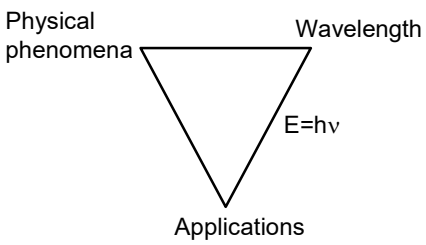
RADIATION SENSORS

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

Vincent Nourrit
Vincent.Nourrit@imt-atlantique.fr
Tel.: 02 29 00 14 91

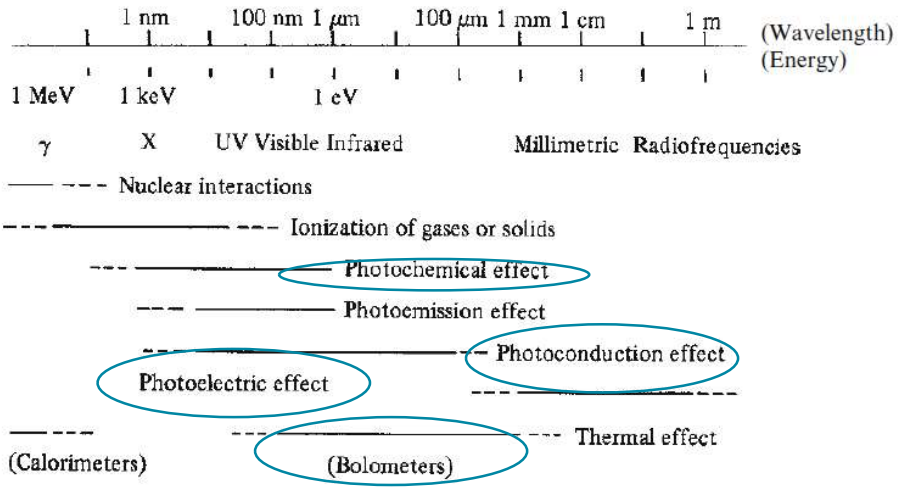
OPTICAL SENSORS

- EM radiations plays a key role in sensing applications.
- Transforming energy from a physical phenomenon → usable signal
- ⇒ nature of the radiation ⇒ type of sensor

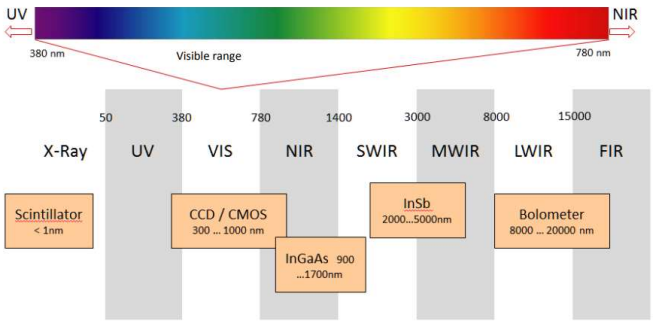


IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

THE PHYSICS OF EM RADIATION DETECTION



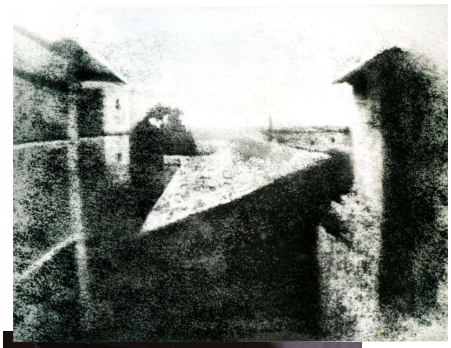
IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom



IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

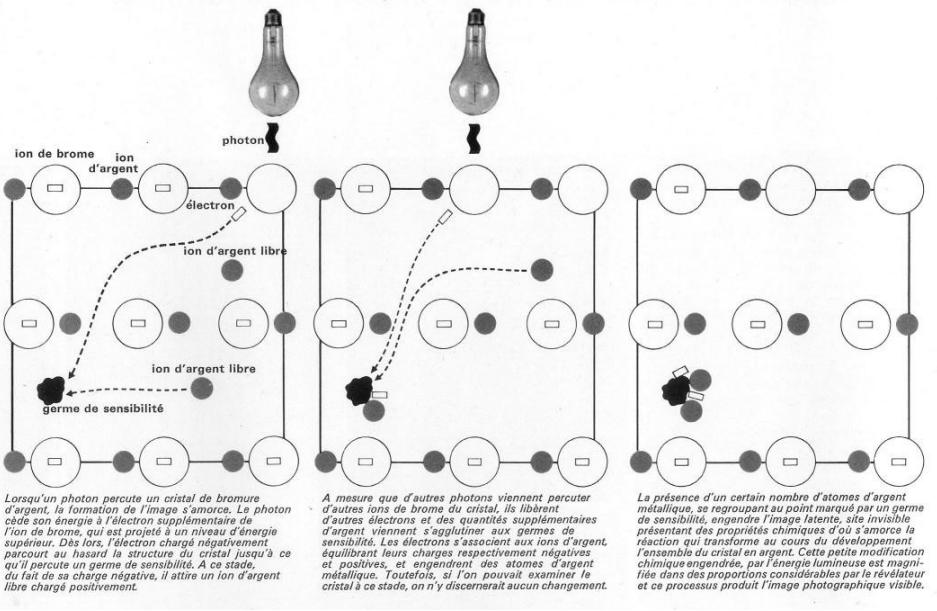
Physical phenomena	Sensor
Photochemical	Analog photography
Photoconductivity	Photoresistor
Photovoltaic effect	Photodiodes CCD and CMOS sensors *Avalanche photodiode, SPAD*
Photoelectric effect	Photomultiplier tube
Radiant heat	Bolometer

1- ANALOG PHOTOGRAPHY



Joseph Nicéphore Niépce
1826 (Heliography)
Wet plate

L' étiquette bleue
1/60s (1890)
Dry plate



IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

LATENT IMAGE FORMATION

CHEMICAL TREATMENTS – DEVELOPMENT & FIXATION

- The principle of “developing” is based on the fact that when a crystal is formed, it expands around the crystals already formed (→ multiplication of Ag grains).
- Under the action of the developer, the latent image intensifies and all the exposed silver halide crystals are completely transformed into metallic silver. The latent image is thus revealed and its macroscopic density becomes sufficient to be exploited.
- Fixer: Only those components of the emulsion that have not received light are removed. The areas that have received light are loaded with metallic silver and therefore appear opaque.

https://www.youtube.com/watch?v=nue495wxlXo

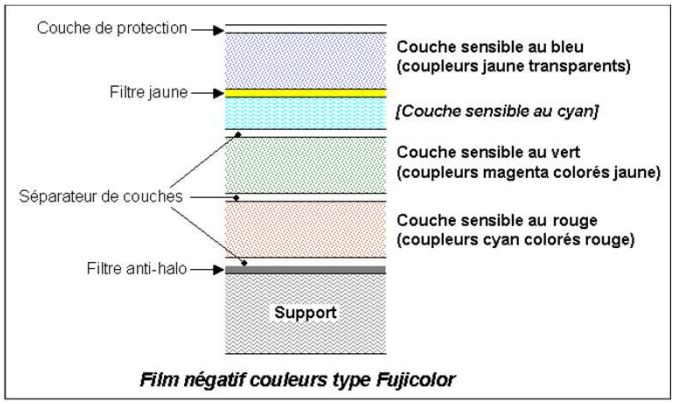
IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

COLOUR FILM

•Three layers of emulsion superimposed

•Need to balance the colors and adapt to the spectrum of the illumination (color temperature)

