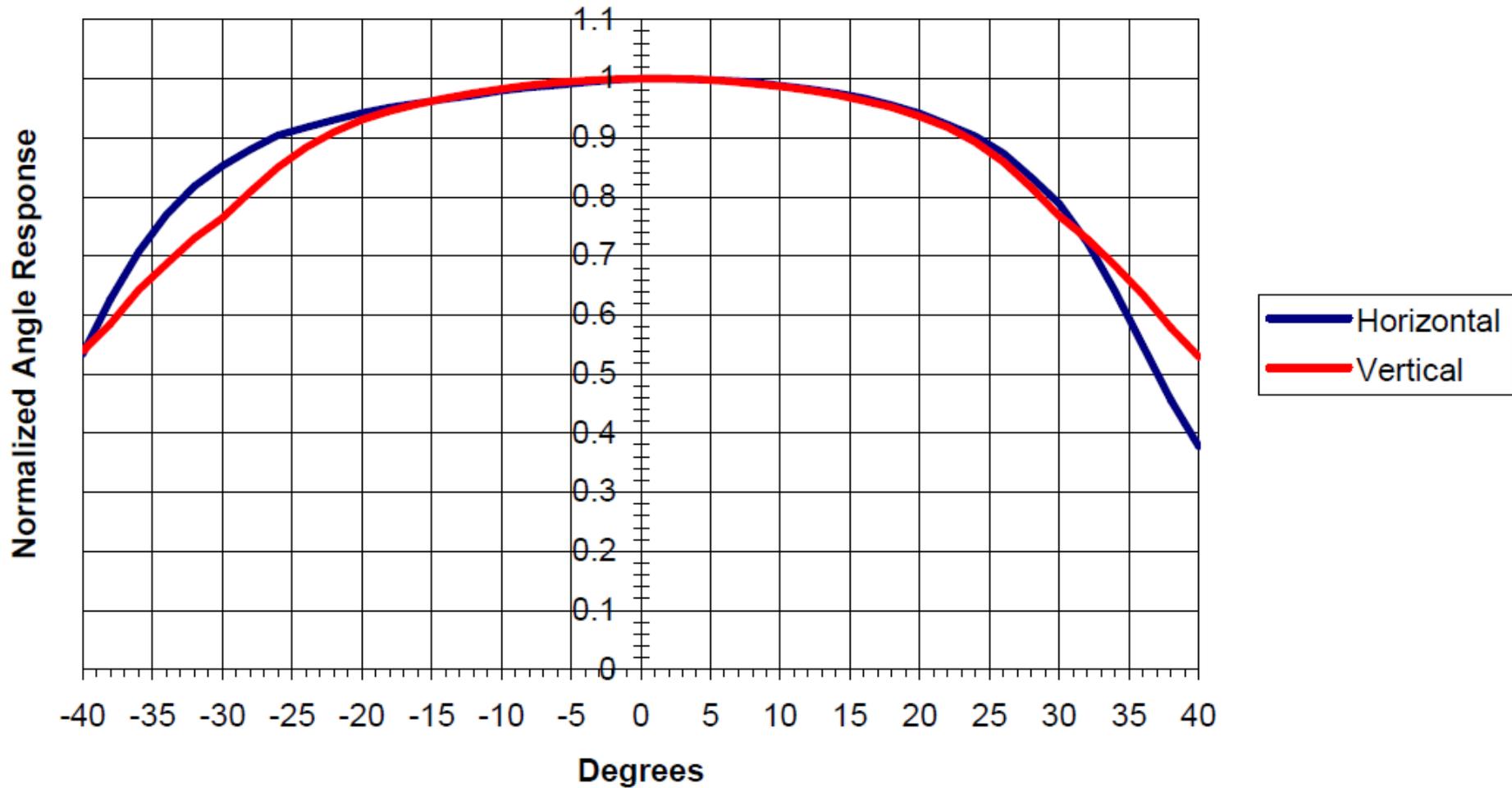
KAF-8300 Angle Response - White Light



KAF-8300 Vertical Angle Response - Green Light

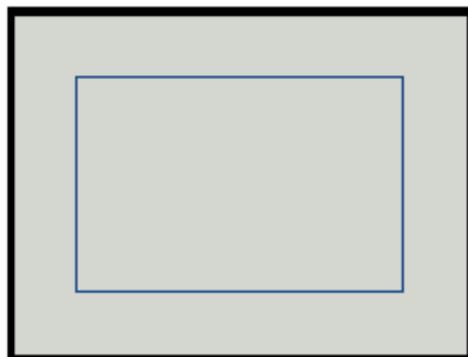


KAF16803 sans microlentilles





La géométrie



Medium format (Kodak KAF 3900 sensor)

50.7×39 mm

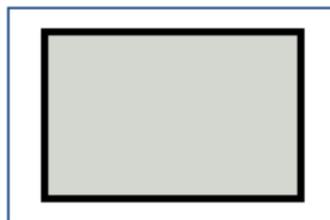
1977 mm²



35 mm "full frame"

36×24 mm

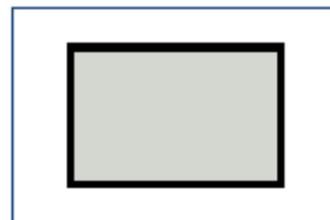
864 mm²



APS-H (Canon)

28.7×19 mm

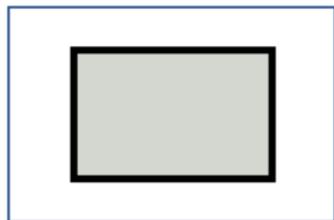
548 mm²



APS-C (Nikon DX,
Pentax, Sony)

$\sim 23.6 \times 15.7$ mm

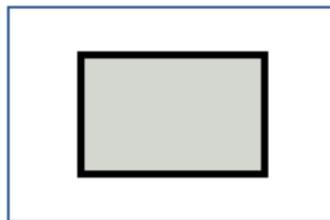
~ 370 mm²



APS-C (Canon)

22.2×14.8 mm

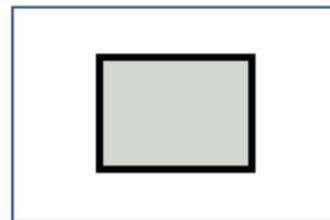
329 mm²



Foveon (Sigma)

20.7×13.8 mm

286 mm²



Four Thirds System

17.3×13 mm

225 mm²



1/1.8"

7.18×5.32 mm

38 mm²

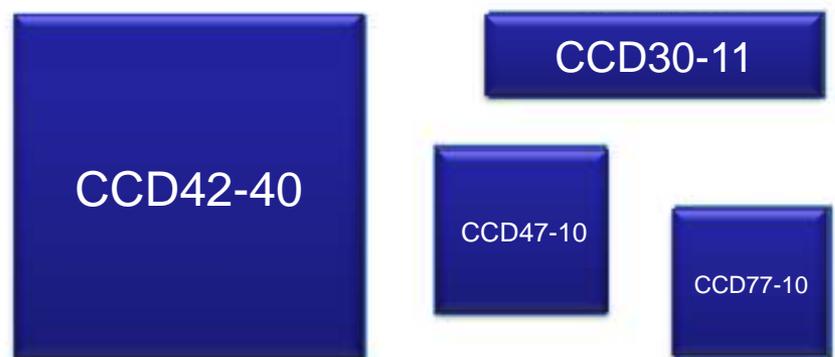
FRONT ILLUMINATED



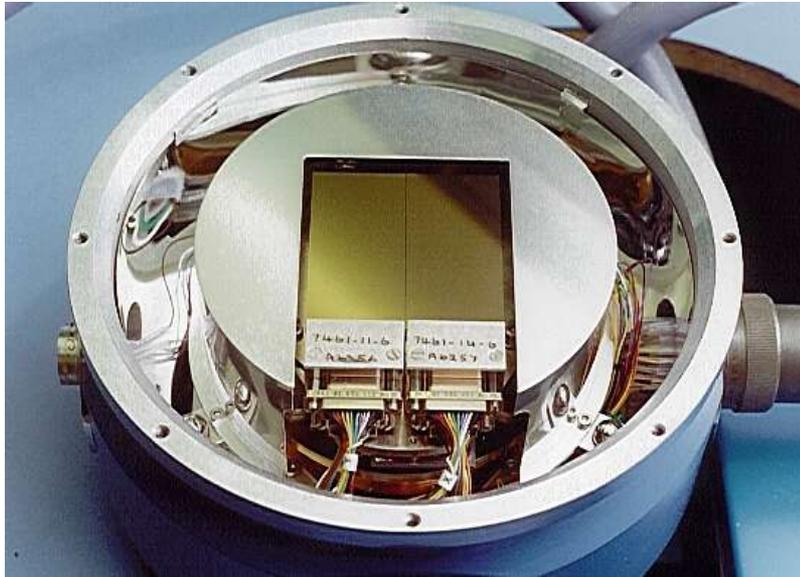
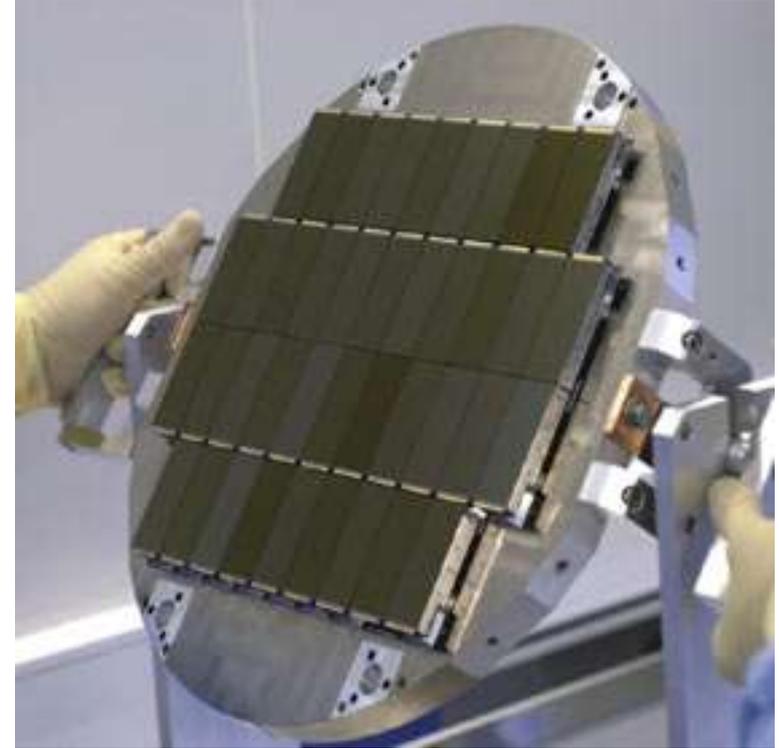
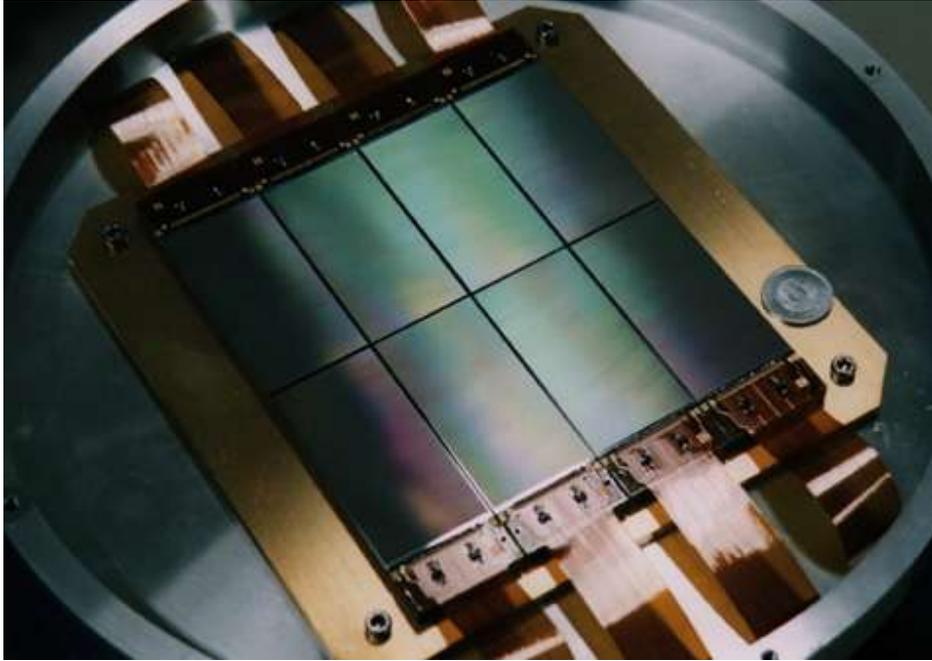
INTERLINES



