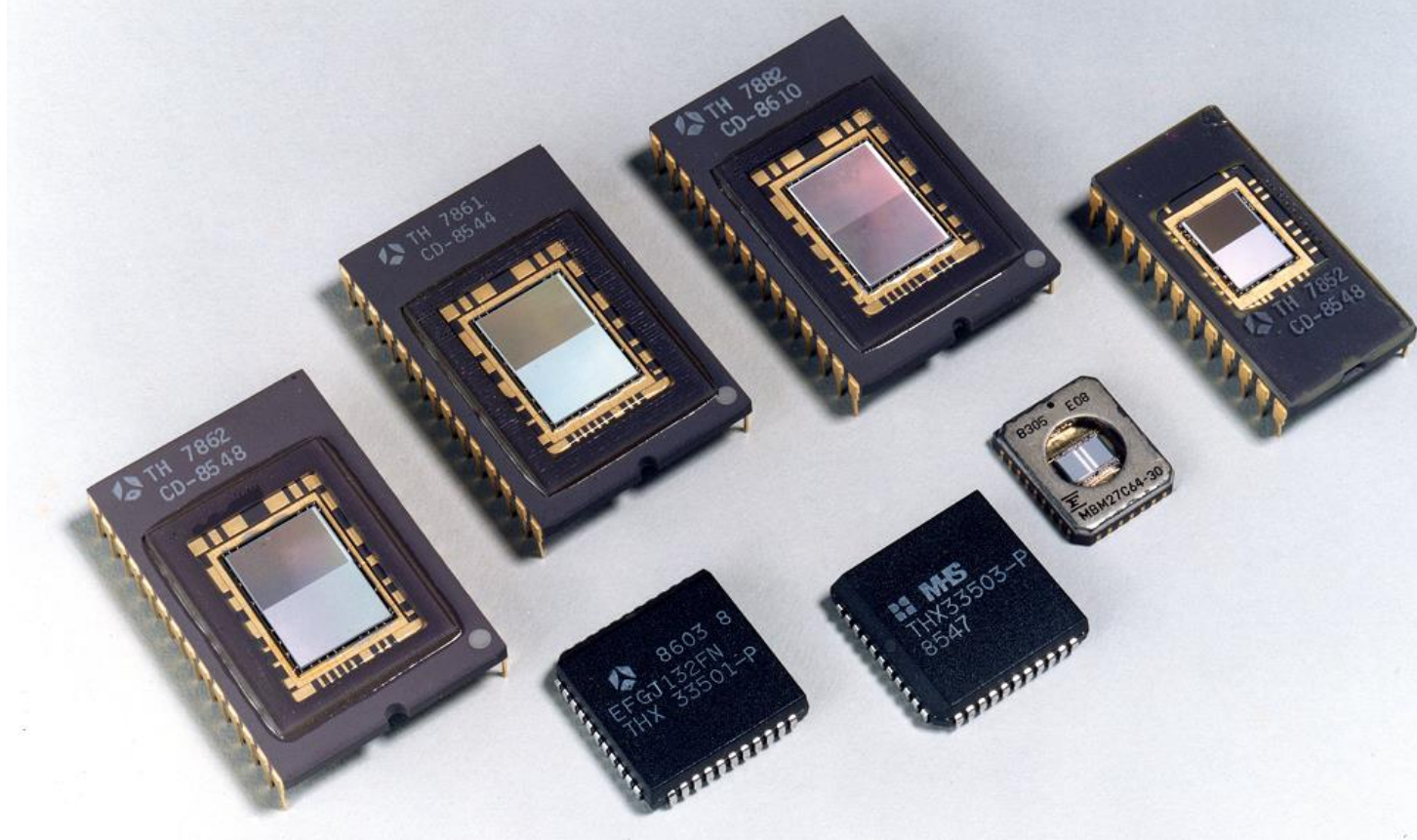




Les détecteurs CCD

à Thomson-CSF Saint-Egrève

Années 1970 -1980

Avant les CCD

Invention des CCD

Premiers CCD à St Egrève

Inefficacité de transfert

Représentation imagée

Choix technologiques

Transfert en volume

Structure standard en 1975

Technologie années 1970

Du labo vers la prod

1^{ère} barrette photosensible

1^{er} capteur matriciel TH 7852

1^{er} capteur format TV : TH 7864

Performances de capteur CCD

TH7882 Monocoup et aminci

Couplage fibres optiques

Capteur TDL couleur

Capteur 1024 x 1024

Les autres capteurs...

Interligne et CMOS

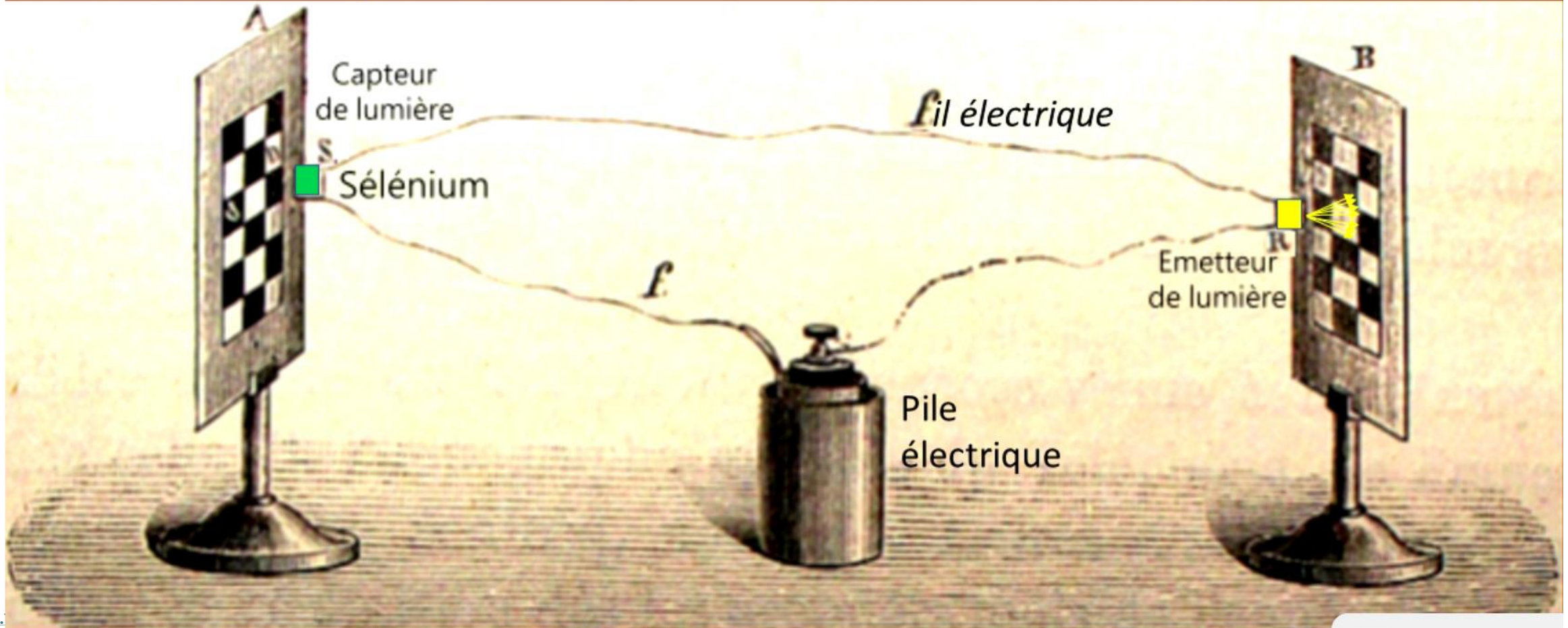
Annexes

➡ L'image électronique avant les CCD

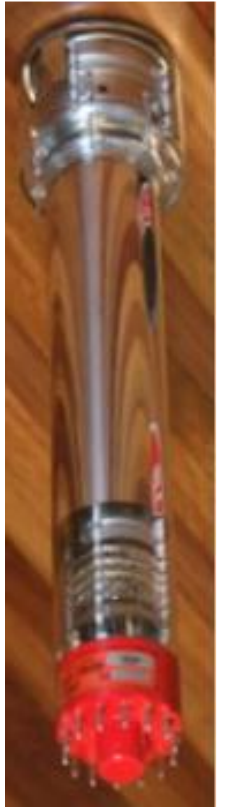
Le rêve de 1891

L'œil électrique

L'écran électrique



➡ L'image électronique avant les CCD



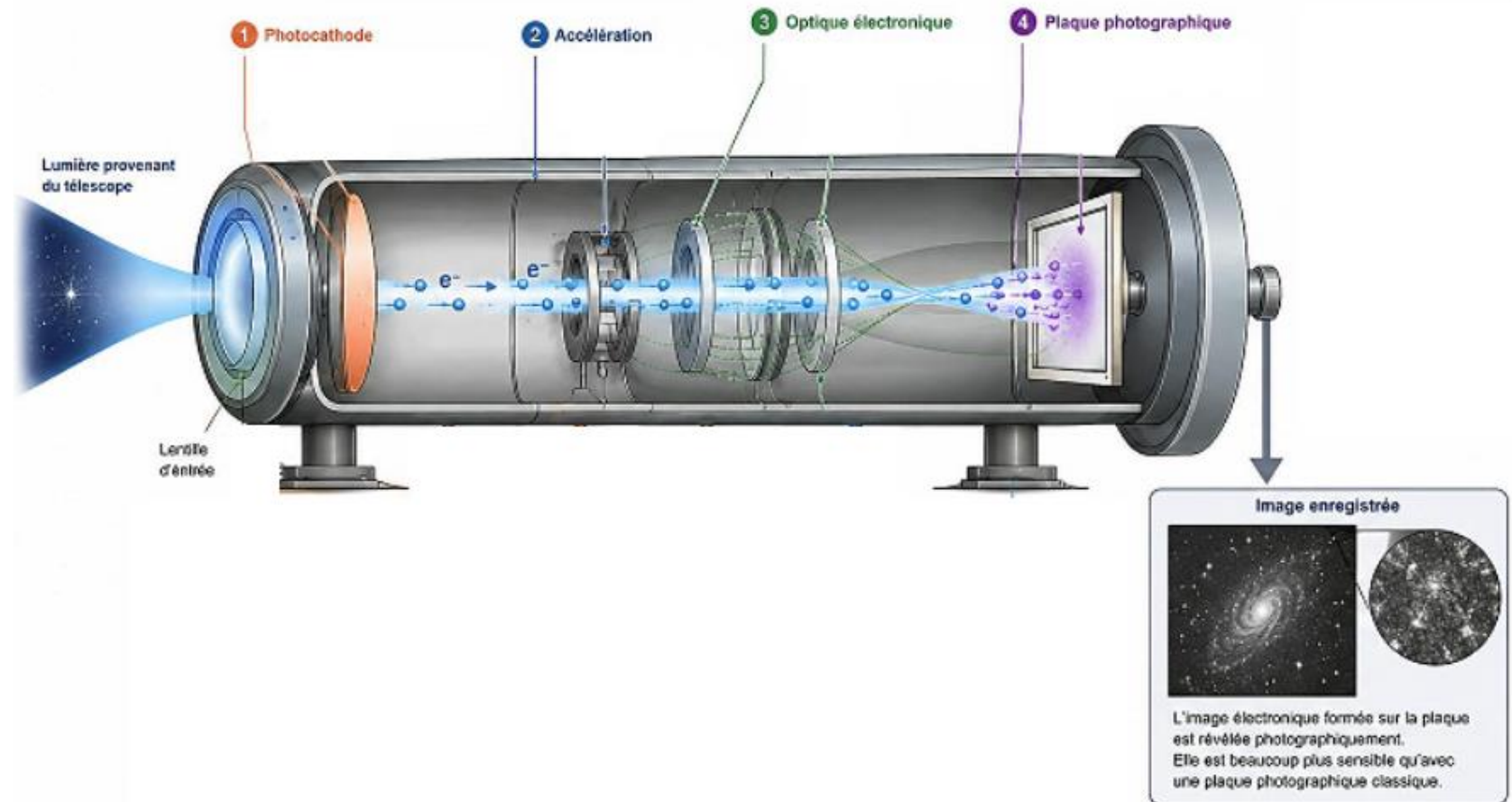
1945
Image Orthicon

➡ L'image électronique avant les CCD – André Lallemand



www.tedimage38.org

La caméra électronique de Lallemand (1936)



<https://observatoiredeparis.psl.eu/les-ateliers-lallemand.html>

PERFORMANCE OF THE VIDICON, A SMALL DEVELOPMENTAL TELEVISION CAMERA TUBE*

BY

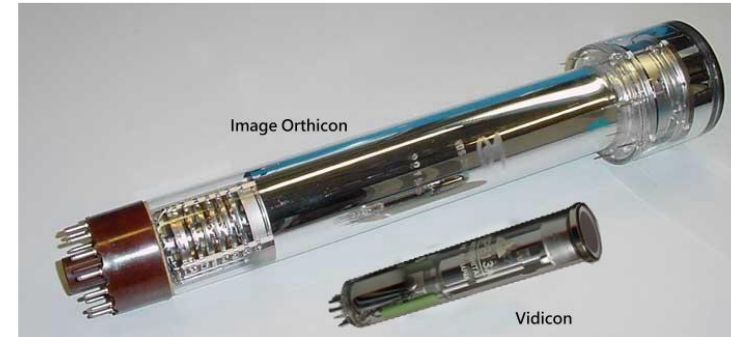
B. H. VINE, R. B. JANES AND F. S. VEITH

Tube Department, RCA Victor Division,
Lancaster, Pa.

Summary—The performance of developmental Vidicons utilizing three different developmental types of photoconductive layers is described in this paper. Data is given on gamma, sensitivity, illumination considerations, spectral response, persistence, and life. Vidicon construction and operation as well as signal-to-noise limitations are discussed.

INTRODUCTION

THE Vidicon is a developmental television camera tube employing a thin layer of photoconductive material as its light-sensitive



RCA REVIEW

March 1952

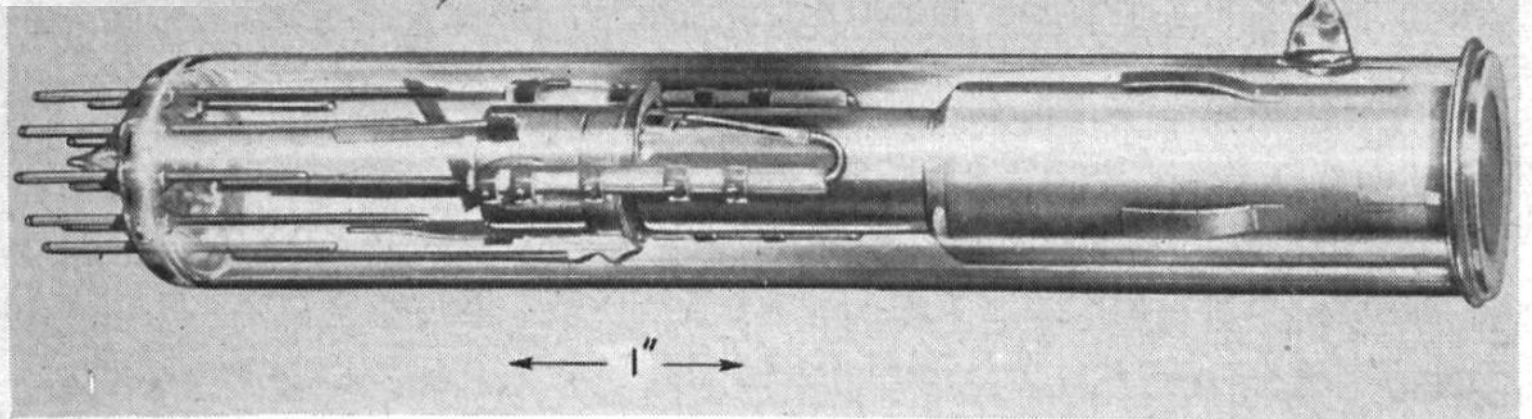
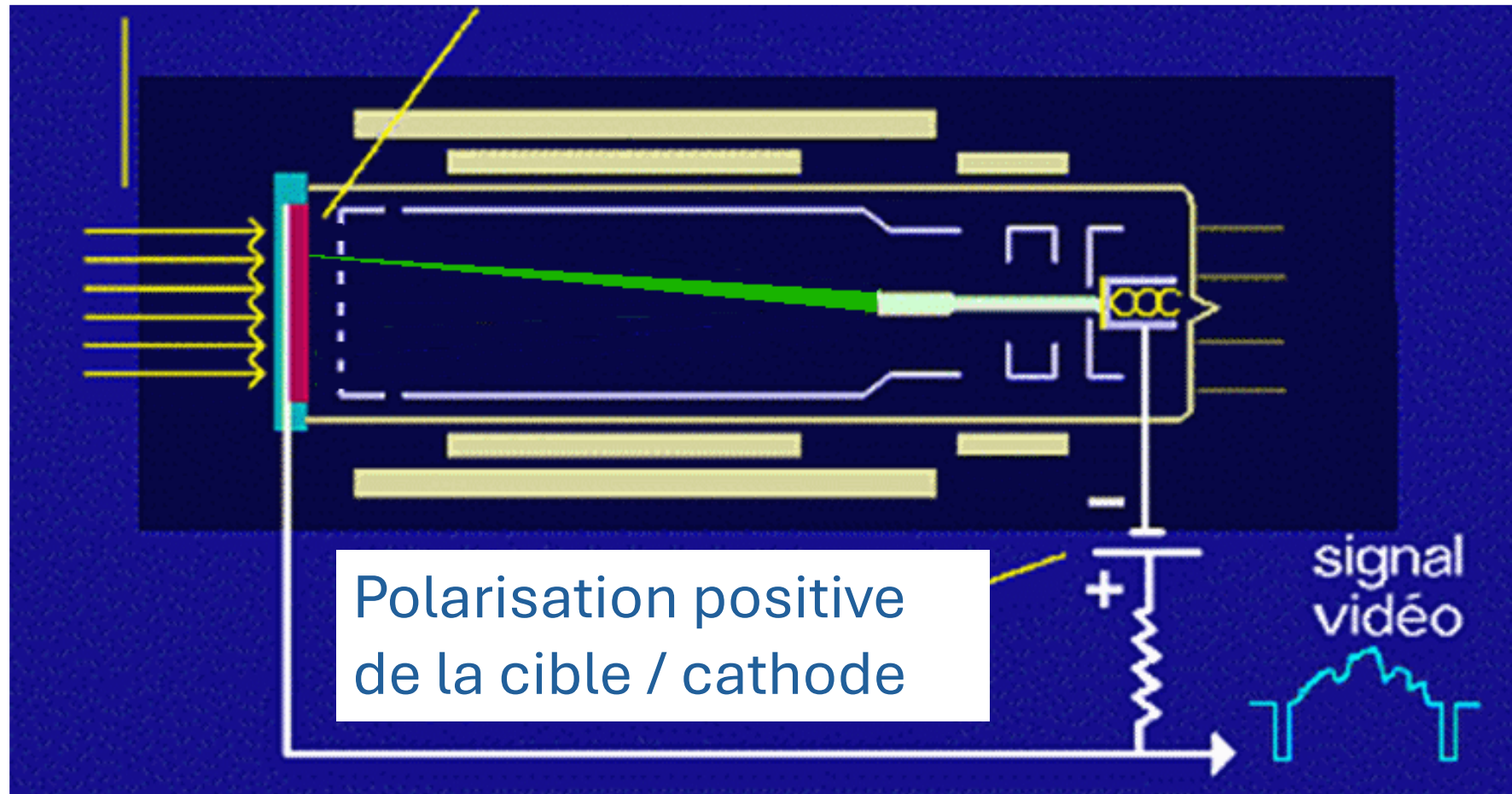


Fig. 3—Photograph of developmental Vidicon.

➡ L'image électronique avant les CCD – **Le vidicon**

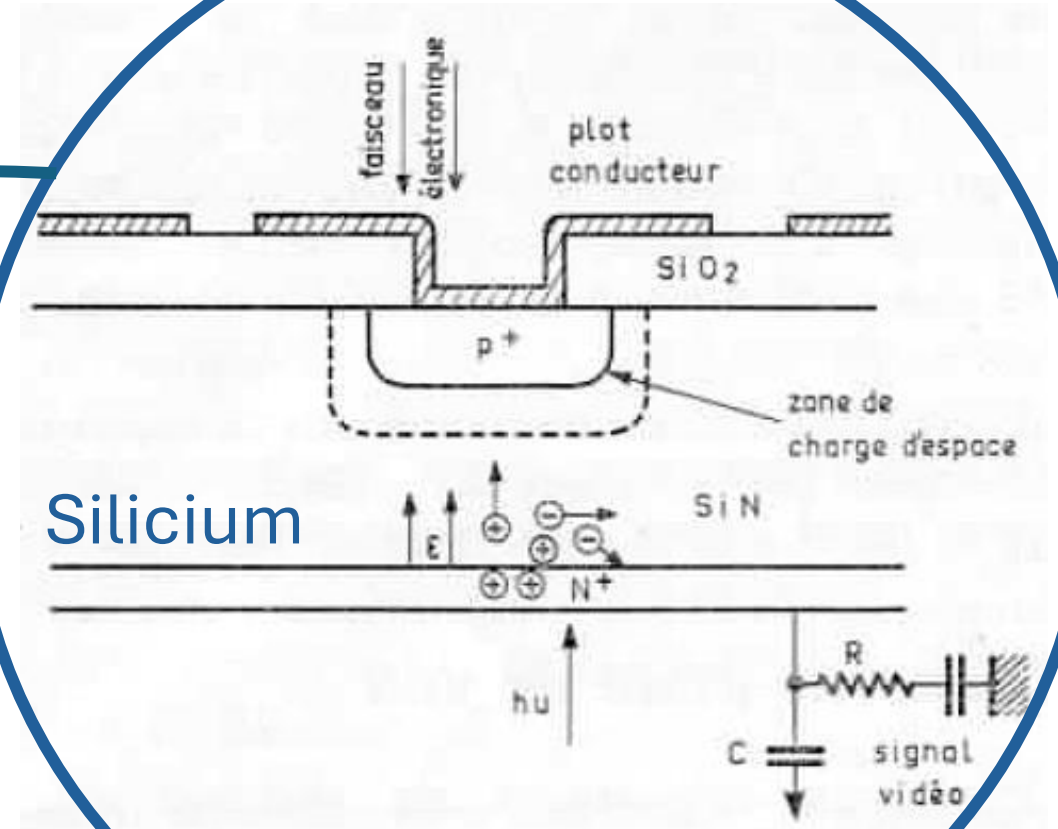
Image focalisée
sur la cible

Balayage de la cible par le
faisceau d'électrons



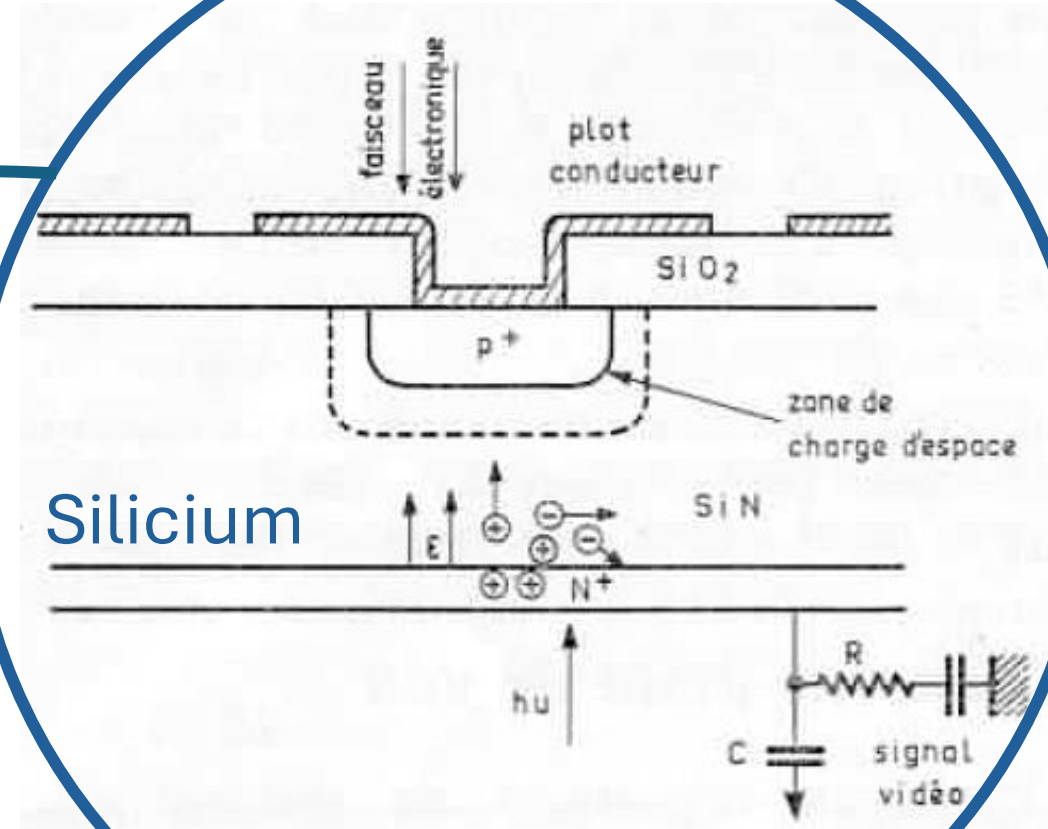
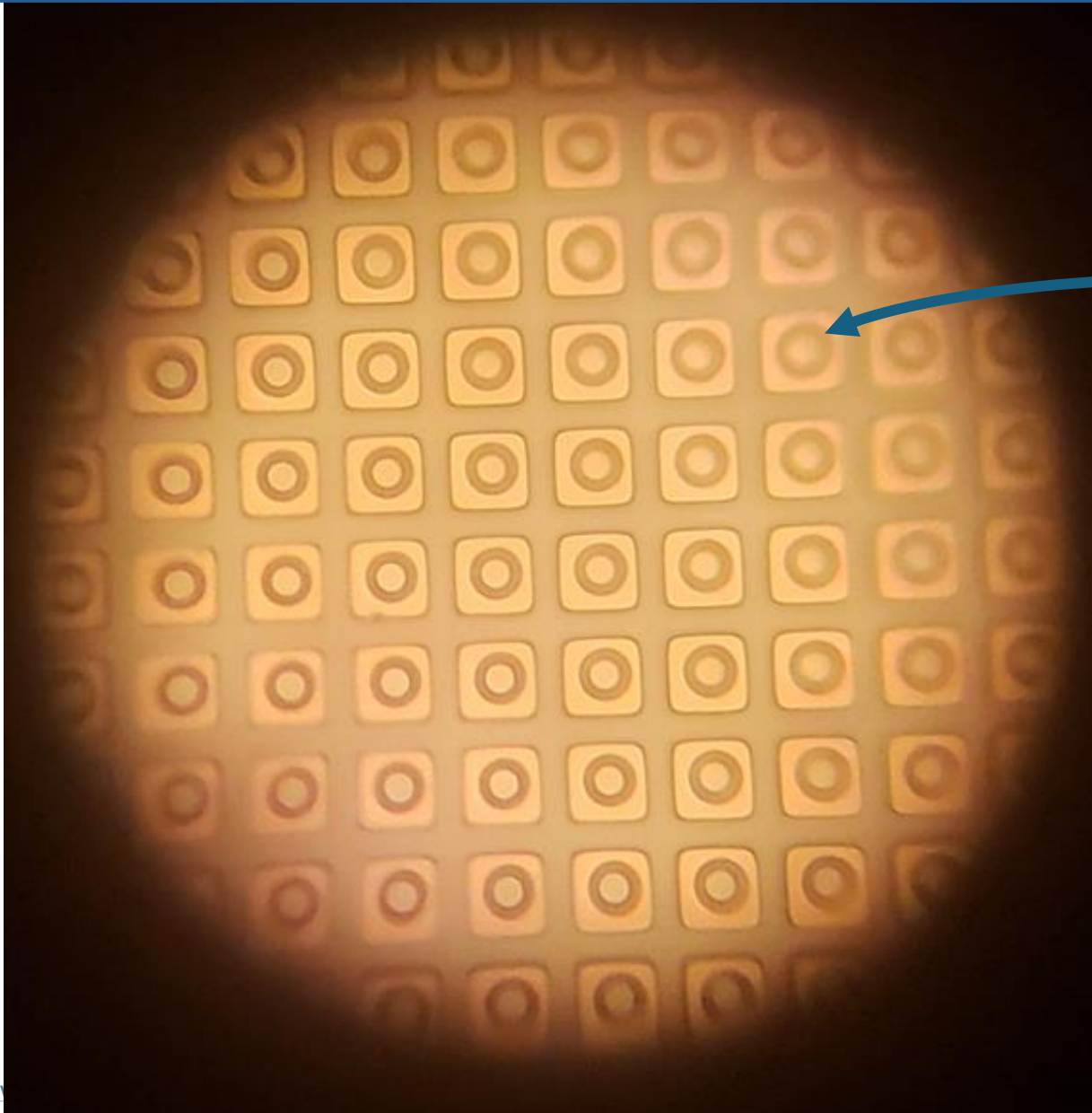
Polarisation positive
de la cible / cathode

Sommaire

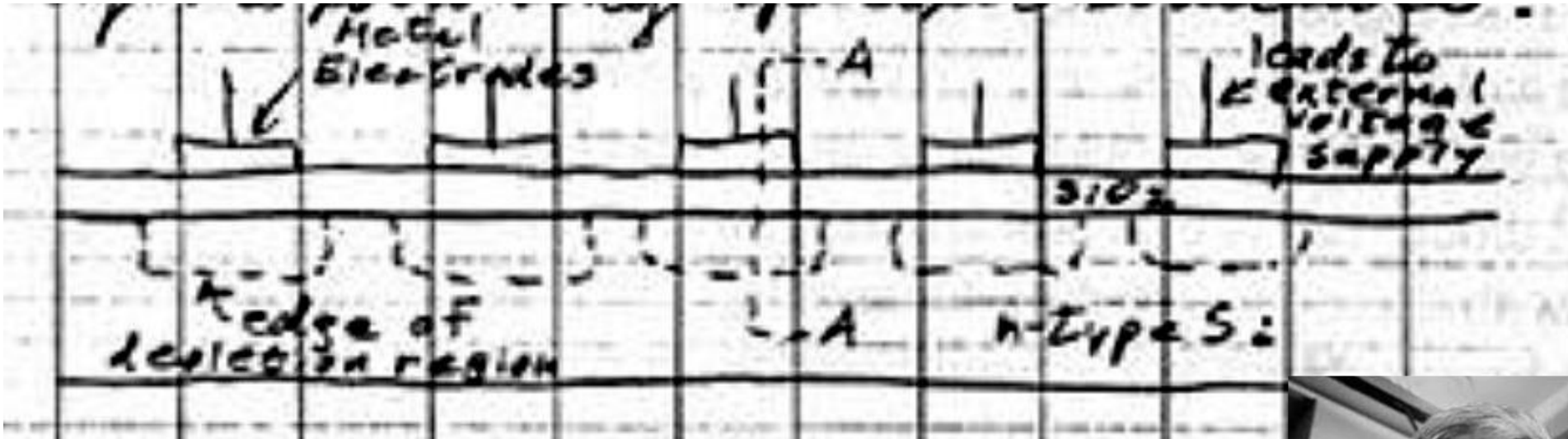


Silicium

➡ L'image électronique avant les CCD – **Le vidicon**



➡ 1969 - Invention des CCD



Première esquisse d'un CCD
le 18 octobre 1969,
par Willard Boyle et George Smith
aux laboratoires Bell



➡ 1969 - Invention des CCD

B.S.T.J. BRIEFS

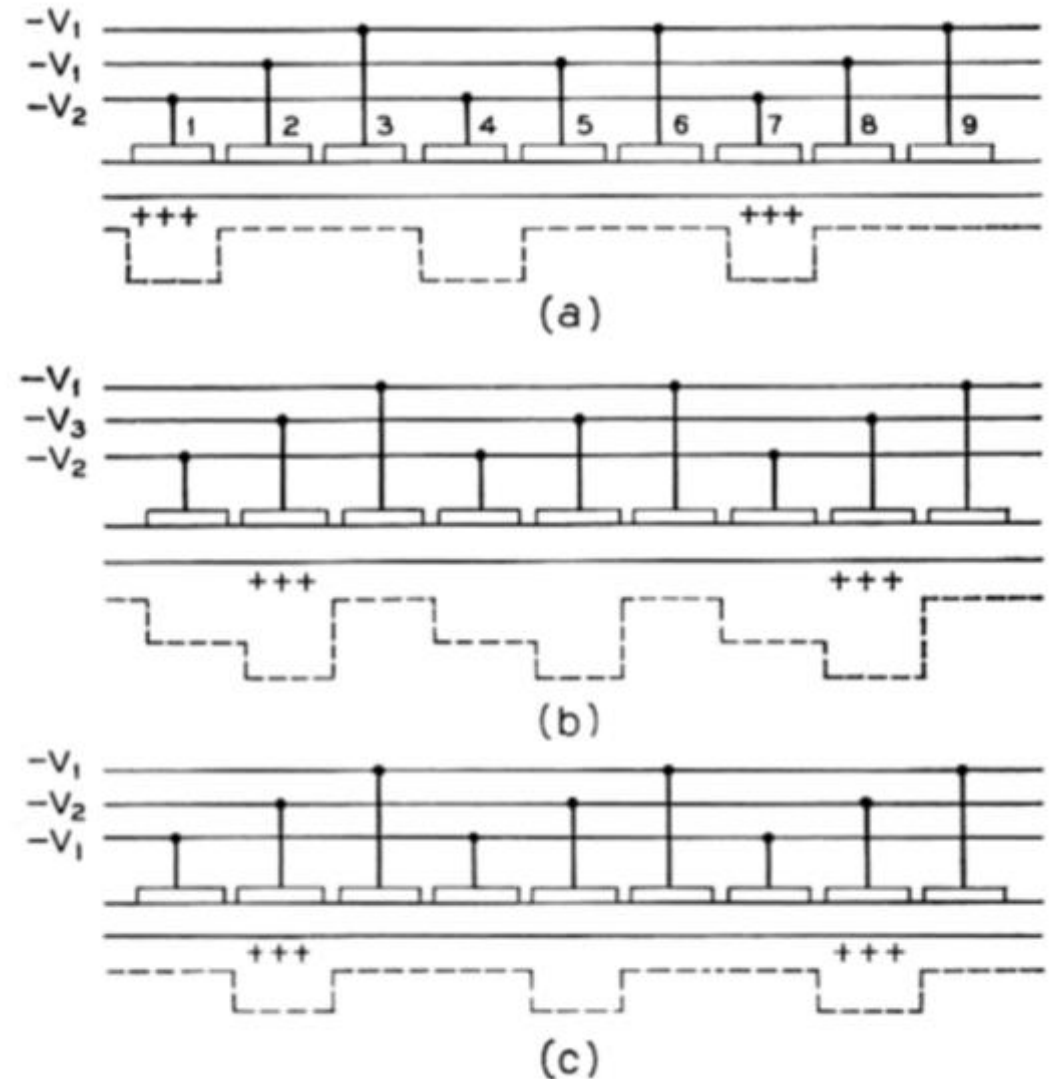
Charge Coupled Semiconductor Devices

By W. S. BOYLE and G. E. SMITH

(Manuscript received January 29, 1970)

In this paper we describe a new semiconductor device concept. Basically, it consists of storing charge in potential wells created at the surface of a semiconductor and moving the charge (representing information) over the surface by moving the potential minima. We discuss schemes for creating, transferring, and detecting the presence or absence of the charge.

In particular, we consider minority carrier charge storage at the Si-SiO₂ interface of a MOS capacitor. This charge may be transferred to a closely adjacent capacitor on the same substrate by appropriate manipulation of electrode potentials. Examples of possible applications are as a shift register, as an imaging device, as a display device, and in performing logic.