•Example : slide



Film négatif couleurs type Fujicolor

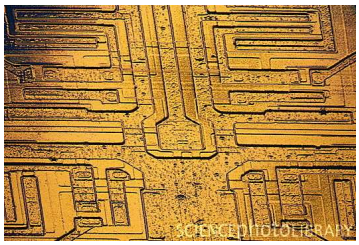
IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

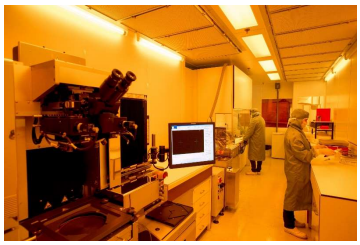
Avantages (3)
- Simplicity
- Integration time
- High resolution
  - Dans le cas d'une pellicule à grains fins (donc peu sensible à la lumière), la taille moyenne d'un grain d'argent est d'environ 20 micromètres. Il y en a donc environ deux millions à la surface d'un négatif de 24 × 36 mm, et près de 180 millions à la surface d'une plaque de 24 × 30 cm

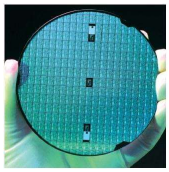
Désavantages (3)
- Non linéarity
- *Limited range (Dynamique réduite)*
- Grain effect
- Analog

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

→ PHOTOLITHOGRAPHY





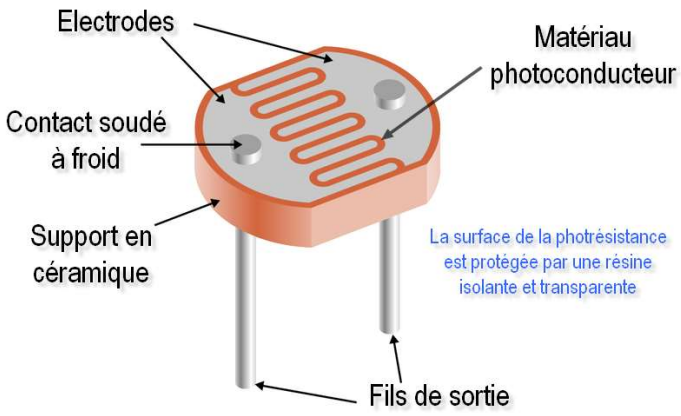


https://kerdry.com/en/photolithography/

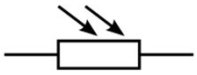
IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

2 - PHOTORESISTOR

LDR = Light Dependant Resistor, cellule photoconductric



IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom



Applications

- Detection of a difference in flow # precise measurement of the flow level
  - Presence detector
  - Switching on public or domestic lighting
- Flame detectors (IR/UV)
- Measurement of external brightness (cameras, computers).

Avantages

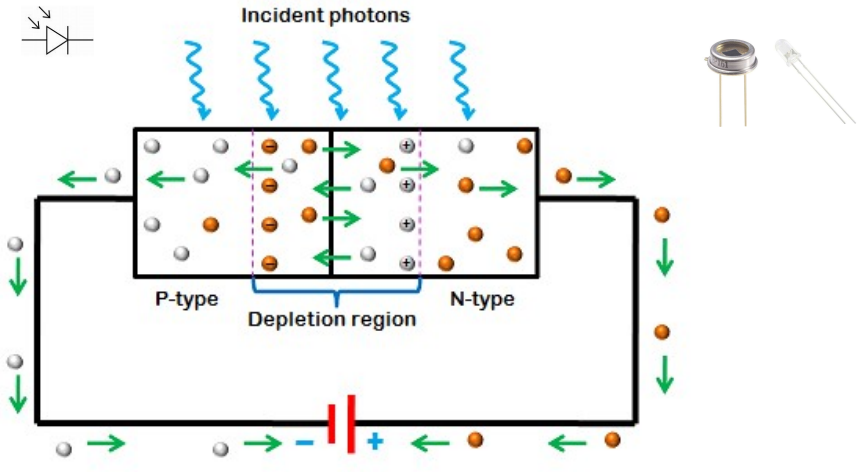
- Cheap
- Large spectral range
- Ease of implementation
- High sensitivity