BACK ILLUMINATED



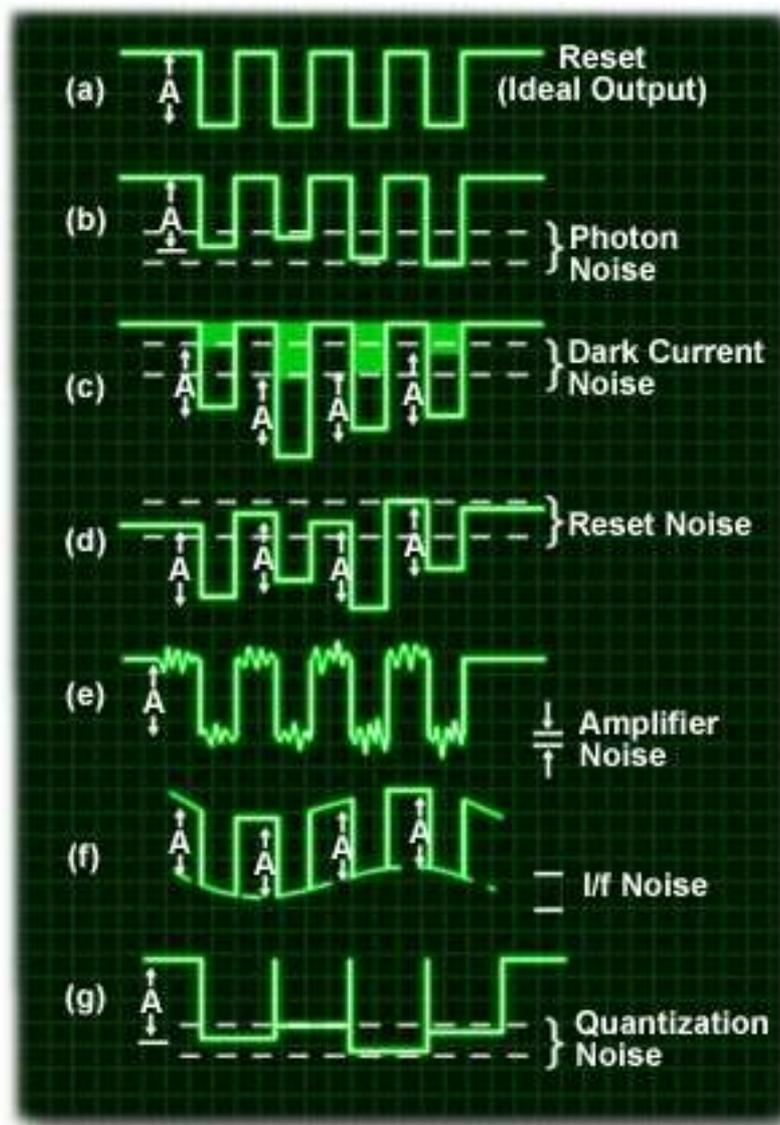
Géométrie : mosaïques



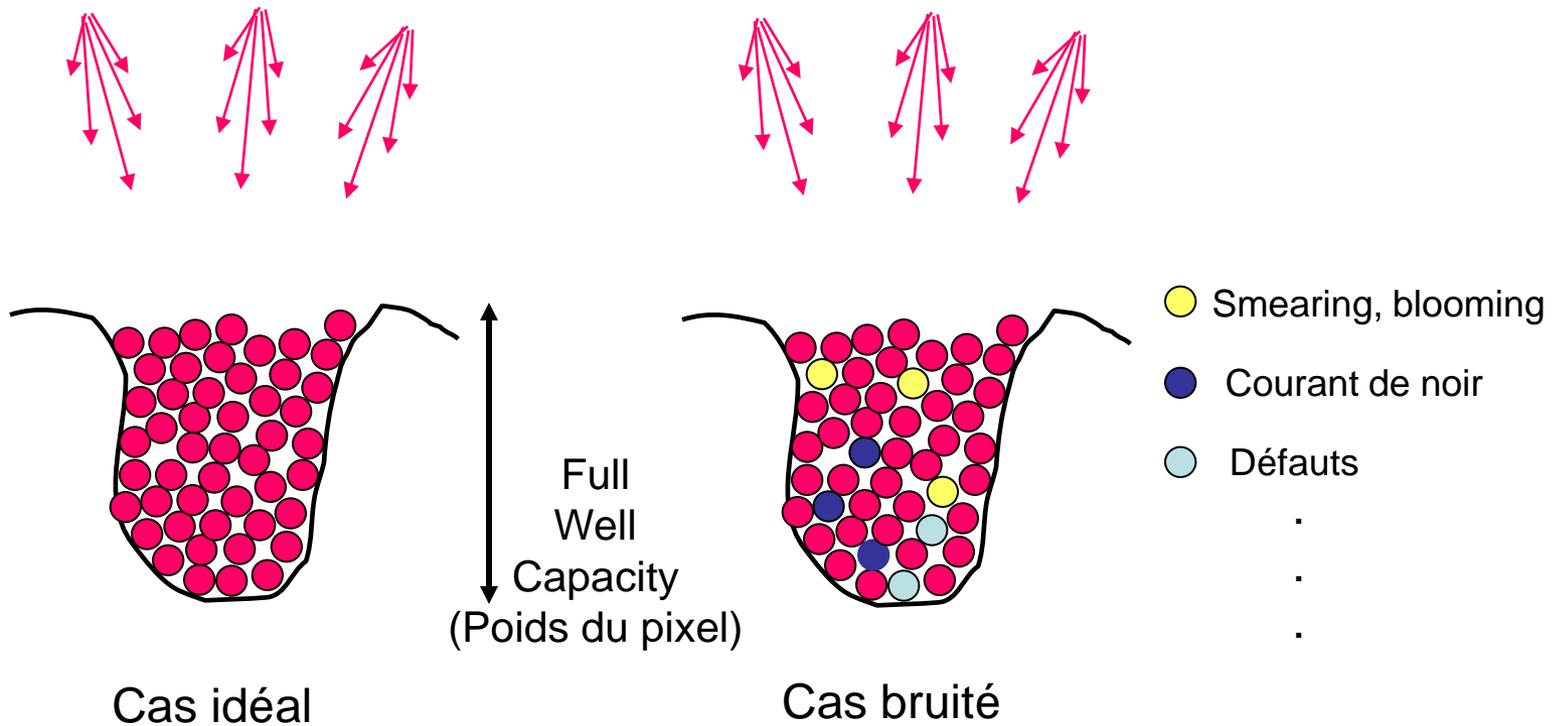


Le bruit

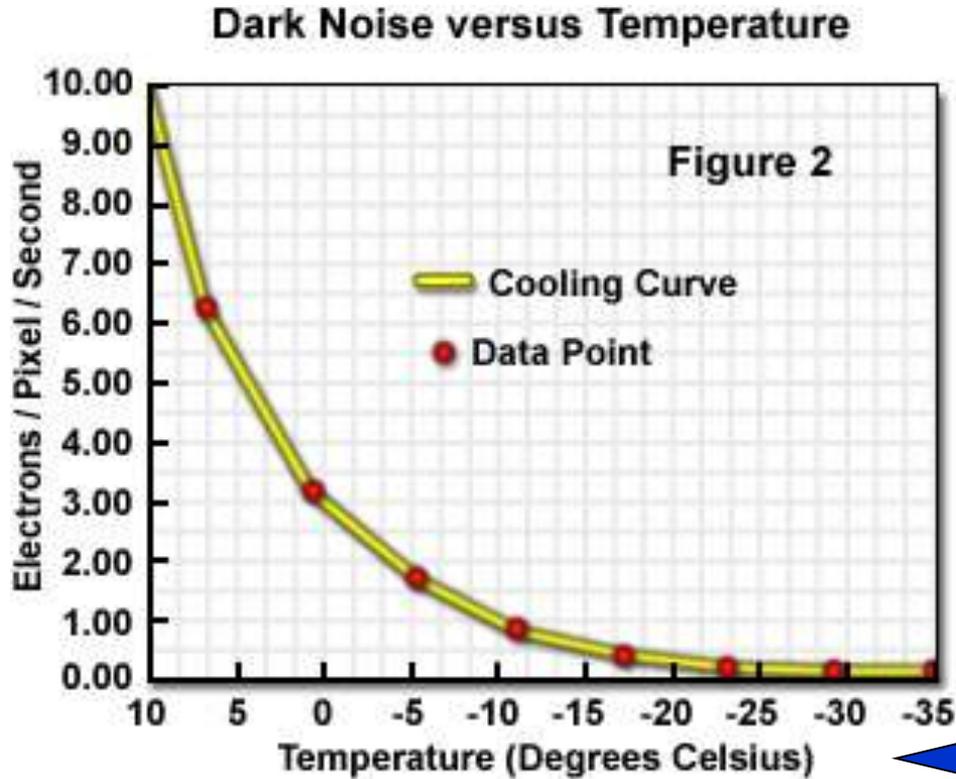
L'origine du bruit



Génération de la charge

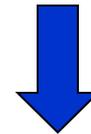


Bruit thermique

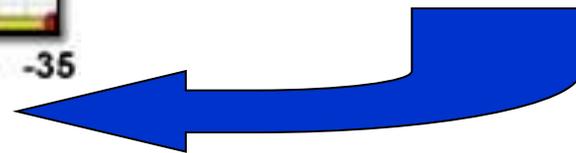


COURANT
DE
NOIR

0,1nA/cm² ->10nA/cm²



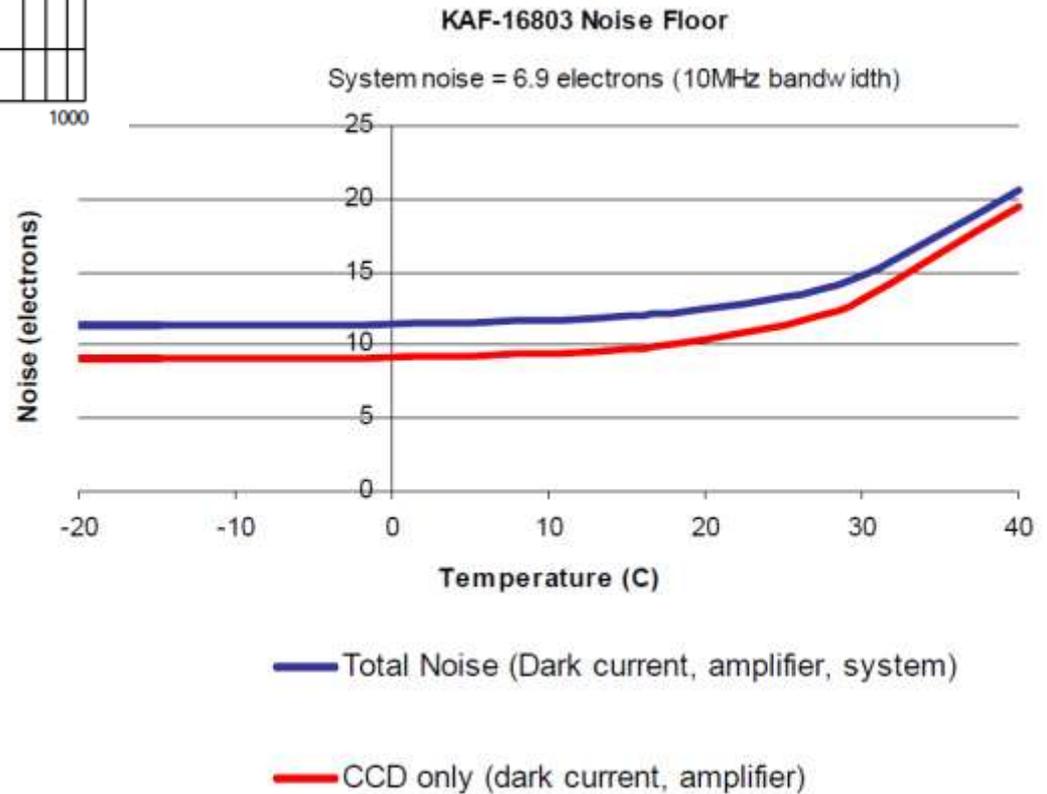
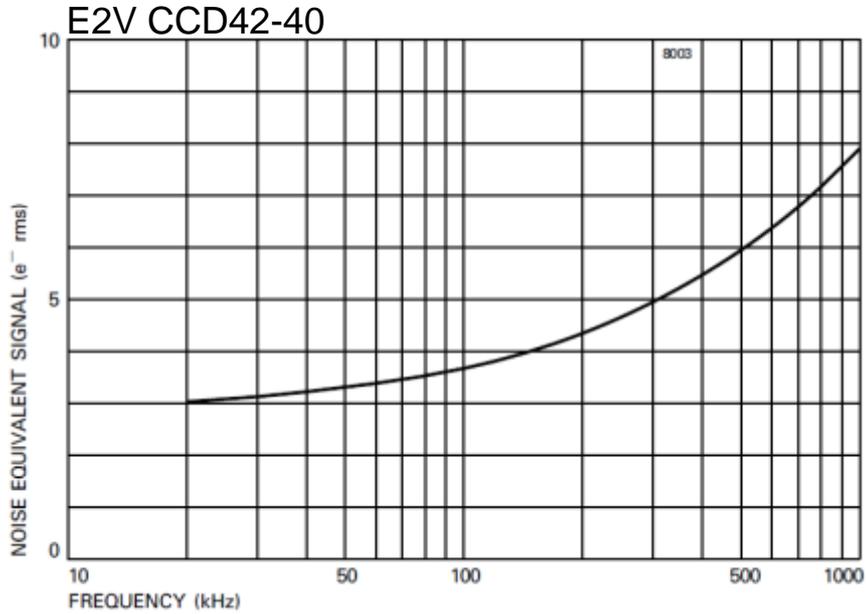
électron/pixel/seconde

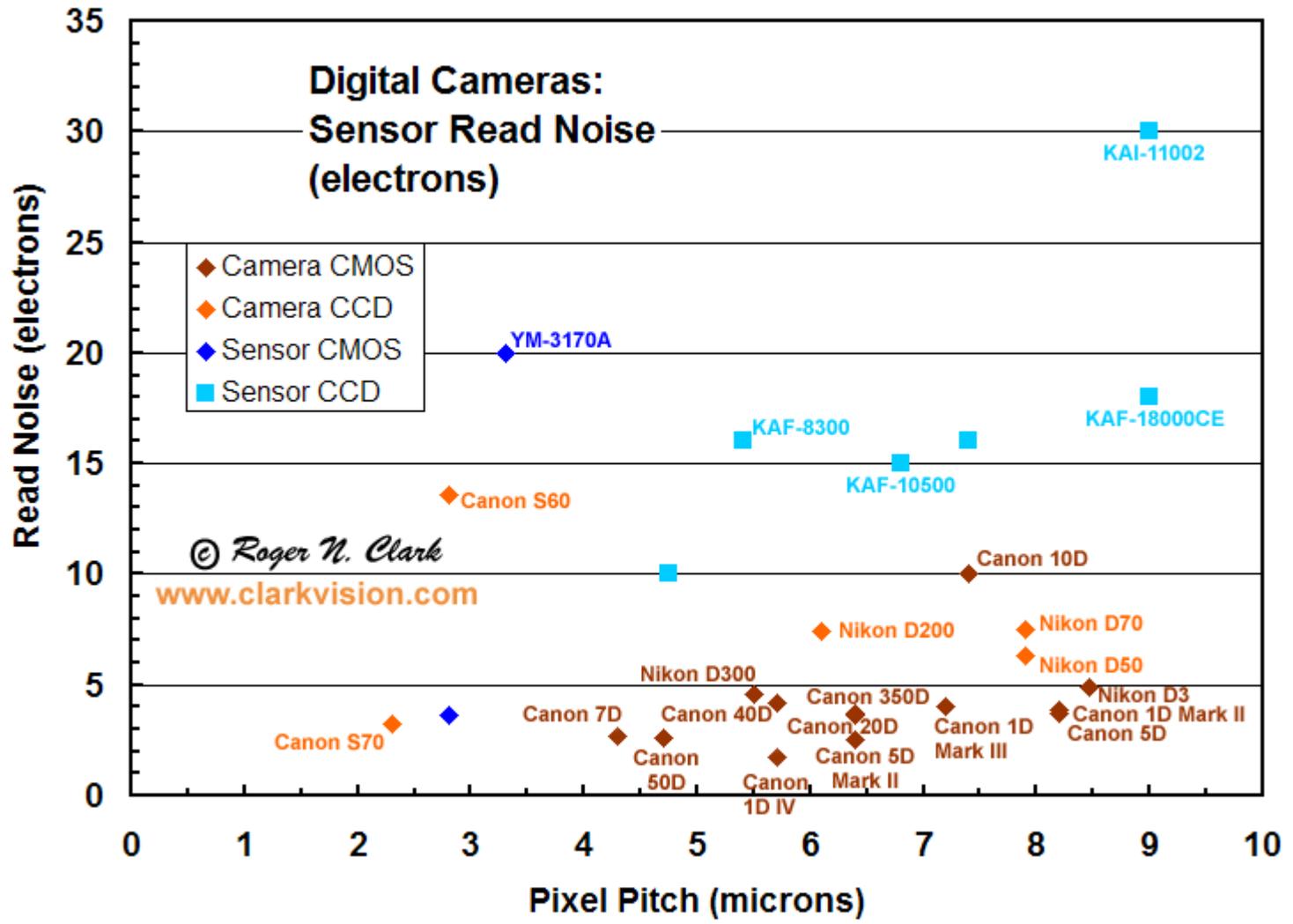


Exemple: 1000pA/cm²=>36000e/p/s, saturation en 10 secondes !!!

Réduction: Diminuer la température de fonctionnement (TEC)
Temps d'intégration courts

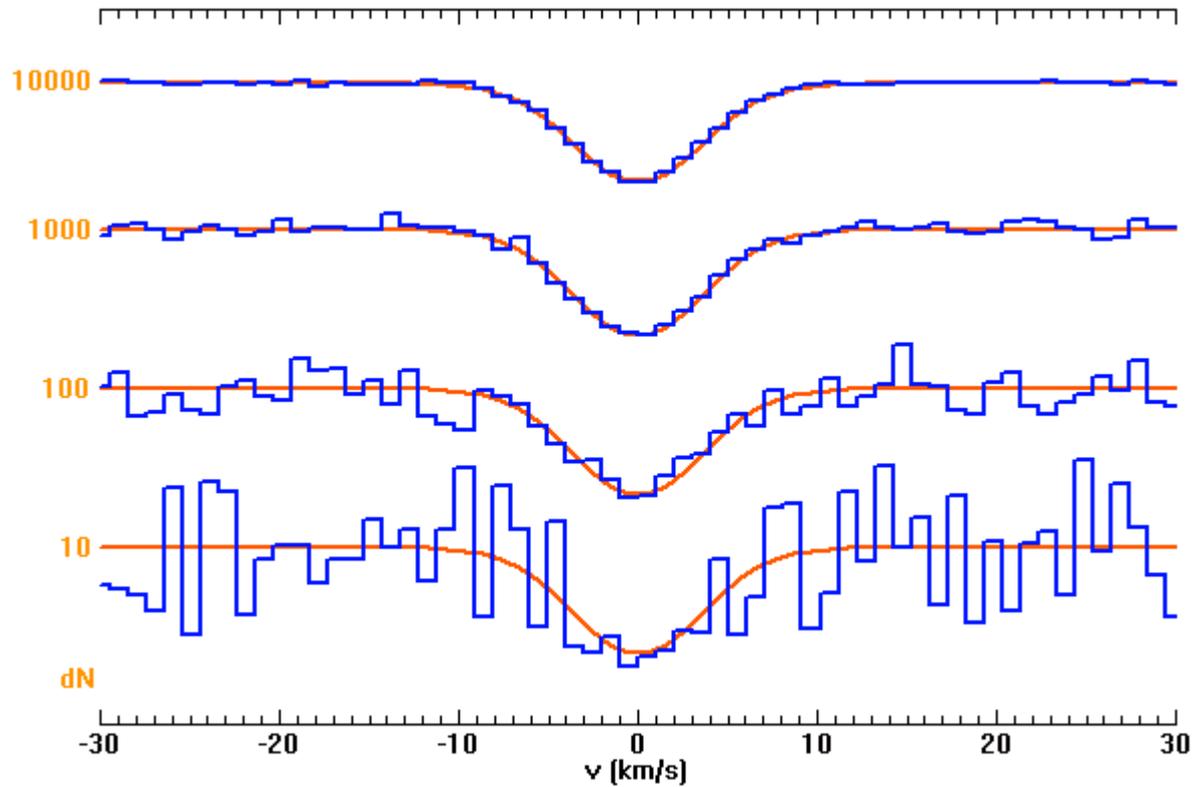
Bruit de lecture





Bruit de photon

$$\text{SNR} = \frac{N}{\sqrt{N}} = \sqrt{N}$$



$$\text{Dynamique} = \frac{\text{Puits de potentiel}_{(e^-)}}{\text{Bruit lecture}_{(e^-)}}$$

$$\text{Dynamique}_{(dB)} = 20 \times \text{Log}(N_{\text{sat}} / N_{\text{bruit}})$$