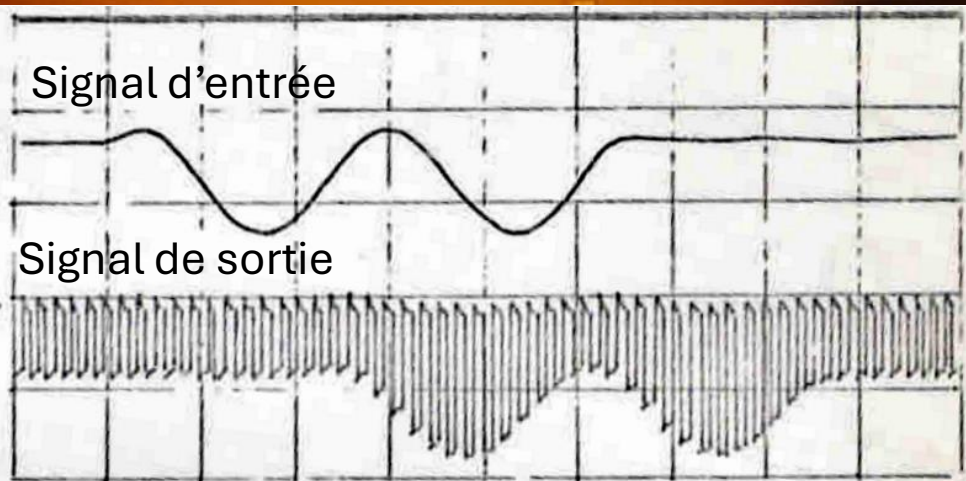
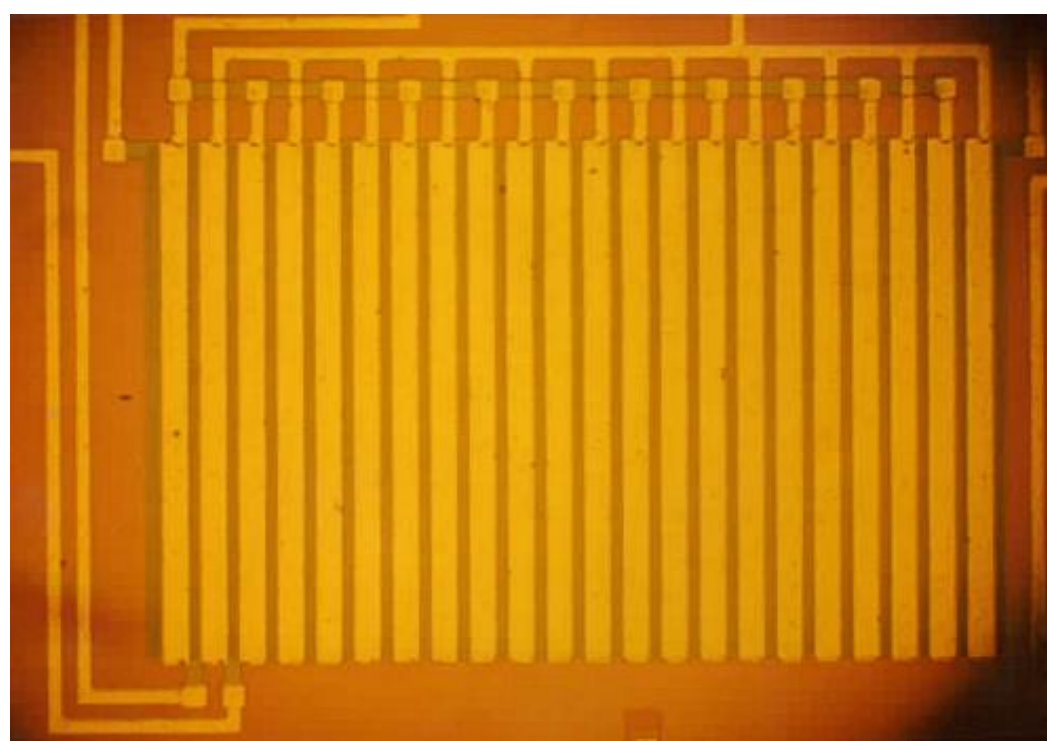
➡ Dispositifs à transfert de charge = **C**harge **C**oupled **D**evelopes



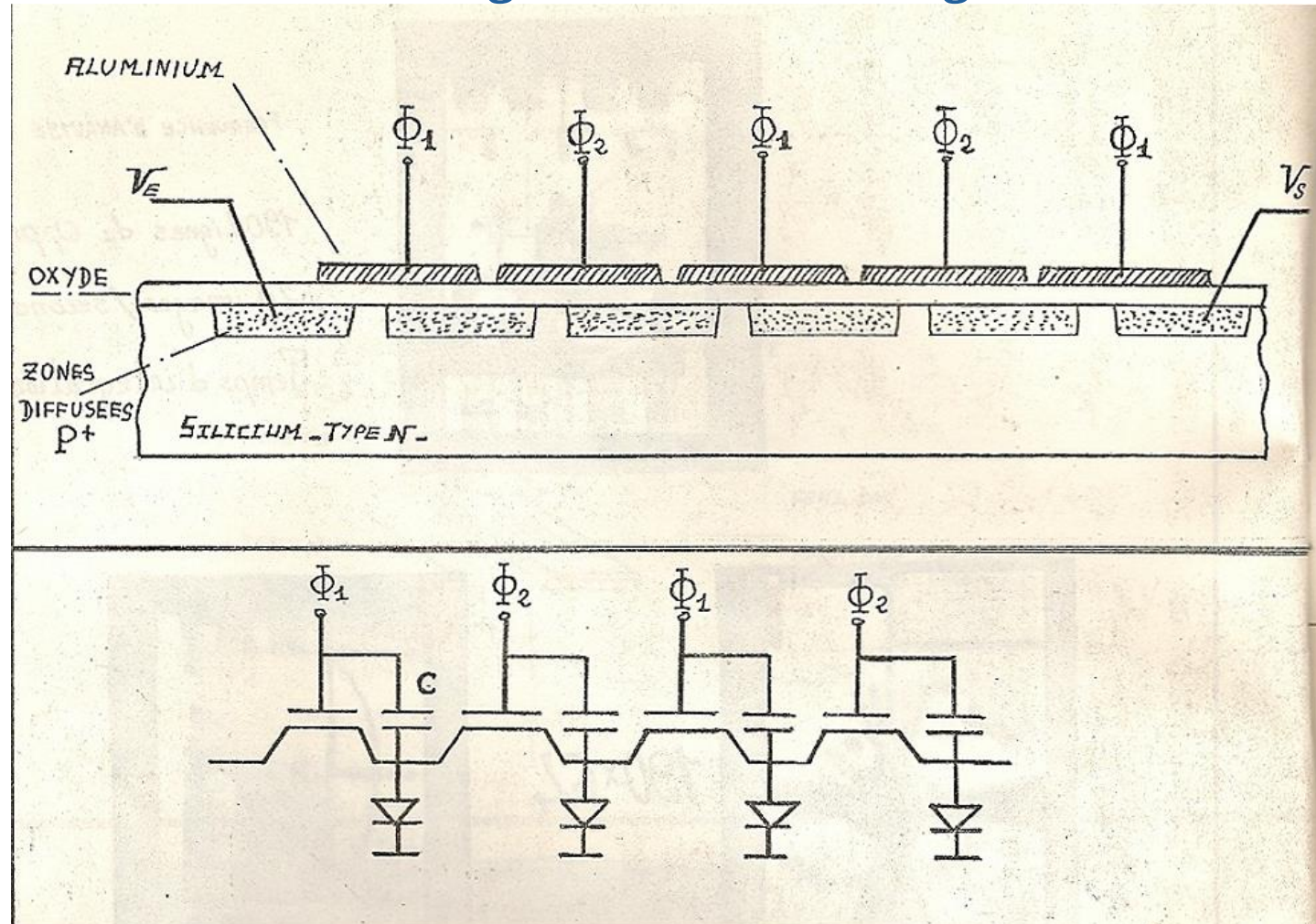
Transfert de charges électriques d'un puits de potentiel vers un autre par une suite de capacités MOS couplées entre elles et commandées par des potentiels périodiques

Les CCD
stockent et déplacent
une information analogique
échantillonnée
sous forme de paquets
de charges électriques
à l'intérieur d'un substrat semi-
conducteur

➡ Début des CCD à TH-CSF Saint-Egrève



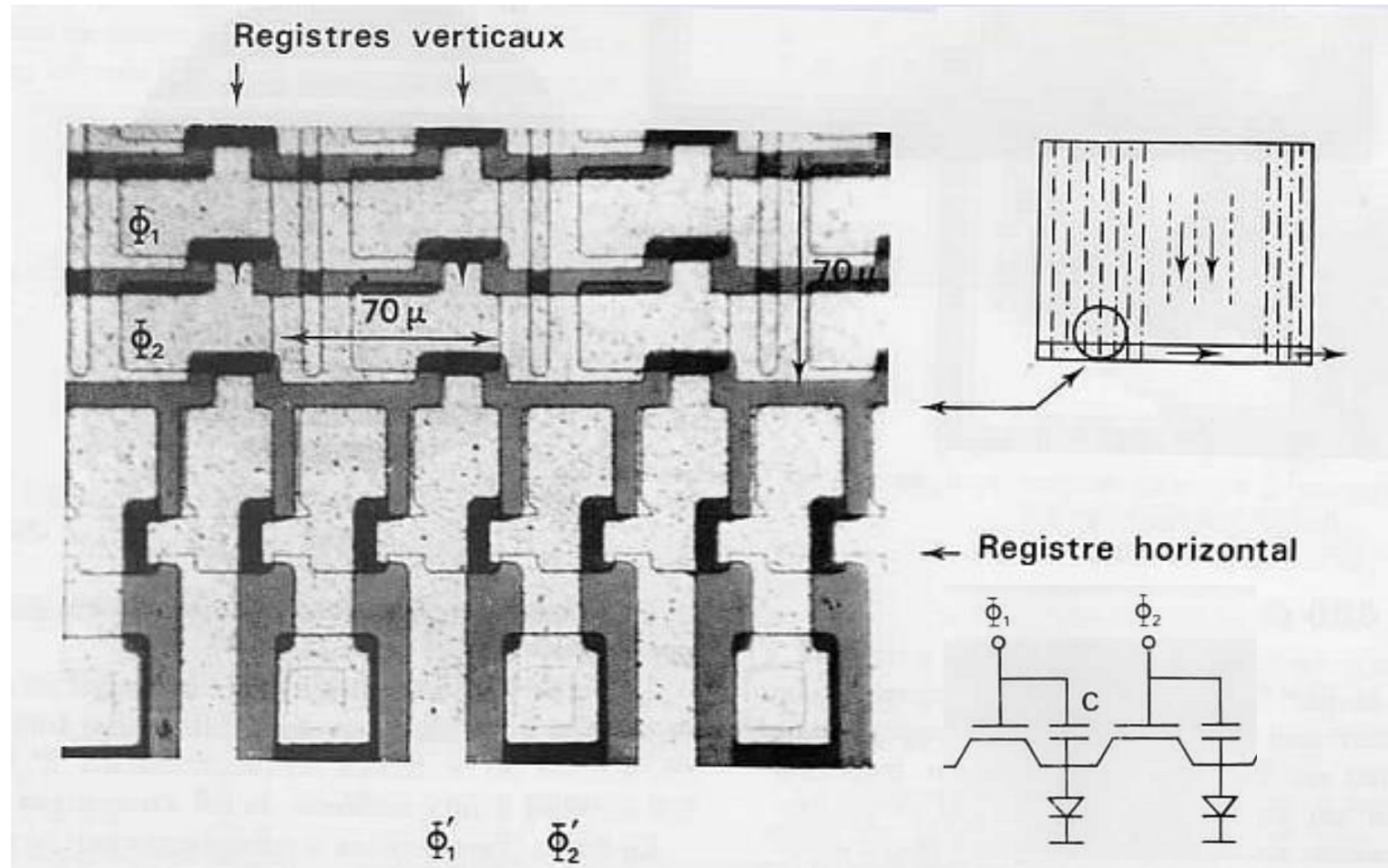
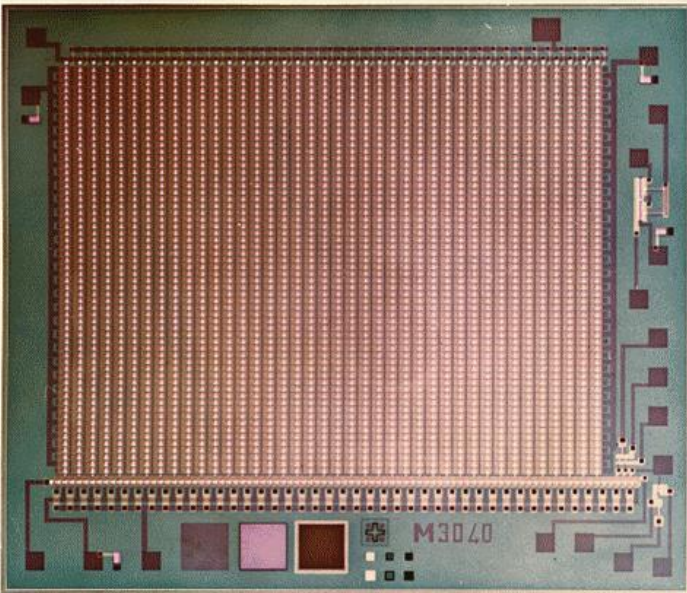
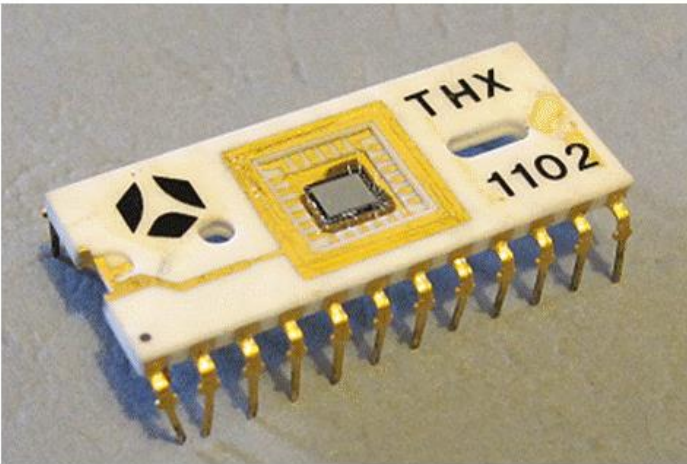
1972 « Bucket Brigade Device » (BBD)
Technologie : métallisation grille alu



➡ Début des CCD à TH-CSF Saint-Egrève

1972 - 73

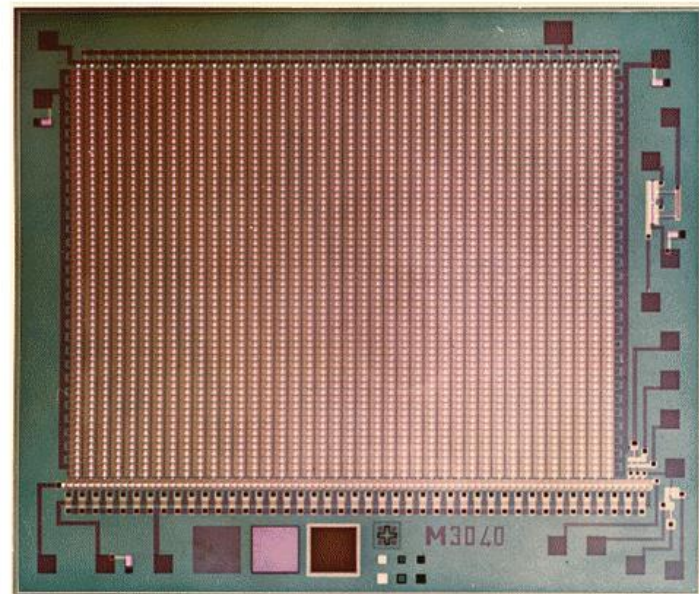
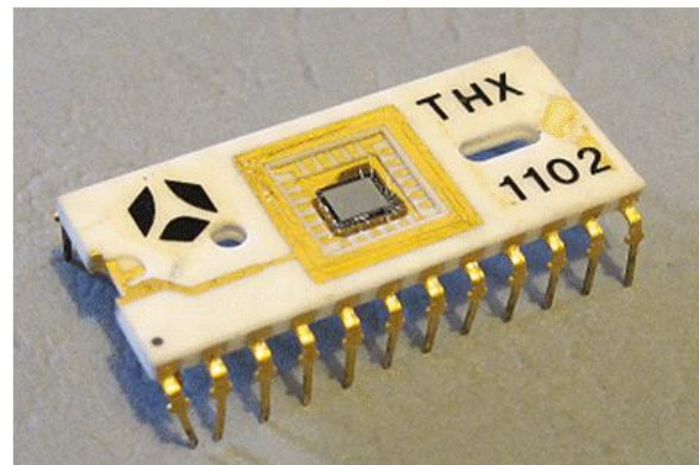
Matrice BBD - 30x40 points – Grille Alu.



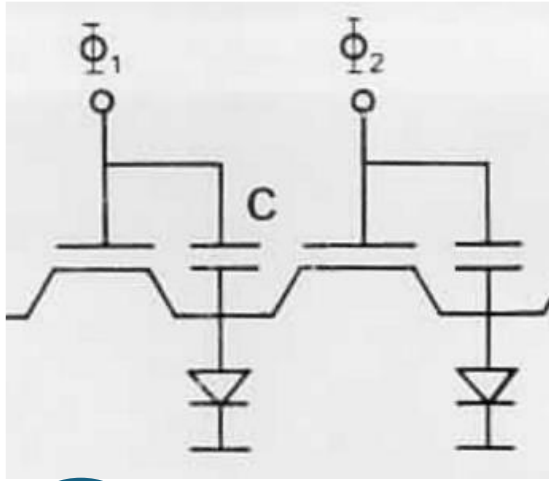
➡ Début des CCD à TH-CSF Saint-Egrève

1972 - 73

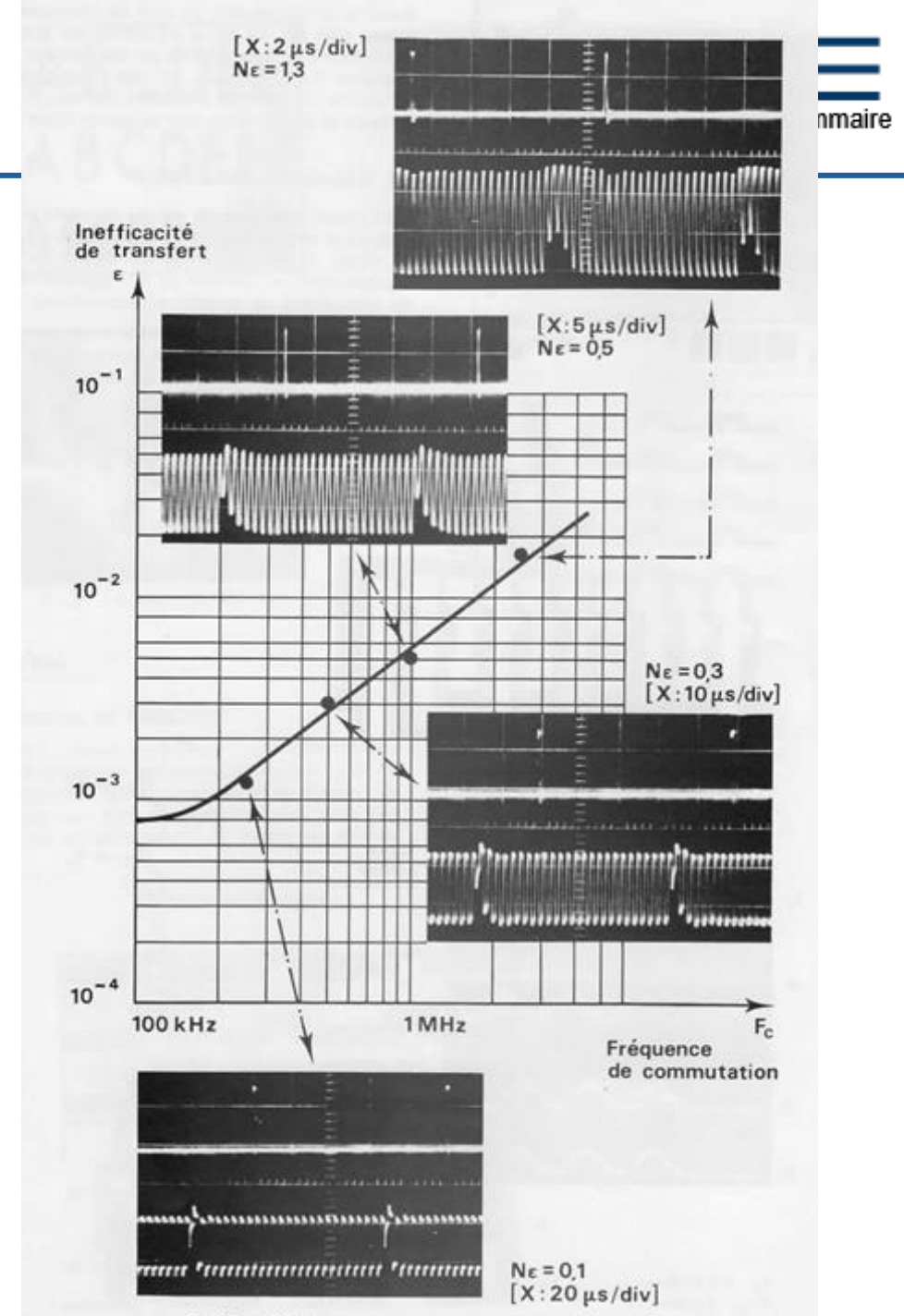
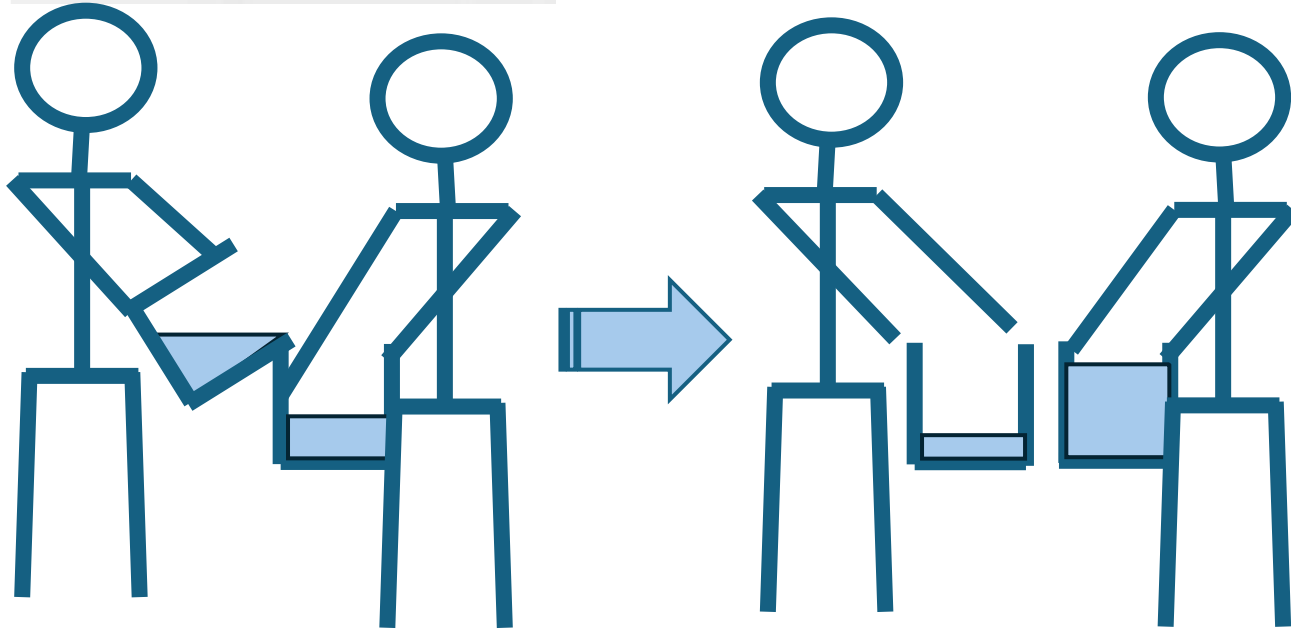
Matrice BBD - 30x40 points – Grille Alu.



➔ Début des CCD à TH-CSF Saint-Egrève



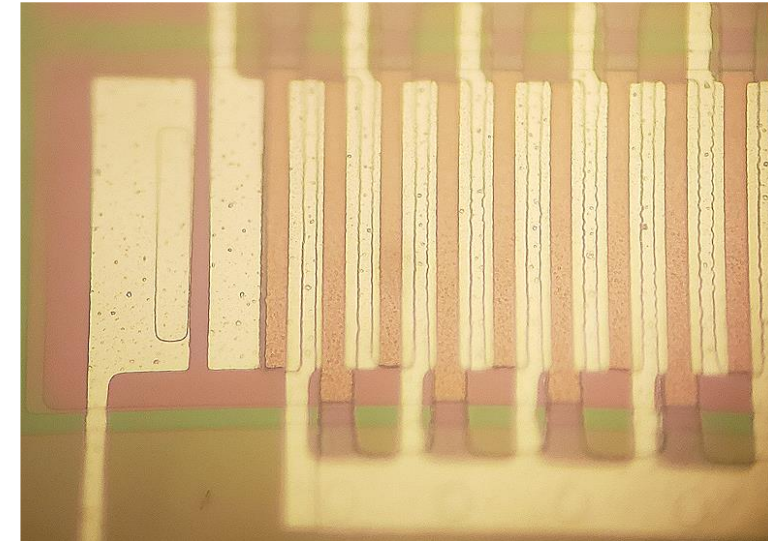
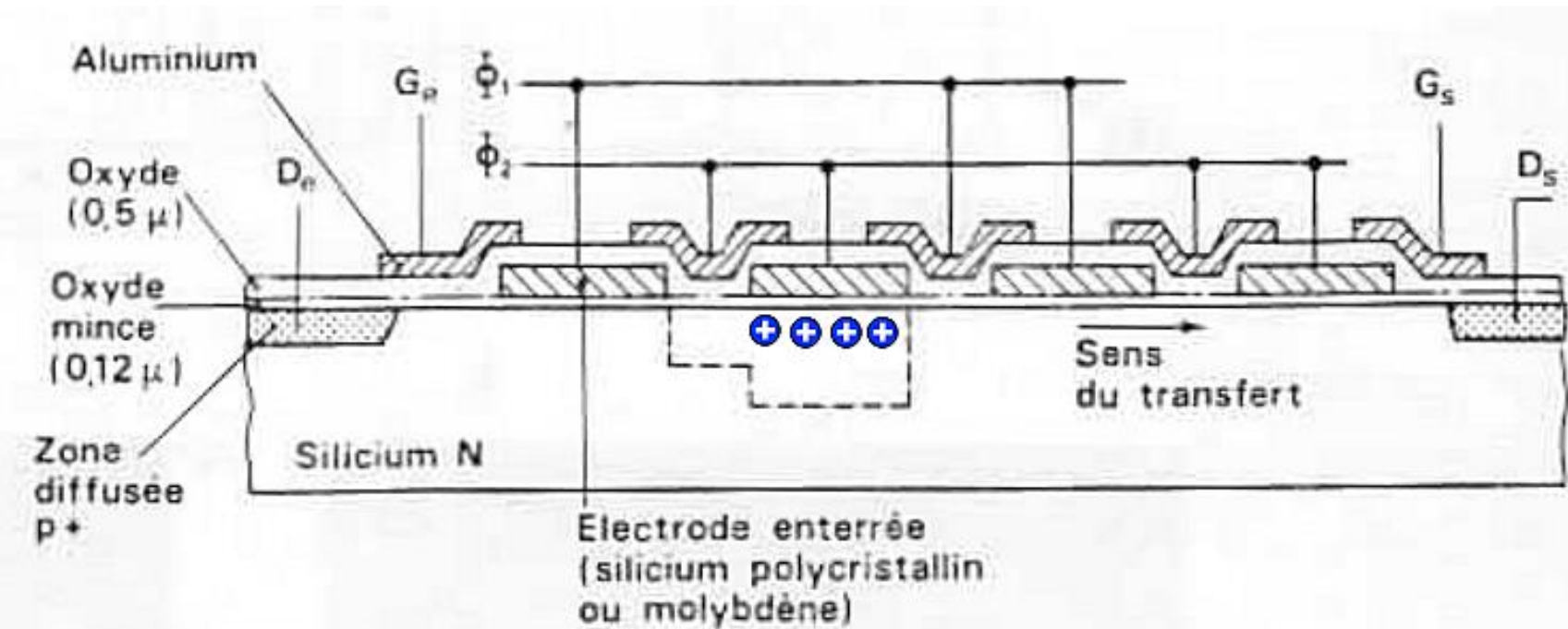
Problème d'inefficacité de transfert !



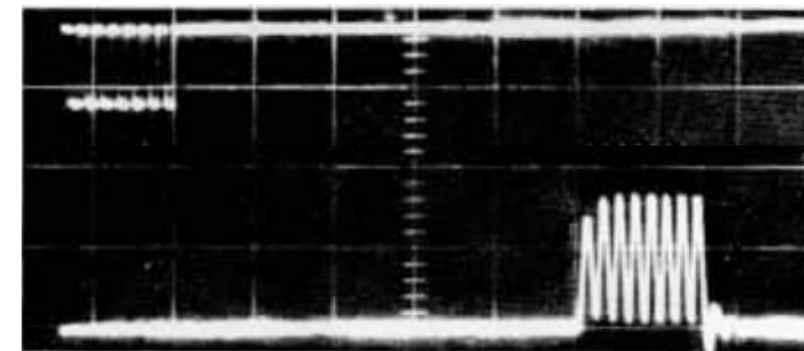
➡ Début des CCD

1973 - Barrette CCD 64 étages

Grilles silicium polycristallin et aluminium

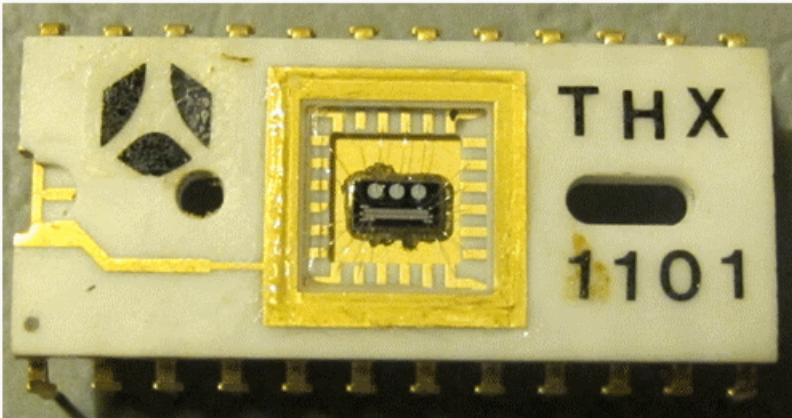


Signal d'entrée



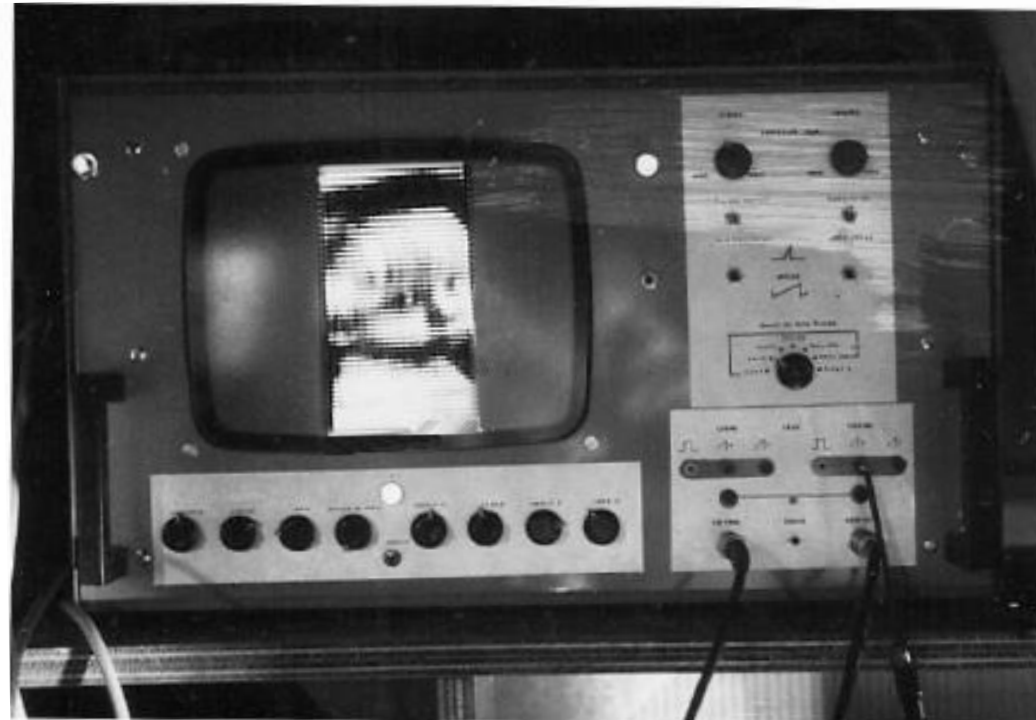
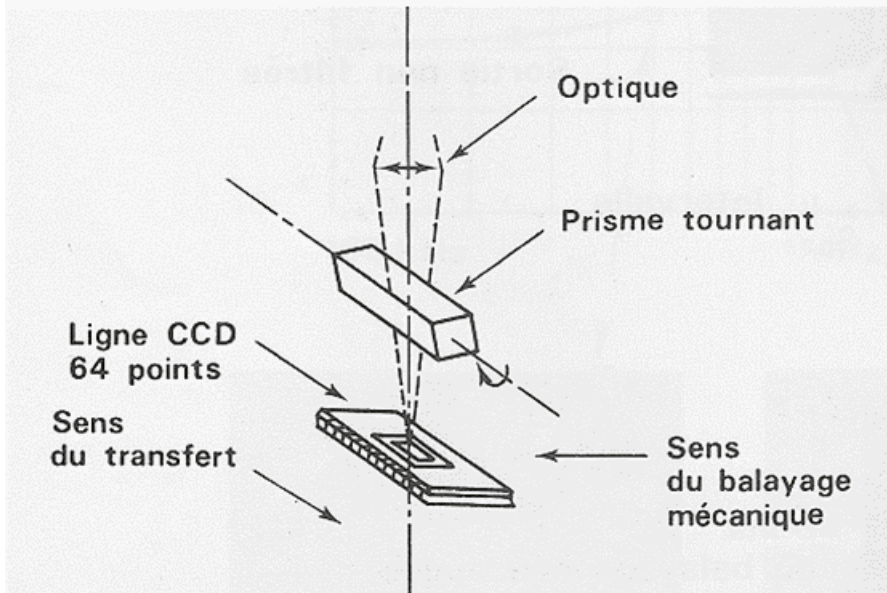
Signal de sortie