Disadvantages

- Non-linearity of the response as a function of the flux.
- Thermal sensitivity
- High response time (0.1 us to 100 ms)
- Instability over time (aging due to heating)

3 - PHOTODIODES

A photodiode is a semiconductor device that converts light into an electrical current



PN Junction photodiode

Reverse biased

www.physics-and-radio-electronics.com

https://www.youtube.com/watch?v=rNoHLOumpI

15

- Capteur actif
- Conçu pour fonctionner en pola inversée (polarisation nulle (mode photovoltaïque)

- Différents types de photodiode : PIN Photodiode, APD, etc.

Material	Electromagnetic spectrum wavelength range (nm)
Silicon	190–1100
Germanium	400–1700
Indium gallium arsenide	800–2600
Lead(II) sulfide	<1000–3500
Mercury cadmium telluride	400–14000

16

Advantages
- Sensitivity
- Relatively linear
- Cost effective (cheap, simple, life span,…)

Disadvantages
- Active sensor
- Not so fast
- Thermal noise greatly affects its performance.

4 - PMT

17

Photoelectric effect
+ : Sensitivity, linearity, UV
- : 1D, <1200nm

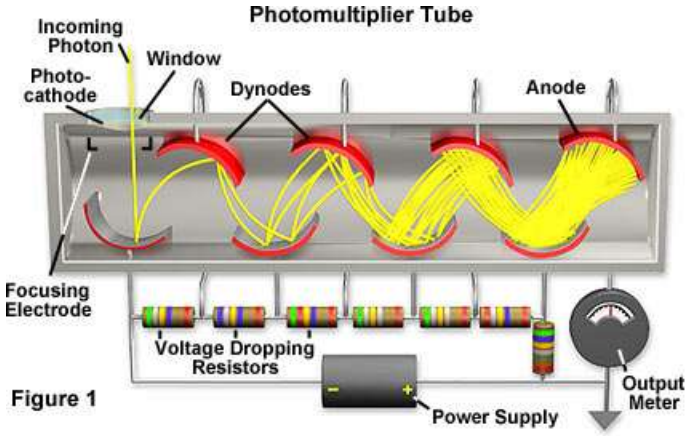


Figure 1

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

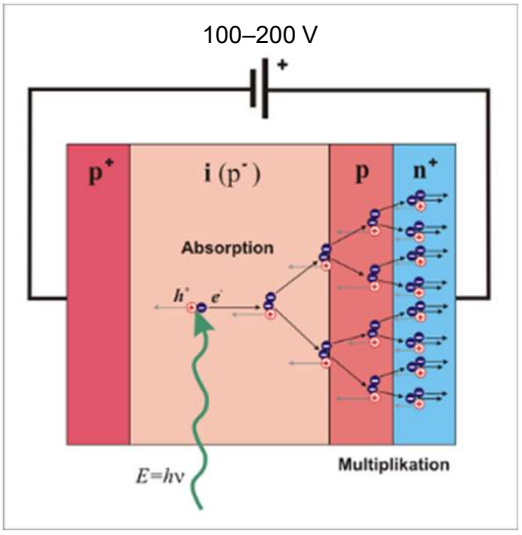
18

Advantages
➡High sensitivity, Low dark current
➡High linearity
➡*Wide spectral response*
➡High stability

Disadvantages
➡Mechanically fragile (made of glass envelope).
➡Shapes and sizes are limited and are physically large.
➡Need stable high voltage power supplies.
➡Expensive, available in hundreds of dollars.
➡Responsivity affected by magnetic fields, hence it requires magnetic shielding in critical applications.