Rapport Signal/bruit CCD

- Bruit généré par le préampli et l'électronique pendant la lecture
- Dans les applications à faible signal, le bruit de lecture est la limitation

$$\frac{[S*QE]}{\sqrt{[(S*QE) + D + \sigma_R^2]}}$$

Bruit de photon²

Bruit thermique²

Bruit de lecture

EMCCD : la nouvelle équation

S/B d'un CCD à multiplication d'électrons :

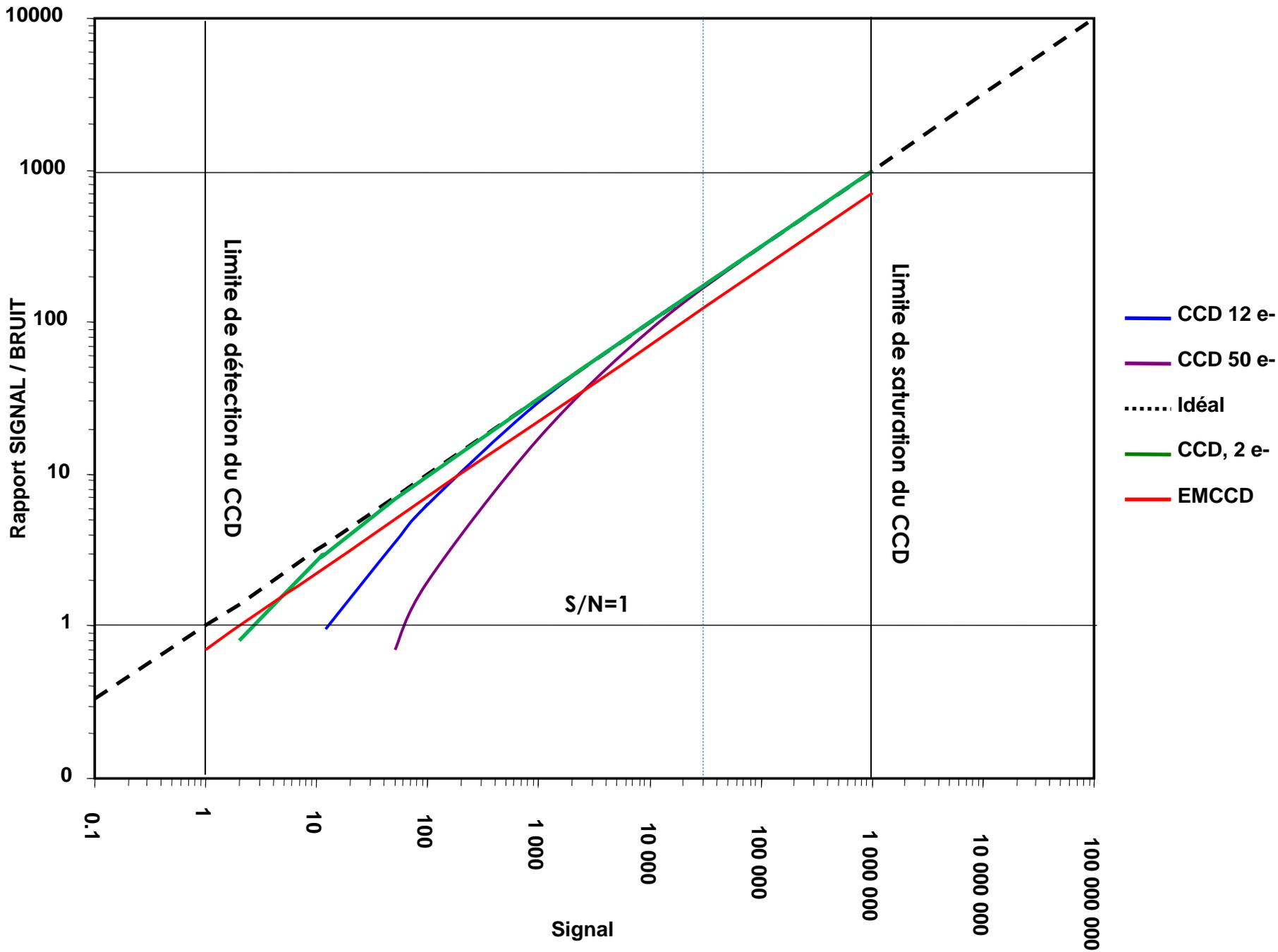
$$[S.QE]$$

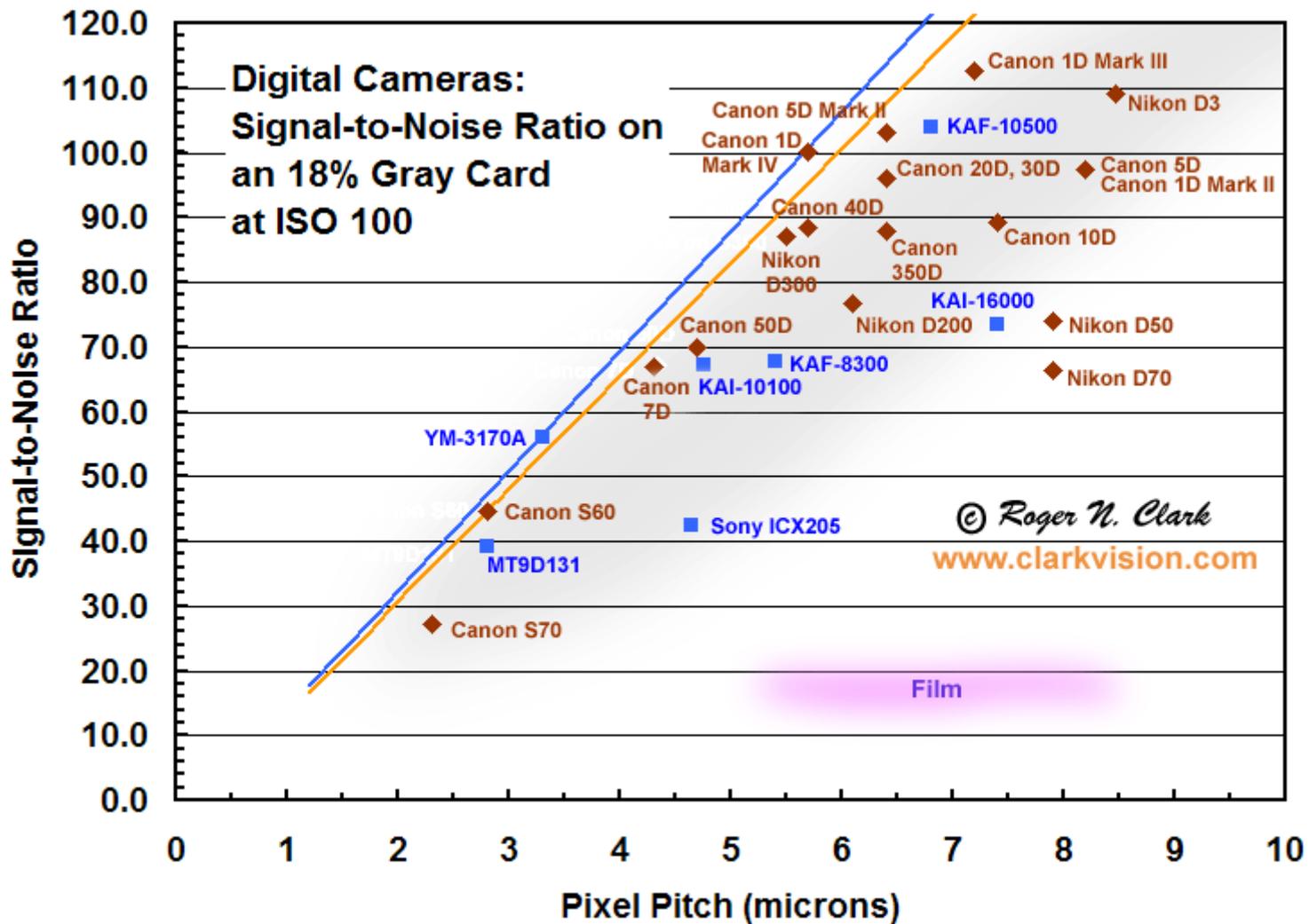
$$\sqrt{[S.QE.F^2 + D.F^2 + \sigma_R^2/G^2]}$$

Total "Dark Related Charge"
D= Dark Charge + Spurious charge

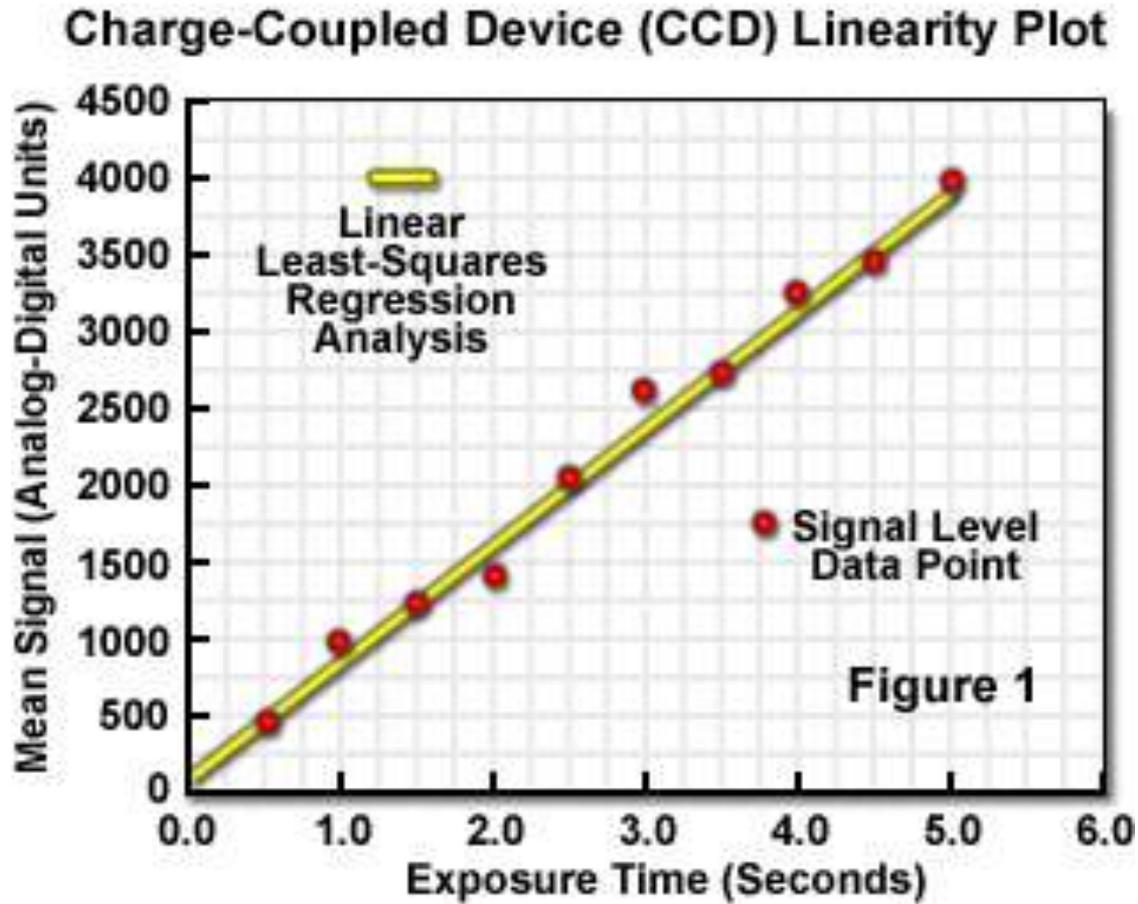
F = excess noise factor :
entre 1.1 et 1.4

By amplifying the signal (by G), the read noise is effectively minimized





Linéarité



Zones de fonctionnement

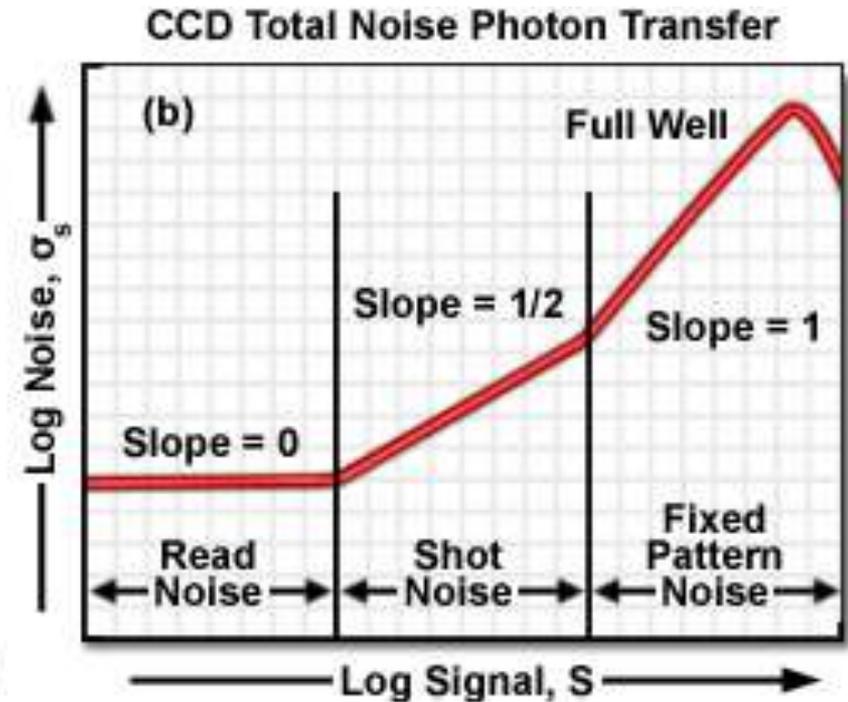
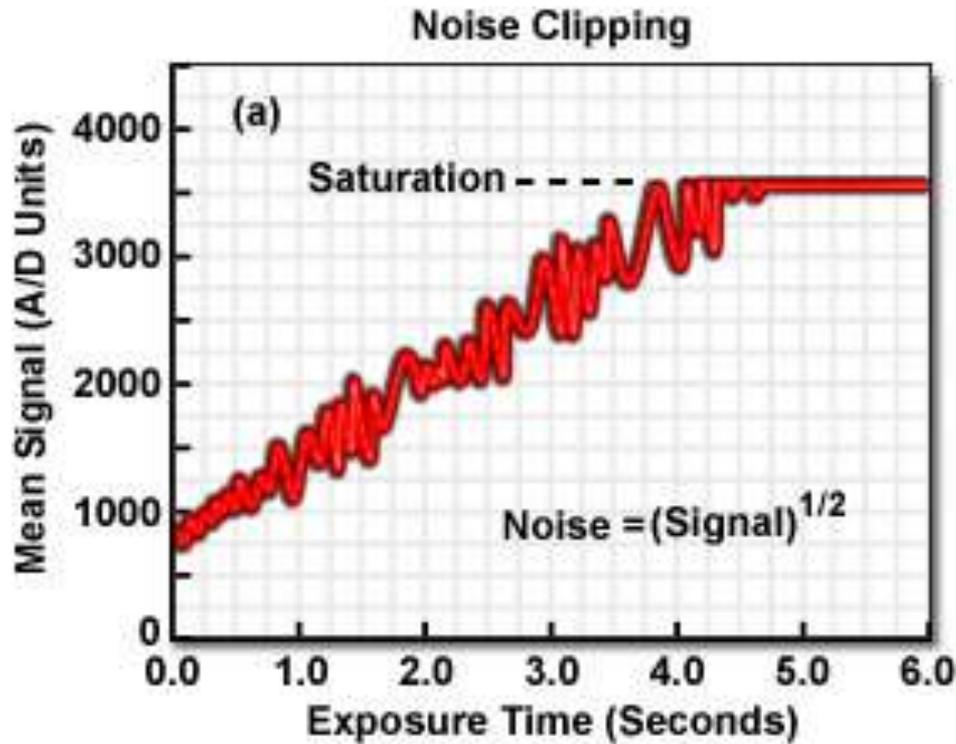
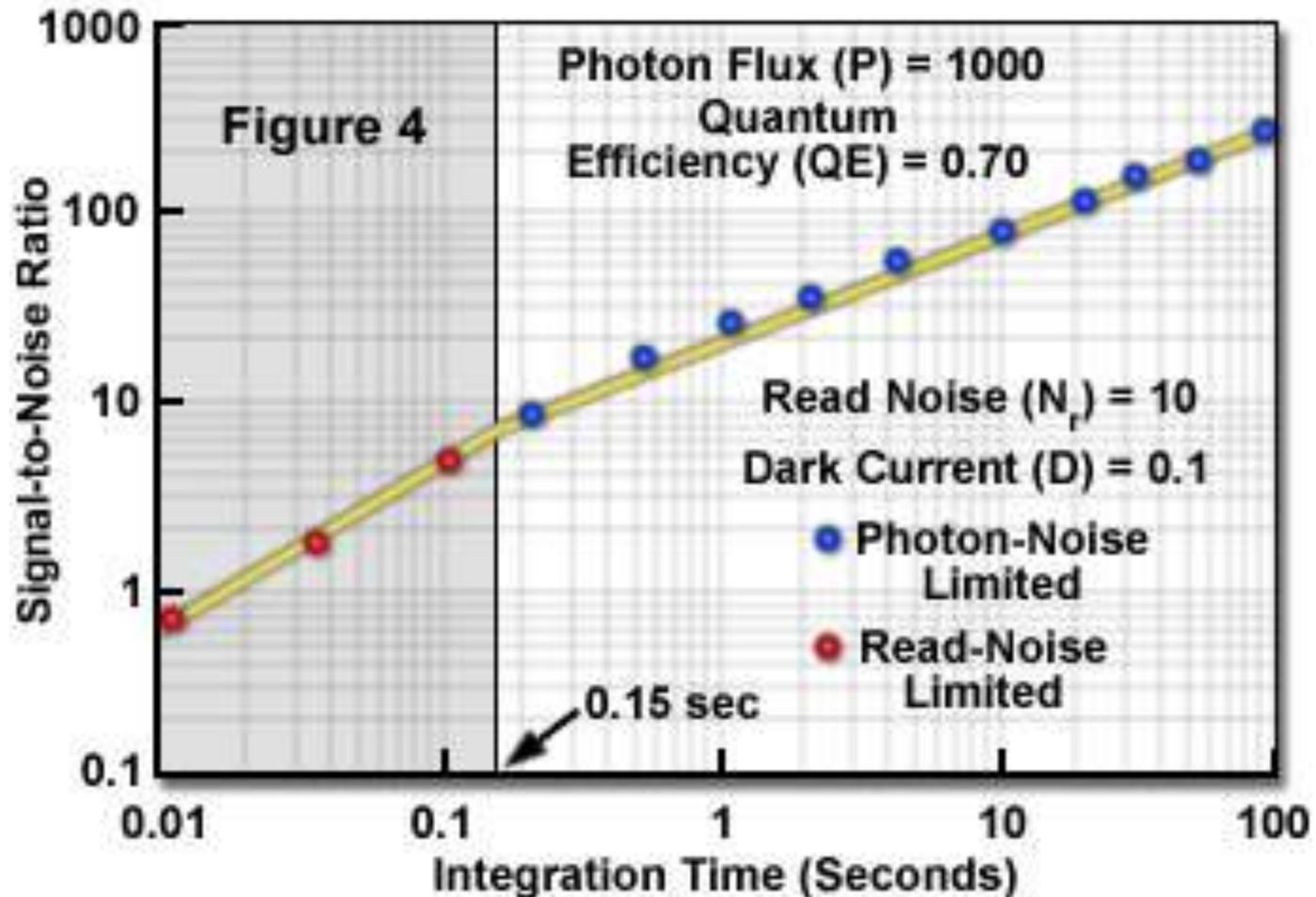