➡ Début des CCD à TH-CSF Saint-Egrève

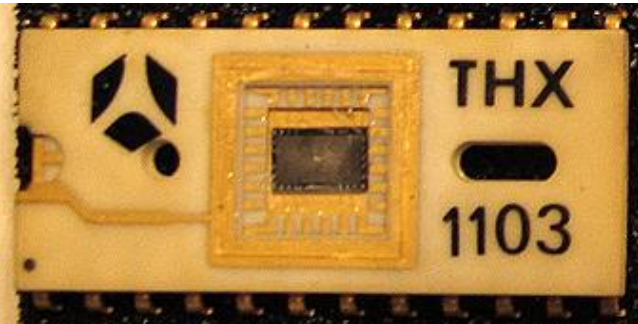


1973 - Barrette CCD 64 étages

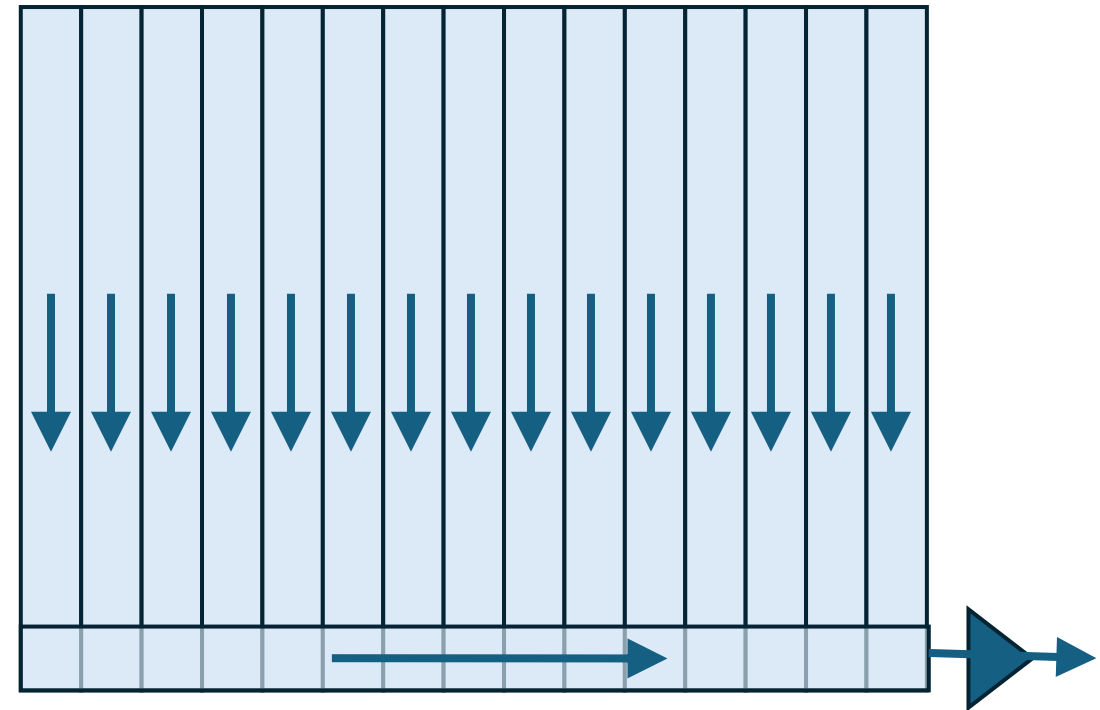
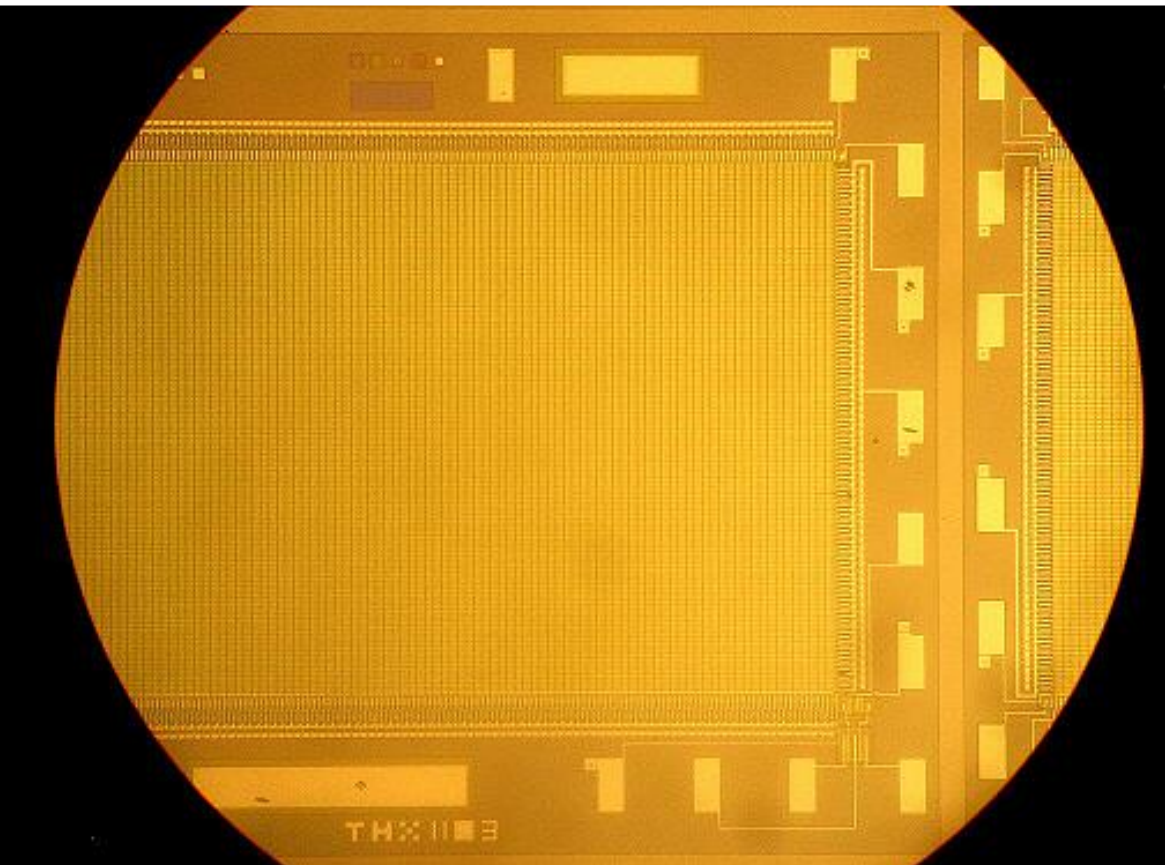
Image avec balayage optique



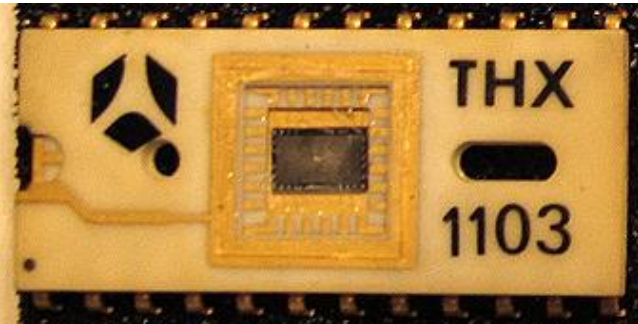
➡ Début des CCD à TH-CSF Saint-Egrève



1974 – Première matrice CCD - 64 lignes x 128 points
Grilles silicium polycristallin et aluminium



➡ Début des CCD à TH-CSF Saint-Egrève



1974 – Première matrice CCD - 64 lignes x 128 points
Grilles silicium polycristallin et aluminium

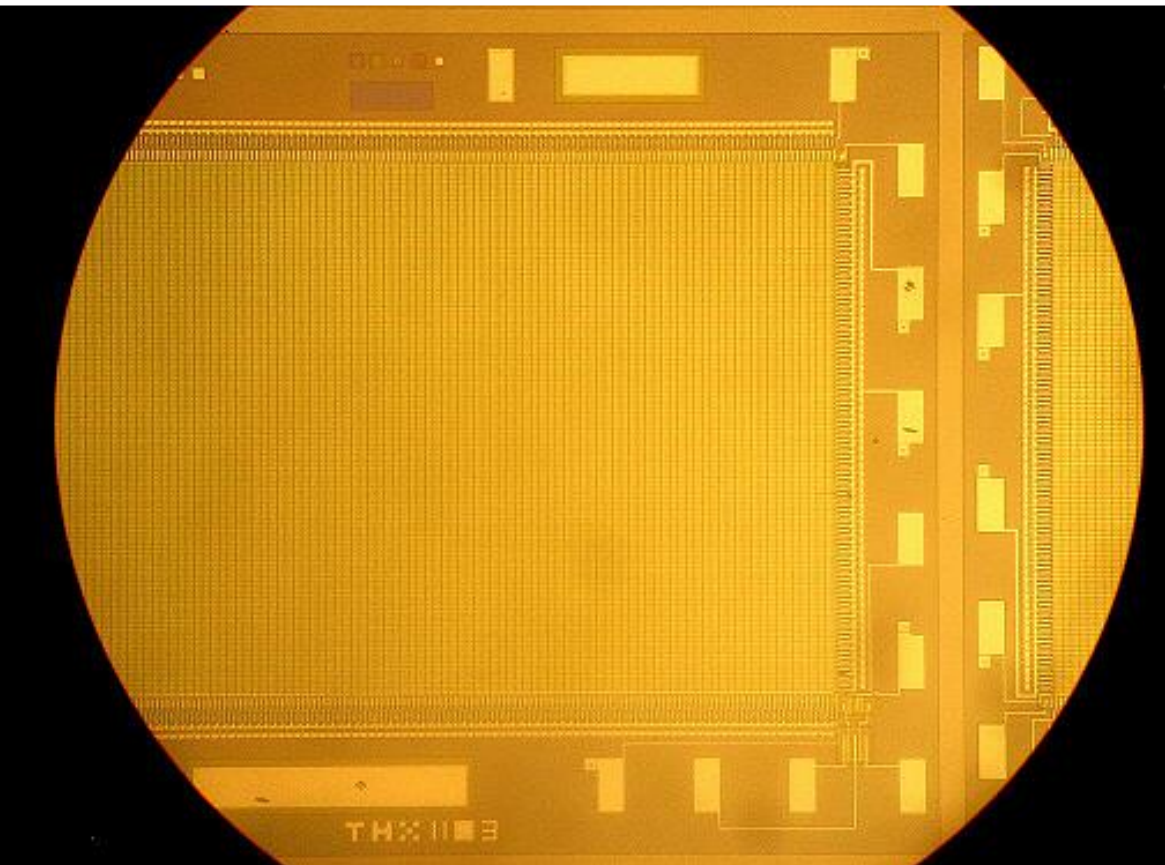
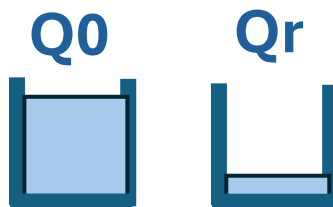
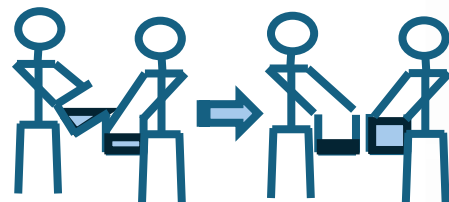
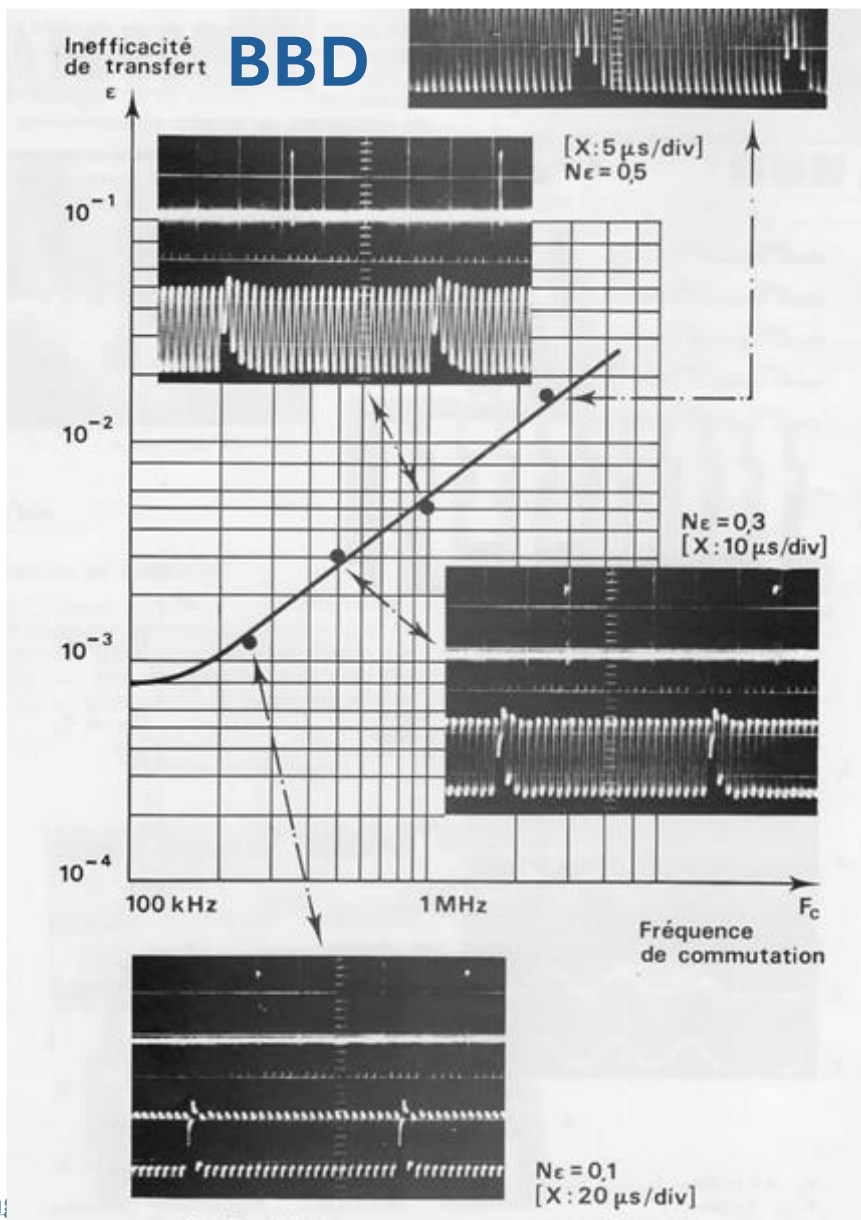
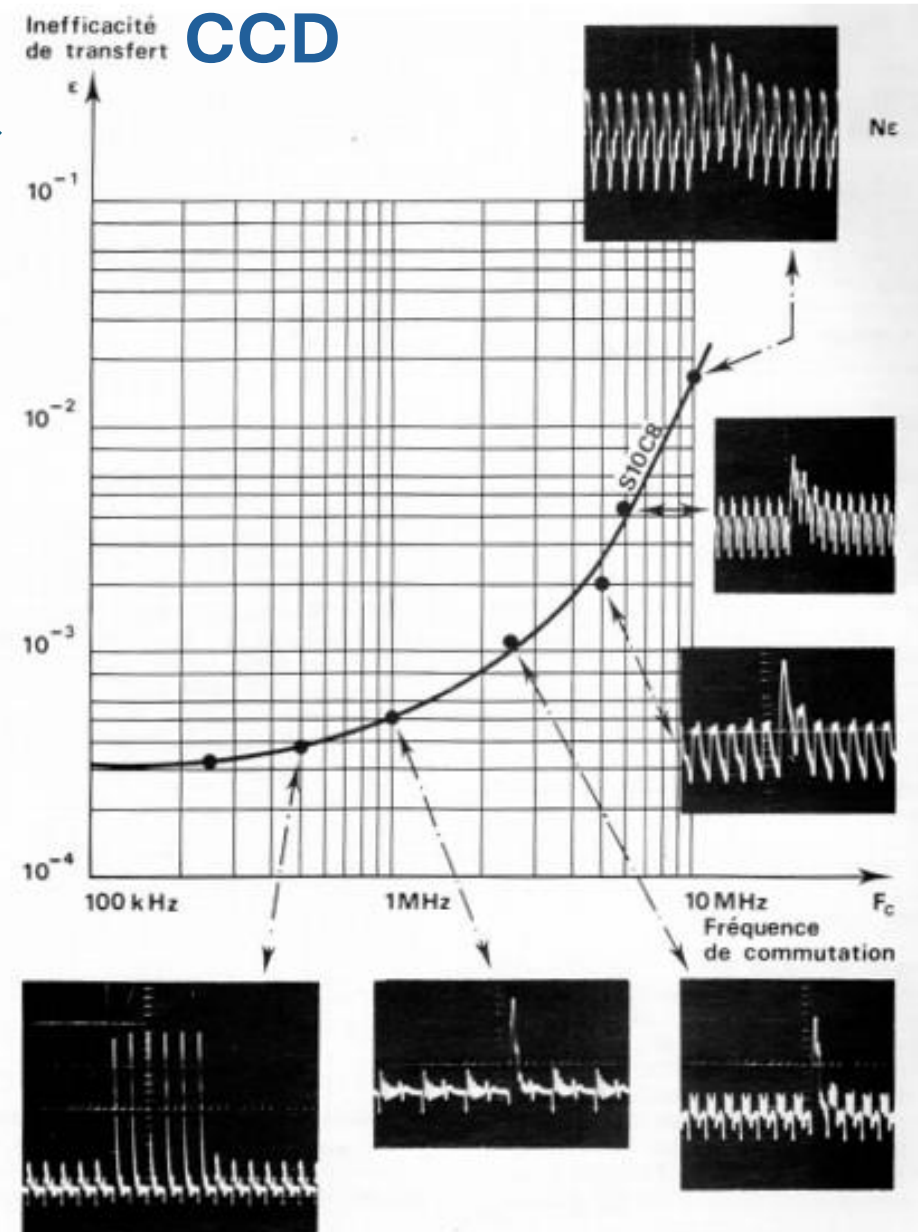


Fig. 11. — Matrice CCD. 64 × 128.

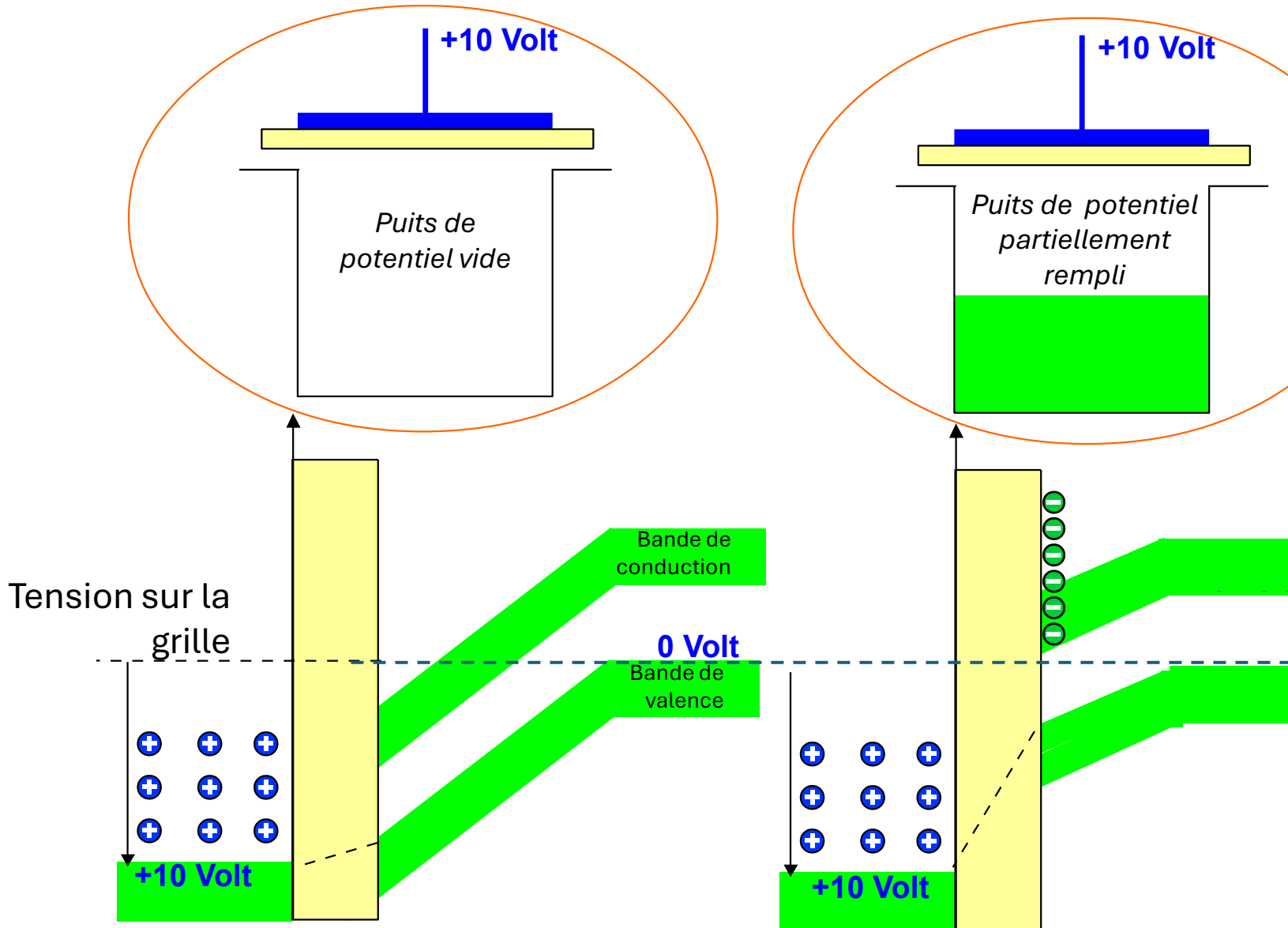
➡ Le problème de l'inefficacité de transfert



$$\text{Inefficacité} = \frac{Q_r}{Q_0}$$



Une image utile pour expliquer les CCD...



Que se passe-t-il vraiment dans le silicium ?

➡ Choix technologiques en 1975

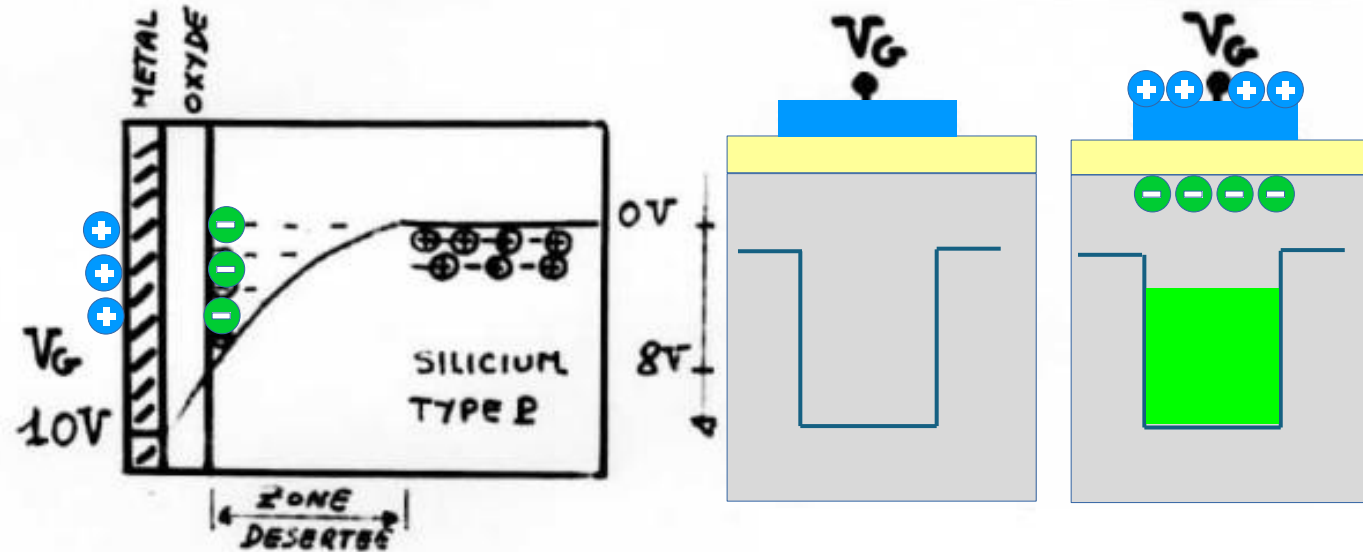
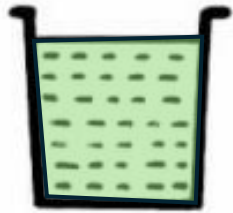
- BBD ou CCD ?
- Substrat de type N ou P ?
- Transfert en surface ou en volume ?
- Phases de commande : 1 ou 2 ou 3 ou 4 ?
- Transfert unidirectionnel ou bidirectionnel ?

➔ Choix technologiques en 1975

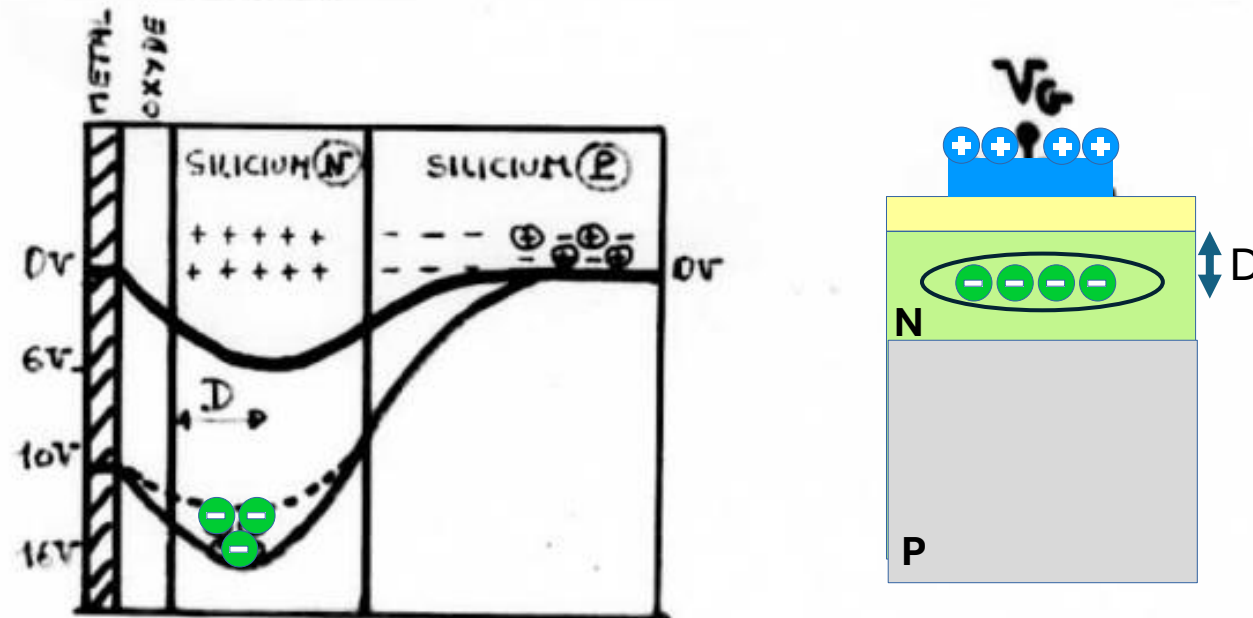
- BBD ou **CCD**
- Substrat de type N ou **P**
- Transfert en surface ou **en volume**
- Phases de commande : 1 ou **2** ou 3 ou **4** 
 2 niveaux de silicium polycristallin
- Transfert unidirectionnel ou bidirectionnel

➔ Stockage en surface et en volume

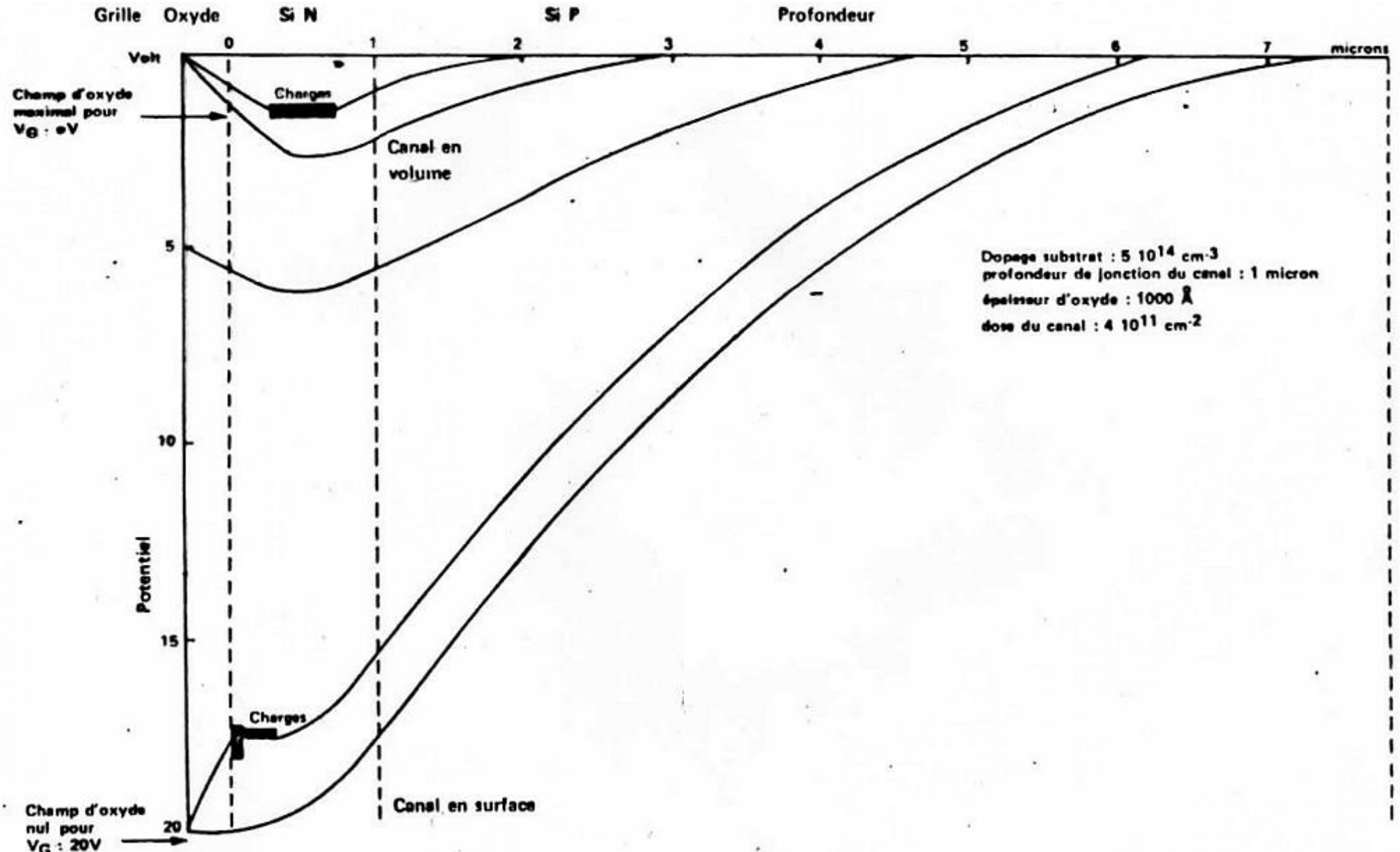
En surface



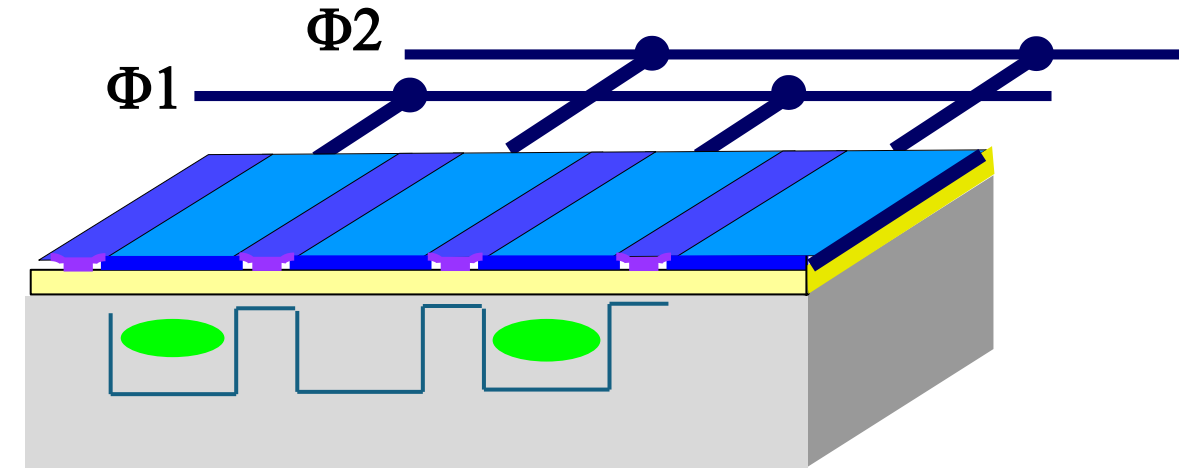
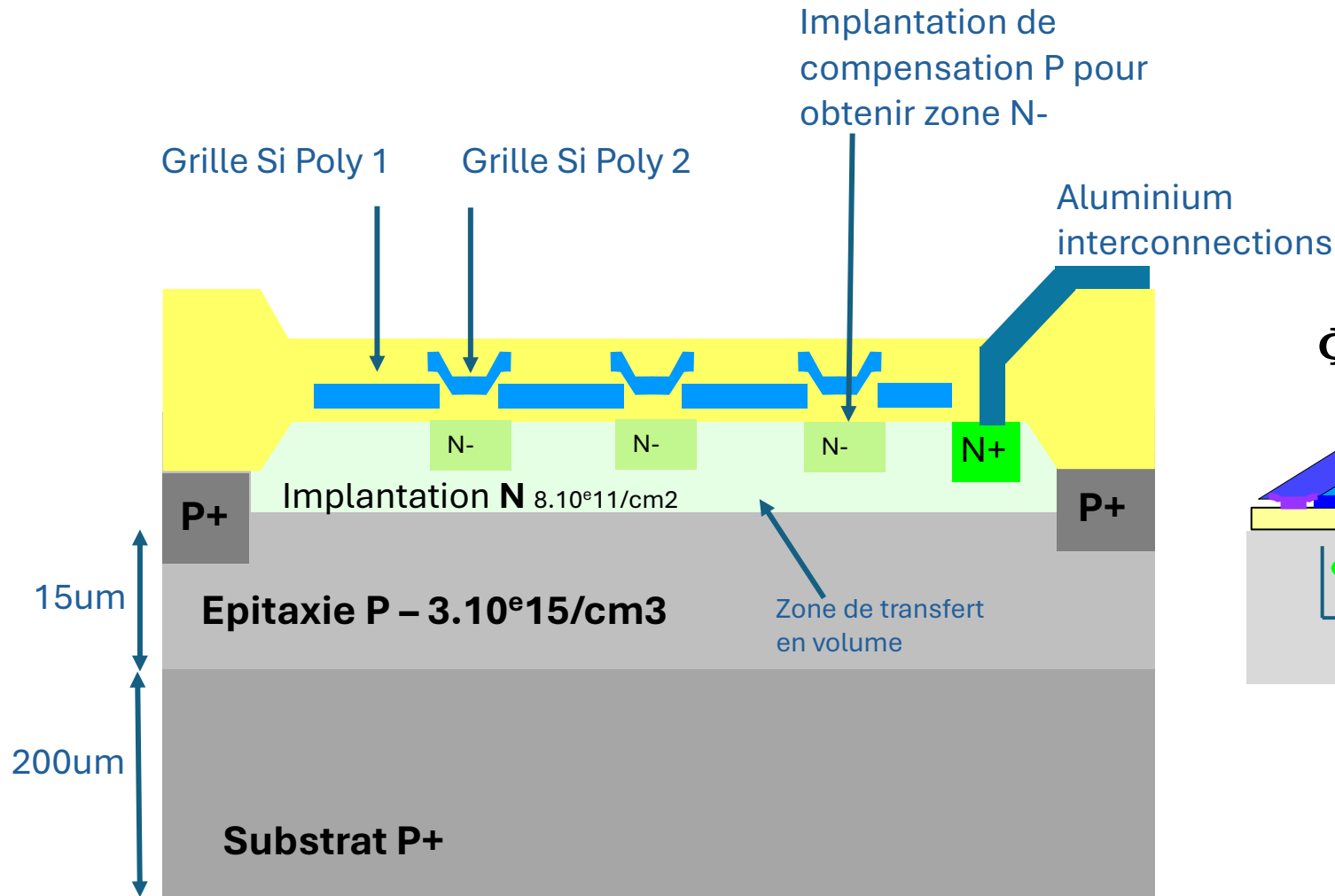
En volume