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

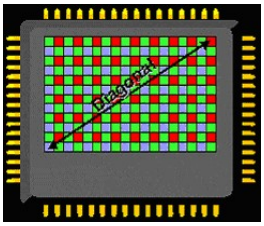
5 - APD, SPAD



IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

6 - IMAGE SENSORS

An image point is composed of a photosensitive element and sometimes local electronics



- **The two main types of image sensors used in digital imaging technology are**
  - **the charge-coupled device (CCD) - based on MOS capacitors**
  - **the active-pixel sensor (CMOS sensor). – based on MOS transistors**

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

MOS CAPACITANCE

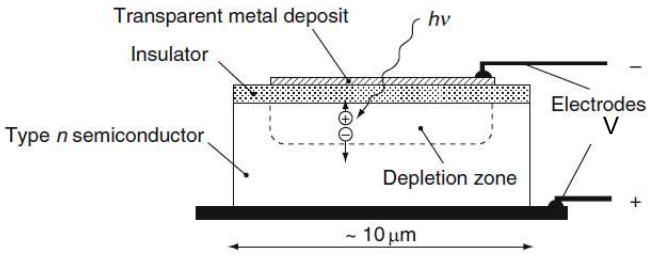
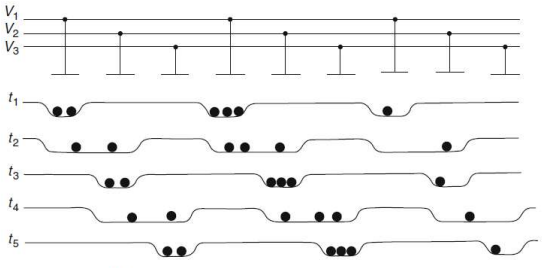


Fig. 7.28 Metal–oxide–semiconductor (MOS) capacitance. The voltage applied at the upper electrode acts on mobile charges in the n-type semiconductor. For $V > 0$, the majority carriers (e^-) accumulate at the surface under the insulator. For $V < 0$, the majority carriers (e^-) are repelled far from the surface, creating a depopulated or *depletion zone*, without mobile charges, which is thus insulating. For $V \ll 0$, a positively charged inversion layer is formed at the surface, and this is a potential well for the minority carriers (+ holes). The photocharges caused by incident photons ($h\nu$) modify the surface potential. The lower electrode can be made transparent to radiation, freeing the upper part for the electrical connections of the readout circuit

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom



Time / Voltages	t_1	t_2	t_3	t_4	t_5
V_1	−5	−5	0	0	0
V_2	0	−5	−5	−5	0
V_3	0	0	0	−5	−5

Fig. 7.29 Principle of charge transfer in the CCD detector. Each pixel is defined by three electrodes. Electrons are represented by balls, which move within the potential wells created by the electrodes, and evolve in time. (After Fauconnier T., doctoral thesis, University of Paris VII, 1983)

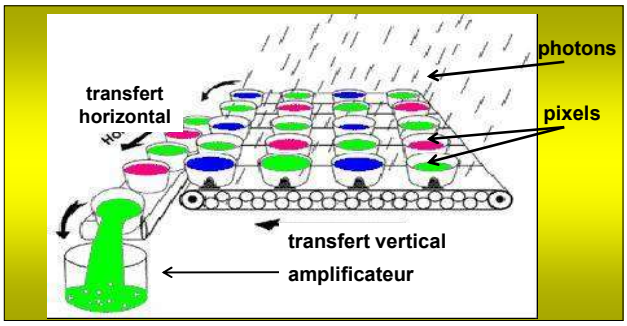
IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

CHARGE-COUPLED DEVICES (CCD)

•Historical technology (1980)

•Transfer of charges sequentially vertically then horizontally to a single destination where they are amplified

•CCD-specific manufacturing technology (external clocks and voltages)



IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

- Avantage
  - digital
  - linearity
  - Thinning cdd allows to increase X sensitivity
- Disadvantage
  - (homogénéité de réponse)
  - Size
  - Dark current
  - CCD controller = essential element manages clock and charge transfer, reading frequency, gain, binning
- Application CCD : Acquisition with minimal noise / Low light intensities
  - Microscopy, astronomy, etc.