Figure 2

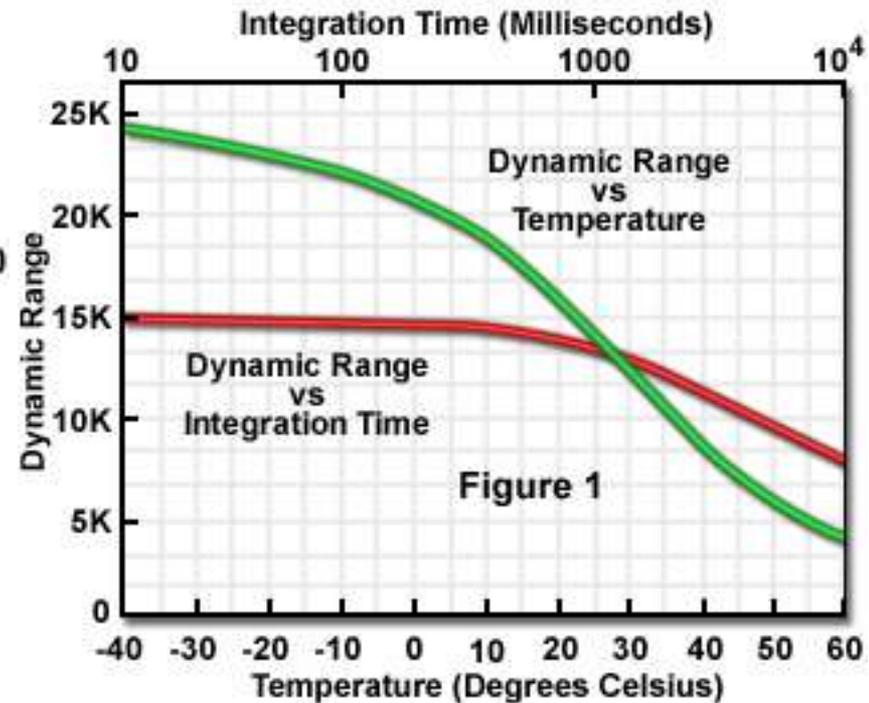
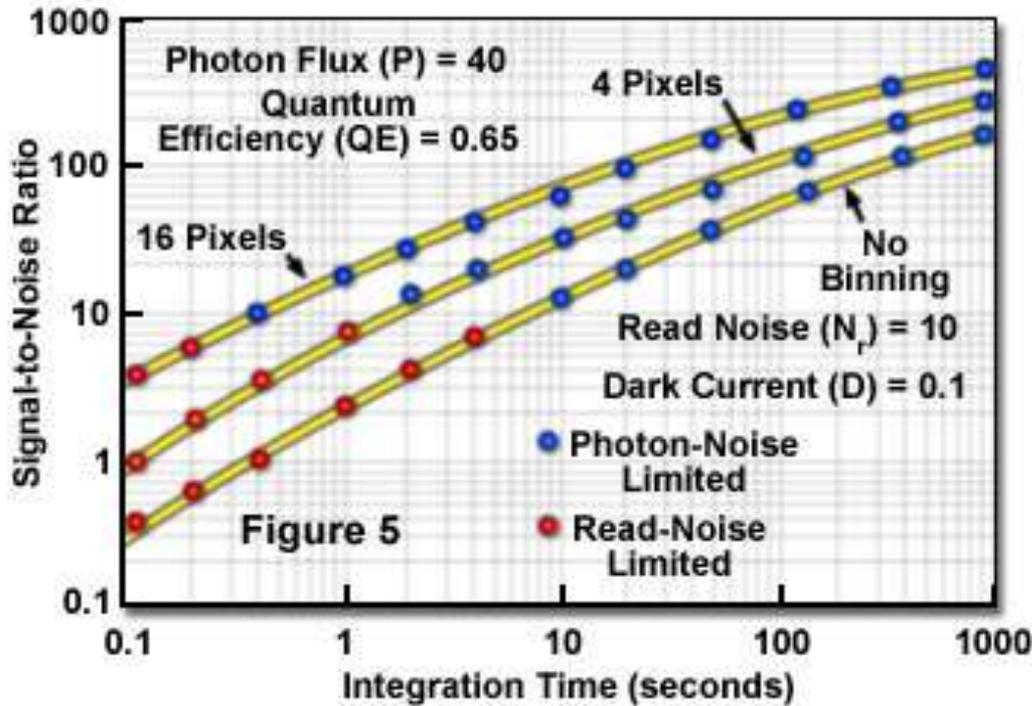
Dynamique

Signal-to-Noise Variation with Integration Time

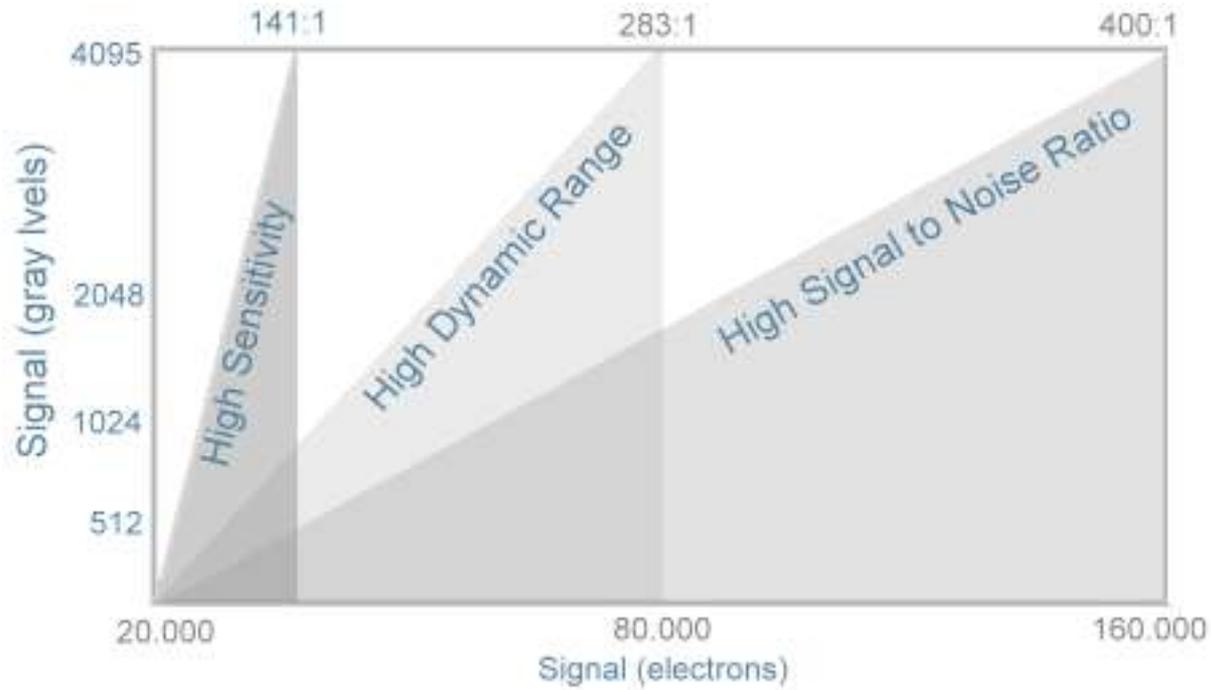


Variables affectant la dynamique

Signal-to-Noise Improvement with Binning



Gain / dynamique



Rapport Signal/bruit de quelques CCD

Capteur	KAF-8300M	KAF-3200ME	KAF-1603ME	KAI-4022	KAF-16803	KAI 11002	ICX-285AL
Fabricant	Kodak	Kodak	Kodak	Kodak	Kodak	Kodak	Sony
Taille pixel (µmm)	5,4 x 5,4	6,8 x 6,8	9 x 9	7,4 x 7,4	9 x 9	9 x 9	6,45 x 4,65
Taille Image (pixel)	3326 x 2504	2184 x 1472	1530 x 1020	2048 x 2048	4096 x 4096	4008 x 2672	1392 x 1040
Capacité Photosites (e ⁻)	25500	50000	100000	40000	100000	60000	17500
Bruit de lecture (e ⁻)	9	10	15	7	9	13	4
Rapport S/B	2833	5000	6667	5714	11111	4615	4375

> 11 bits

> 12 bits

> 12 bits

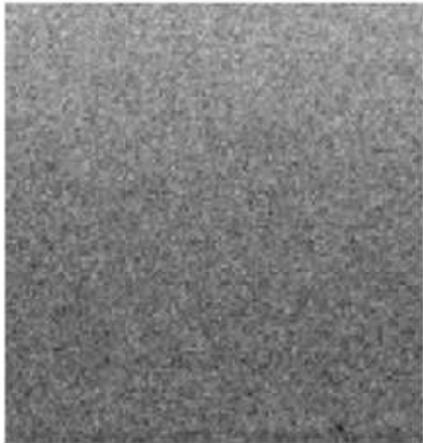
> 12 bits

> 13 bits

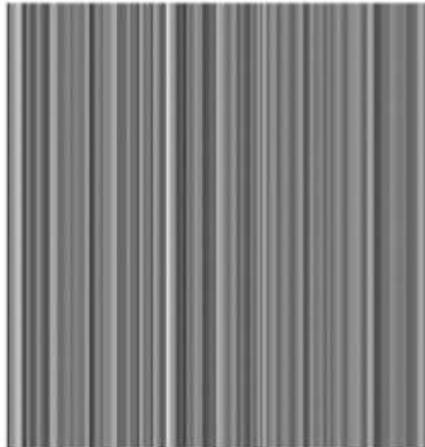
> 12 bits

> 12 bits

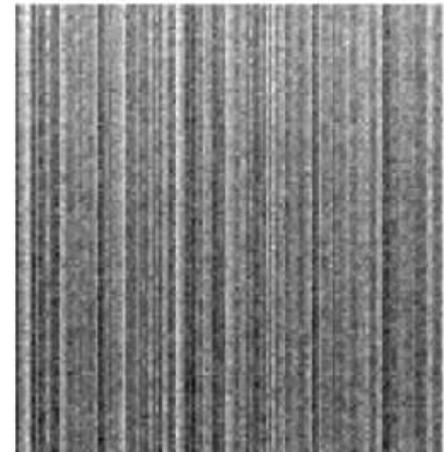
Bruit CMOS : Fixed Pattern Noise



Bruit pixel



Bruit colonne



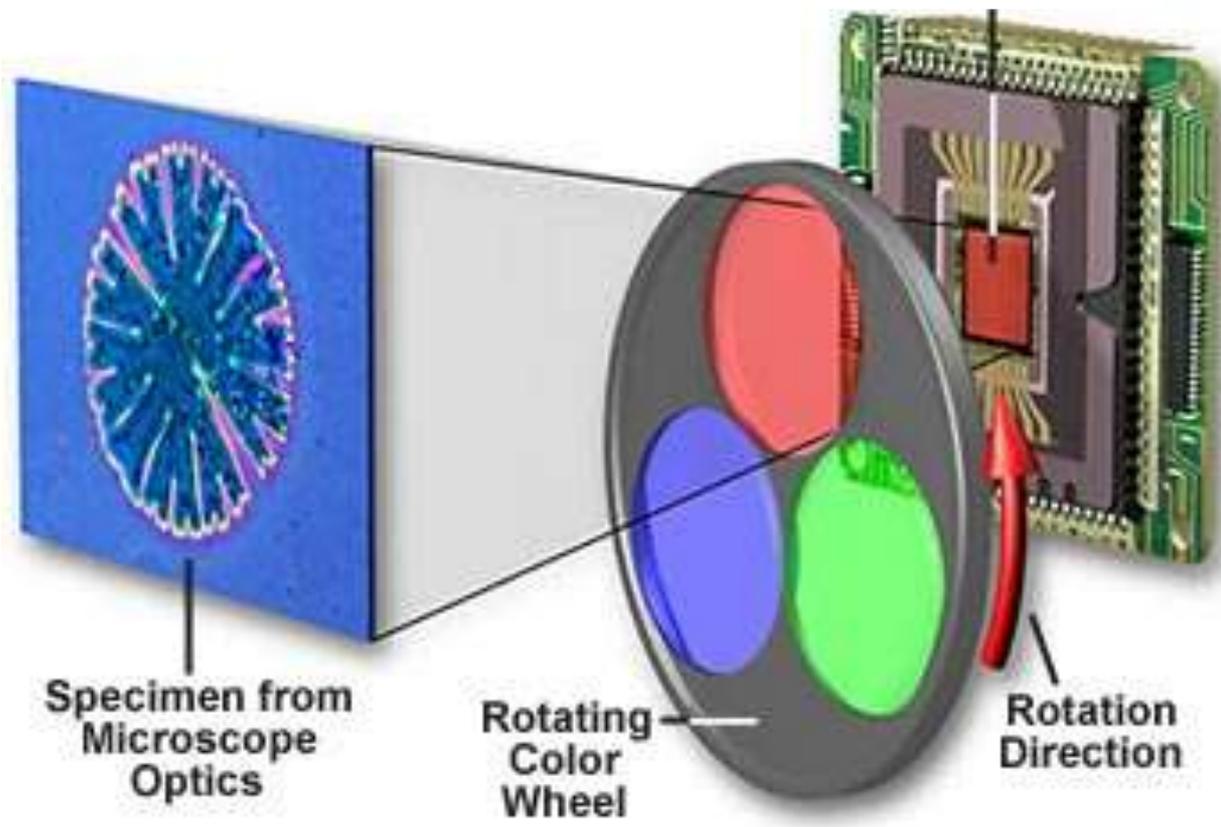
Bruit total

A square integrated circuit chip with a purple surface and gold pins. The chip is shown at an angle, highlighting its three-dimensional structure. The text "La couleur" is overlaid on the purple surface.