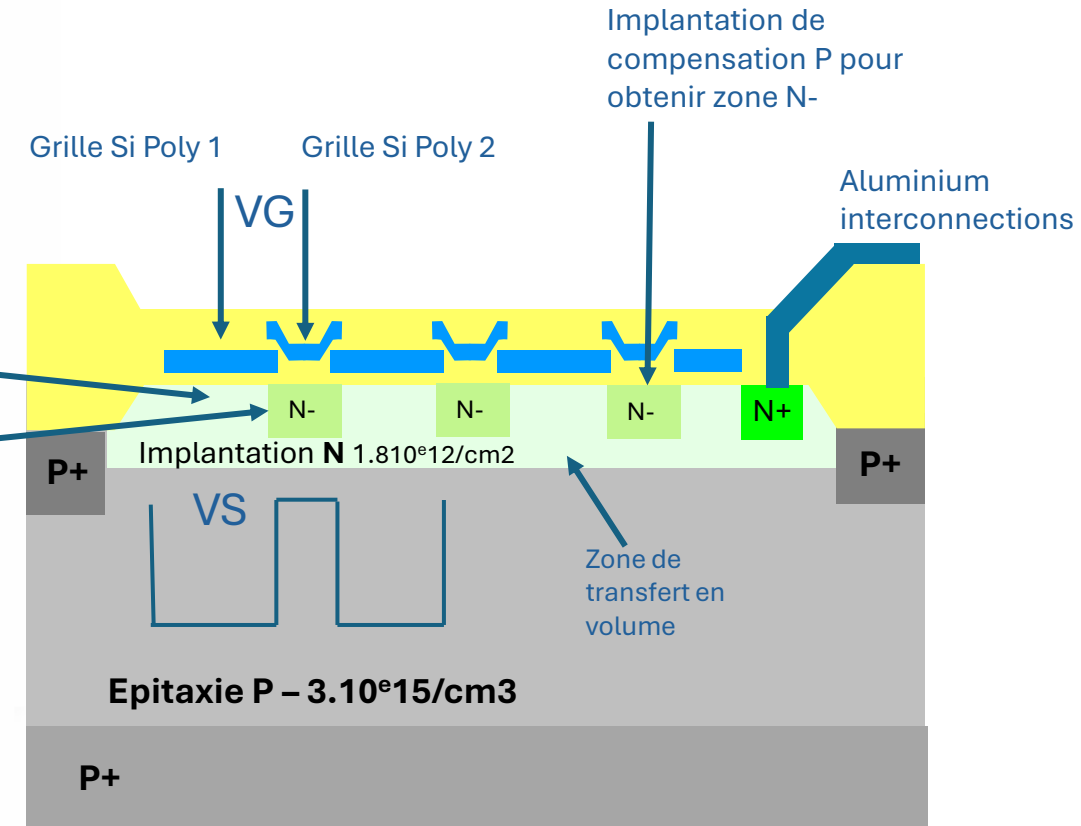
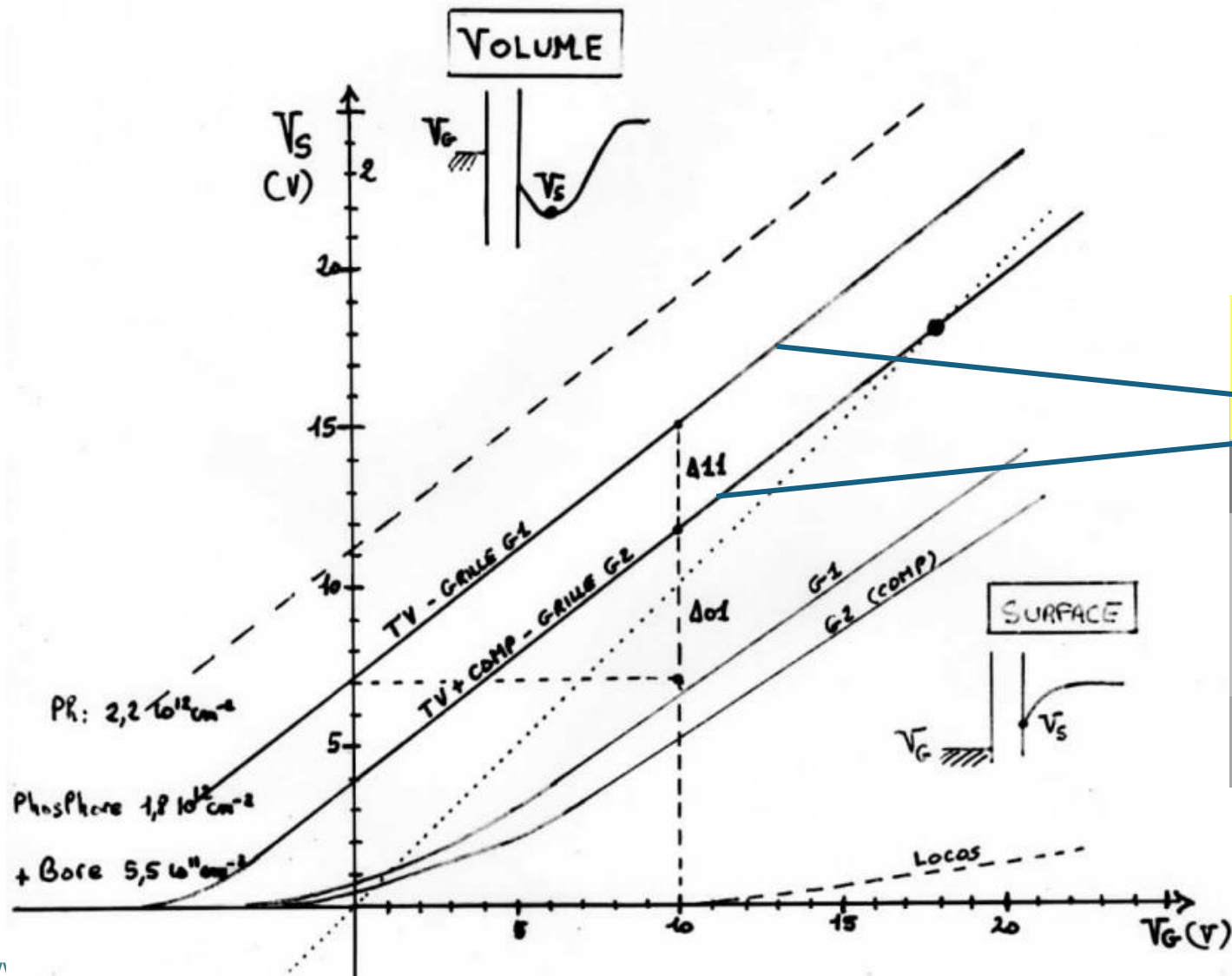
➔ Stockage en surface et en volume



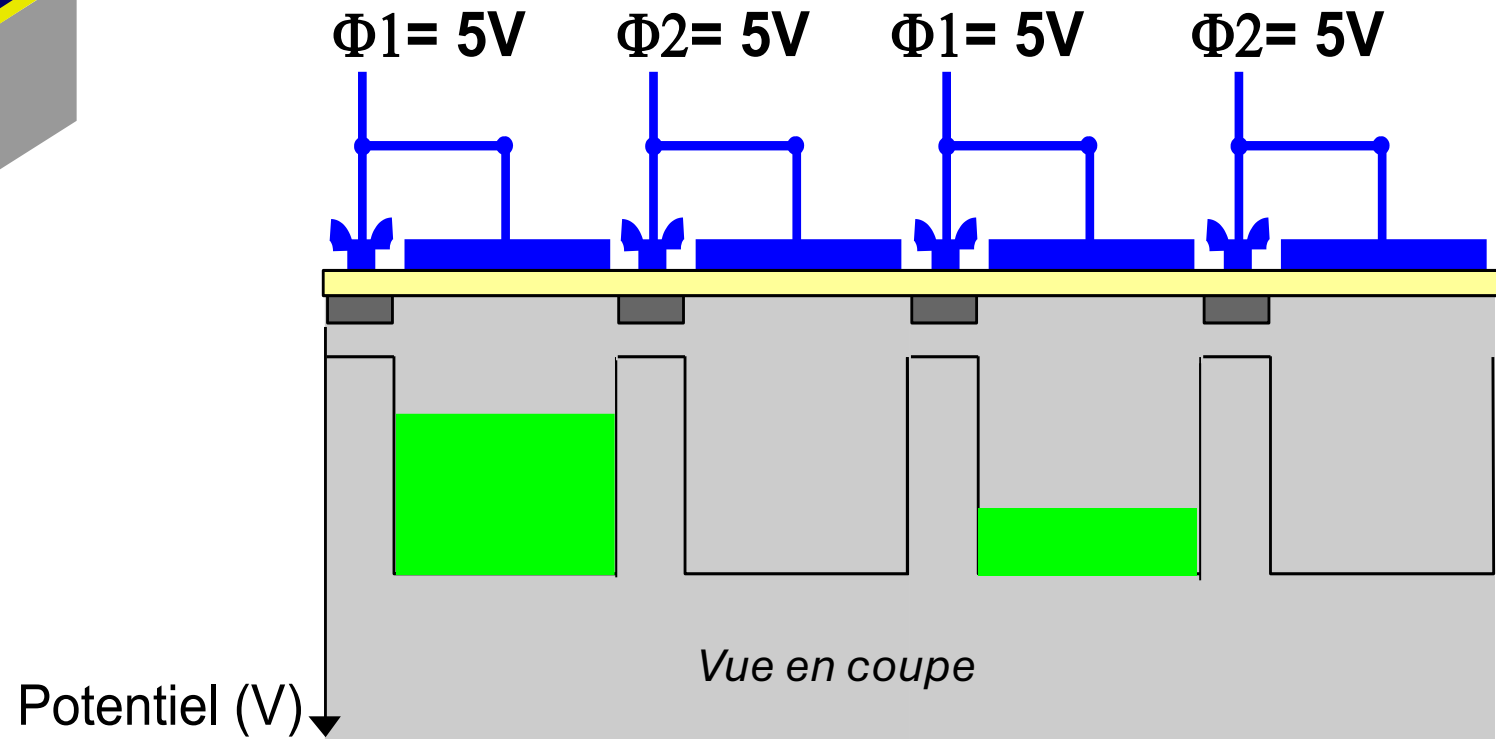
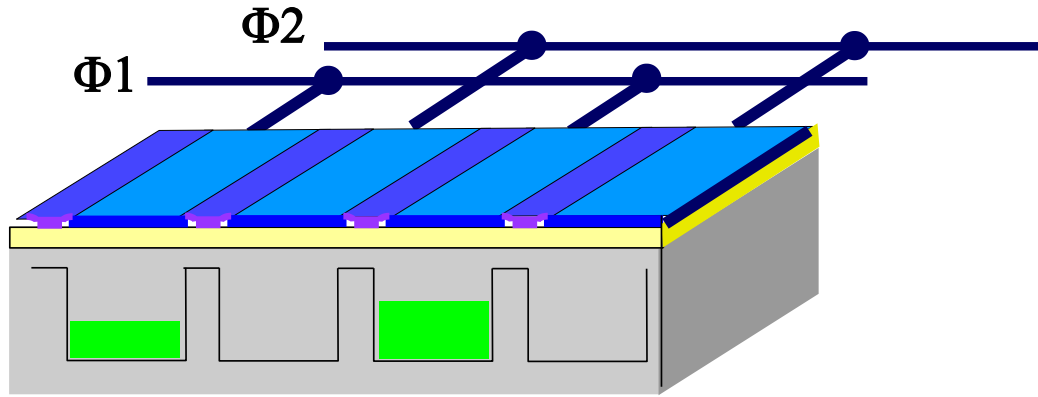
Structure standard de 1975 à 1985



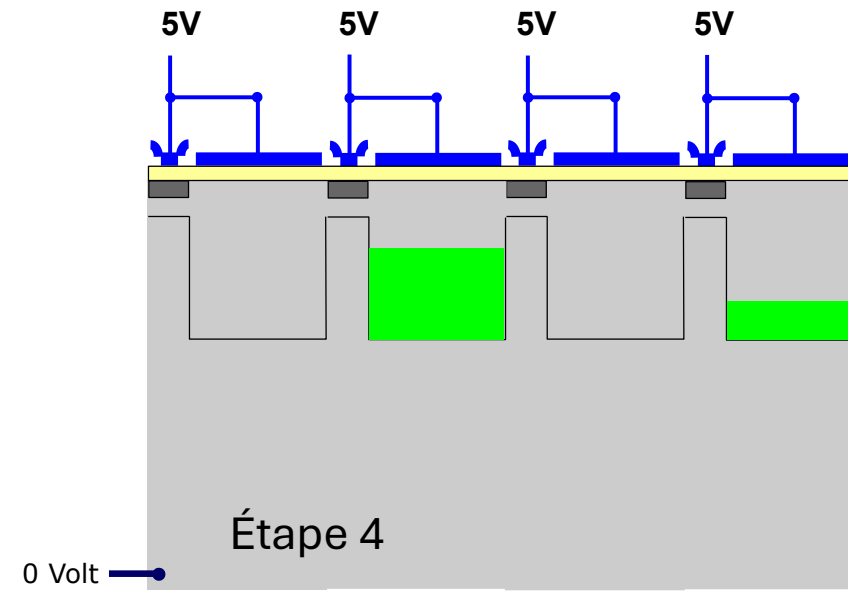
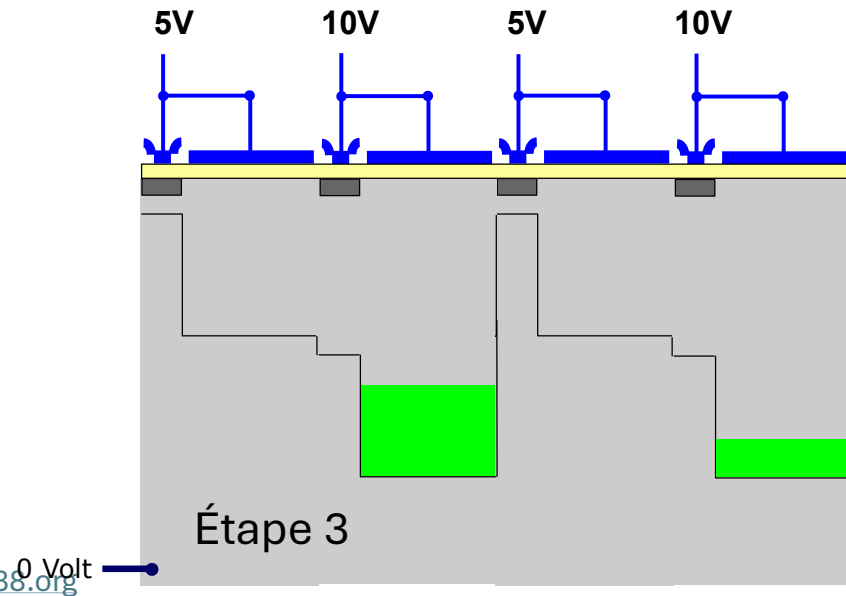
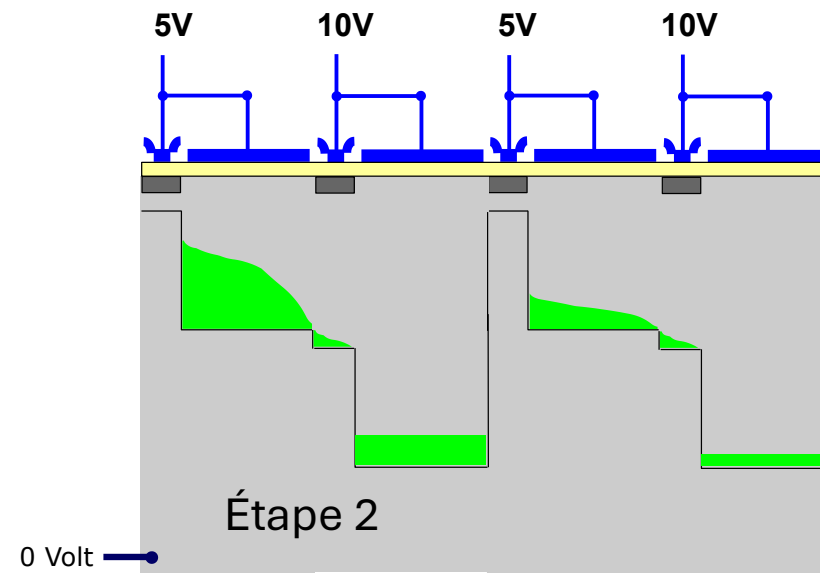
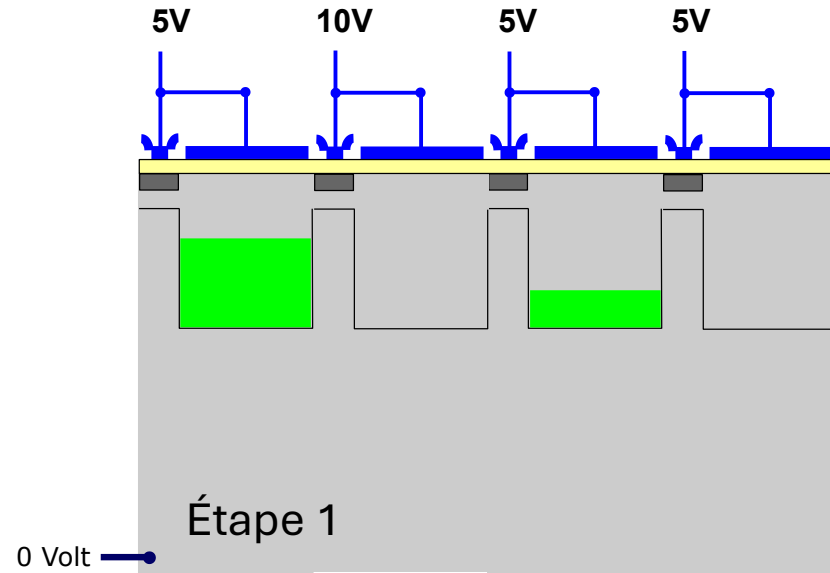
➡ Structure standard de 1975 à 1985



Structure standard de 1975 à 1985



➡ Détail du transfert de charges



➡ La technologie à ses débuts



➡ Du labo vers la production



Catalogue 1988
200 pages

➡ Premiers produits commerciaux : Lignes à retard

THOMSON-CSF

DIVISION TUBES ELECTRONIQUES

NOTICE TEV 3219

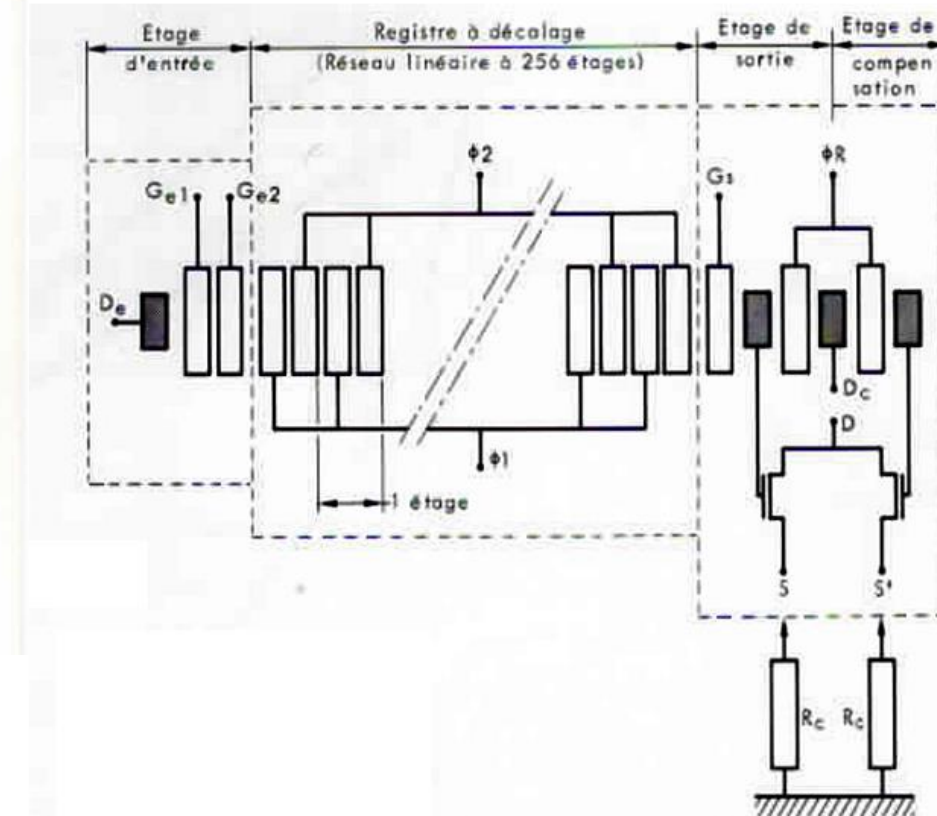
THX 1105

Novembre 1975 - Page 1/7

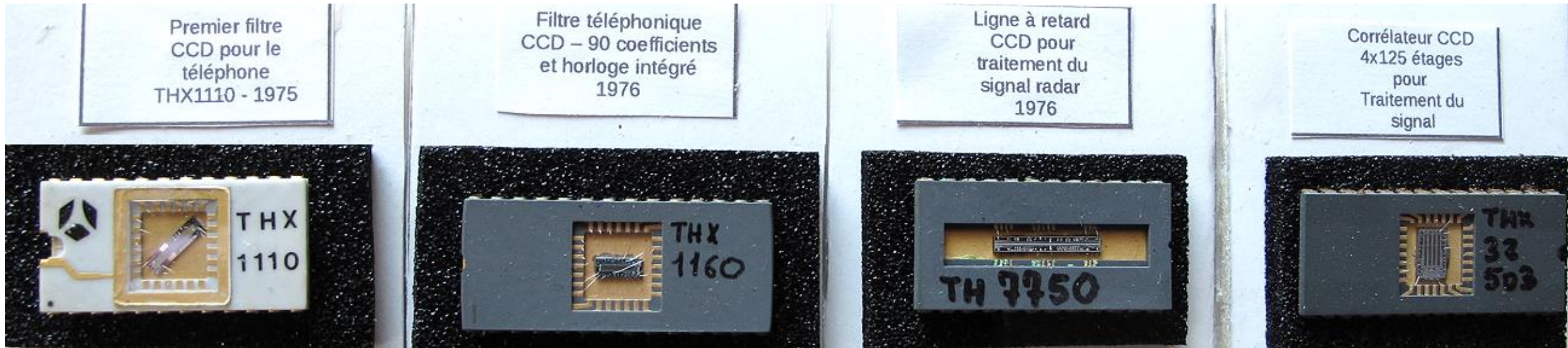
THX 1105

LIGNE A RETARD ANALOGIQUE A TRANSFERT DE CHARGE (DTC) 256 ETAGES

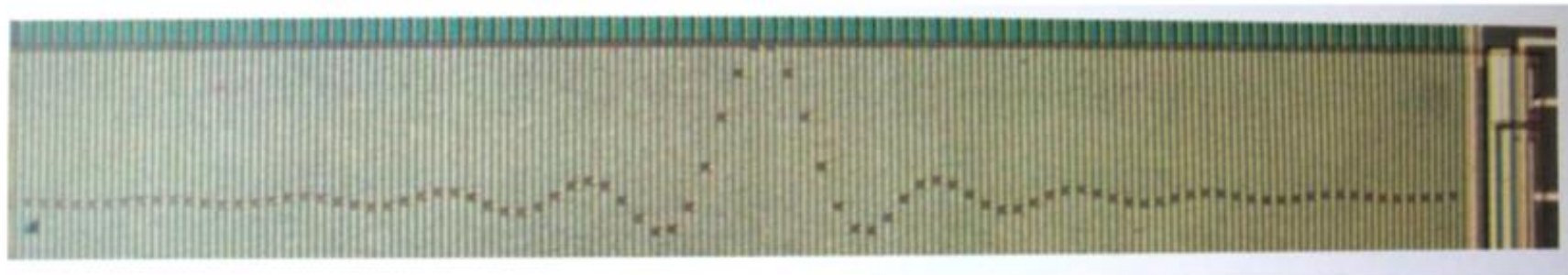
- DYNAMIQUE : 50 dB
- DISTORSION : 1 %
- PRODUIT [RETARD x BANDE PASSANTE] : 128
- BANDE PASSANTE MAXIMALE : 5 MHz
- AMPLIFICATEUR DE SORTIE INTEGRE –
SORTIE SUR FAIBLE IMPEDANCE
- COMPENSATION INTERNE DU PARASITE D'HORLOGE



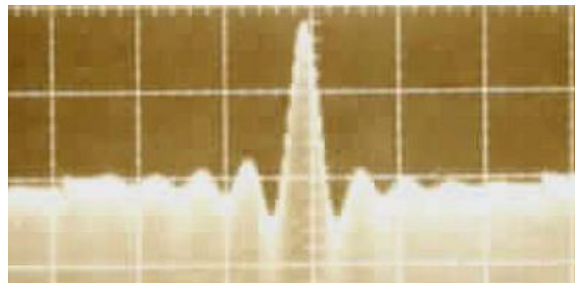
Circuits CCD pour le traitement du signal : 1975 à 1980



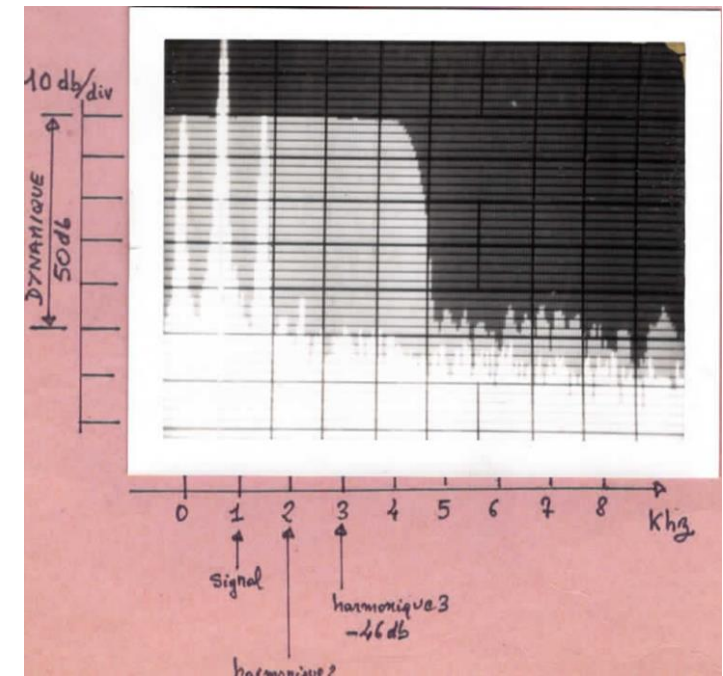
Filtre passe-bas 4kHz pour téléphonie : CCD avec grilles coupées en $\sin x/x$



Réponse
impulsionnelle



Réponse en
fréquence



➡ Barrettes photosensibles



- **Haute résolution : 1024 photodiodes**
- **Domaine spectral étendu : 300 à 1000 nm**
- **Réponse spectrale uniforme**
- **Grande sensibilité**
- **Faible signal d'obscurité**
- **Dynamique 4500:1**
- **Boîtier céramique hermétique**
- **Fenêtre optique en verre**
- **Mise en œuvre simplifiée :**
 - Deux phases de commande externes
 - Echantillonnage et maintien intégrés
 - Référence du niveau d'obscurité disponible

➡ Barrettes photosensibles

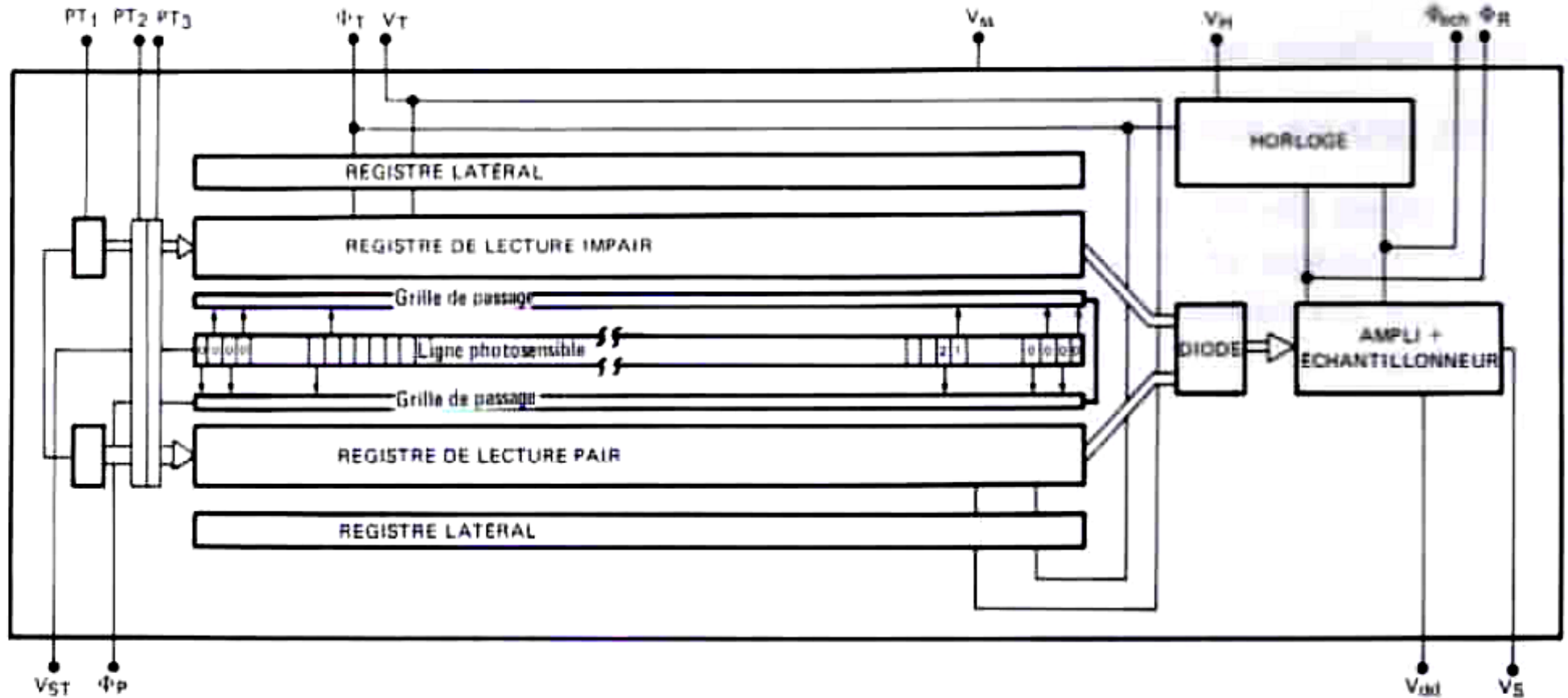
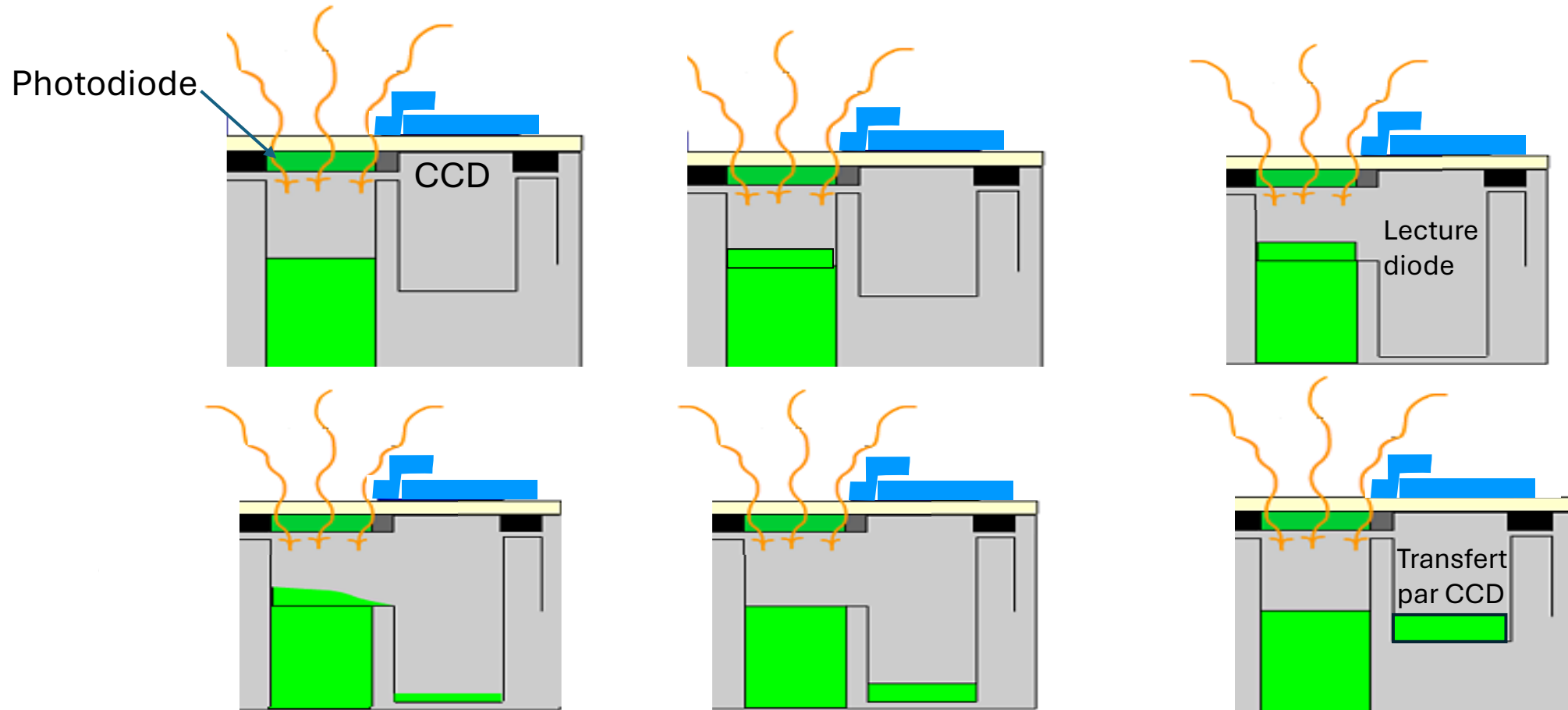


Figure 1 — Schéma fonctionnel du TH 7802

➡ Barrettes photosensibles



➡ Capteur surfacique à transfert de trame

THOMSON-CSF
DIVISION TUBES ELECTRONIQUES

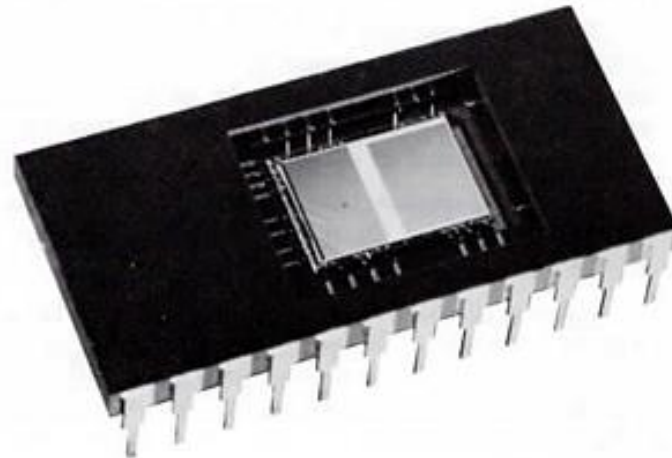
TH 7852
(ex-TH X31138)

Octobre 1983

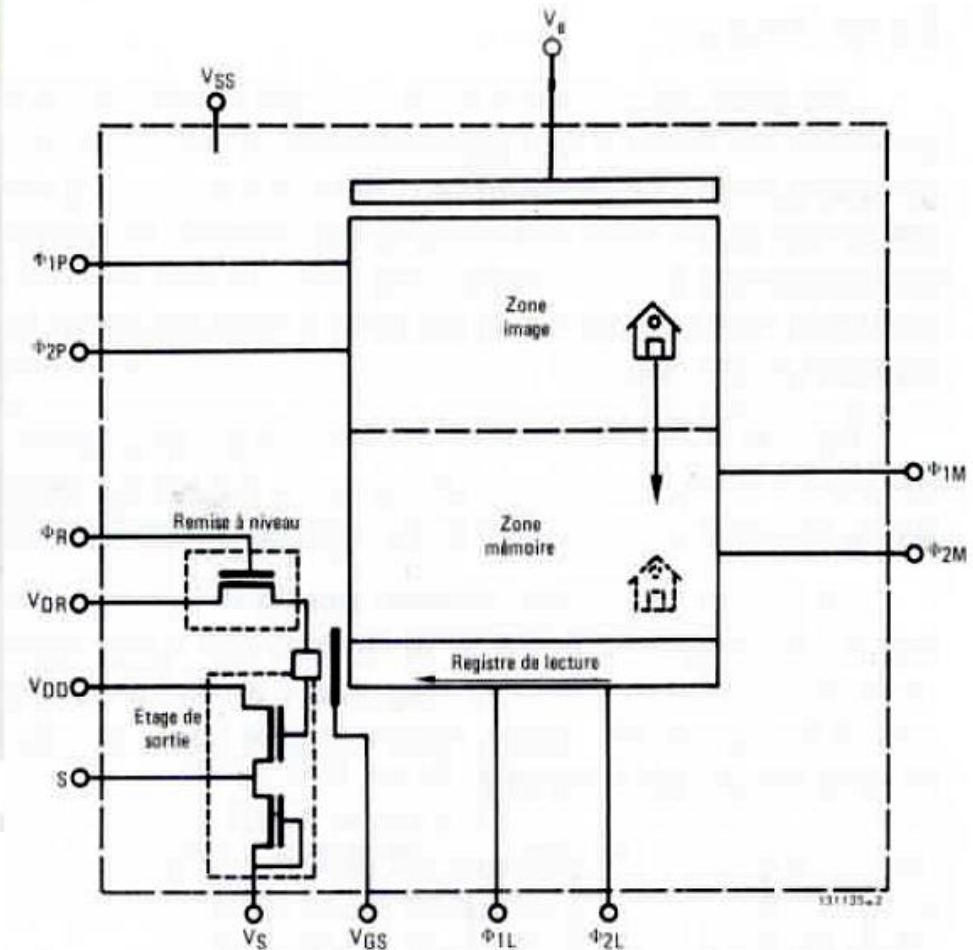
Capteur optique matriciel à transfert de charges (DTC)