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

Hover to zoom

Hasselblad H6D-400c Multi-Shot Medium Format Digital Camera Body

Once again Hasselblad has pushed image quality to the limit with our latest Multi-Shot camera. The amazing H6D-400c MS, delivers the highest resolution, most colour accurate medium format images available on the market today.

Brand: **Hasselblad**
Sku: **HAS3013774** Manufacturer SKU: **3013774**

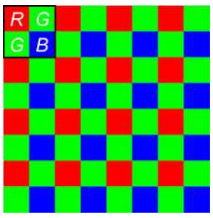
Excl. Vat: **£36,250.00**
Incl. Vat: **£43,500.00**

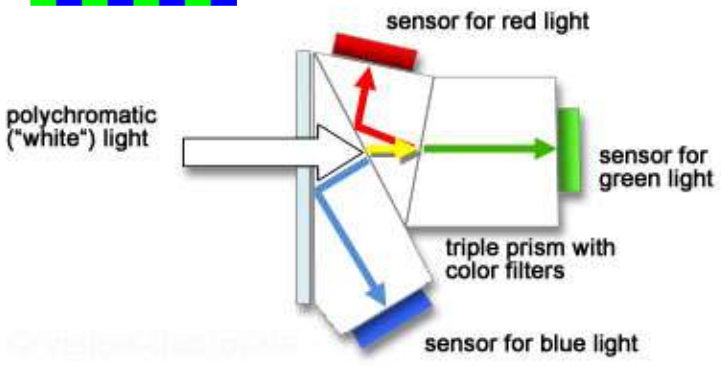
Appareil Photo Lubitel 166b
Particulier
30,00 EUR
ou Offre directe
0 enchères
3 j 16 h
Remise en

APPAREIL PHOTO ARGENTIQUE LUBITEL 166B LOMO
Particulier
60,00 EUR
15,00 EUR de frais de livraison

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

COLOUR CAMERA





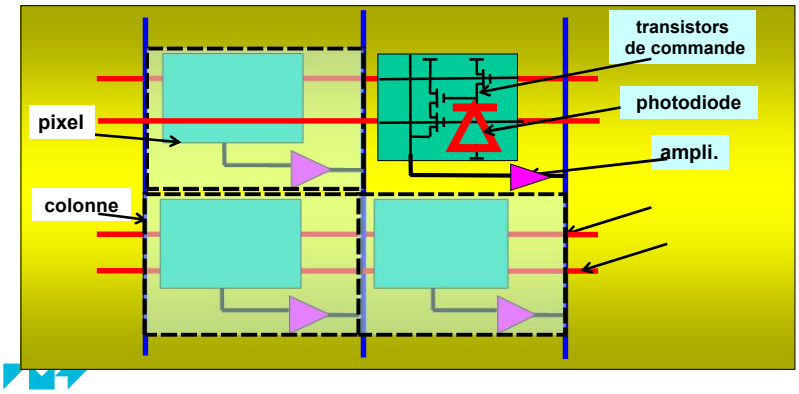
C-MOS

.Chaque point image contient :

.une photodiode qui effectue la conversion des photons en charges électriques

.un convertisseur charges-tension, des transistors de sélection et de reset

.un amplificateur de tension local



IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

COMPARAISON CCD ET C-MOS

•Capteur CCD

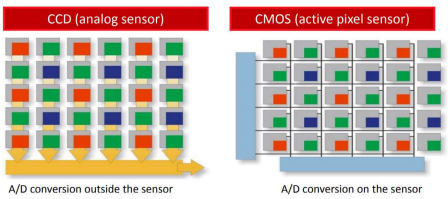
- ☺ **Meilleur taux de remplissage (=> sensibilité)**
- ☹ **nombreuses alimentations et horloges extern**
- ☹ **pas d'intégration locale du traitement d'image**
- ☹ **technologie spécifique coûteuse (composant**