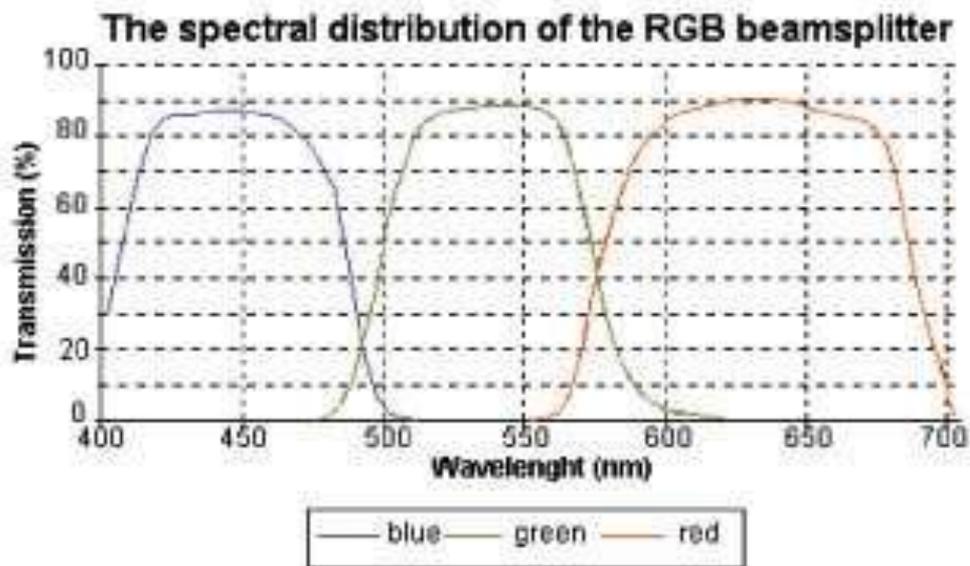
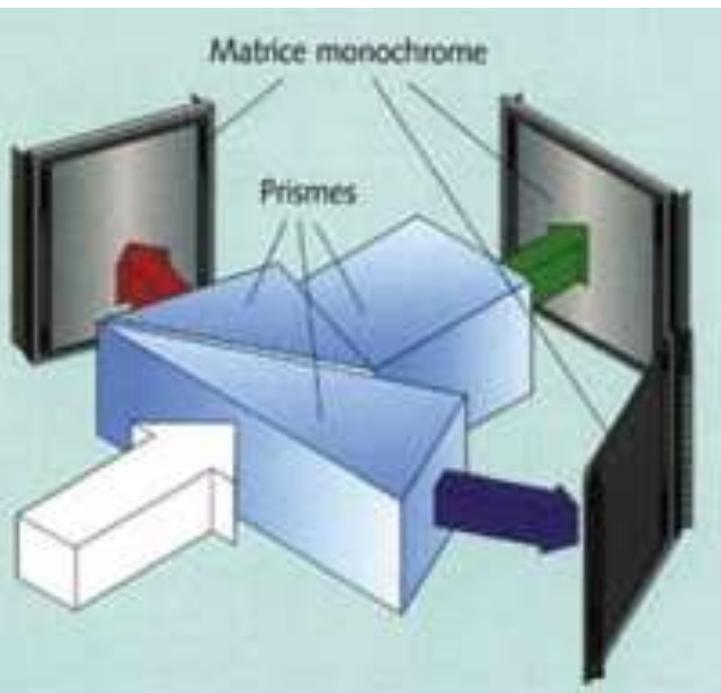
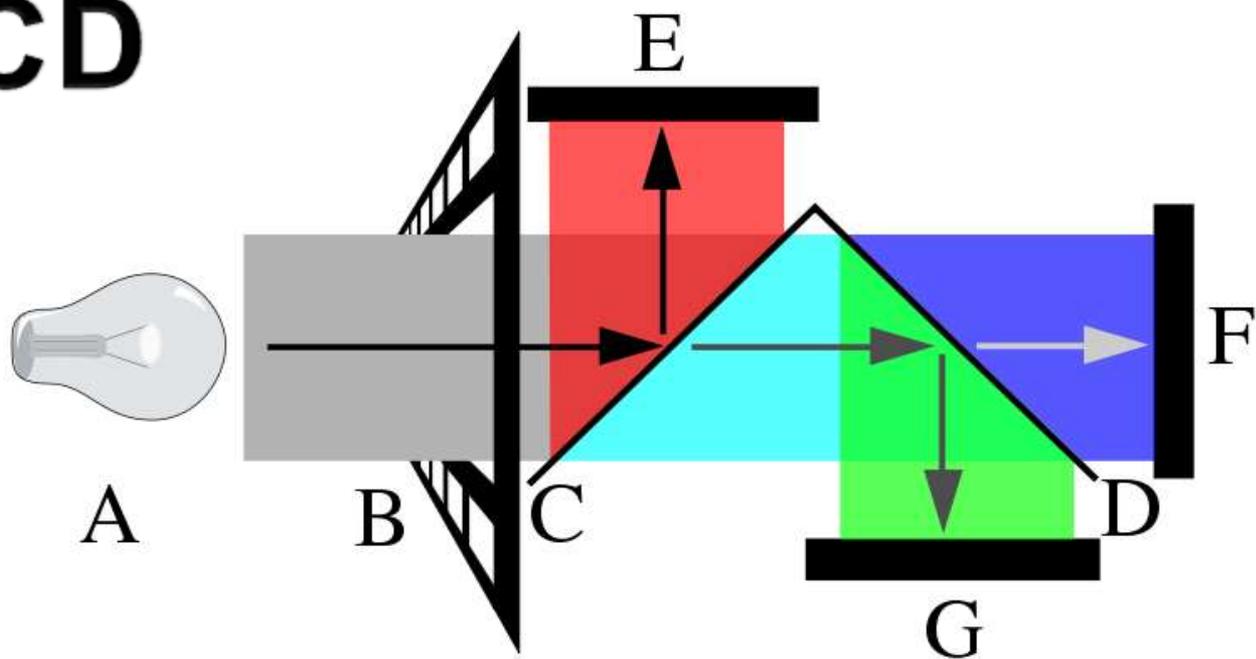
La couleur

La roue à filtres

Sequential Color Three-Pass CCD Imaging System

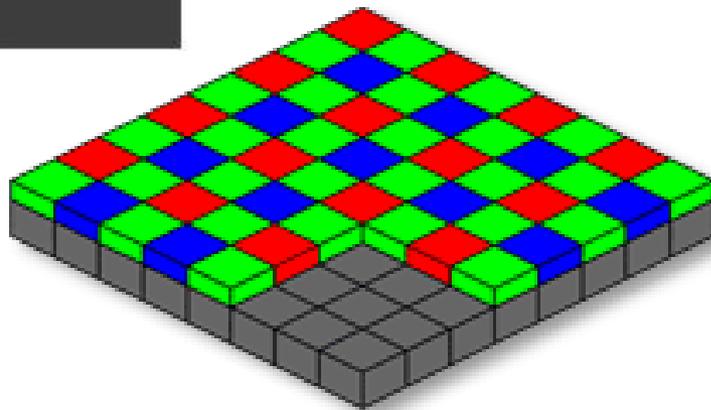
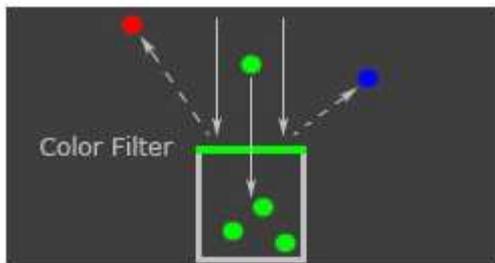
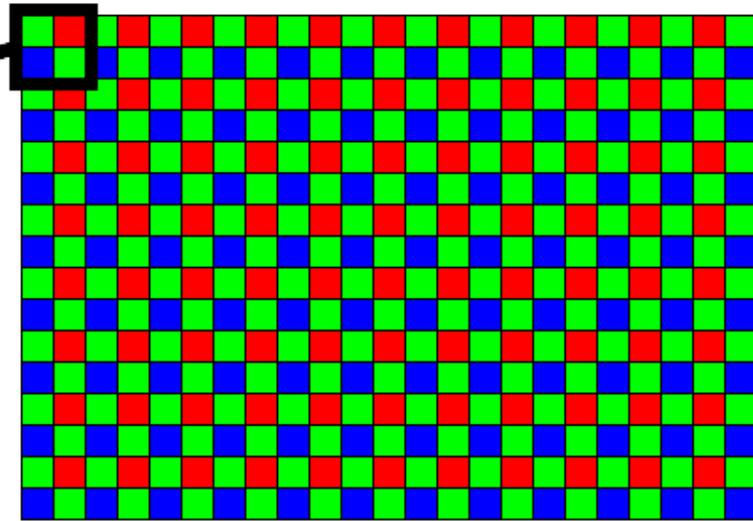
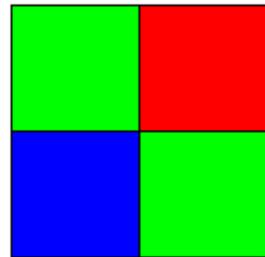


Le Tri-CCD



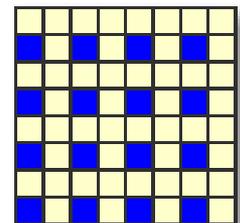
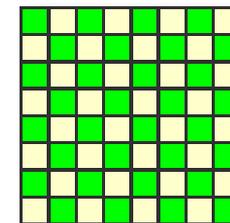
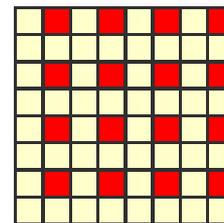
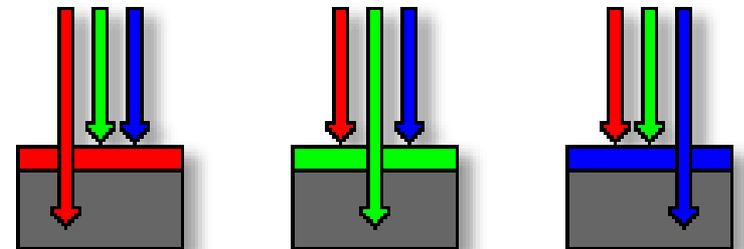
Le capteur COULEUR