288 lignes x 208 points
élémentaires

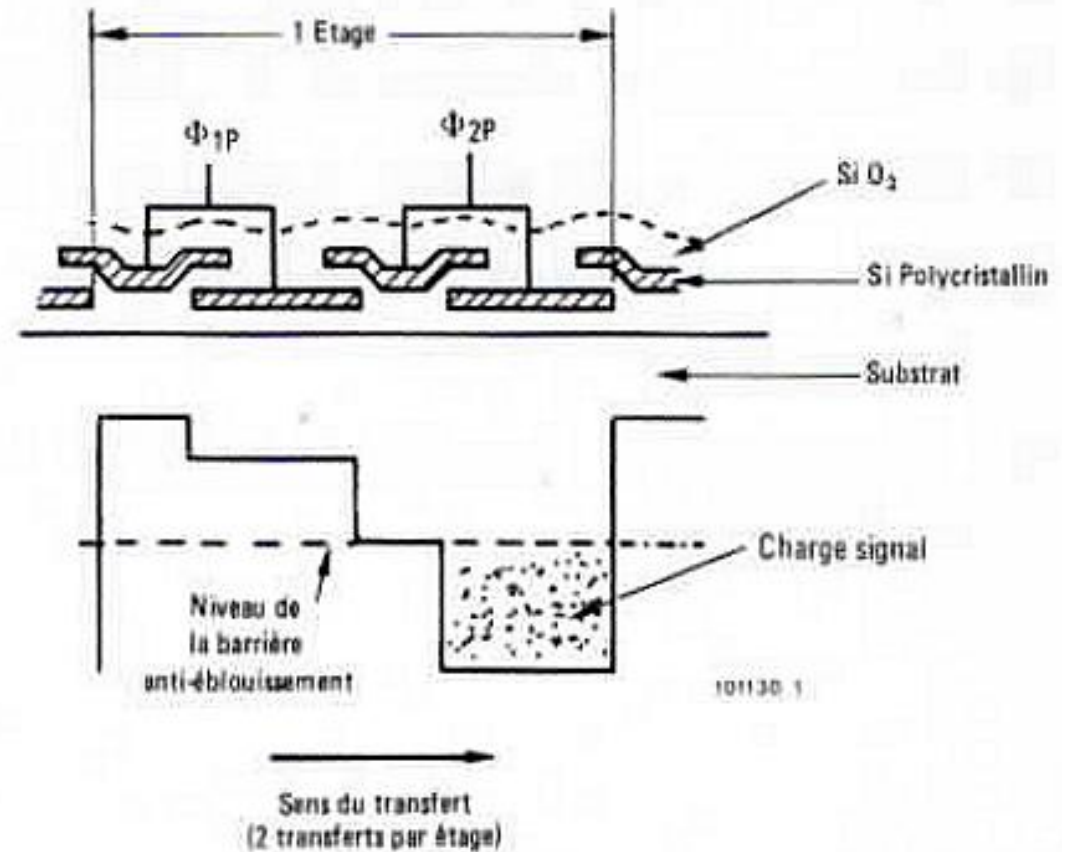
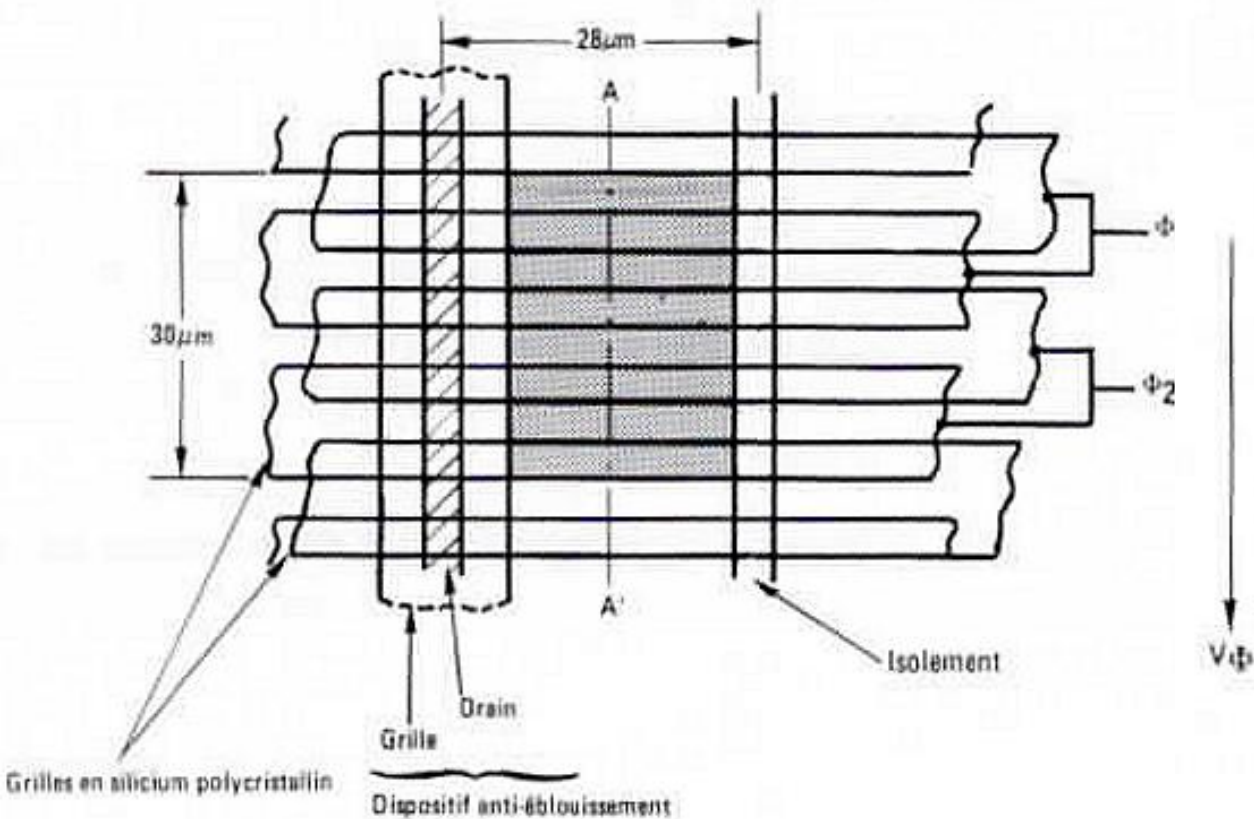
Antiéblouissement incorporé



Le TH 7852 (ex-TH X31138) est un capteur optique matriciel à l'état solide qui fournit 288 lignes, comportant chacune 208 points élémentaires (pels), destiné à l'imagerie dans de nombreux domaines industriels et scientifiques.



➡ Capteur surfacique à transfert de trame : TH 7852 [sommaire](#)



➡ Capteur surfacique à transfert de trame

August 1987



TH 7864

Area Array CCD* Image Sensor

576 x 550 Pixels
with Antiblooming

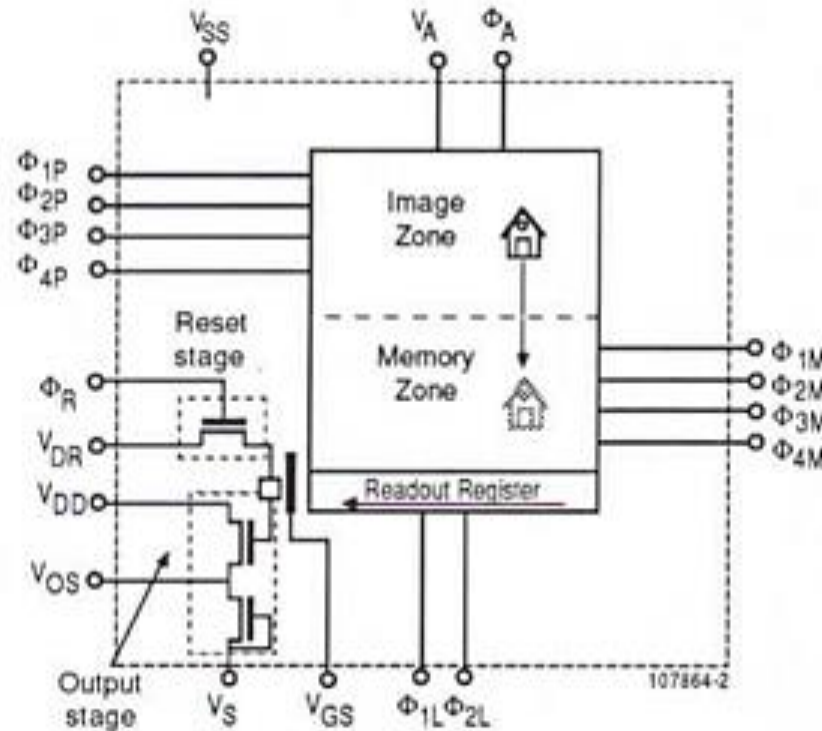


Figure 1 - TH 7864 Organization

- Fully Compatible with CCIR TV Standard
- 2/3" Optics Compatible Image Format (11 mm Diagonal)
- Frame Transfer Organization (Dynamic Range : 4000/1)
- Optimized Resolution and Responsivity in the 400-1100 nm Spectrum (Visible + Near Infrared)
- Antiblooming efficiency : $E_{SAT} \times 1000$
- Sensitivity : 30 dB S/N at 40 milli-lux
- High Contrast : 80 % Modulation at 412 TV Lines
- Low Aliasing (moiré)
- No negative bias needed
- Exposure time reduction capability (Iris effect) : 10 times min
- Minimum Field Readout Time: 12 ms

➡ Capteur surfacique à transfert de trame : TH7864

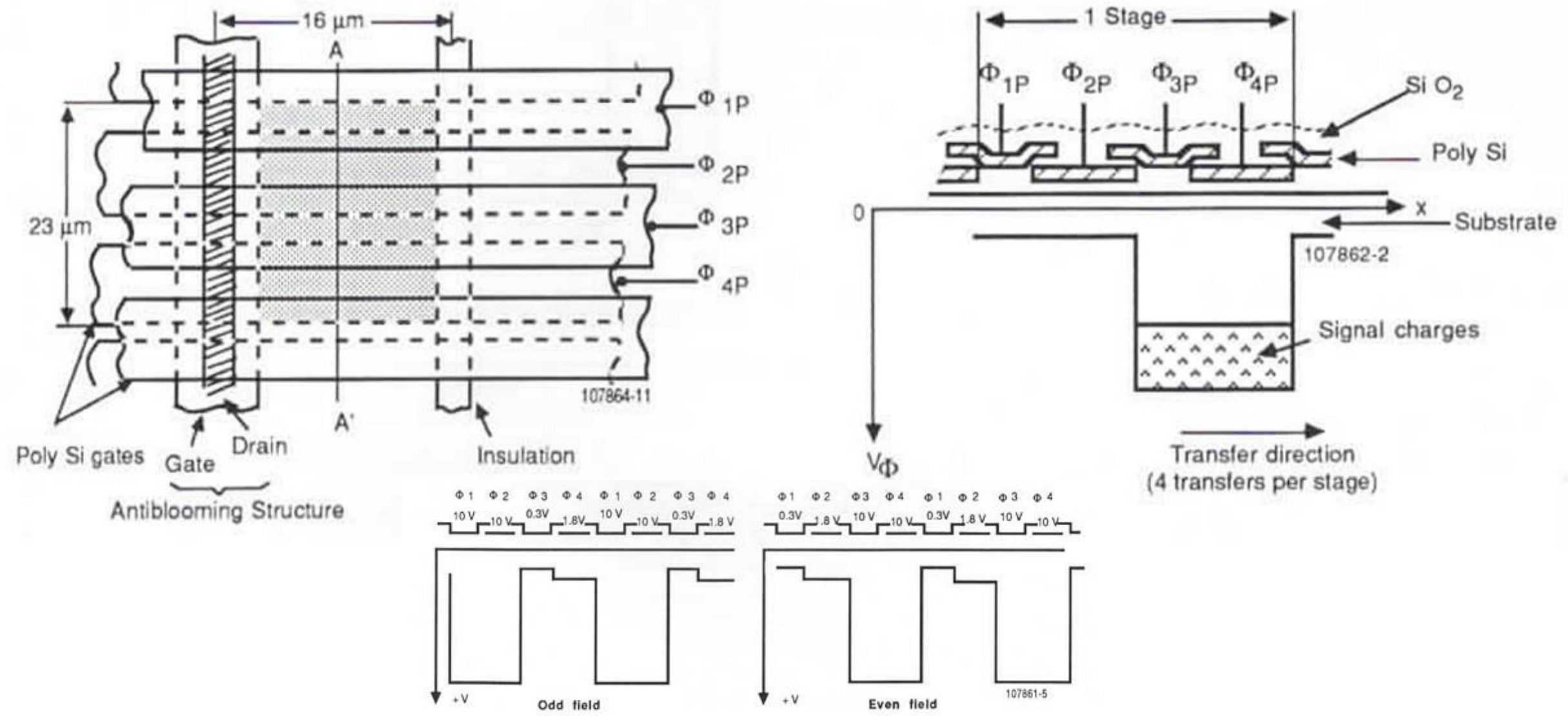
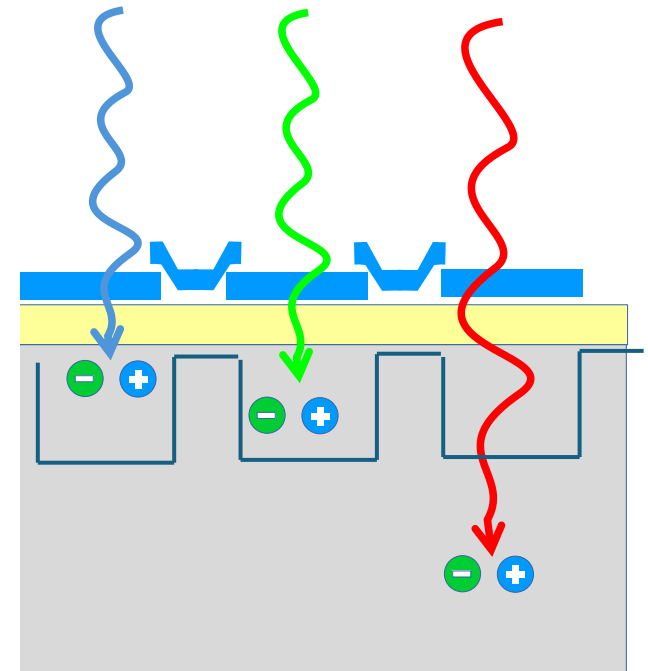
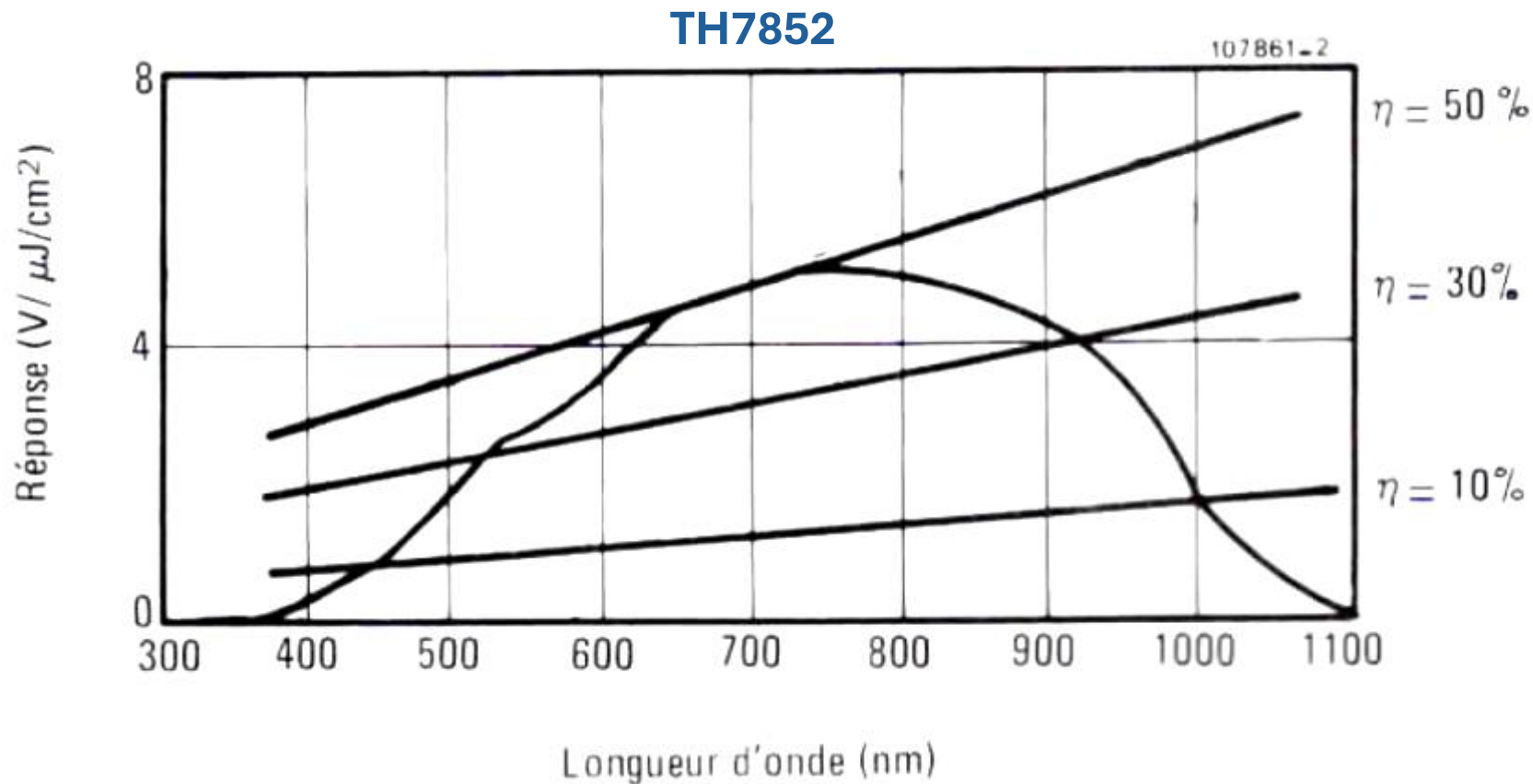


Figure 3 - Image zone potential wells during integration period

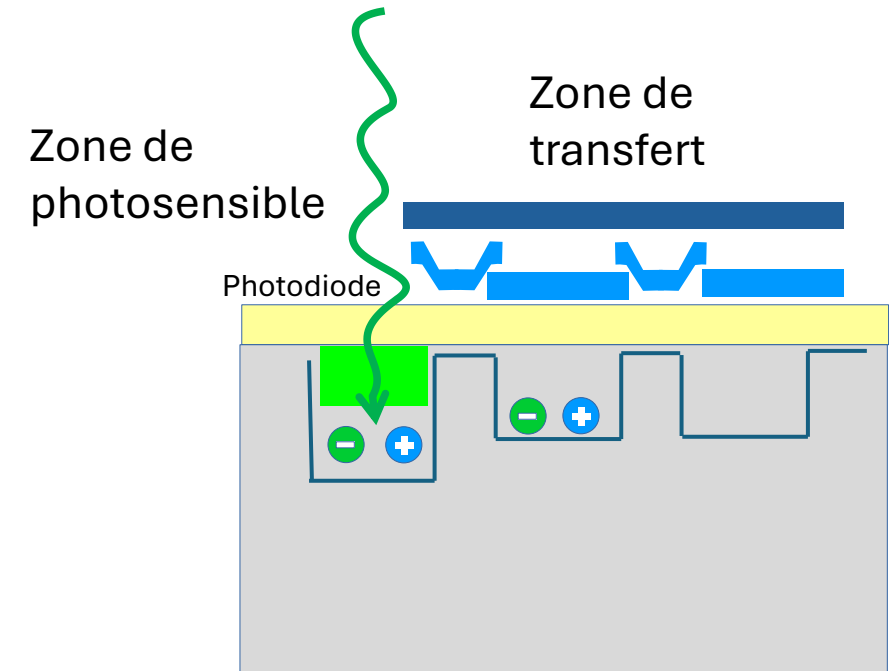
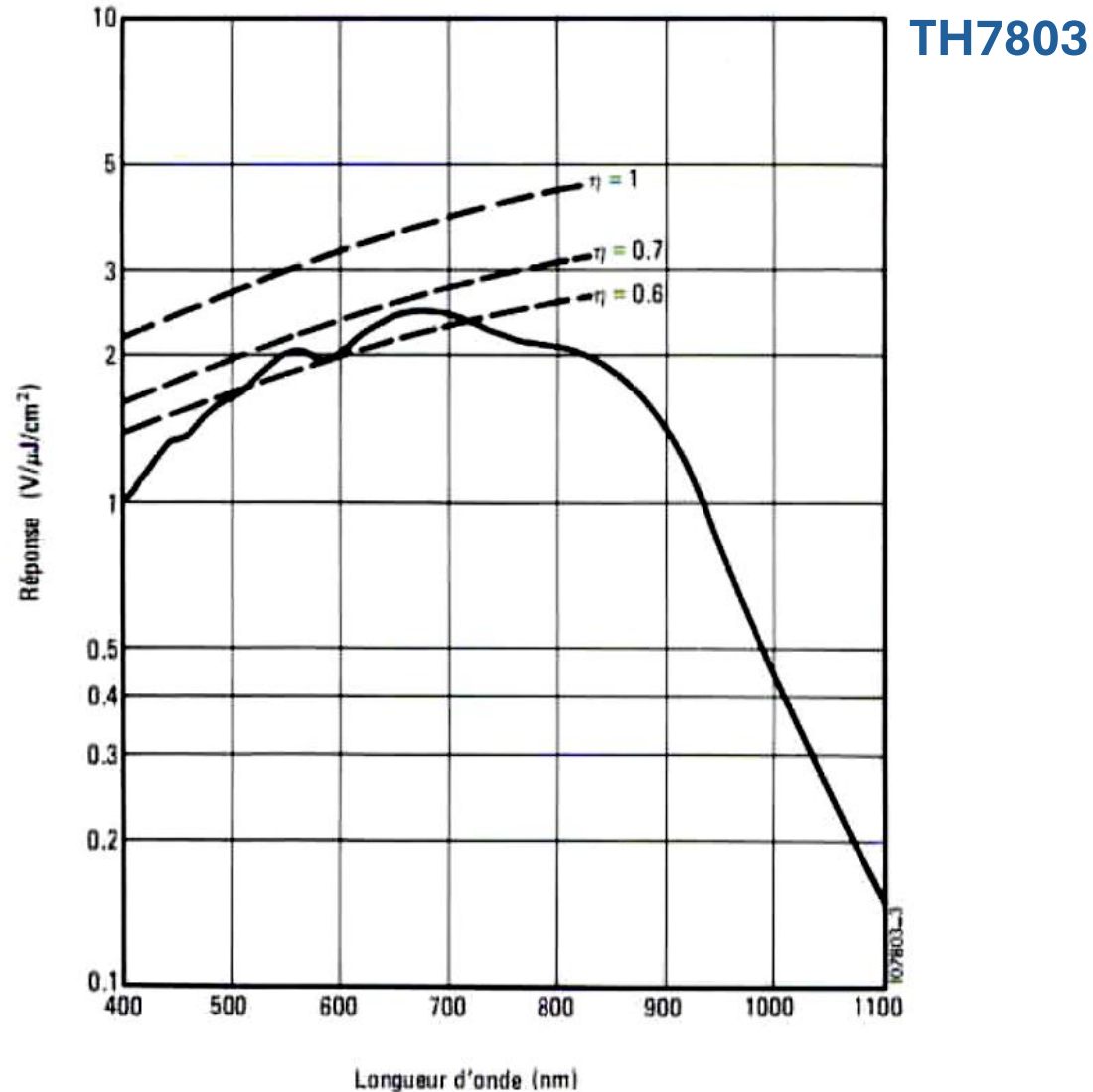
➡ Les performances d'un capteur CCD

La réponse spectrale d'une matrice



➡ Les performances d'un capteur CCD

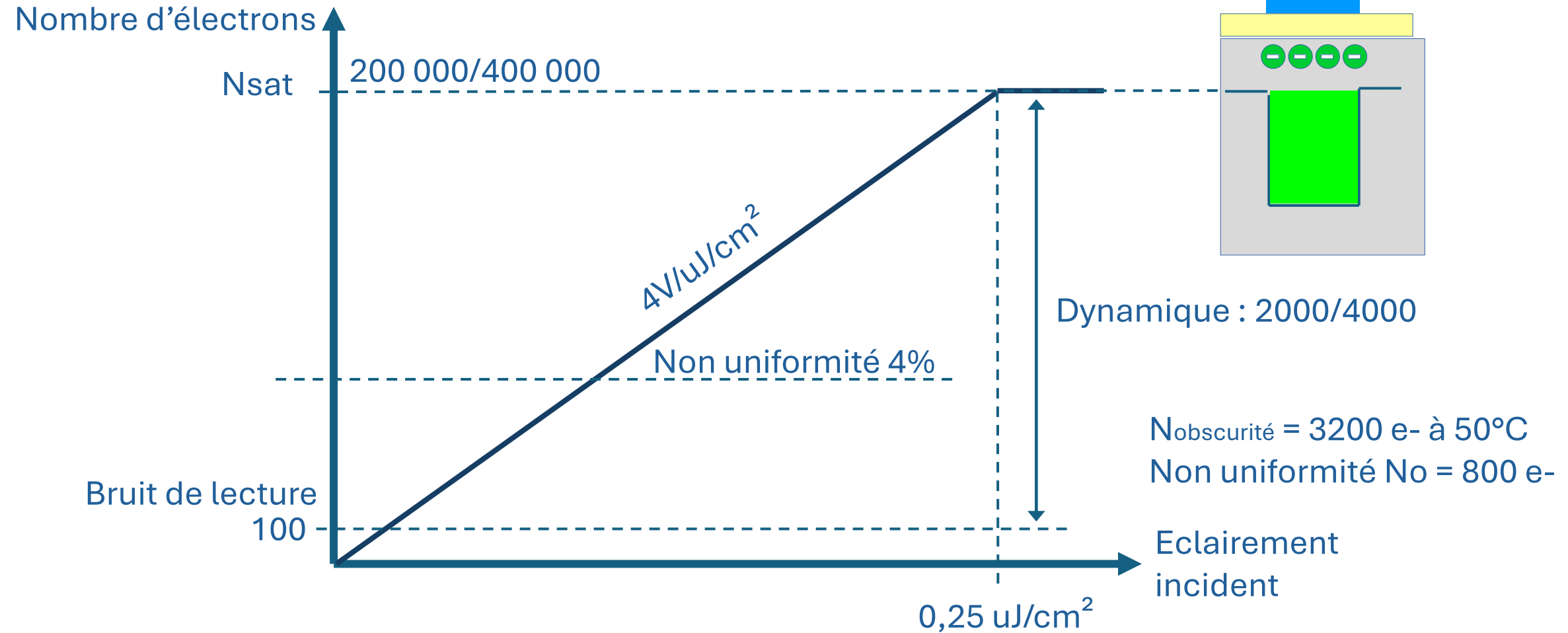
La réponse spectrale d'une barrette



➔ Les performances d'un capteur CCD

La dynamique de capteurs surfaciques

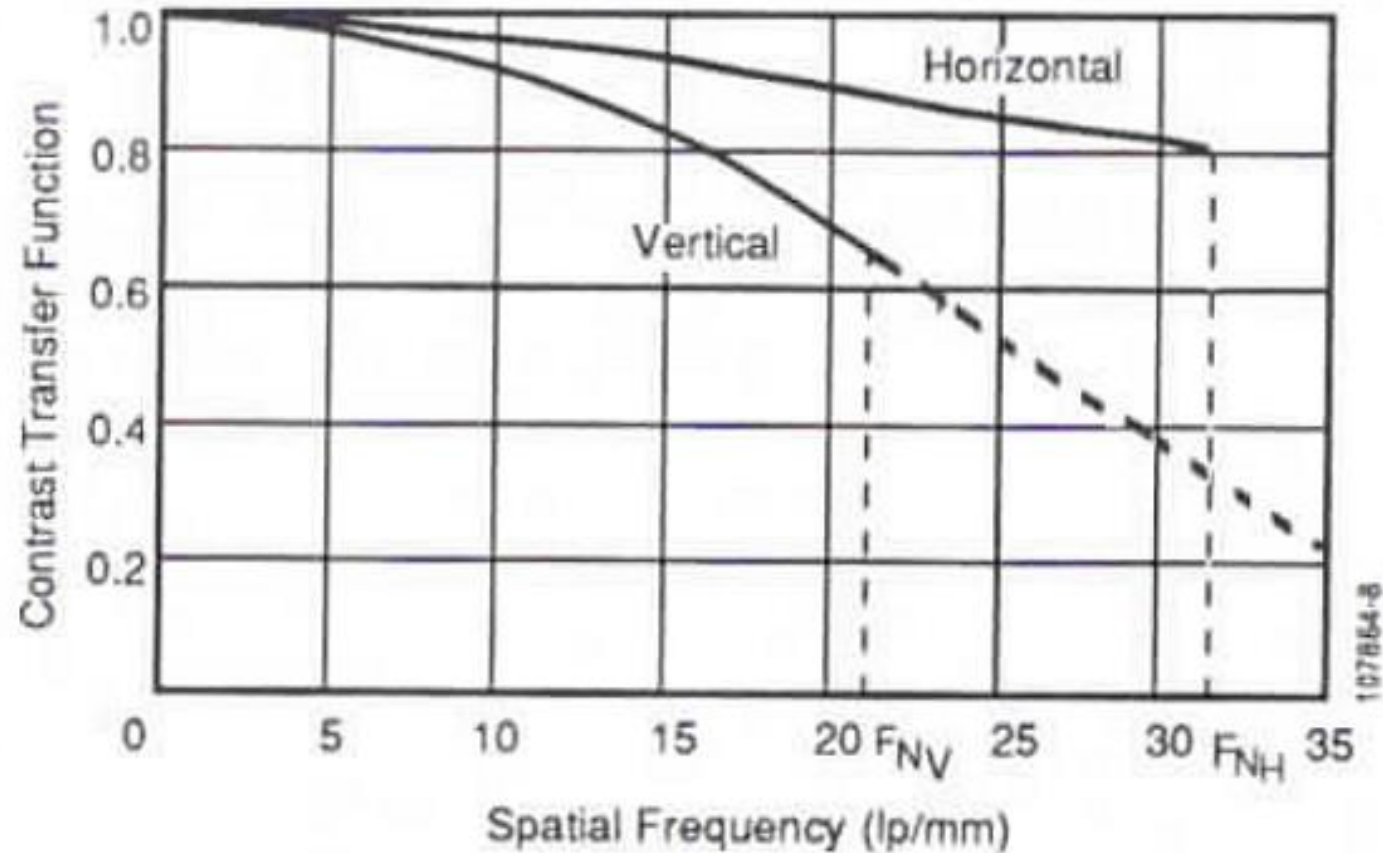
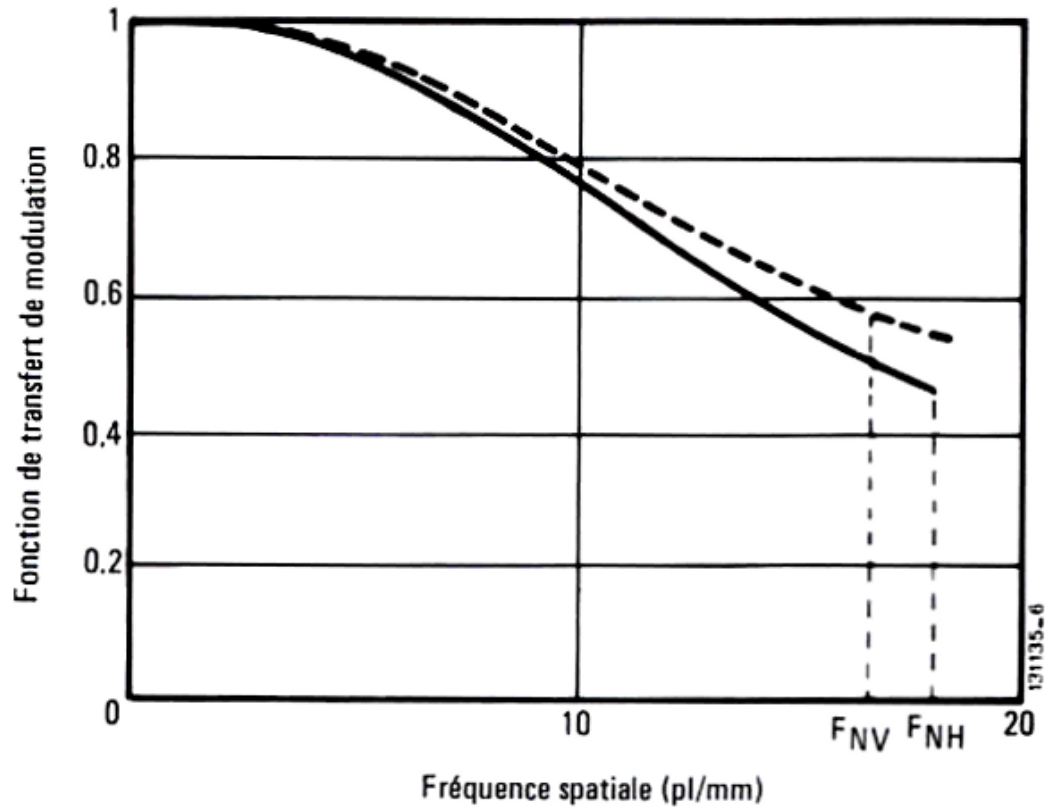
TH7852 (2 ph – 288x208) / **TH7864** (4ph - 576x550)



Les performances d'un capteur CCD

La résolution de capteurs surfaciques

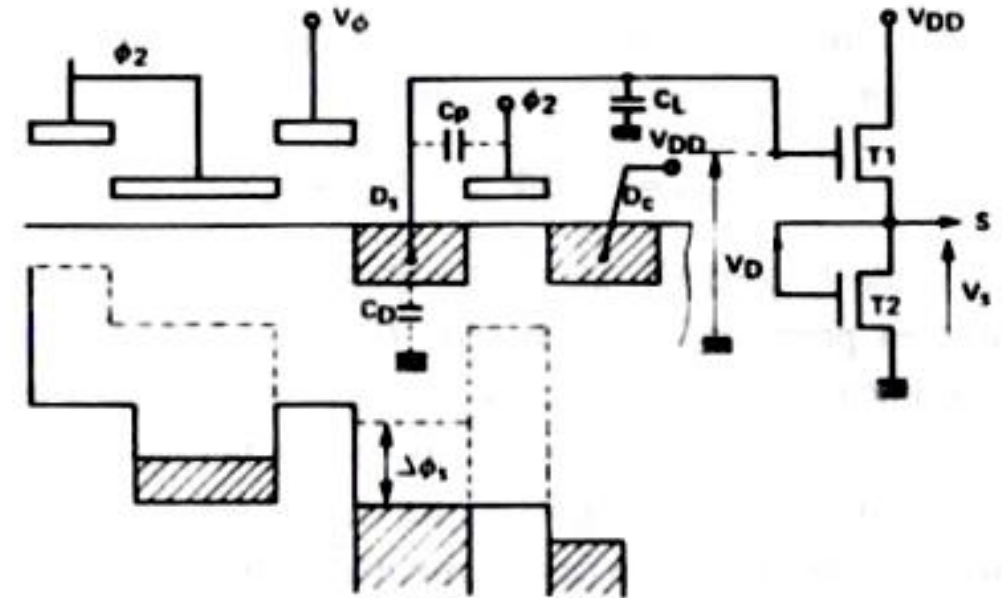
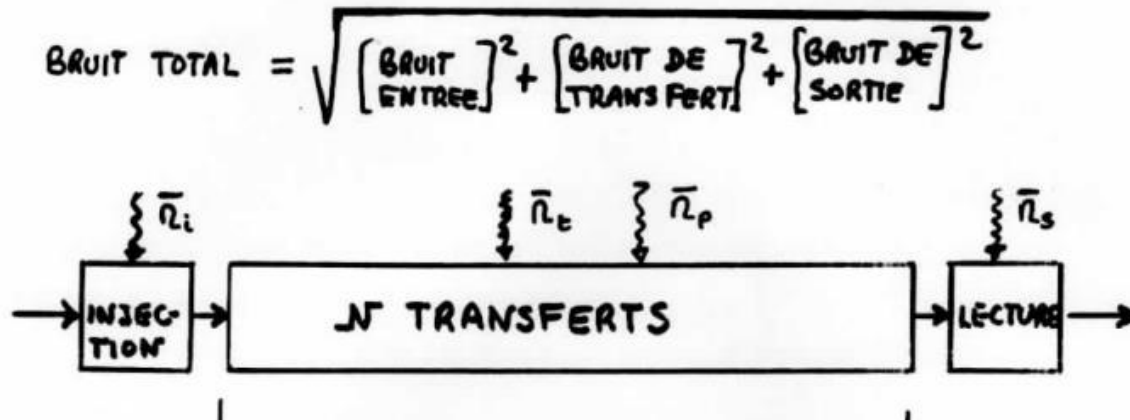
TH7852 (2 ph – 288/208)/ **TH7864** (4ph - 576x550)