•Capteur C-MOS

- ☺ **intégration des mémoires et processeur d'ima**
- ☺ **système rapide adapté à la vidéo**
- ☺ **faible consommation (0.1 W @ 3.3 V)**
- ☺ **bénéficie de la technologie C-MOS (loi de Moore) composant pas cher (/ 10)**
- ☹ **sensibilité moyenne**
- ☹ assez fort niveau de bruit
- ☹ ***Rolling shutter***

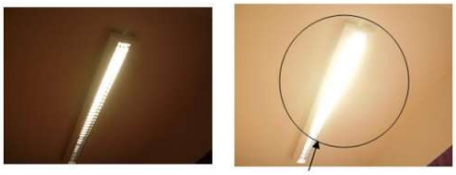
Sensors for the visible spectrum: CCD- and CMOS sensors

Advantages of CCD:	Advantages of CMOS:
High image quality:	High frame rates, even at hi
Low spatial noise (FPN)	Faster and more flexible rea (e.g. several AOIs)
Typically low dark current	High dynamic range
High fill factor (relation of the photo sensitive area to the whole pixel area) generally by larger pixels	HDR mode → Acquisition of extremely bright objects
Perfect global shutter	No blooming or smear conts
→ Increased sensitivity	Integrated control circuit on
→ Good signal quality at low light	More cost-effective and less consumption than compara
Modern CCDs with multi tap technologies → n times readout speed compared to single tap sensors	

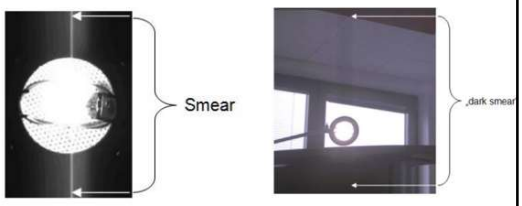


IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

Blooming:
Charge overflow (> full well capacity) between neighboring pixels
→ Corrective action: reduction of the incoming light



Smear:
During readout photons generate a charge in the vertical shift register
→ Corrective action : increase of the exposure time, use of a mechanical or LCD shutter, use of flash illumination



IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

- Applications CMOS : high speed
  - Fast tracking“ - motion analysis with markers @ 200 – 400 frames per second
  - Motion analysis for sports and wildlife, generation of slow motion picture, etc.

Recent CMOS sensors deliver:
- improved **global shutter**
- **low dark** and **spatial noise** as well
- Good image quality in **low light condition**
- **higher quantum efficiency** too

Together with the existing advantages in **speed** and **cost** which makes CMOS sensors suitable for a lot of vision applications!

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom

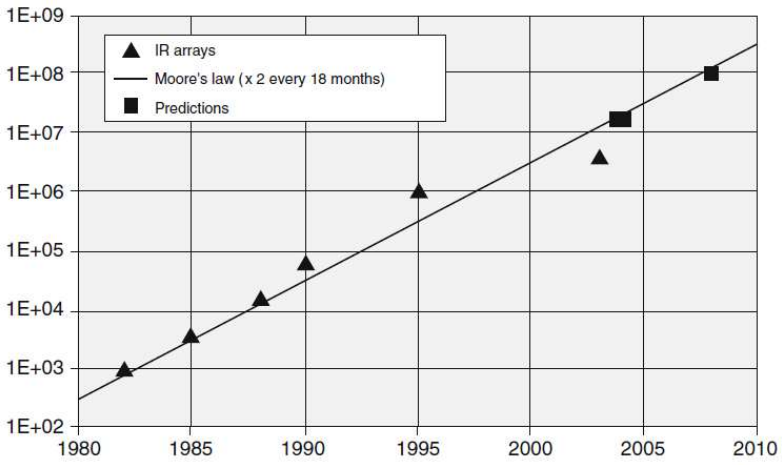
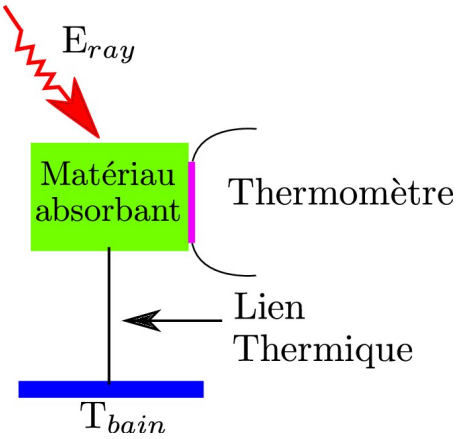
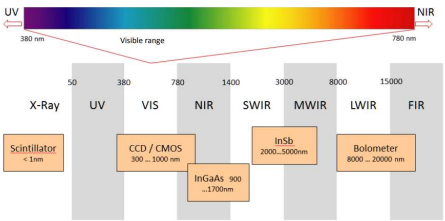