La matrice de Bayer

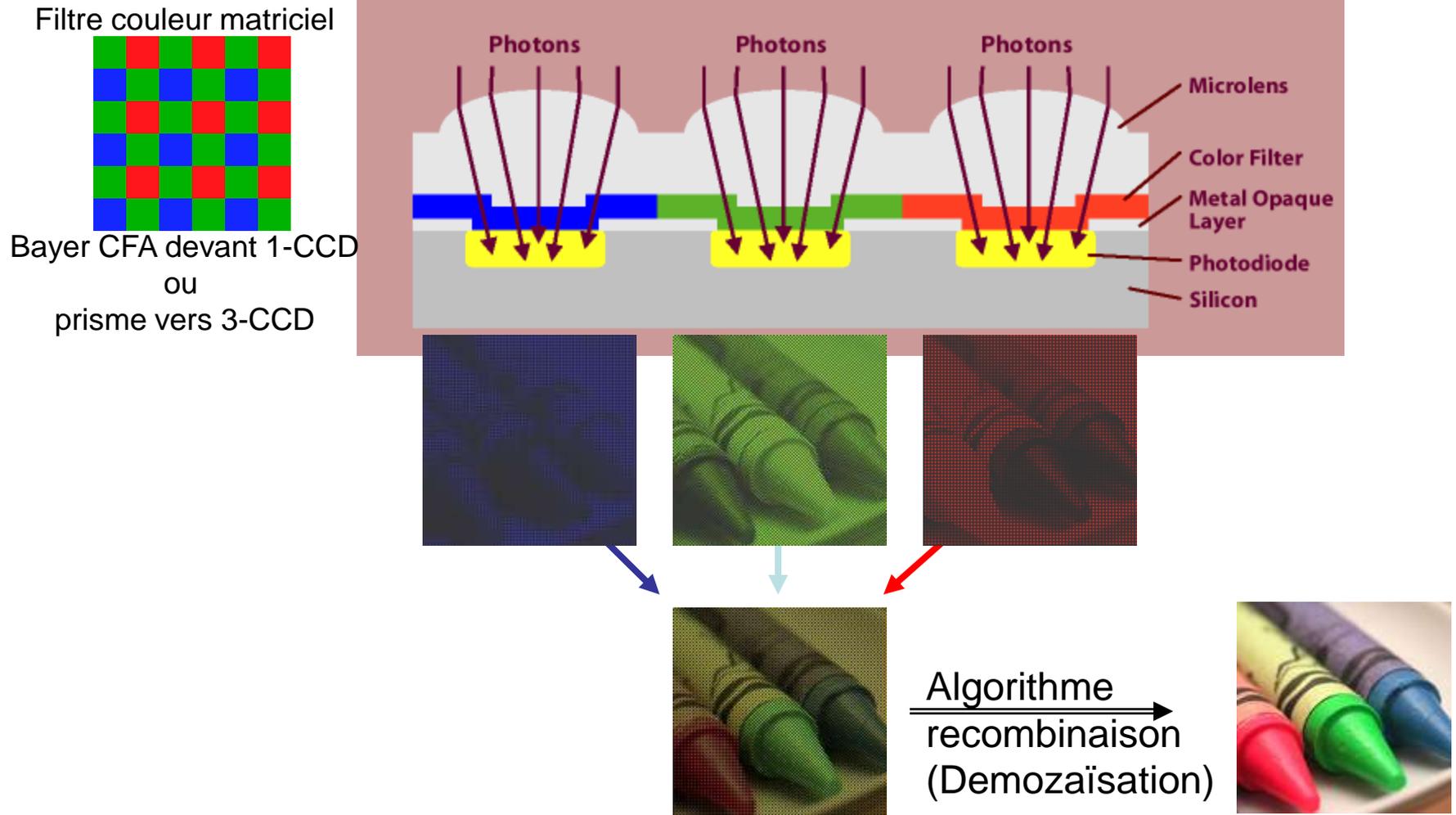


Capteur photosensible recouvert d'une grille de Bayer

Rayonnement

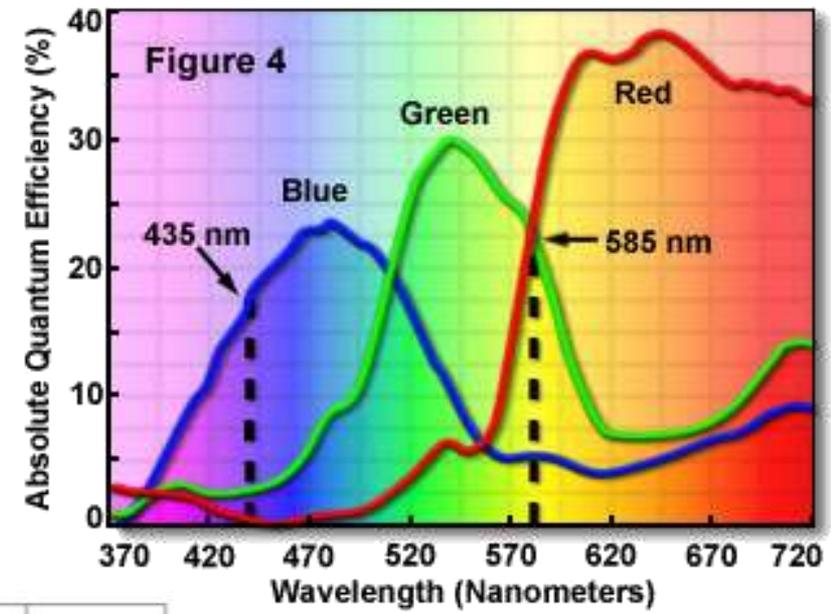


La matrice de Bayer

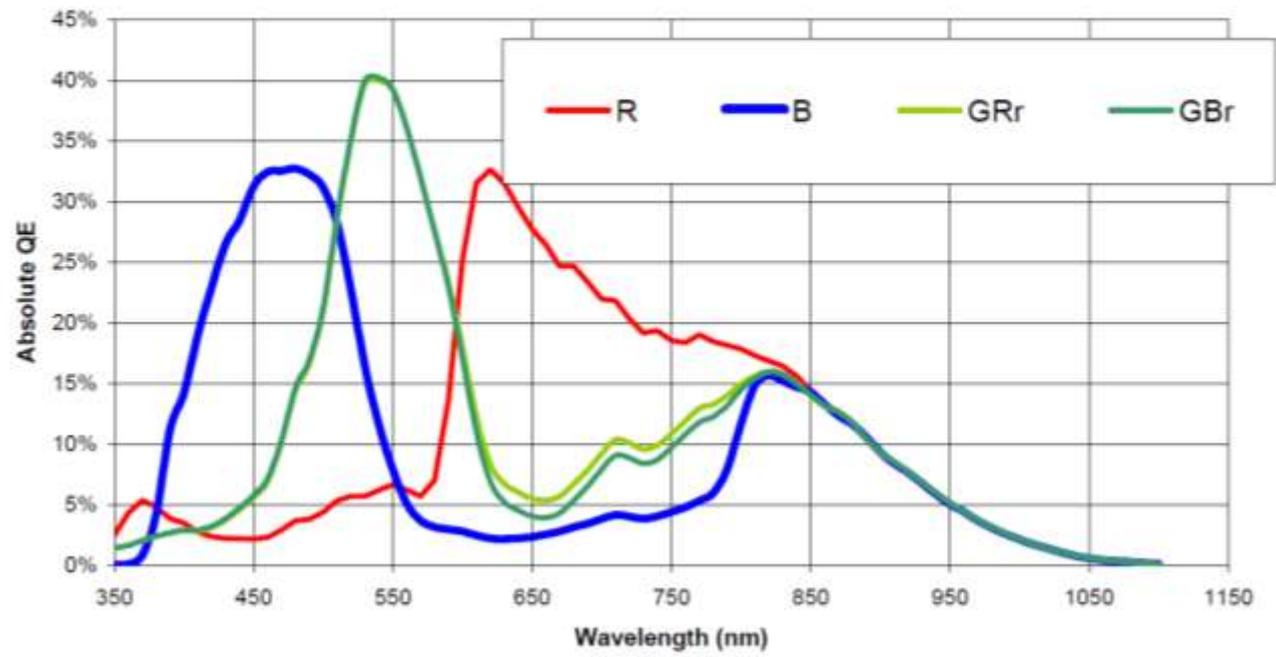


La matrice de Bayer

Bayer Filter Transmission Spectral Profiles



KAF-8300 Quantum Efficiency



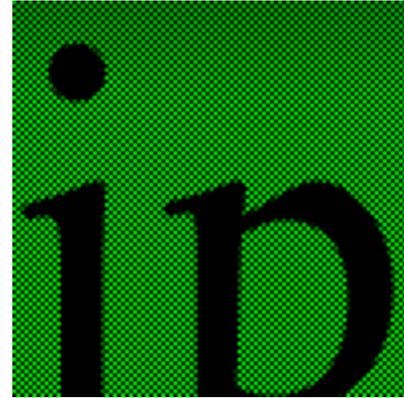
Le problème du dématricage



RAW



R



V



B



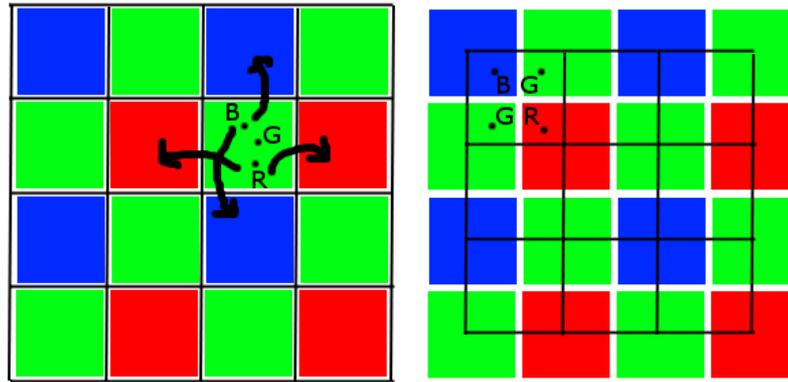
original



dématriqué

Les améliorations

- Par des algorithmes d'interpolation

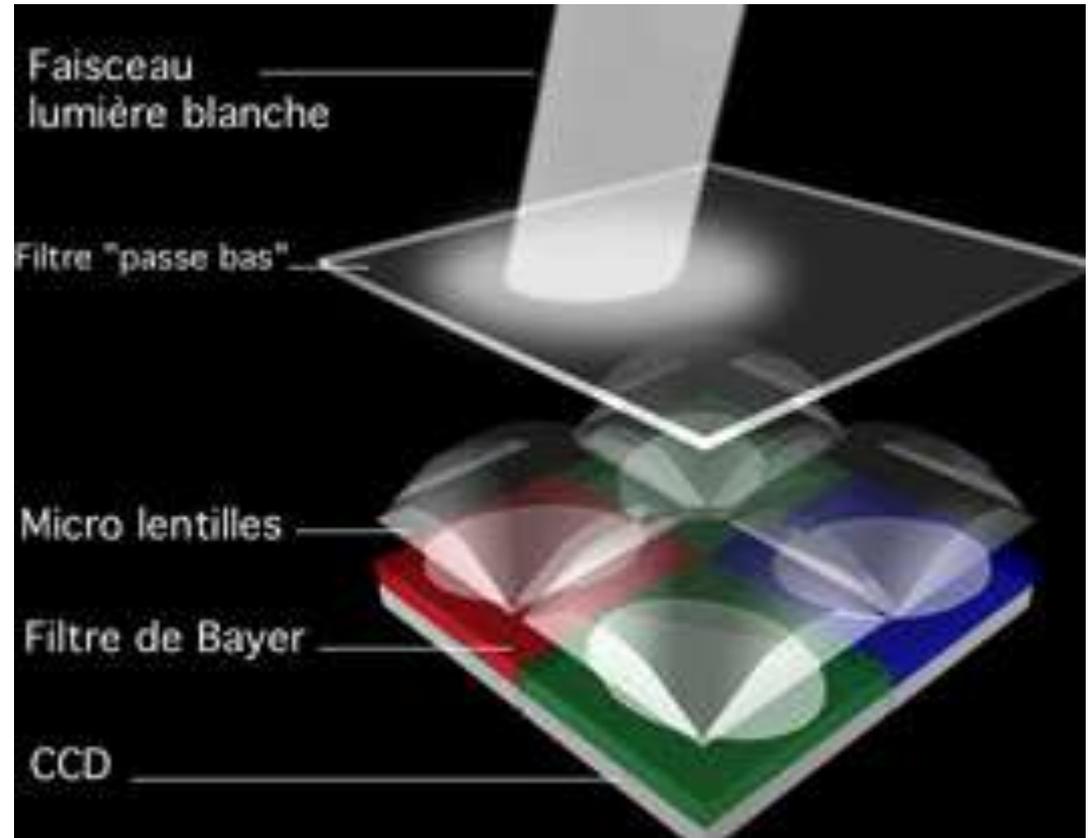


- Par des technologies différentes

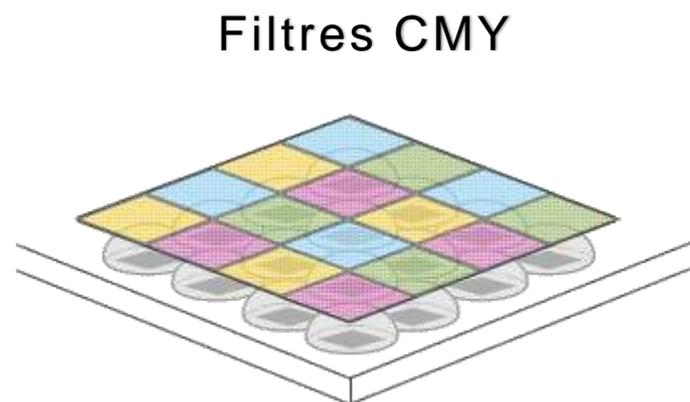
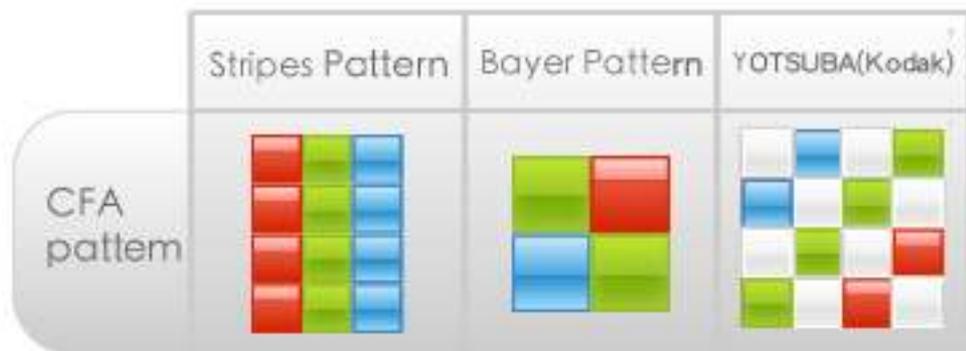
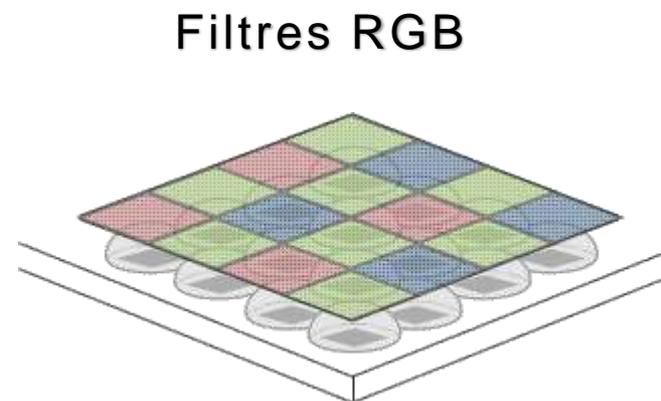
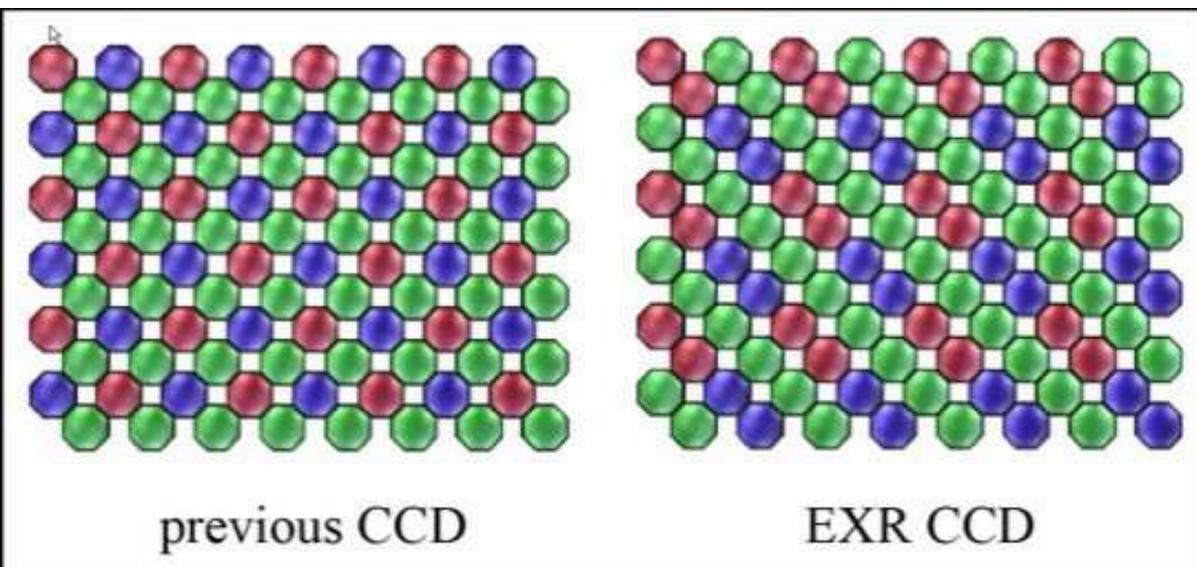
Filtre « anti-aliasing »

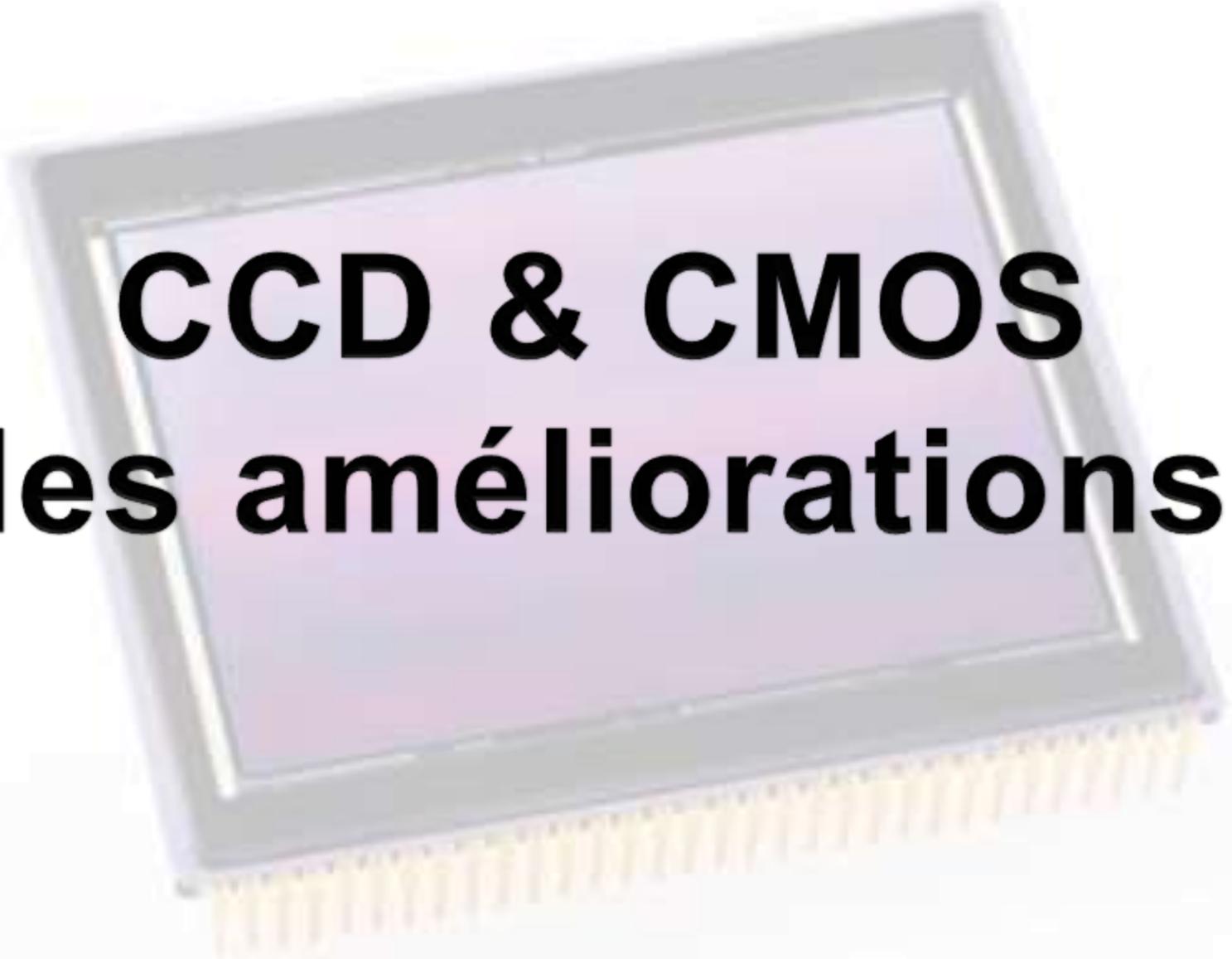
Un filtre passe bas optique est donc placé sur le filtre de Bayer : l'image est donc rendue « floue »

La résolution réelle de l'image couleur est inférieure a celle du nombre de pixels du capteur CCD