➡ Les performances d'un capteur CCD

Le bruit de lecture d'un CCD

Conversion charge > tension
 $2 \mu\text{V} / e^-$ - $500 e^-$ par mV

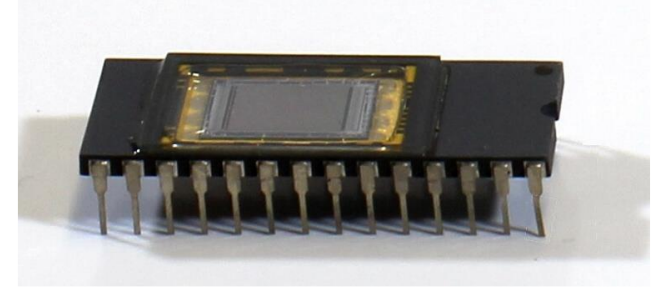
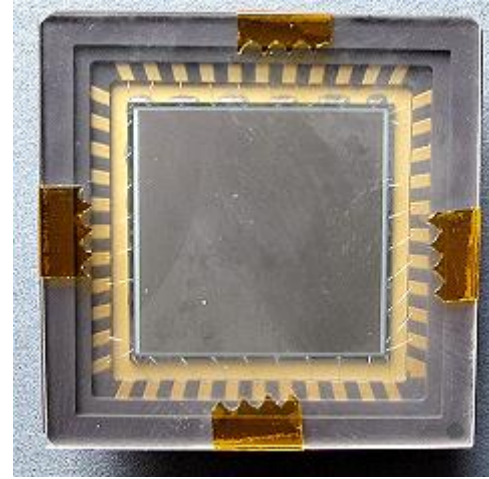
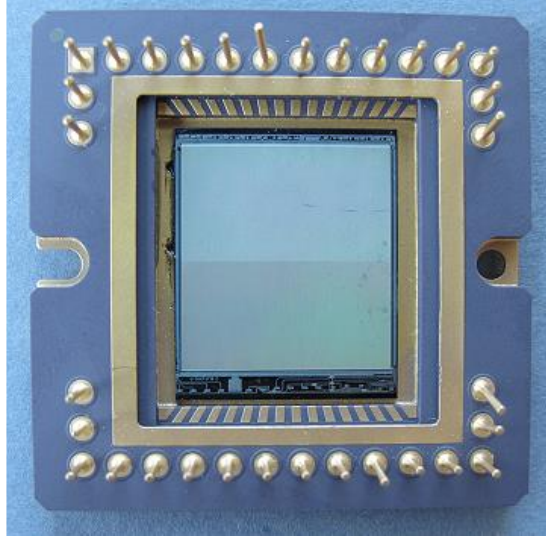


Bruit dominant = bruit de la capacité de lecture

$$N_{en} = \sqrt{kTC/q^2} = 400 \sqrt{C} \text{ (pF) à } 20^\circ\text{C}$$

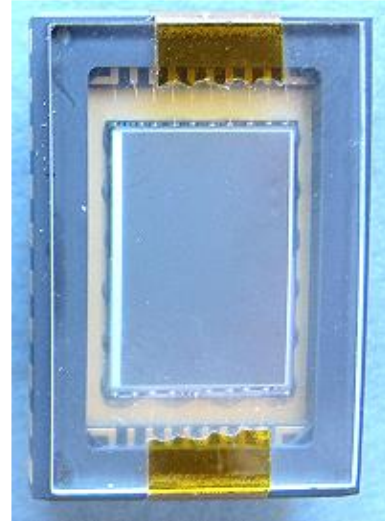
Valeur typique $C \approx 0,05 \text{ pF} \rightarrow Q_n = 90 \text{ à } 100 e^-$

➡ Quelques capteurs remarquables



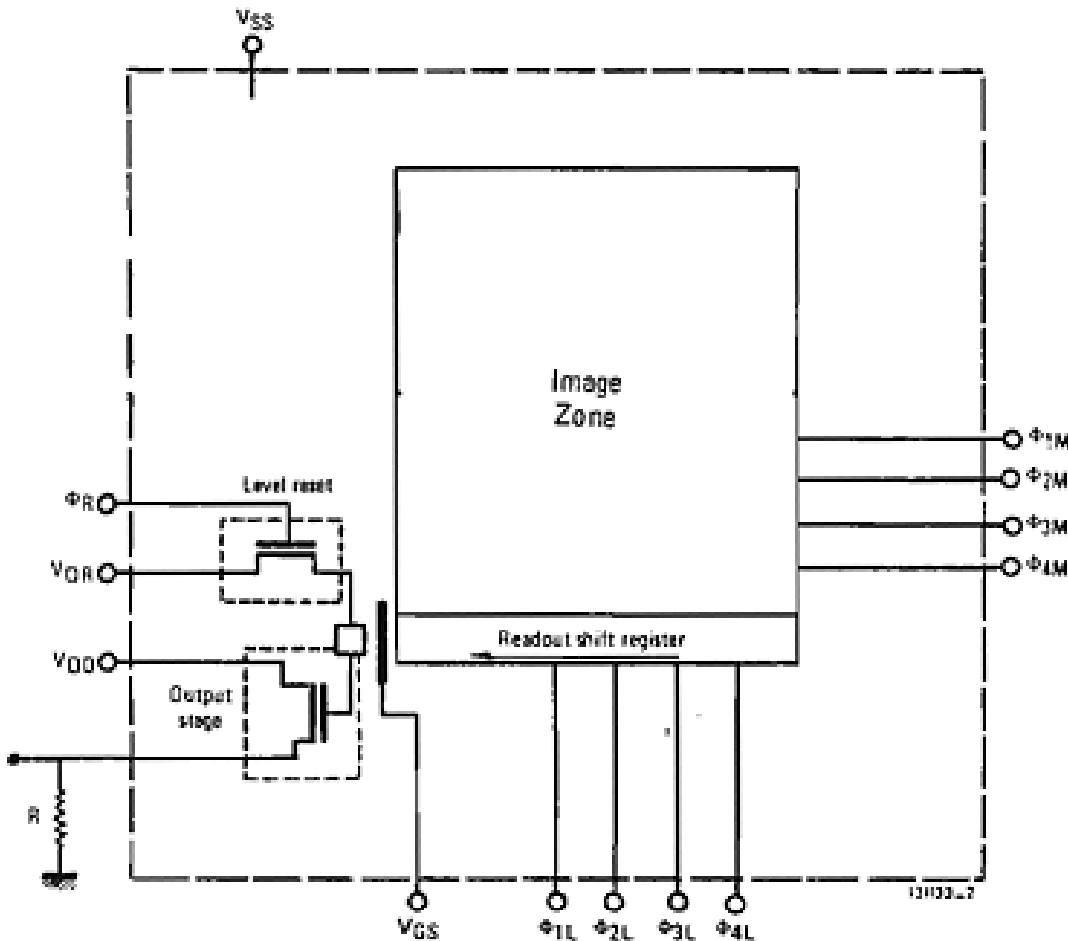
➡ Matrice « monocoup » sans mémoire de trame

Capteur TH7882 576 x 384

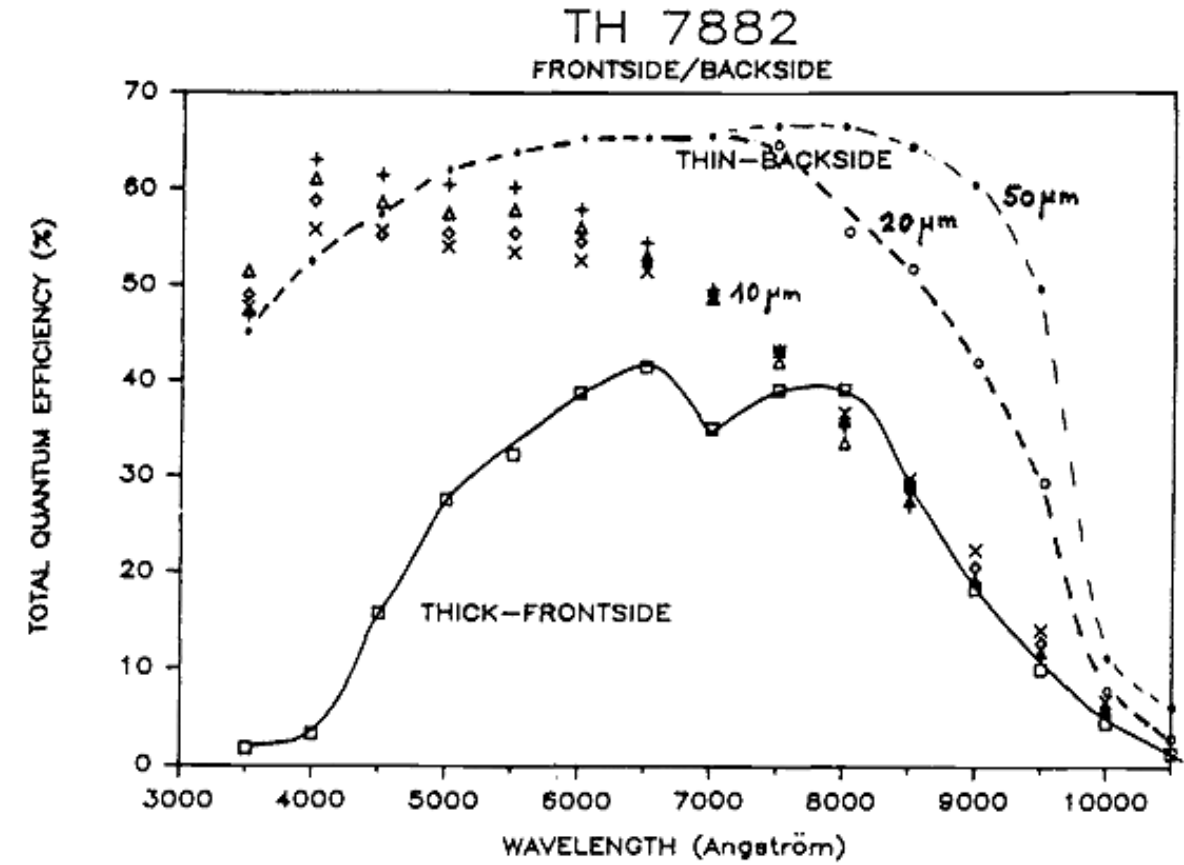
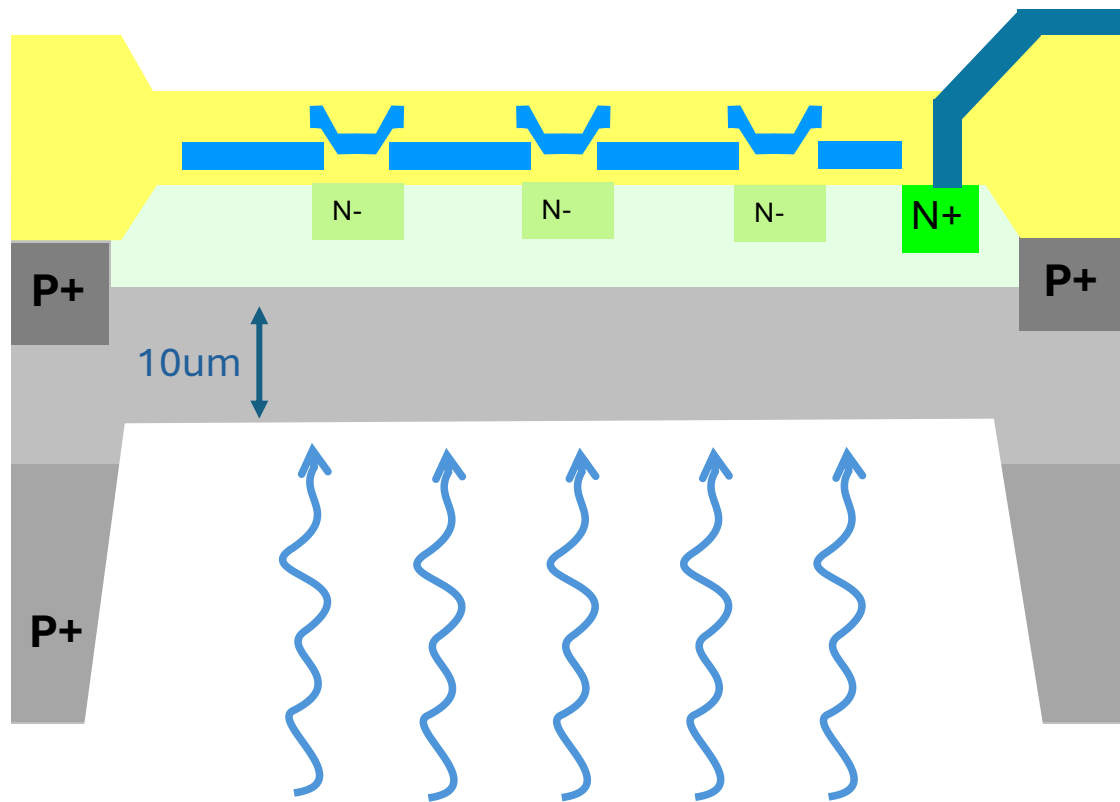


Caractéristiques

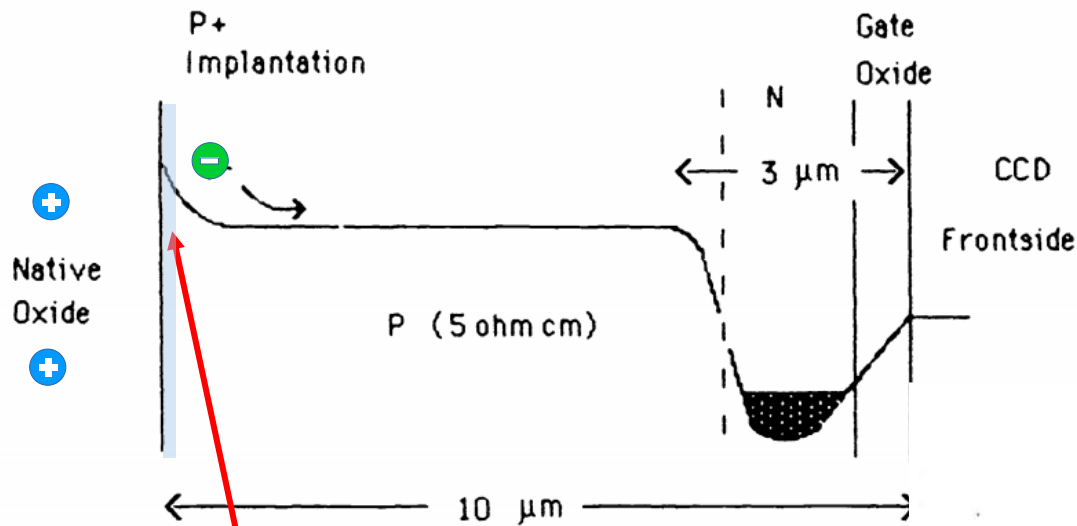
Sensor type	Full-frame, frame transfer
Format	576 V x 384 H
Pixel size	23 p,m x 23 \im
Image area	13.248 mm (V) x 8.832 mm (H)
Drive clock sequencing	4-phase
Full well capacity	6.10 5 e ⁻
Output sensitivity (RL = 2.2 kq)	0.6 p,V/e ⁻
Dark current (+ 25 °C)	1 to 2 nA/cm ²
Readout noise	5 to 10 e ⁻ r.m.s.



➔ Matrice TH7882 amincie face arrière (BSI)

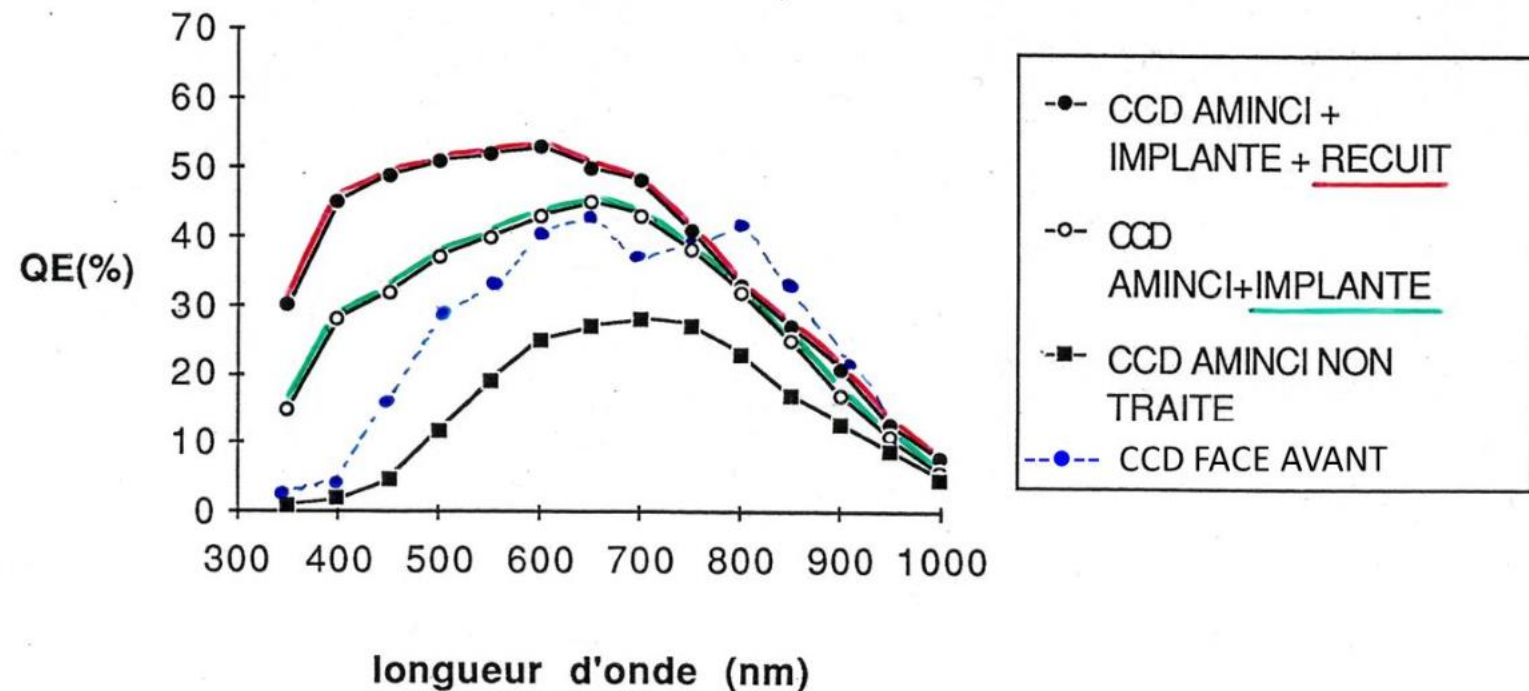


➡ Traitement matrice amincie face arrière (BSI)

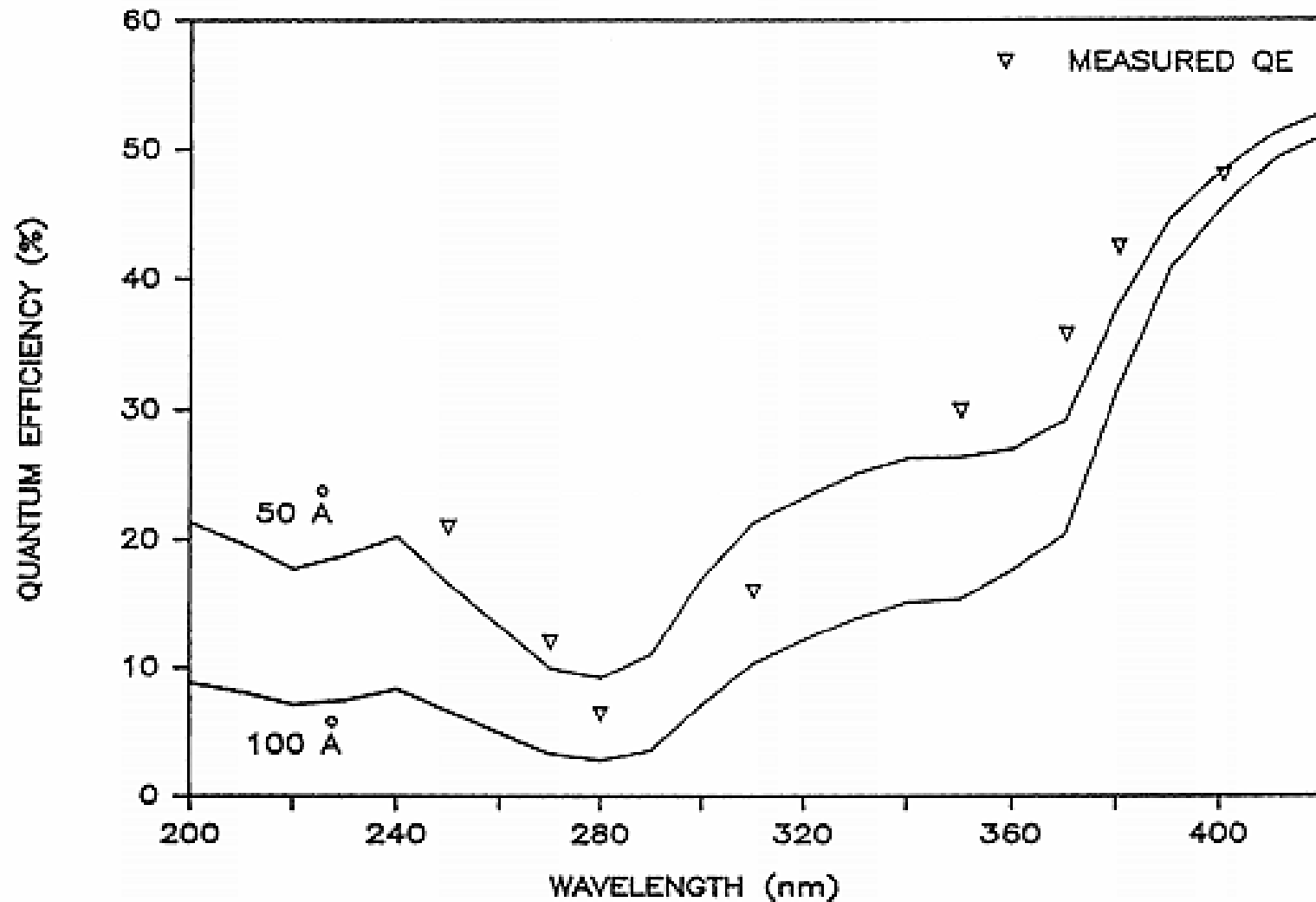


Fine zone implantée P+ permettant de créer un gradient de potentiel favorable à la collecte des photos électrons

REPONSES SPECTRALES



➡ Traitement matrice amincie face arrière (BSI)

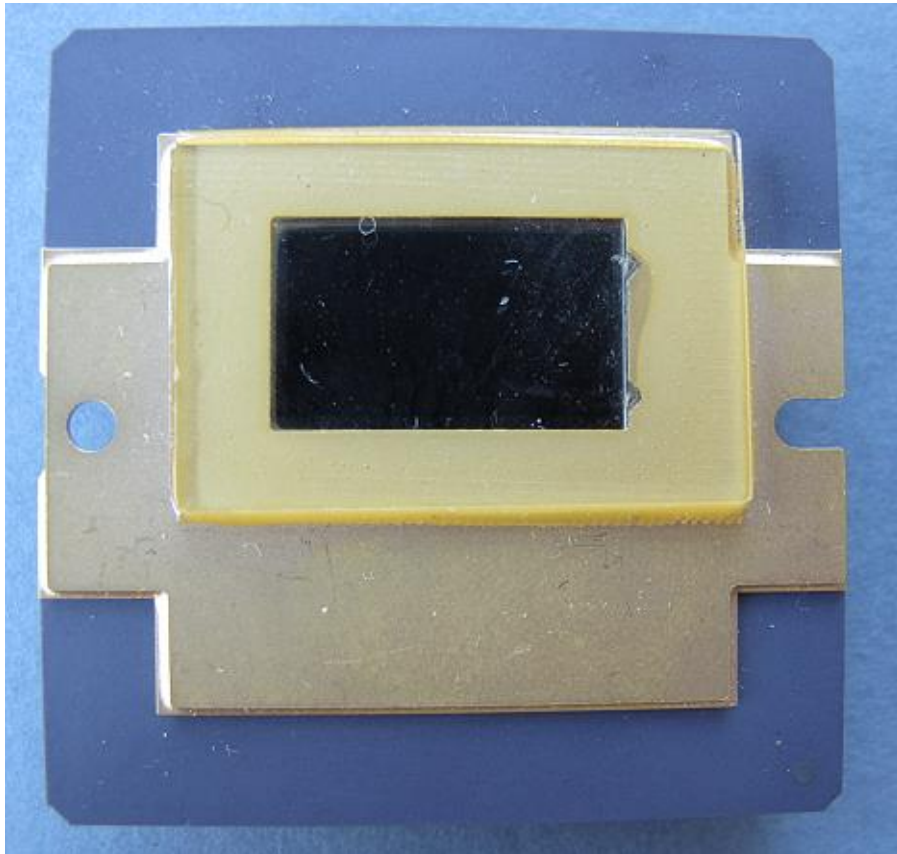


Measured quantum efficiency of implanted and laser annealed 576 x 384 CCD.
Calculated QE_B with 50 Å and 100 Å "dead layer" are shown for comparison

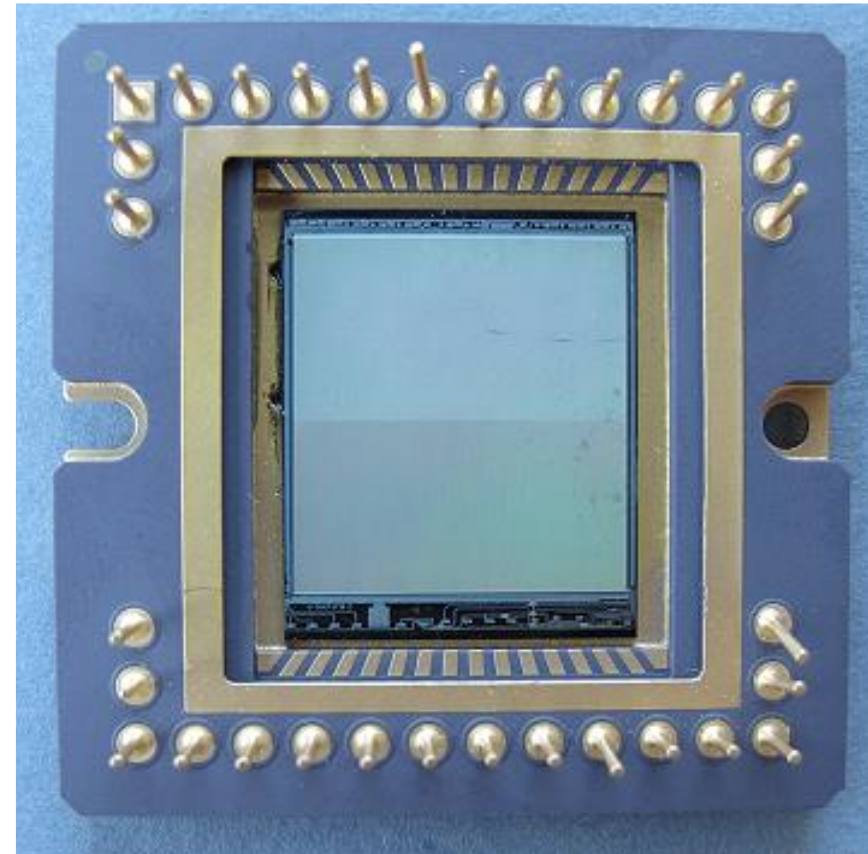
C. Tassin, Y. Thenoz, J. Chabbal, "Thinned Backside Illuminated CCDs for Ultra-violet Imaging", Ultraviolet Technology II, SPIE Proc, Vol. 932, pp 305-310, Orlando, 1988.

➡ Matrices amincies haute résolution

Matrice 1 '' THX 31167 (TH 31163 amincie) 1160 x 576 pixels)

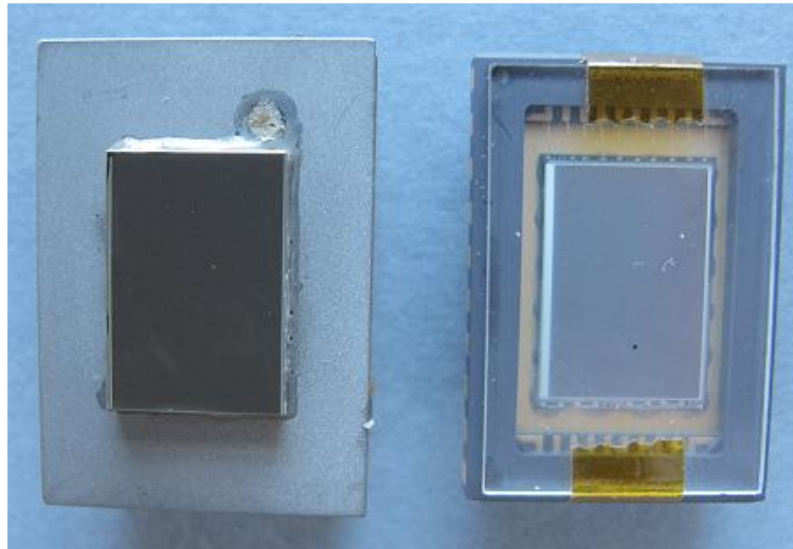


Face d'entrée = face arrière
du capteur

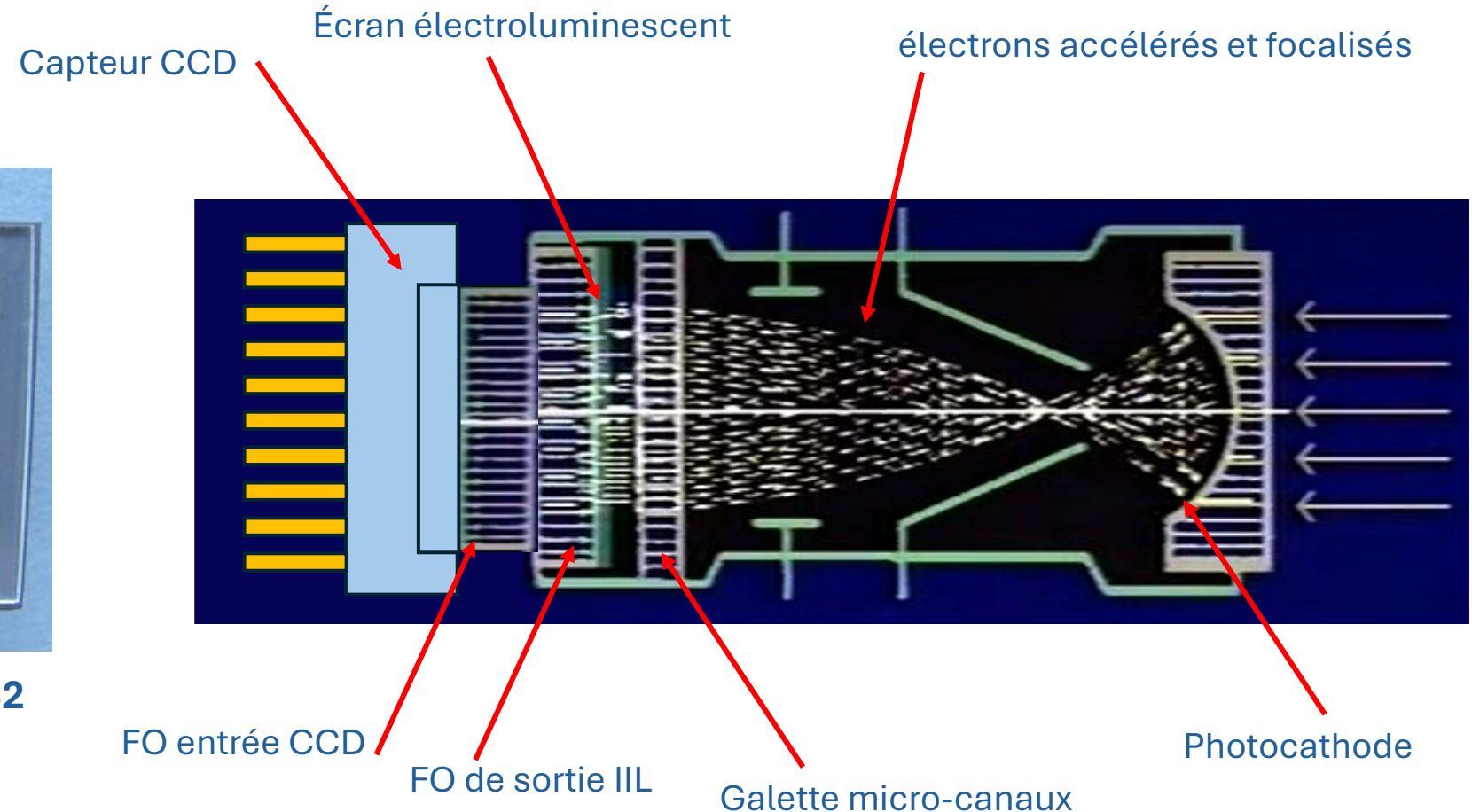


Face avant du capteur

➔ Capteur avec fibre optique – couplage IIL



Fenêtre fibre optique sur TH7882



Cf Herpe, G., Boulesteix, J., Marcelin, M., et al. (1991)
 "An Intensified CCD Camera for Telescope Guidance"
Experimental Astronomy, **2**, 163–174.

Proxitronic : [FiberOpticCouplings.pdf](#)

Capteur à transfert de ligne : 576 x 720 pixels

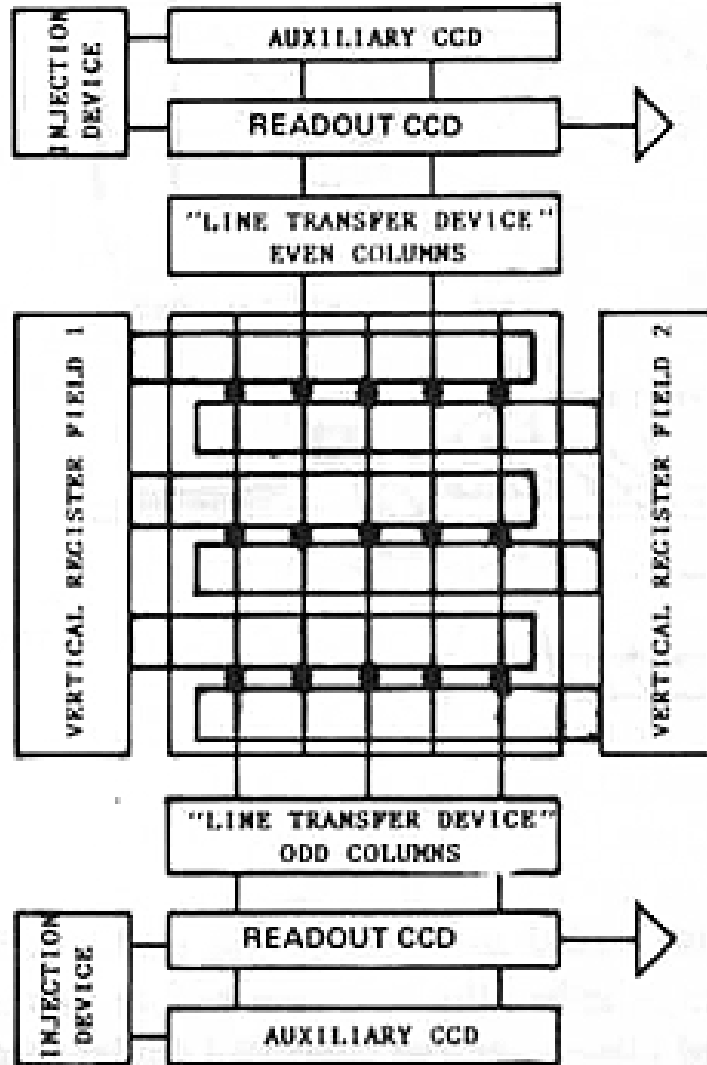


Fig. 1. The line-transfer organization.