Fig. 7.31 Growing formats of imaging detectors in the near and mid-infrared using CMOS technology. *Ordinate*: Number of pixels on the detector. The *straight line* shows a doubling every 18 months (known as Moore's law). Figure established in 2004, courtesy of Hodapp K.W., Hall D.N., University of Hawaii

BOLOMETER

32



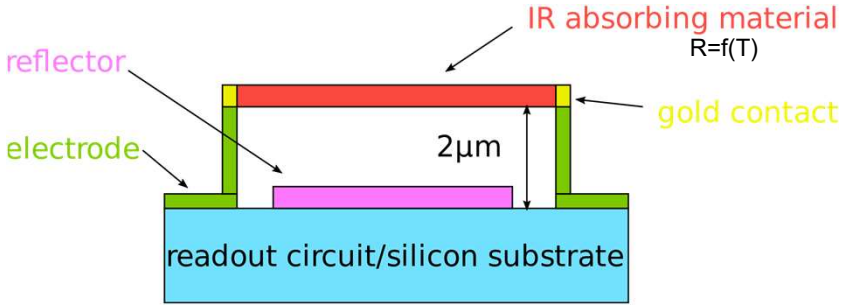


IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

22/10/2024

33

Microbolometer



IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

34

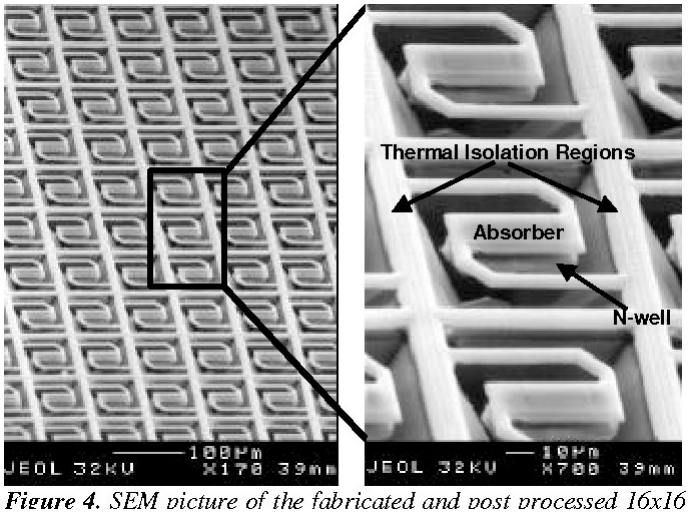


Figure 4. SEM picture of the fabricated and post processed 16x16

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Télécom

•DOI:10.1109/MEMSYS.2001.906604

OTHER SENSORS

High-energy sensors
- X (0.1-10keV) : CCD; Bolometers, etc.
- Gamma (100keV-10 MeV) : Scintillators,…

Neutrinos detection

Gravitationnal waves detection

IMT Atlantique
Bretagne-Pays de la Loire
Ecole Mines-Telecom