Des filtres différents

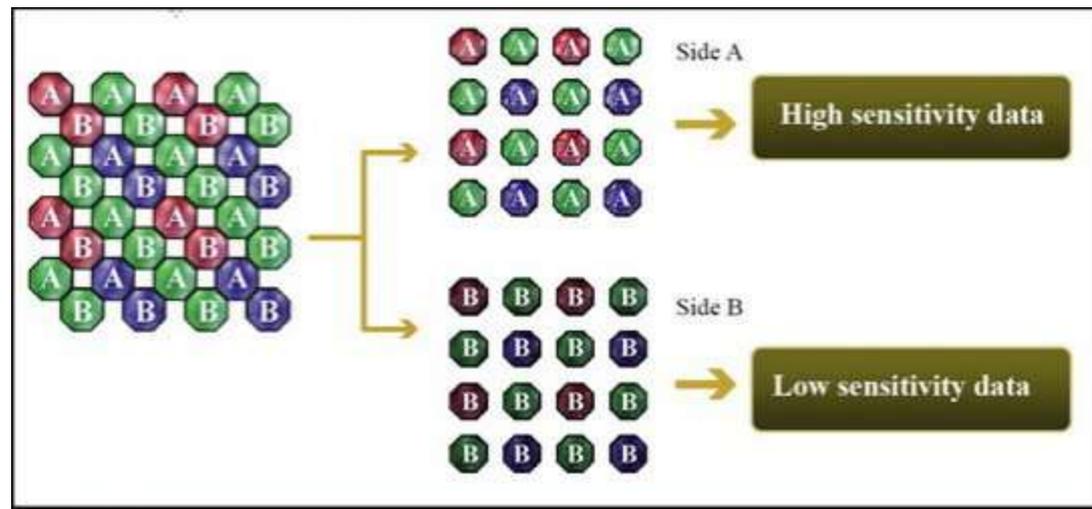
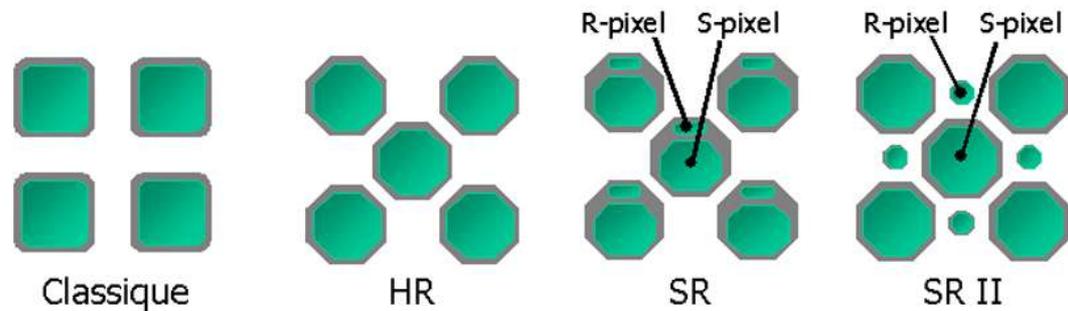
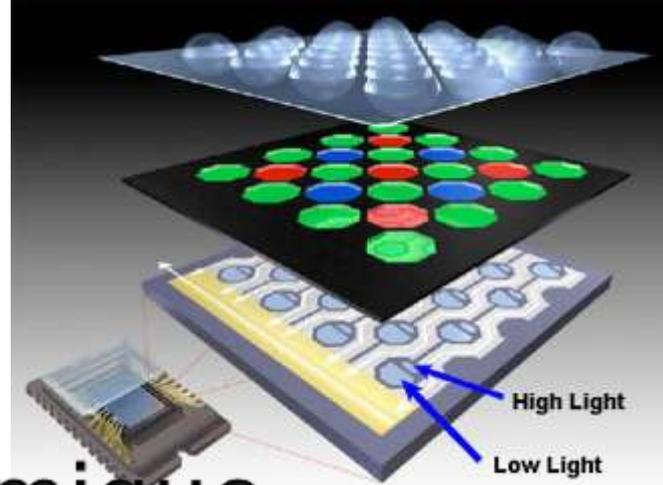




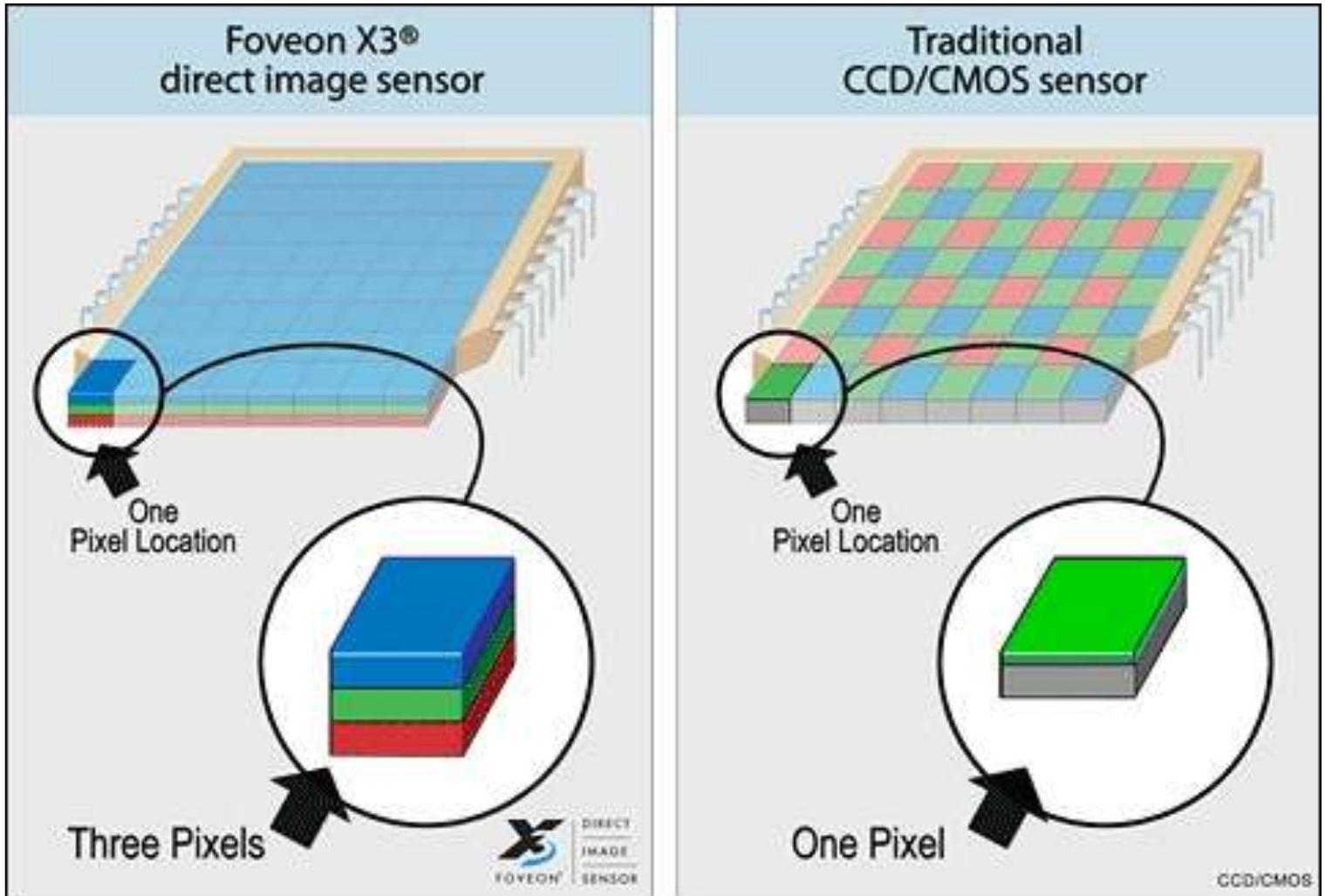
CCD & CMOS **les améliorations**

Des pixels différents

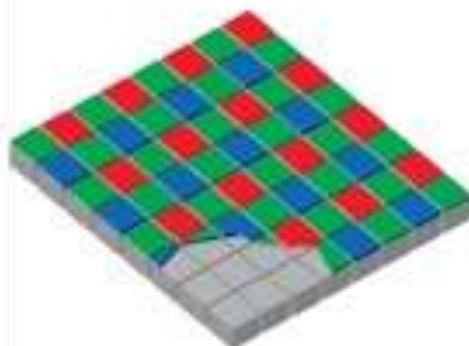
Augmentation de la dynamique



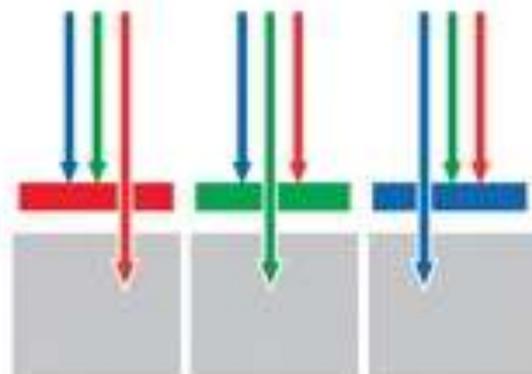
Nouvelles technologies



Mosaic Capture



In conventional systems, color filters are applied to a single layer of photodetectors in a tiled mosaic pattern.

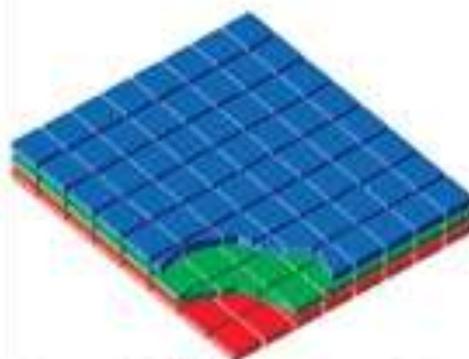


The filters let only one wavelength of light - red, green or blue - pass through to any given pixel, allowing it to record only one color.

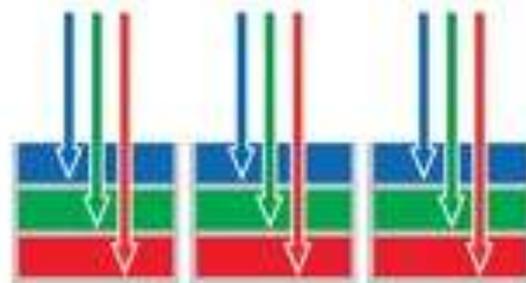


As a result, mosaic sensors capture only 25% of the red and blue light, and just 50% of the green.

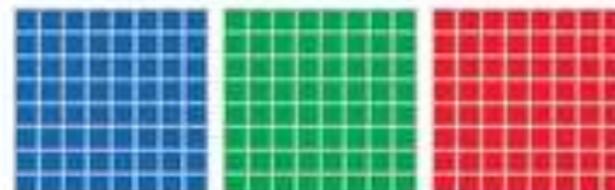
Foveon® X3™ Capture



A Foveon® X3™ image sensor features three separate layers of photodetectors embedded in silicon.



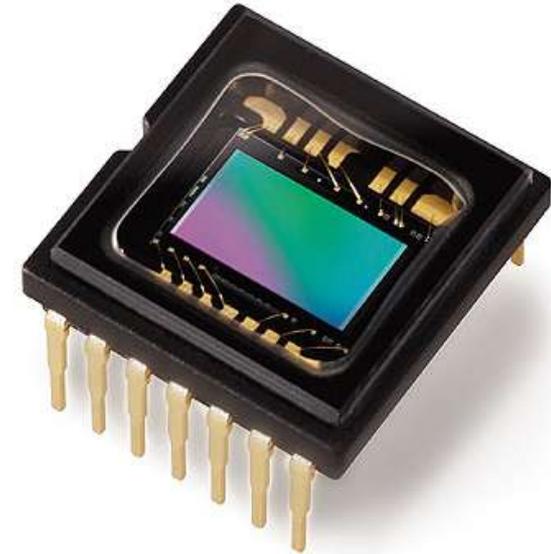
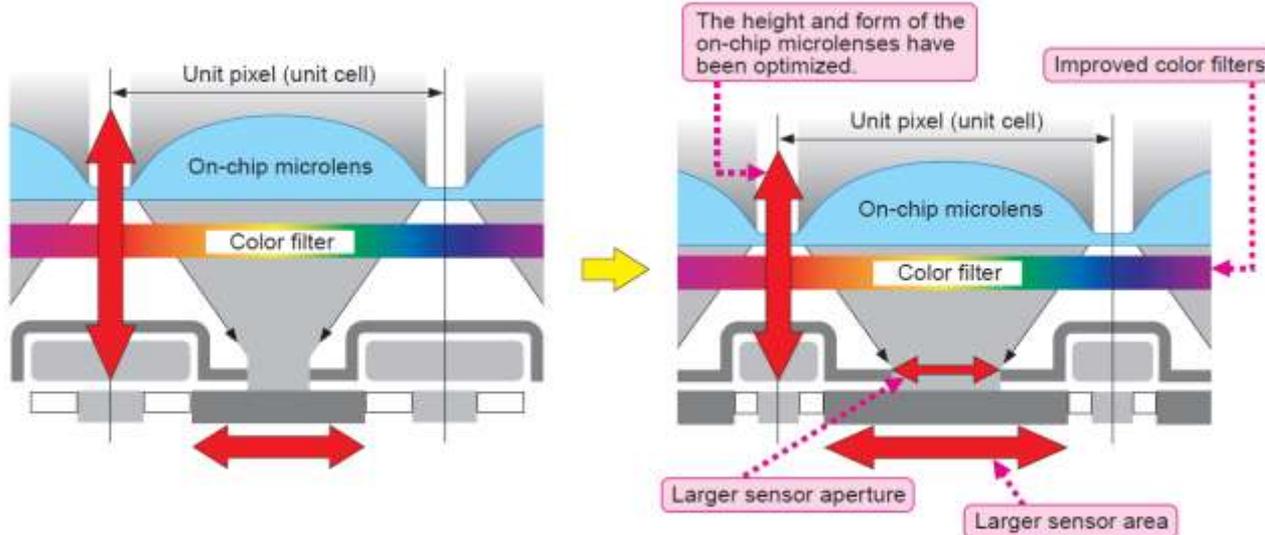
Since silicon absorbs different colors of light at different depths, each layer captures a different color. Stacked together, they create full-color pixels.



As a result, only Foveon X3 image sensors capture red, green and blue light at every pixel location.

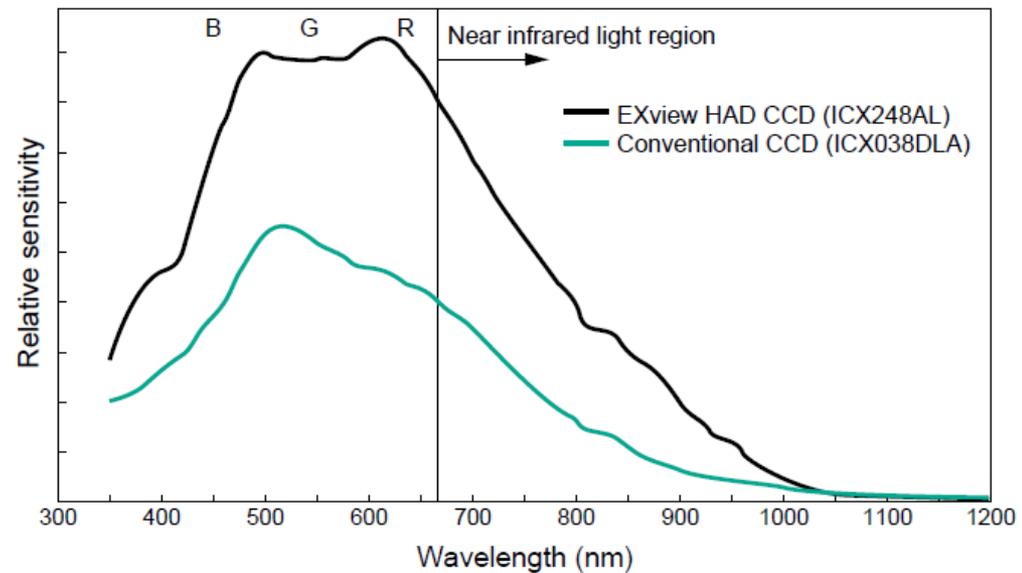
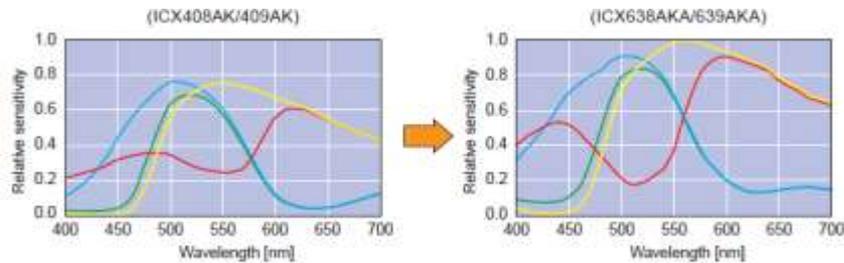
Exview & Super HAD CCD