THX 1143 – 1145 - 1148

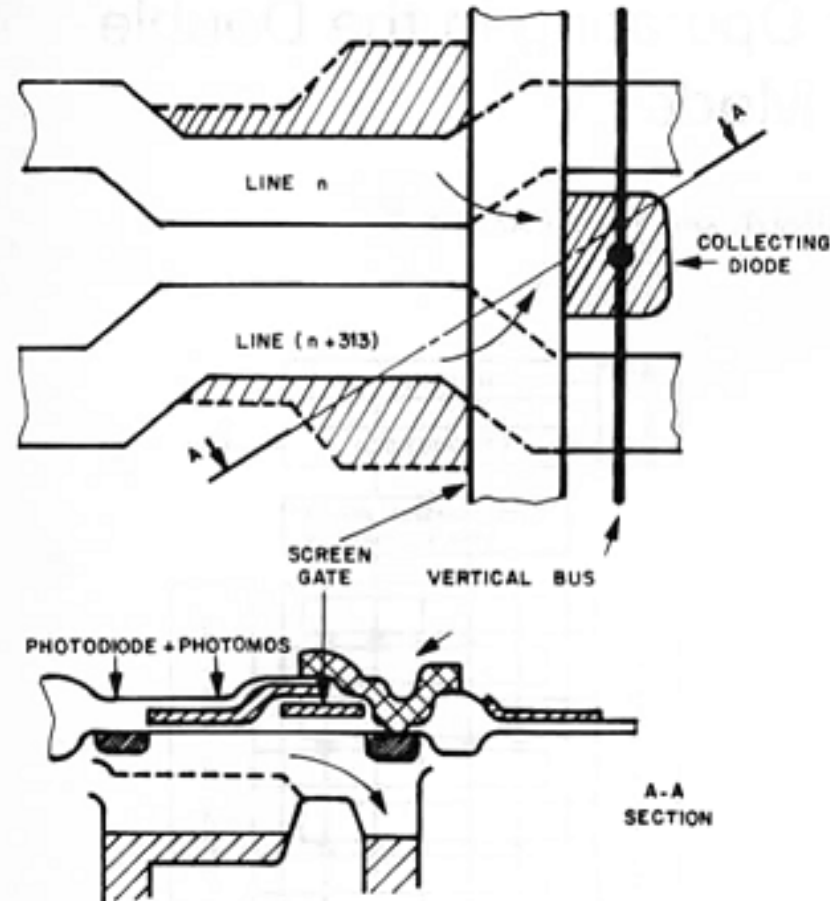
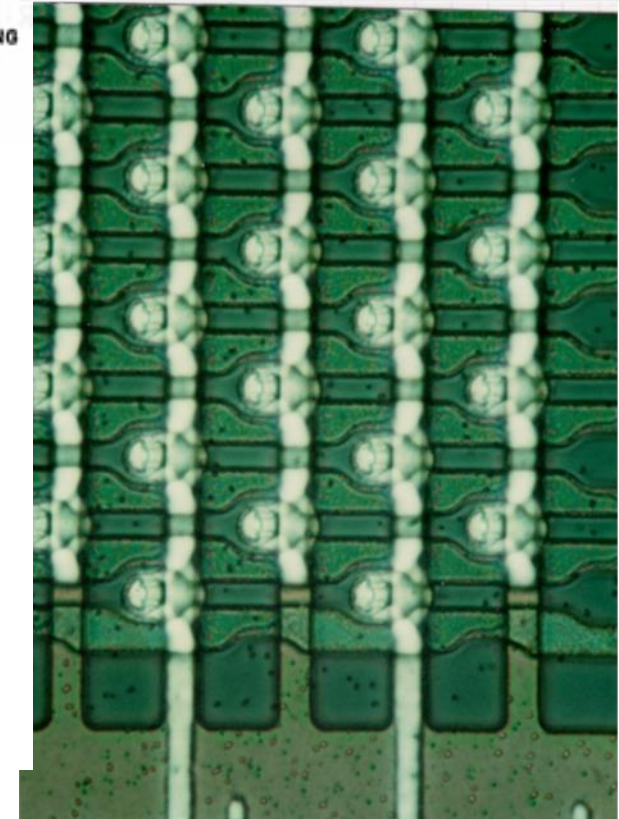
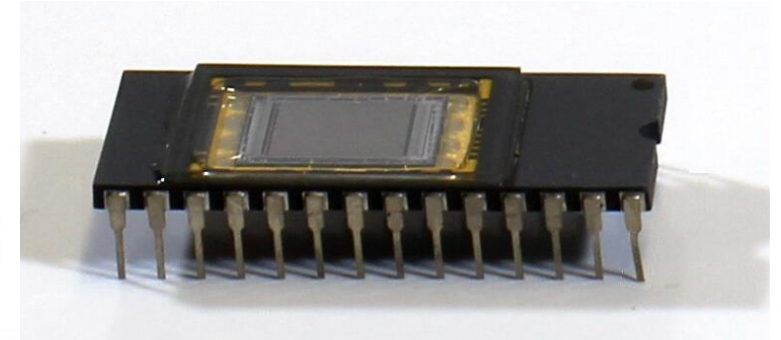
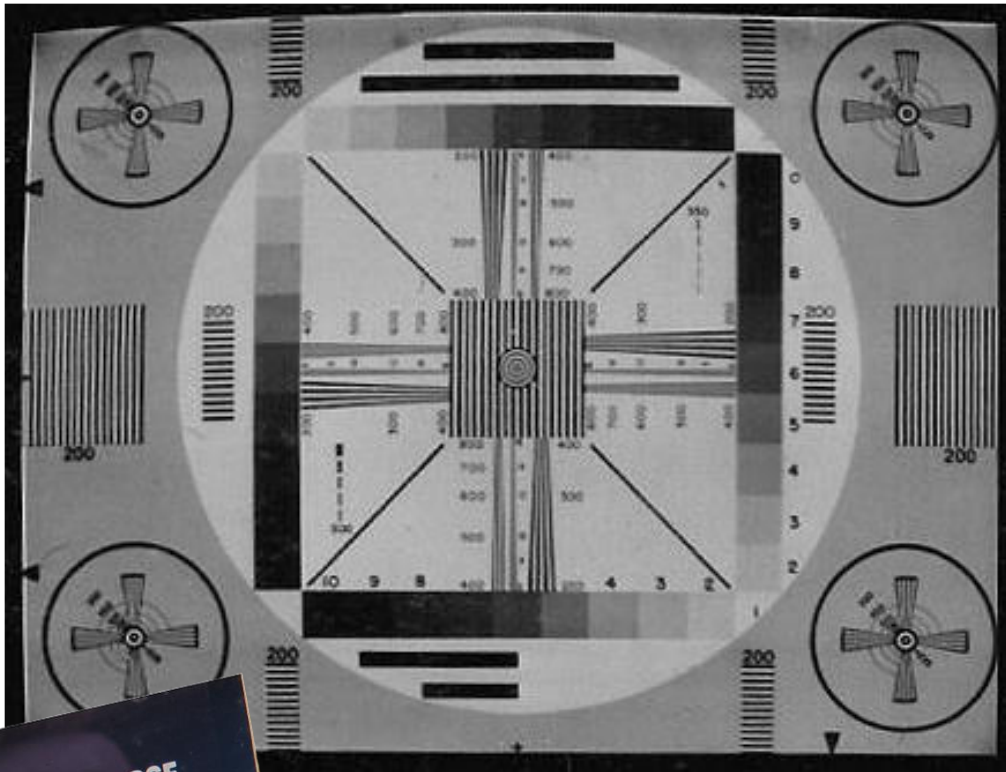


Fig. 2. Detail of photosite.



➔ Capteur à transfert de ligne monochip couleur : 576 x 702 pixels



Etude pour visiophone avec
caméra numérique couleur

➡ Capteur à transfert de ligne : 576 x 702 pixels

CHARACTERISTICS OF LINE-TRANSFER IMAGE SENSOR

NUMBER OF ELEMENTS	576 (V) x 462 (H)
IMAGING AREA	6.4 (V) x 8.8 (H) mm ²
PIXEL SIZE	11.5 (V) x 19 (H) μ ²

• DYNAMIC RANGE AT 30 °C :

SATURATION CHARGE	8×10^5 electrons	(900 nA)
THERMAL CHARGE	1×10^3 electrons	(3.5 nA)
BIAS CHARGE (Q1, Q2)	2.7×10^5 electrons	(300 nA)
VERTICAL FPN (peak-peak)	250 electrons	(0.28 nA)
TEMPORAL NOISE	700 electrons rms	(0.79 nA)
SHEAR FACTOR	1.2×10^{-5}	
BLOOMING FACTOR	1.5×10^{-4} (30 Q·cm) to 5×10^{-5} (5 Q·cm)	

• RESPONSIVITY :

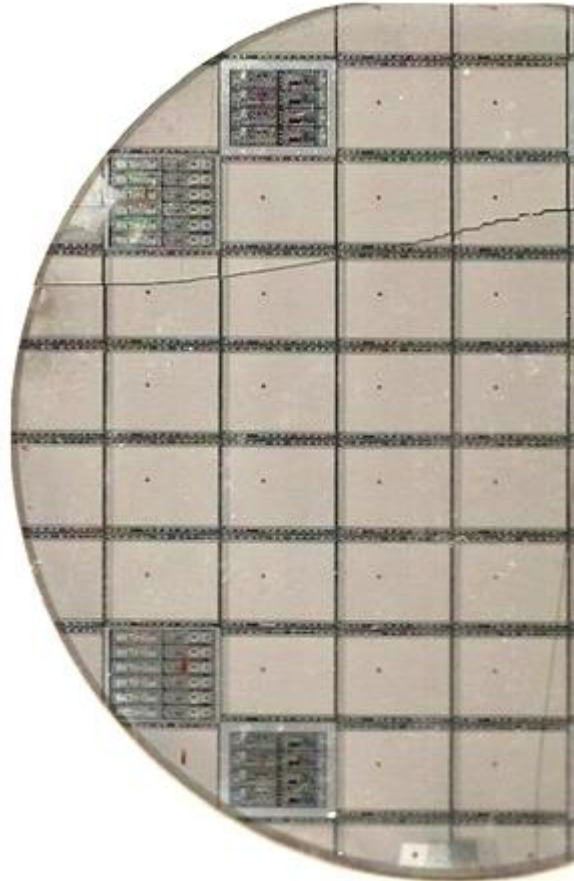
WHITE LIGHT (*)	1.6×10^4	(QE = 34 %)
(SINGLE CHIP	BLUE (λ = 460 nm) 1.9×10^3	electrons (QE = 12 %)
COLOR IMAGER)***	GREEN (λ = 520 nm) 4.5×10^3	Lux** (QE = 22 %)
	RED (λ = 600 nm) 4.5×10^3	(QE = 20 %)

• SPATIAL RESPONSE (MTF) :

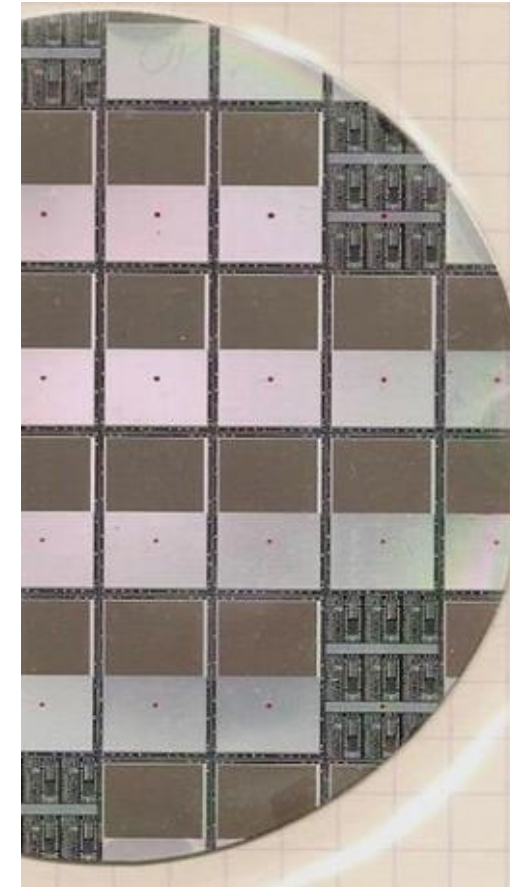
HORIZONTAL	80 % at Nyquist frequency (= 350 TVL)
VERTICAL	70 % at Nyquist frequency (576 TVL)

• LAG AND BUILD UP (****)

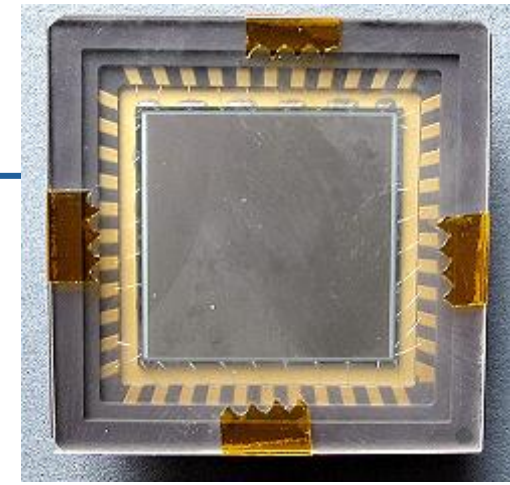
- 1ST frame after increase in illumination > 95 %
- 1ST frame after illumination cut-off < 5 %



THX 1143 - TDL
576 x 702
36 puces /plaque 3 ''



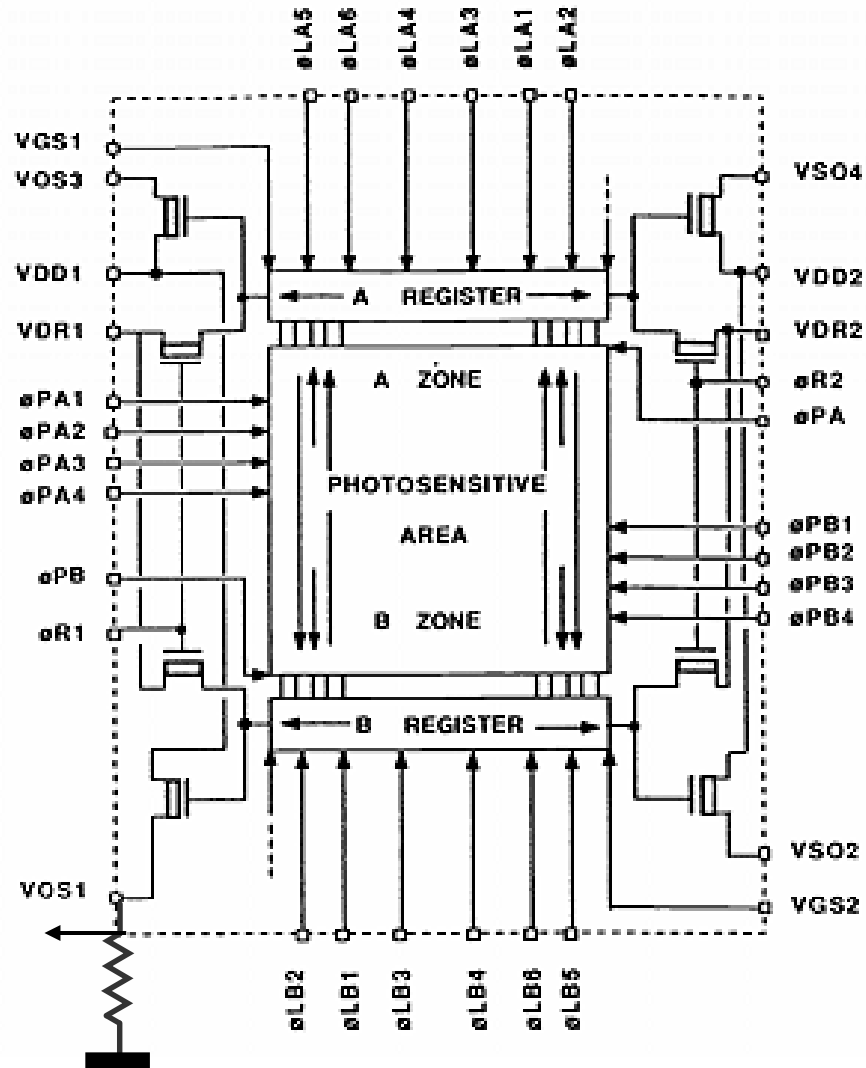
TH 7862 - TDT
576 x 384
20 puces /plaque 3 ''



➔ Matrice 1024 x 1024 – TH 7896 (THX 31156)

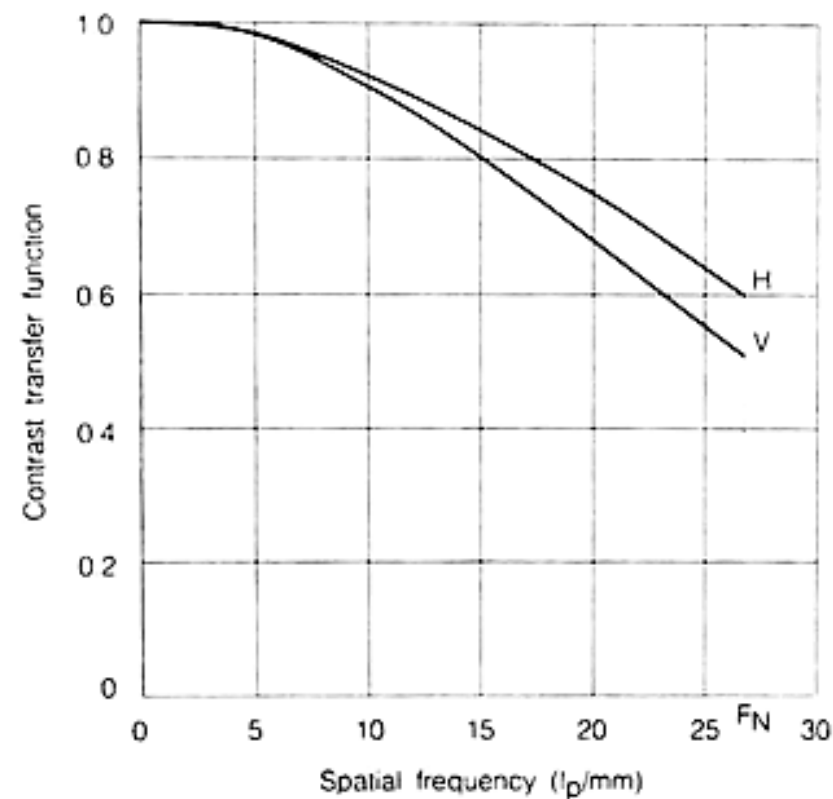
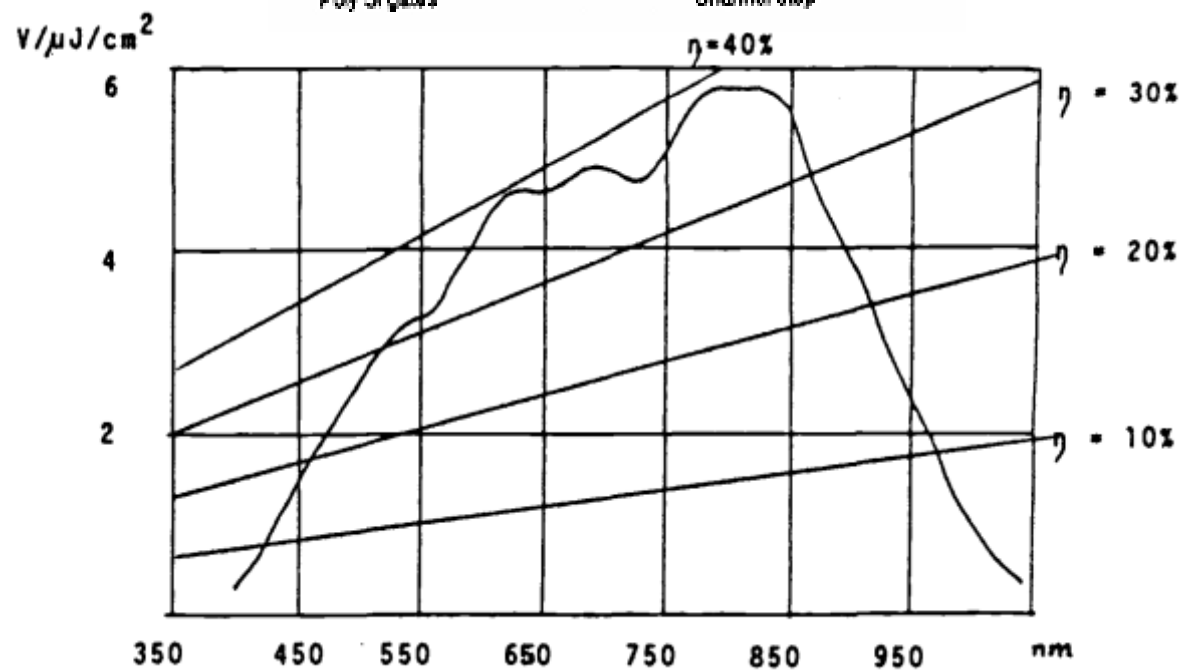
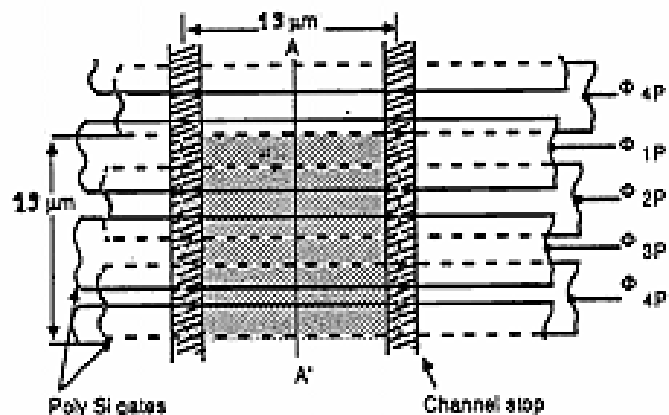
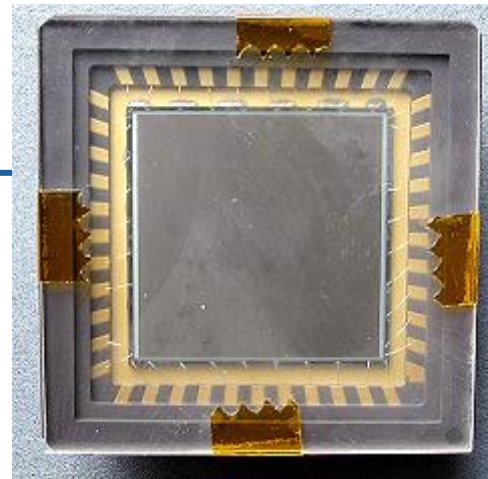
Capteur conçu spécialement pour astronomie et applications scientifiques

- Optimisé pour une haute sensibilité
- Bruit de sortie 4 e⁻ à -40°C (avec CDS)
- $V_{sat} = 450\,000\text{ e}^-$
- Transistor de sortie à canal enterré et résistance externe
- Pixel 19x19μm Ouverture 100%
- Réponse spectrale 400nm à 1100nm
- Efficacité de transfert 0,999998
- Courant obscurité 10 e⁻ /pixel/sec à -40°C
- Dispositif de mesure de température intégré
- Pilotage 4 phases



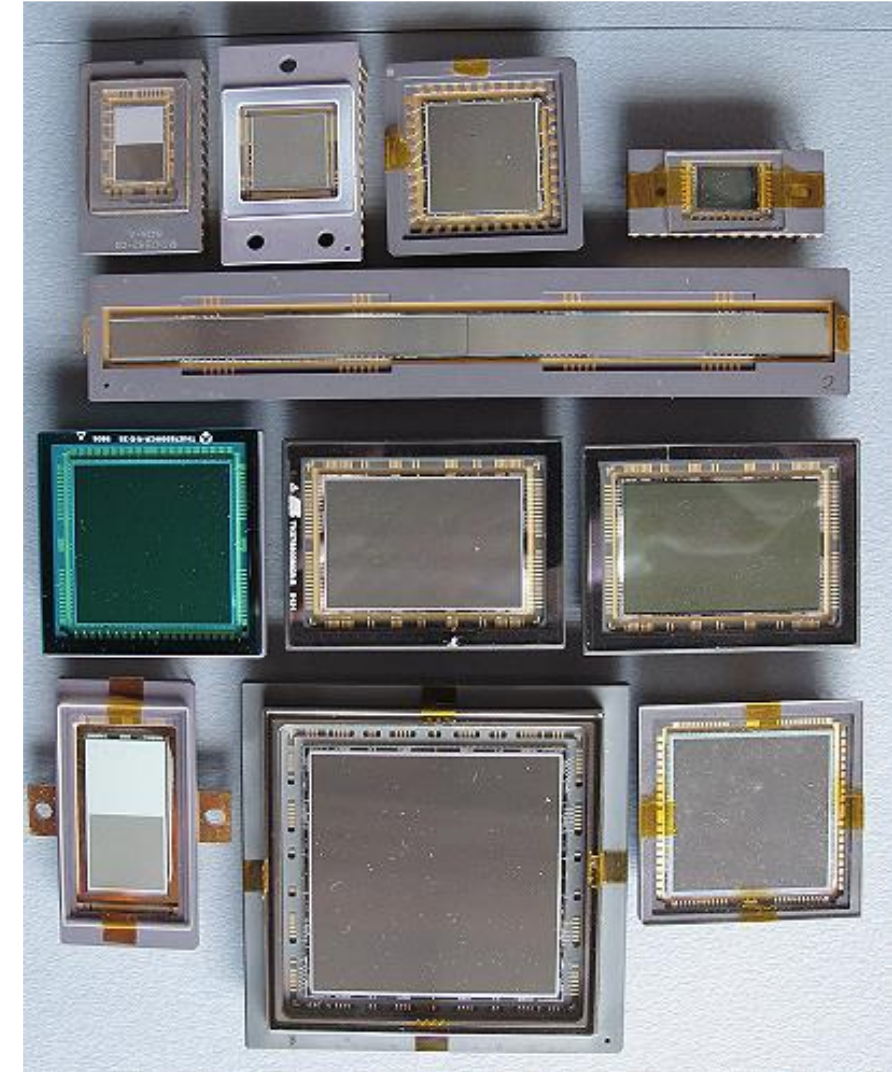
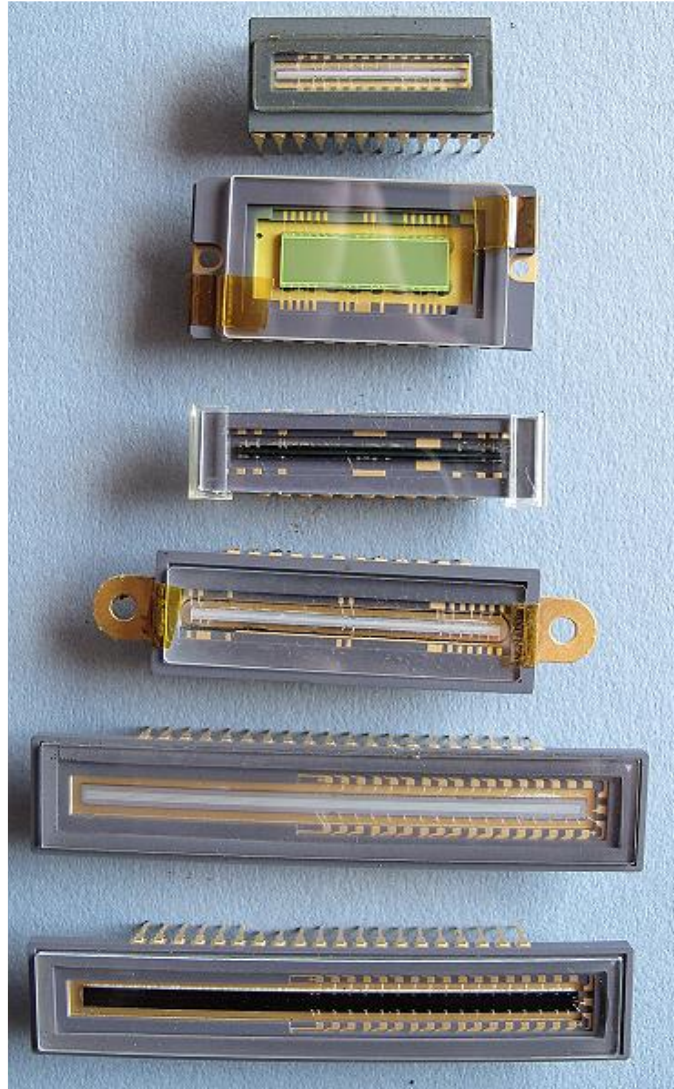
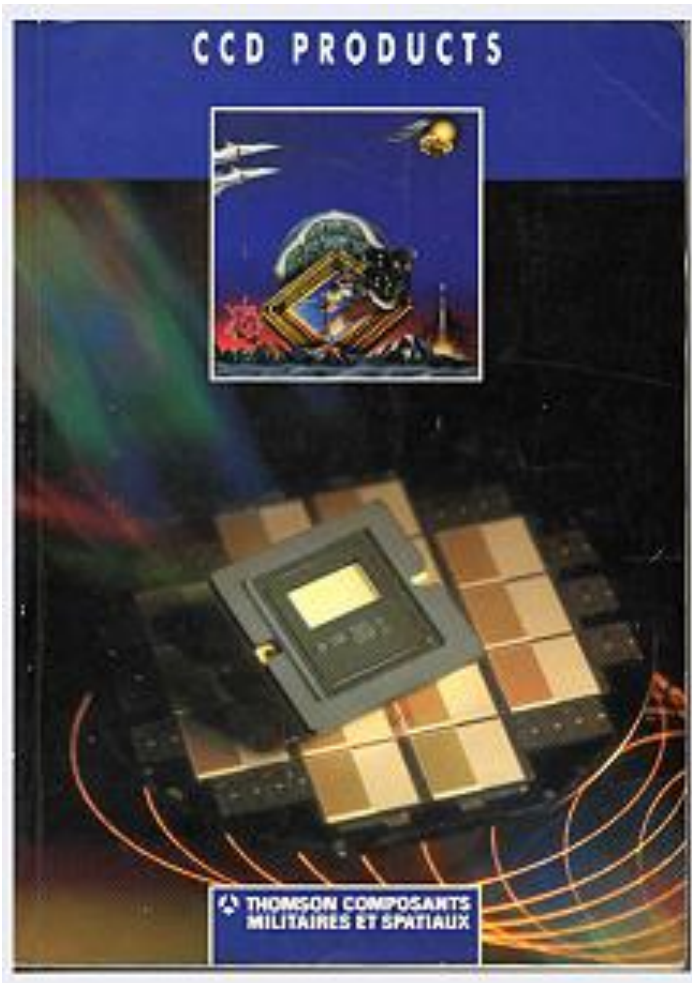
1.5 μV/e⁻ sur R 2,2 kΩ

➡ Matrice 1024 x 1024 – THX 31156



➡ Les autres capteurs CCD fabriqués à St Egrève...

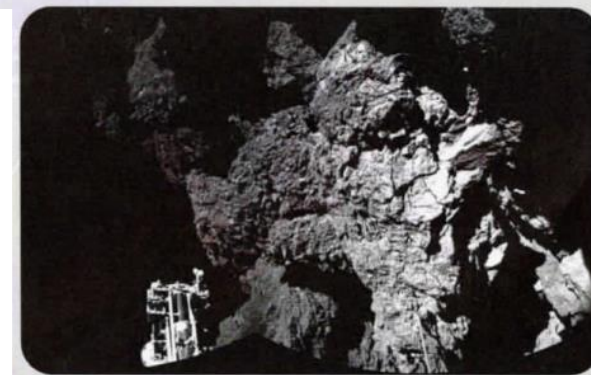
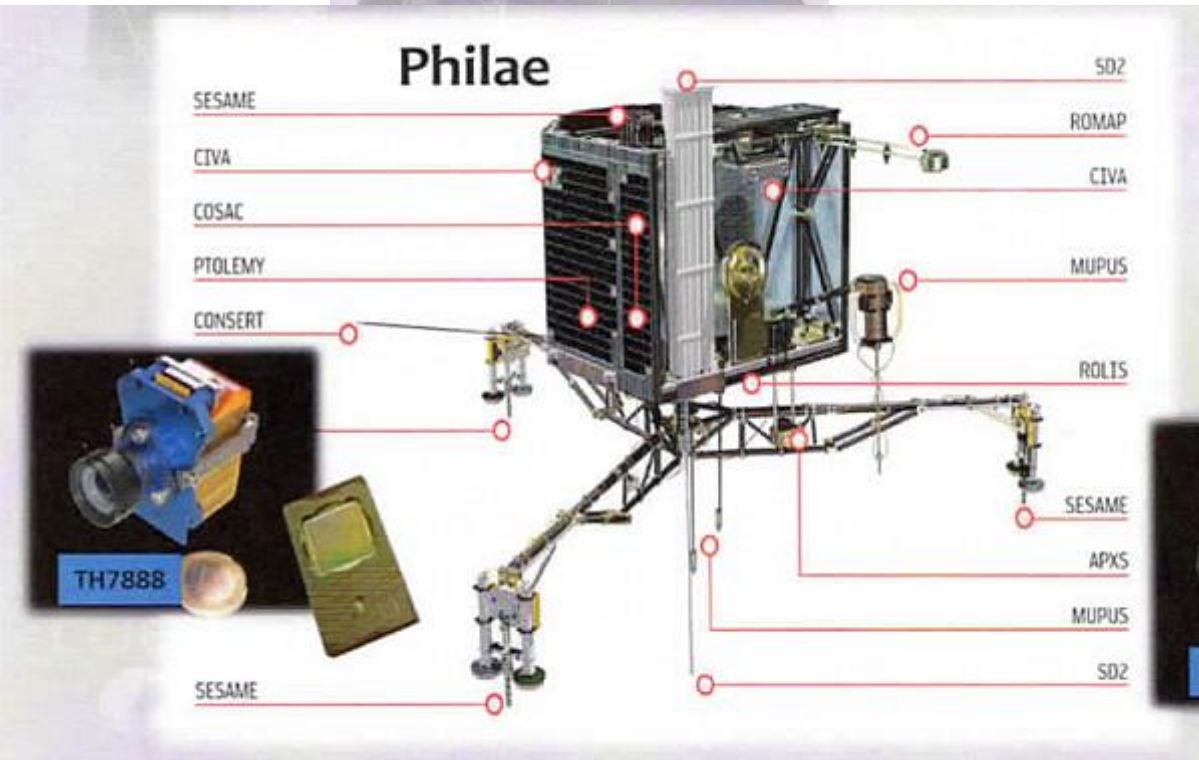
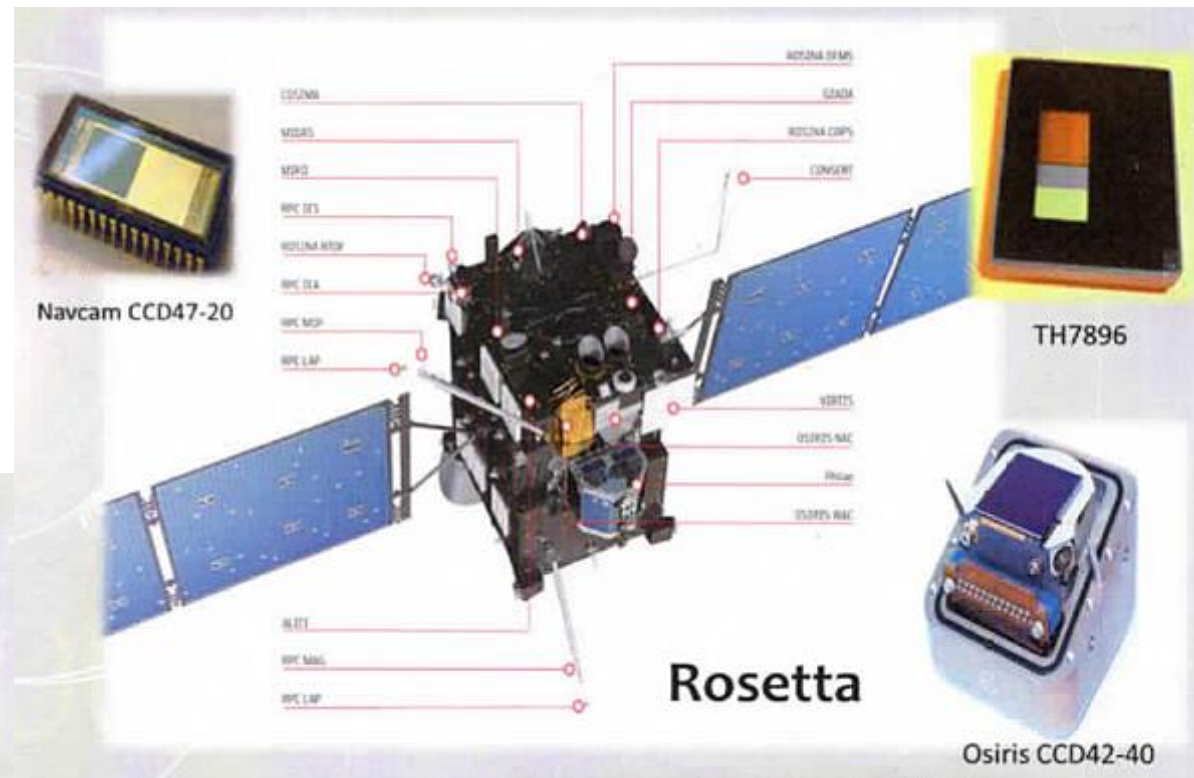
Catalogue 1992 – 93
600 pages



➡ Les autres capteurs CCD fabriqués à St Egrève...