Super Hole Accumulation Diode

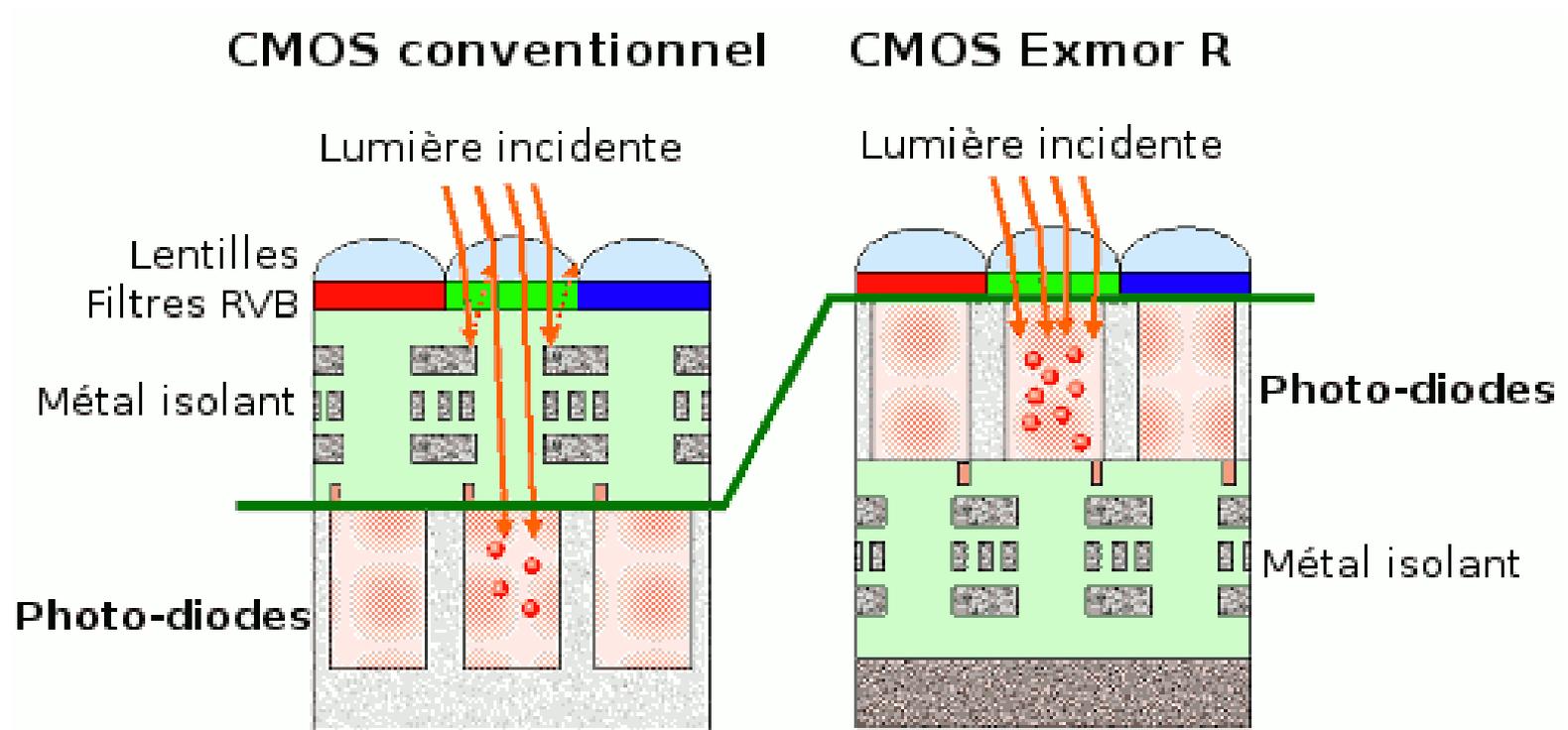


Super HAD CCD

Super HAD CCD II



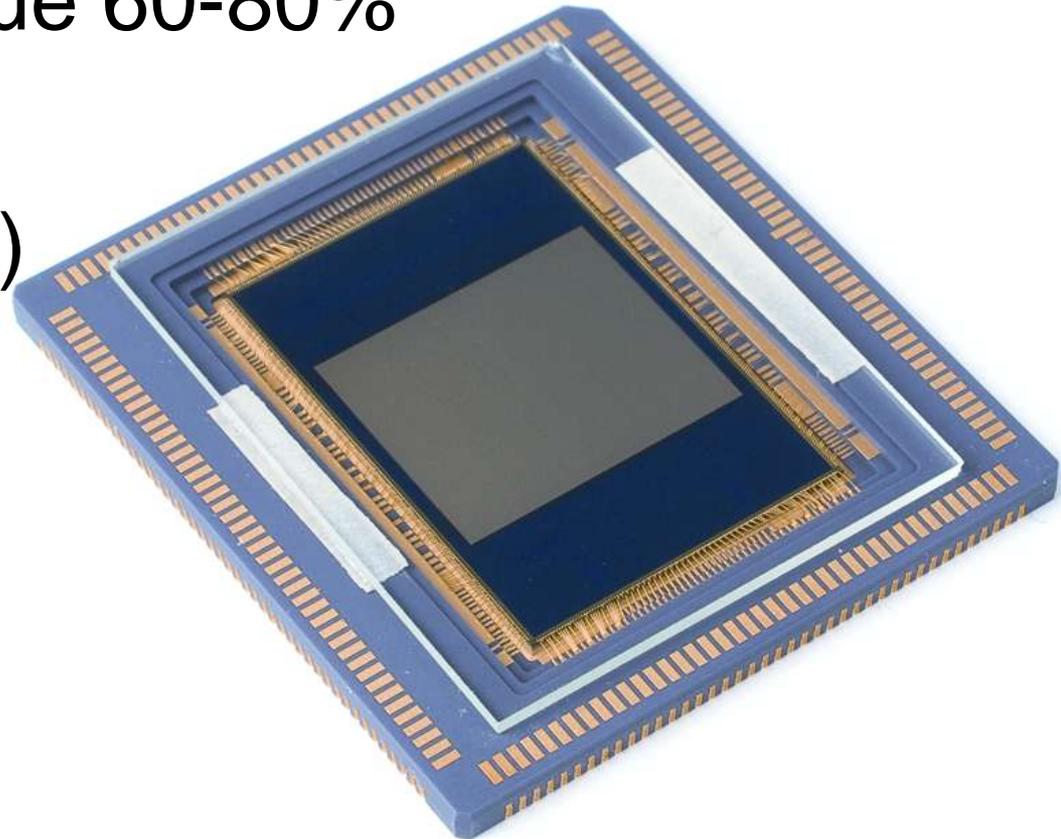
Nouvelles technologies : **CMOS BACK-ILLUMINATED**



Nouvelles technologies :

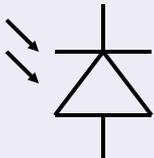
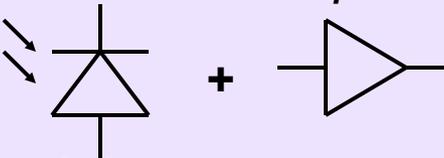
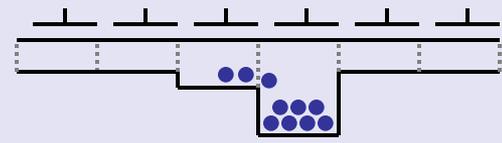
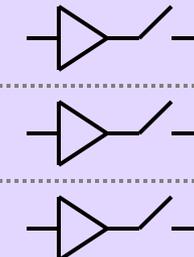
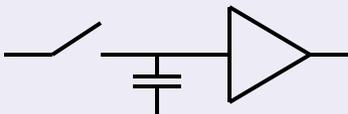
sCMOS : Scientific CMOS

- Bruit de lecture de 1 à 3 e⁻
- Rendement quantique 60-80%
- Rapide (30-100 fps)
- Résolution (2-5Mpix)
- 12 – 14 bits
- Refroidissement



Sony, Fairchild

En résumé

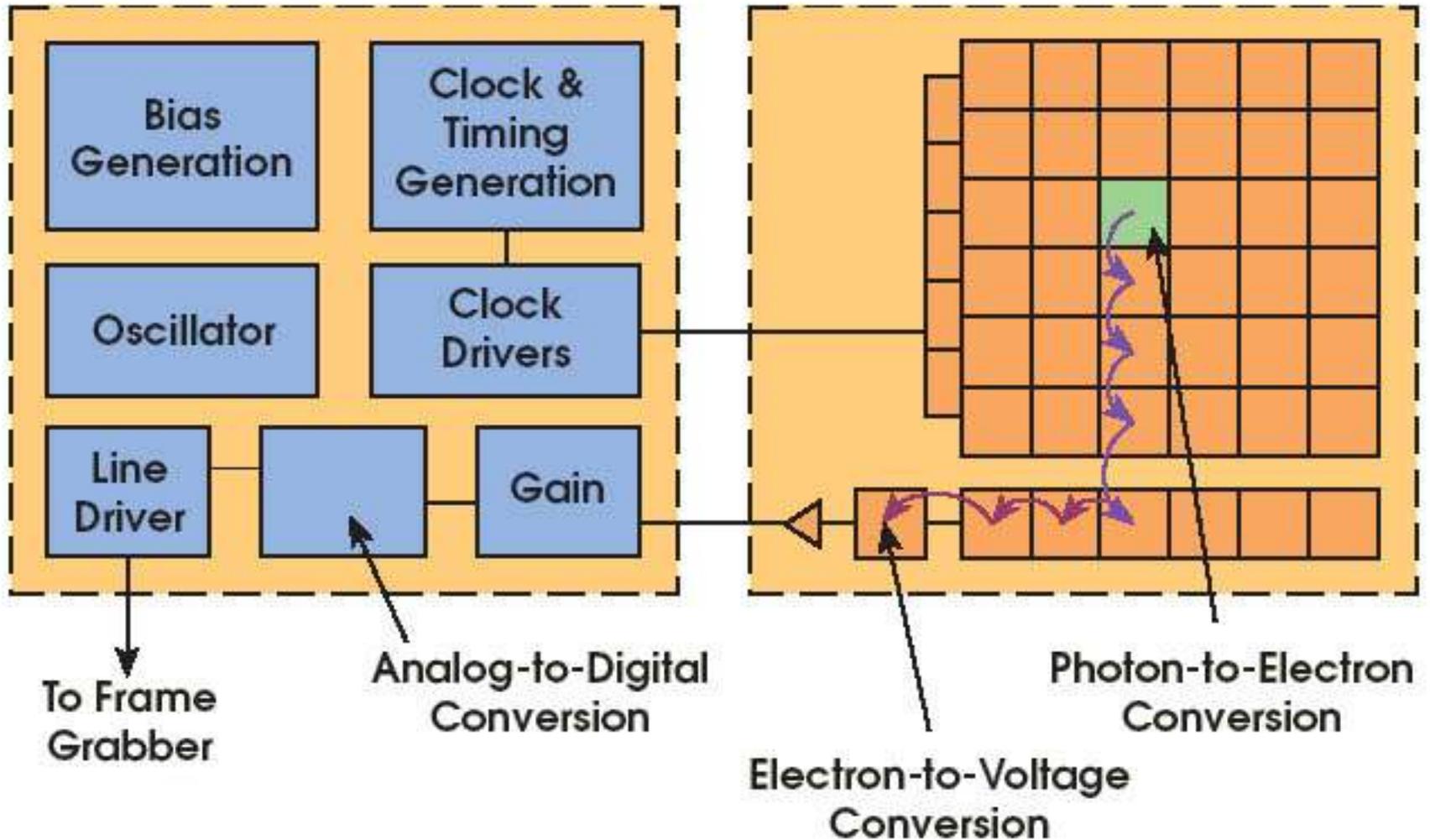
	CCD	CMOS
Pixel	<p><i>Photodiode</i></p>  <p>Génération de charge Intégration de charge</p>	<p><i>Photodiode</i> + <i>Amplifier</i></p>  <p>Génération de charge Intégration de charge Conversion en tension</p>
Lecture	 <p>Transfert de charge Pixel à pixel</p>	 <p>Multiplexage des tensions des pixels : connexion successive des amplificateur au bus commun</p>
Sortie	 <p>Ampli de sortie : conversion charges - tension</p>	<p>Options possibles :</p> <ul style="list-style-type: none"> - pas d'autre circuit (analogique) - amplis supplém. (analogique) - conversion A/N (numérique)

Résumé

CCD

Camera (Printed Circuit Board)

Charge-Coupled Device Image Sensor

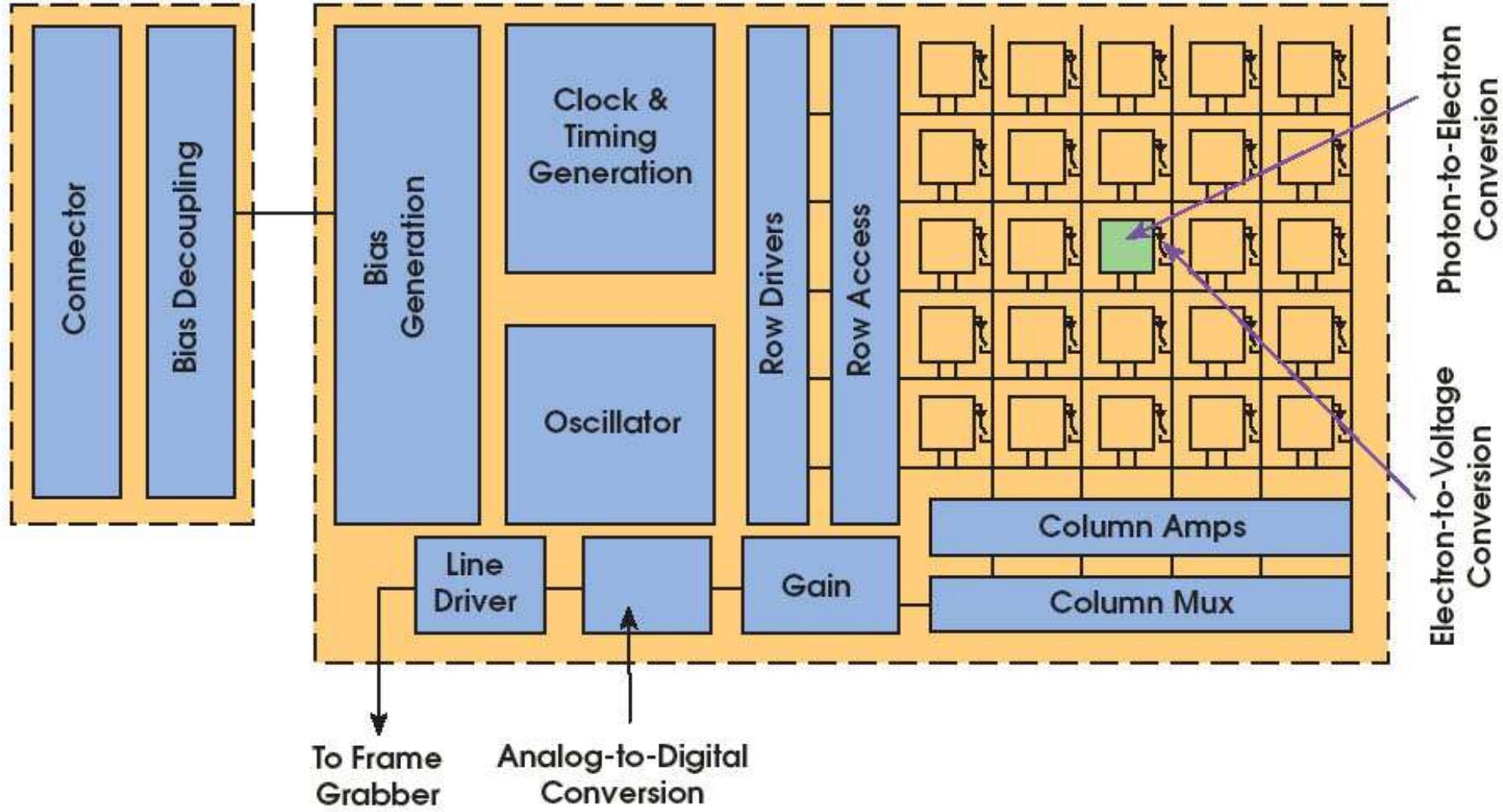


Résumé

CMOS

Camera
(Printed Circuit Board)

Complementary Metal Oxide Semiconductor
Image Sensor



A blue tablet with a green screen and gold connectors. The word "Merci..." is written in large black letters on the screen.

Merci...