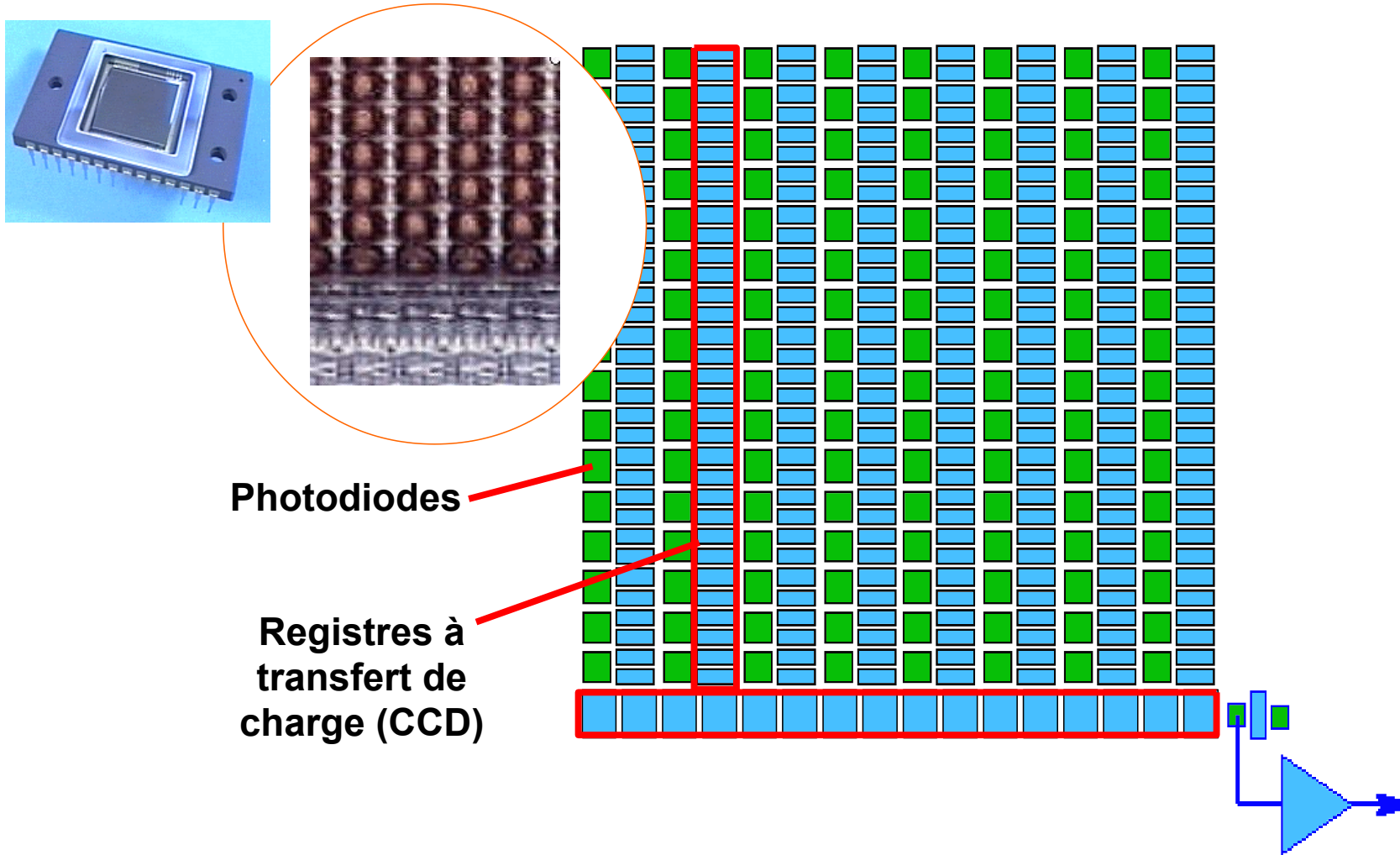


10 ans de trajet
6,5 milliards de
km parcourus

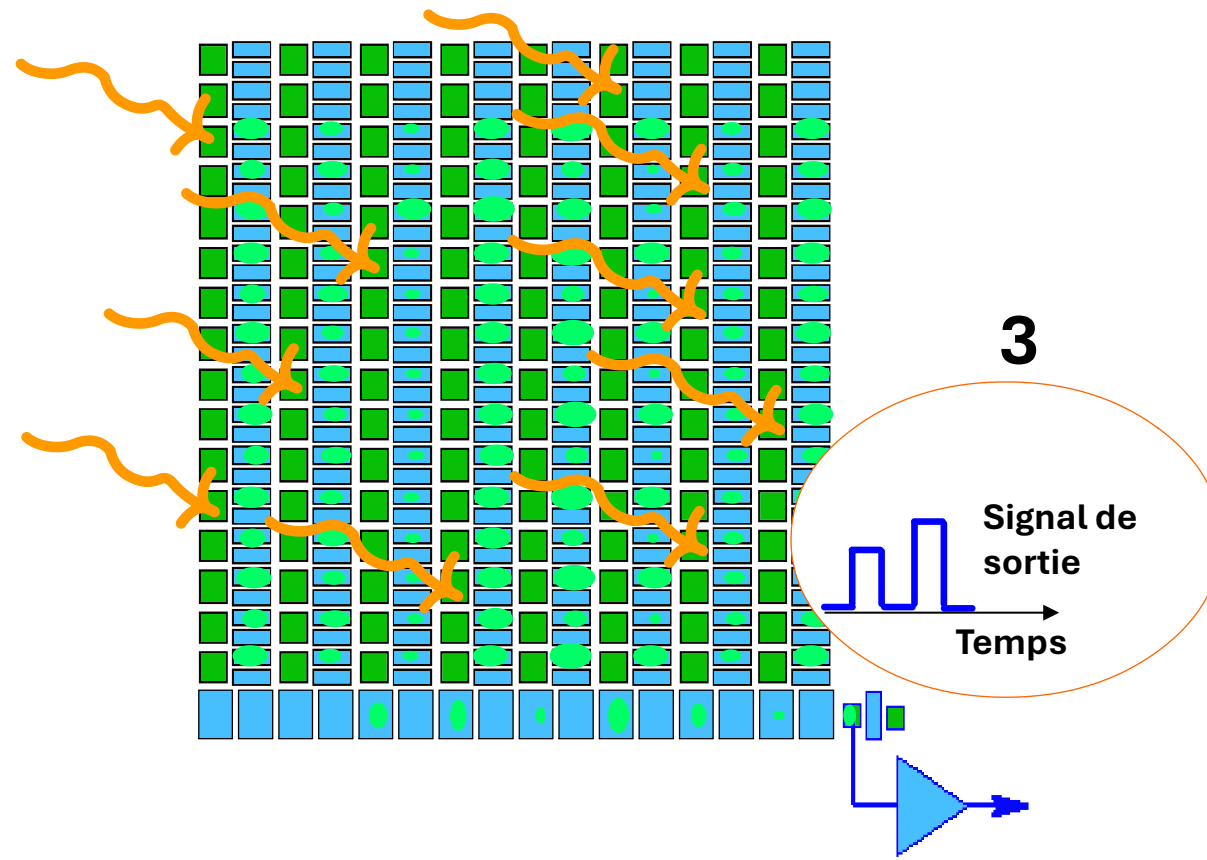
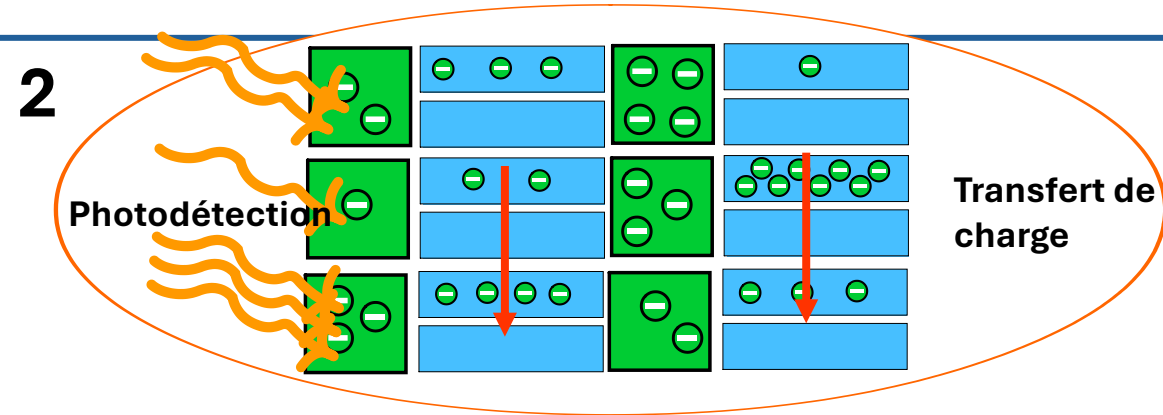
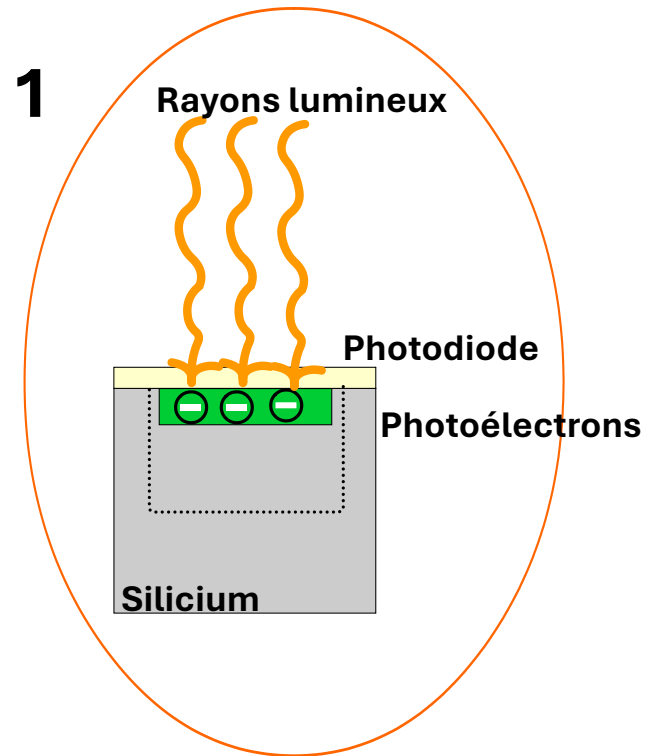


La 1^{ère} image prise par Philae
avec le TH7888

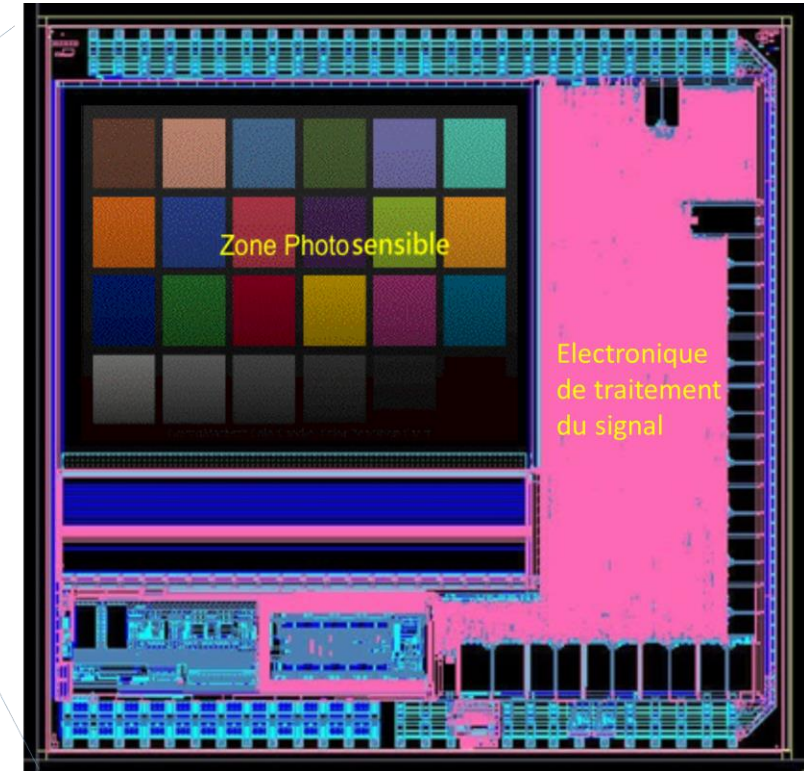
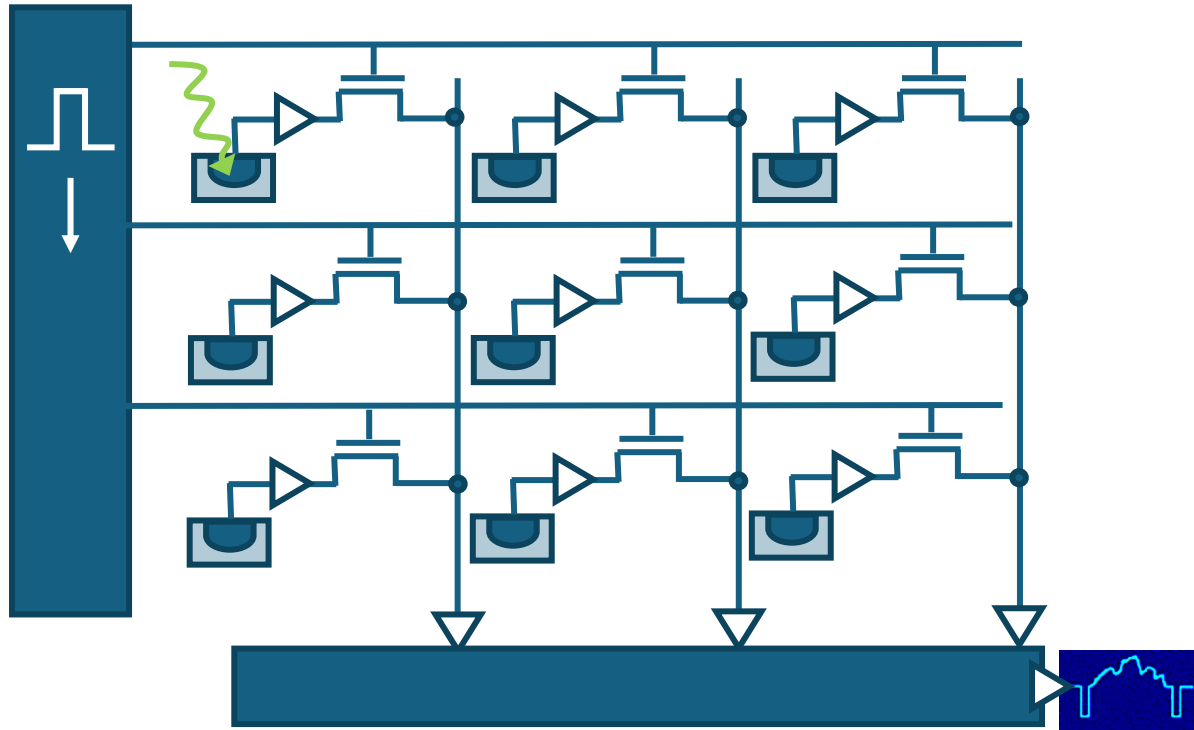
➡ Autres configurations de capteurs - Interligne



Autres configurations de capteurs - Interligne



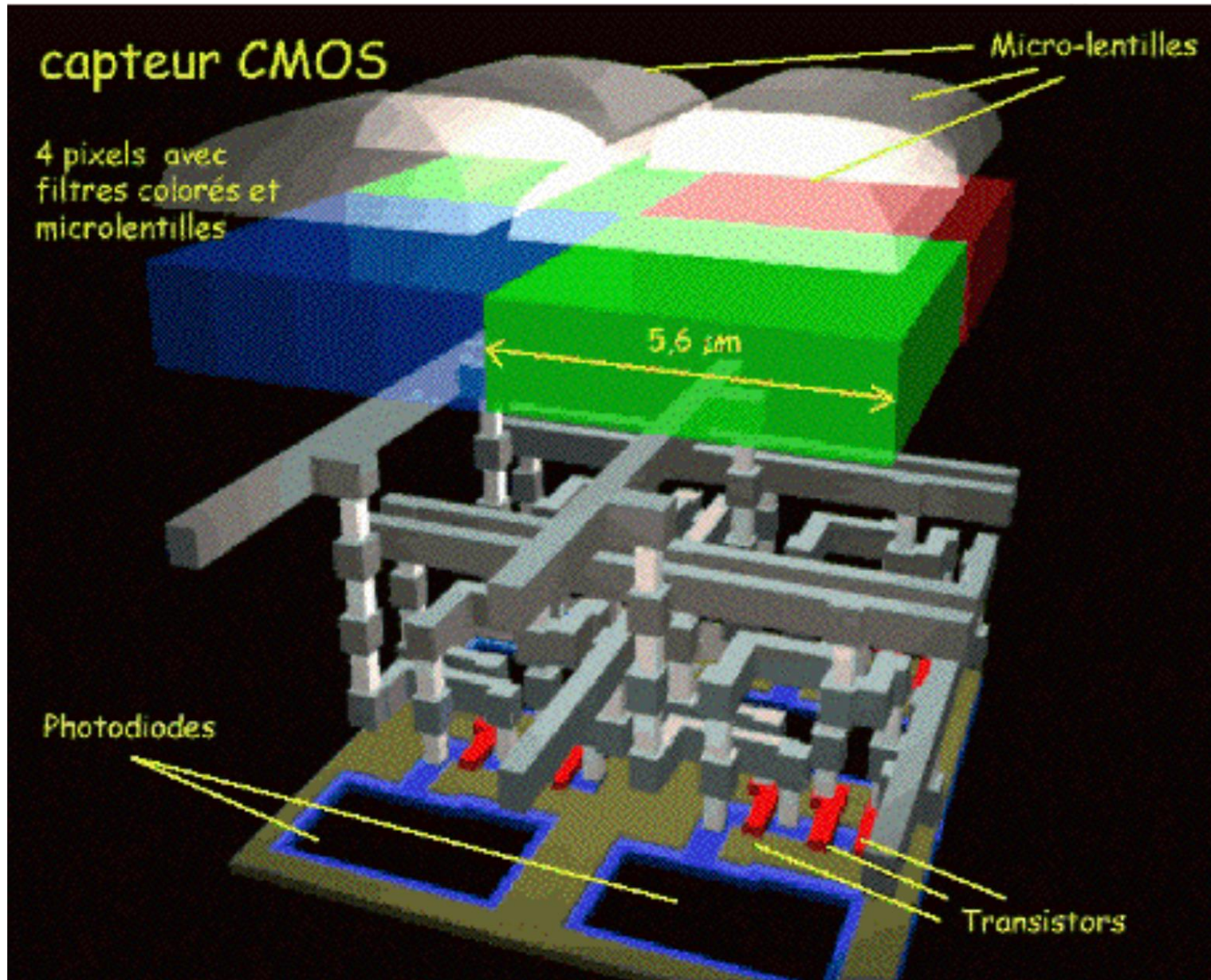
➔ Autres configurations de capteurs – Capteur CMOS



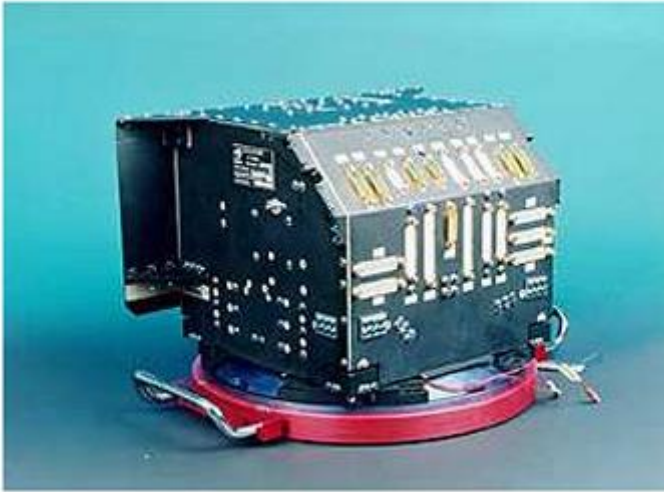
Développé à Saint-Egrève sans débouché commercial

Fabriqué à ST depuis 2000

➡ Capteur CMOS en 3D



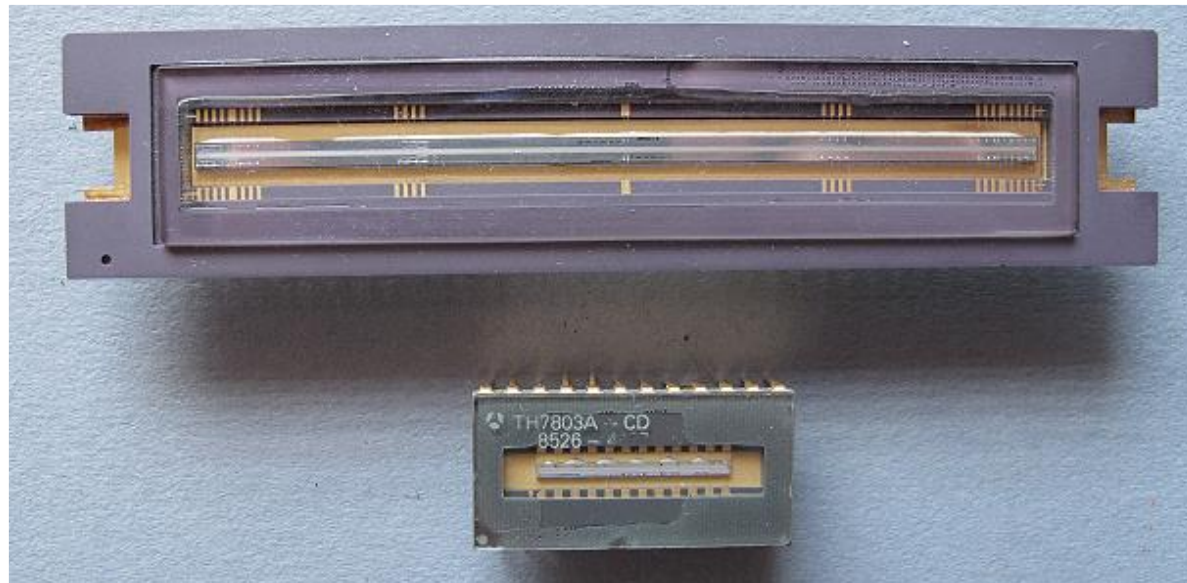
➔ TH 7834 – 12000 points pour SPOT 5



Boitier de détection

Dans le boîtier de détection, les détecteurs utilisés sont :

- pour la voie PAN, un **détecteur TH7834 (THX31535) de TCS, constitué de deux lignes détectrices de 12000 détecteurs élémentaires utiles au pas de $6.5\ \mu\text{m}$** ; ces deux lignes étant séparées d'une distance de $3.5\ \mu\text{m}$ au plan focal,
- pour chacune des voies B1, B2, B3 on utilise un détecteur TH7834 de TCS constitué d'une ligne détectrice de 12000 détecteurs élémentaires utiles au pas de $6.5\ \mu\text{m}$,
- pour la voie MIR, un détecteur TH31903 de TCS, constitué de 3000 détecteurs élémentaires utiles au pas de $26\ \mu\text{m}$ alignés sur une même ligne géométrique.



➡ TH 7834 – 12000 points pour SPOT 5

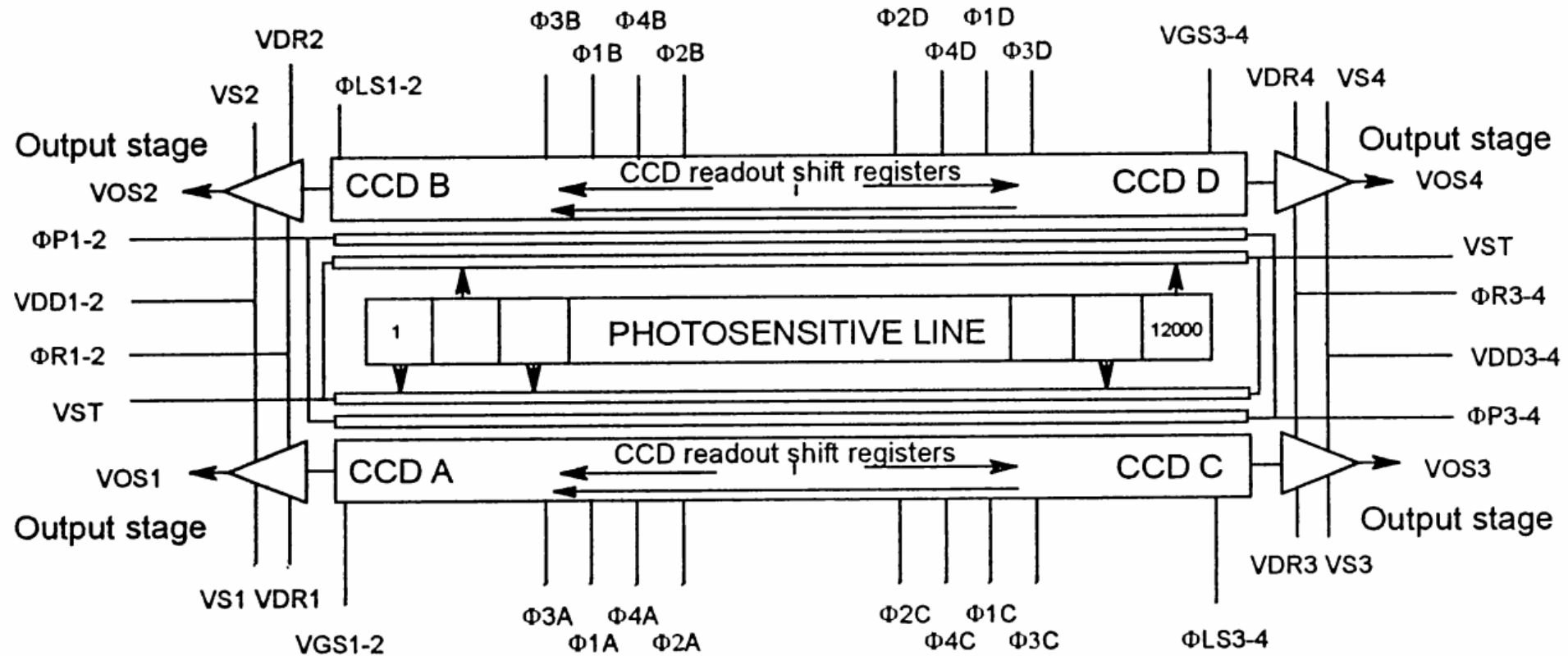


Fig.1 : TH 7834 block diagram.

➡ TH 7834 – 12000 points pour SPOT 5

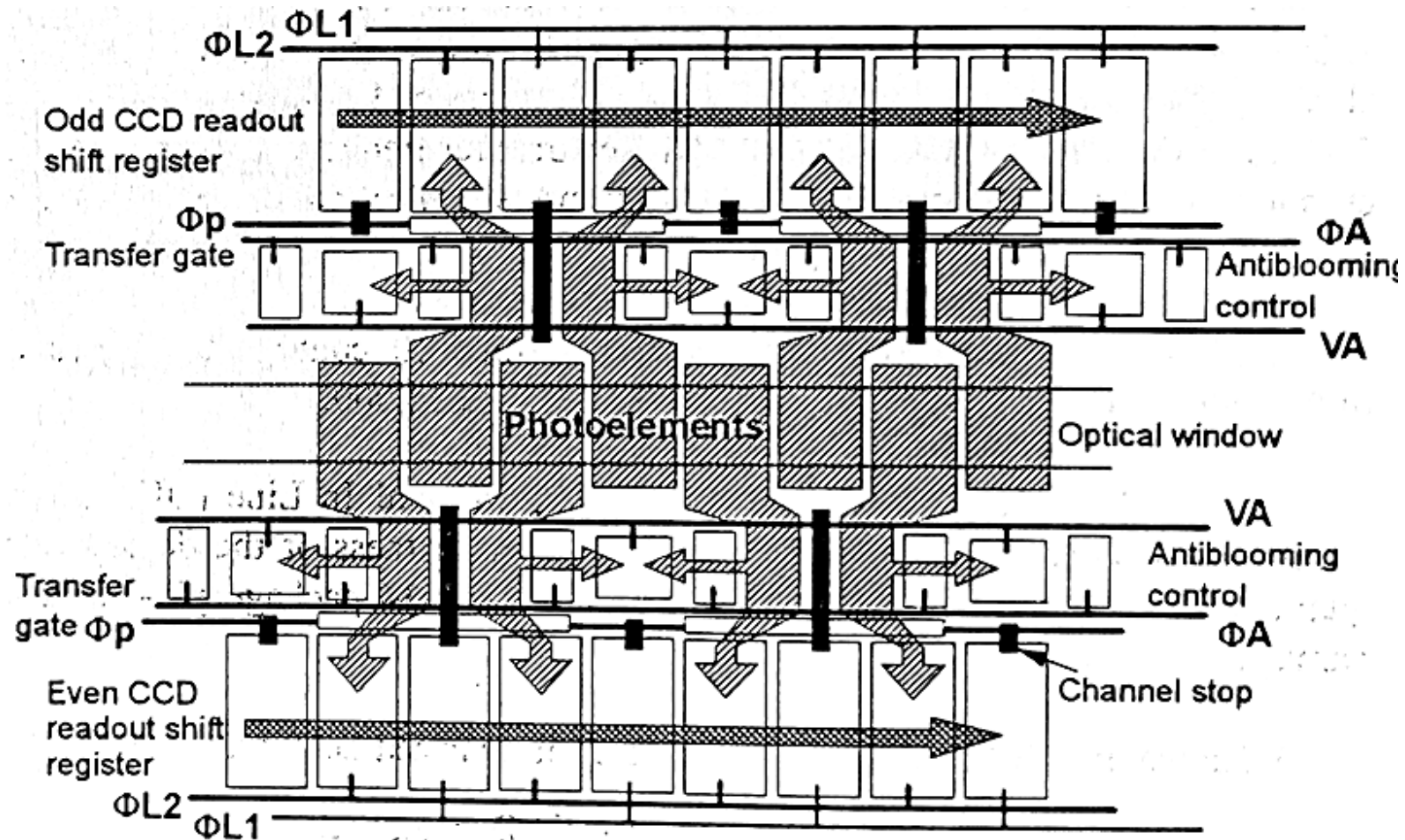


Fig.3. TH 7834 pixel architecture.

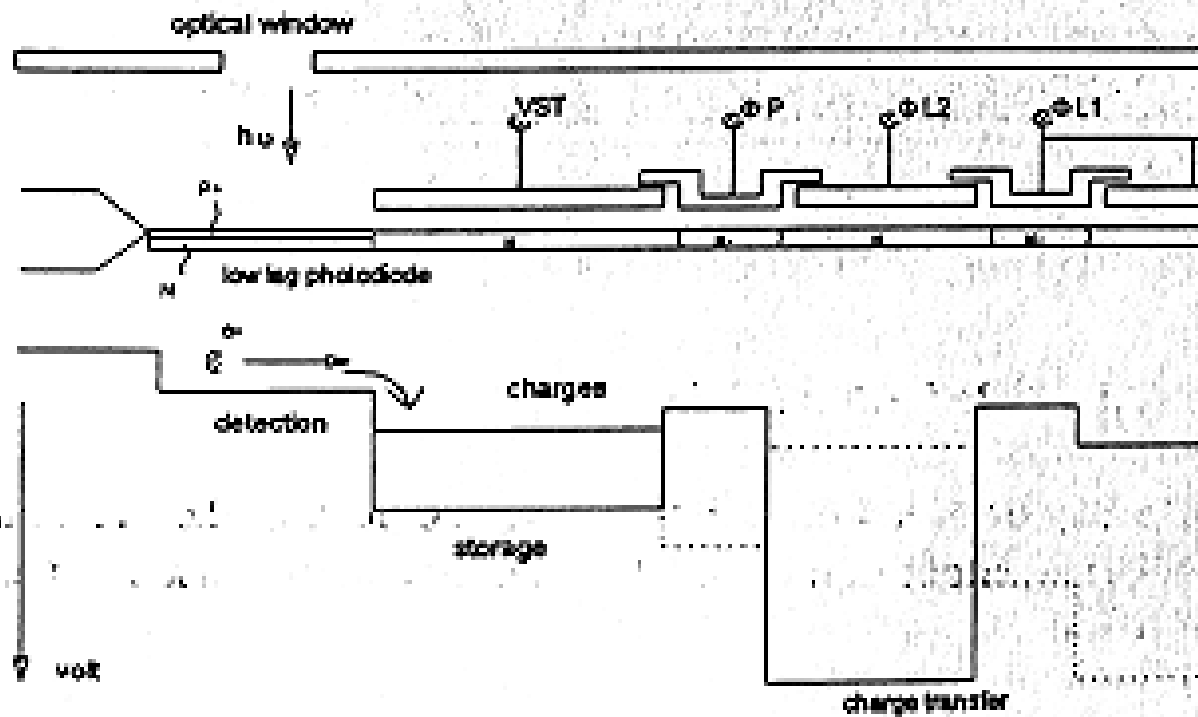


Fig.6. Potential from photodiode to CCD.

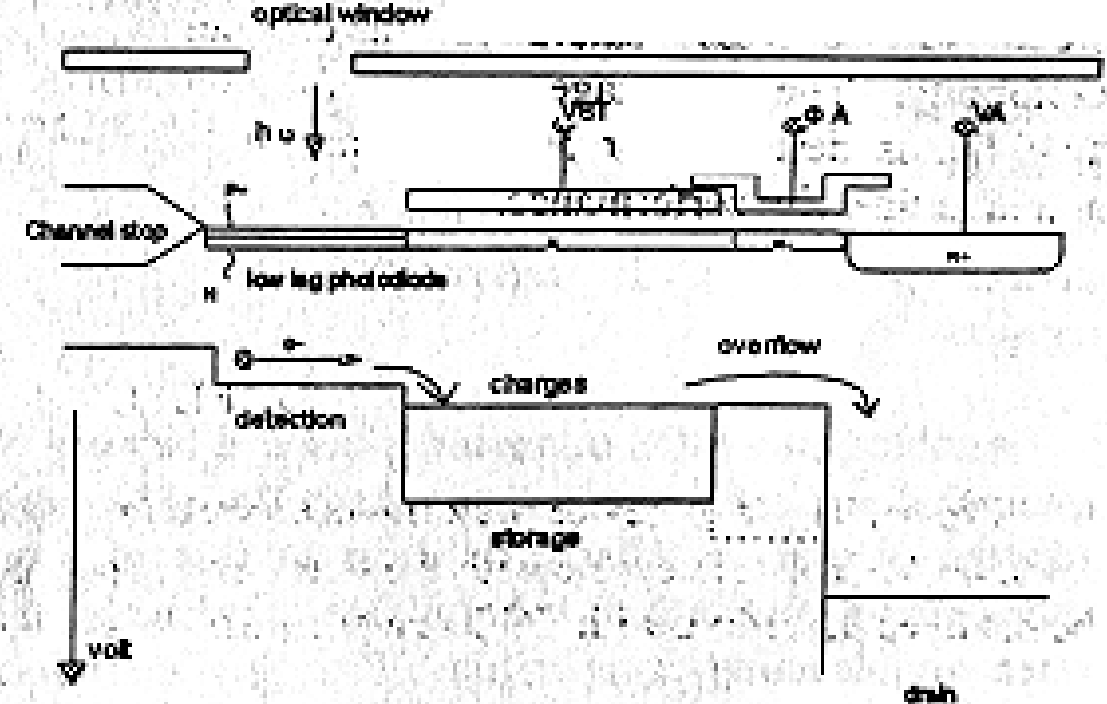


Fig.7. Potential from photodiode to antiblooming drain.

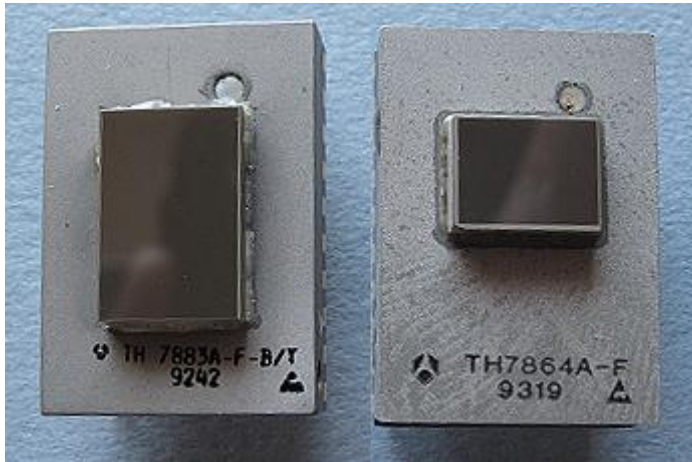


Observations avec TH7883

<http://www.observatoire-binou.fr/MISSION%20AU%20PIC%20DU%20MIDI%20EN%201993.html>

<https://ui.adsabs.harvard.edu/abs/1987OptEn..26..902B/abstract>

Couplage fibre optique TH 7883 : <https://finesensing.com/iiimaging/doc/FiberOpticCouplings.pdf>



- TH7834 [1997-12000_elementsMonolithic_CCD_Linear_Sensor_for_HR.PDF](#)
- TH7896 [1024_1024_CCD_Array_scientific_application.pdf](#)
- TH7882 [backside_illuminated_CCD.pdf](#)