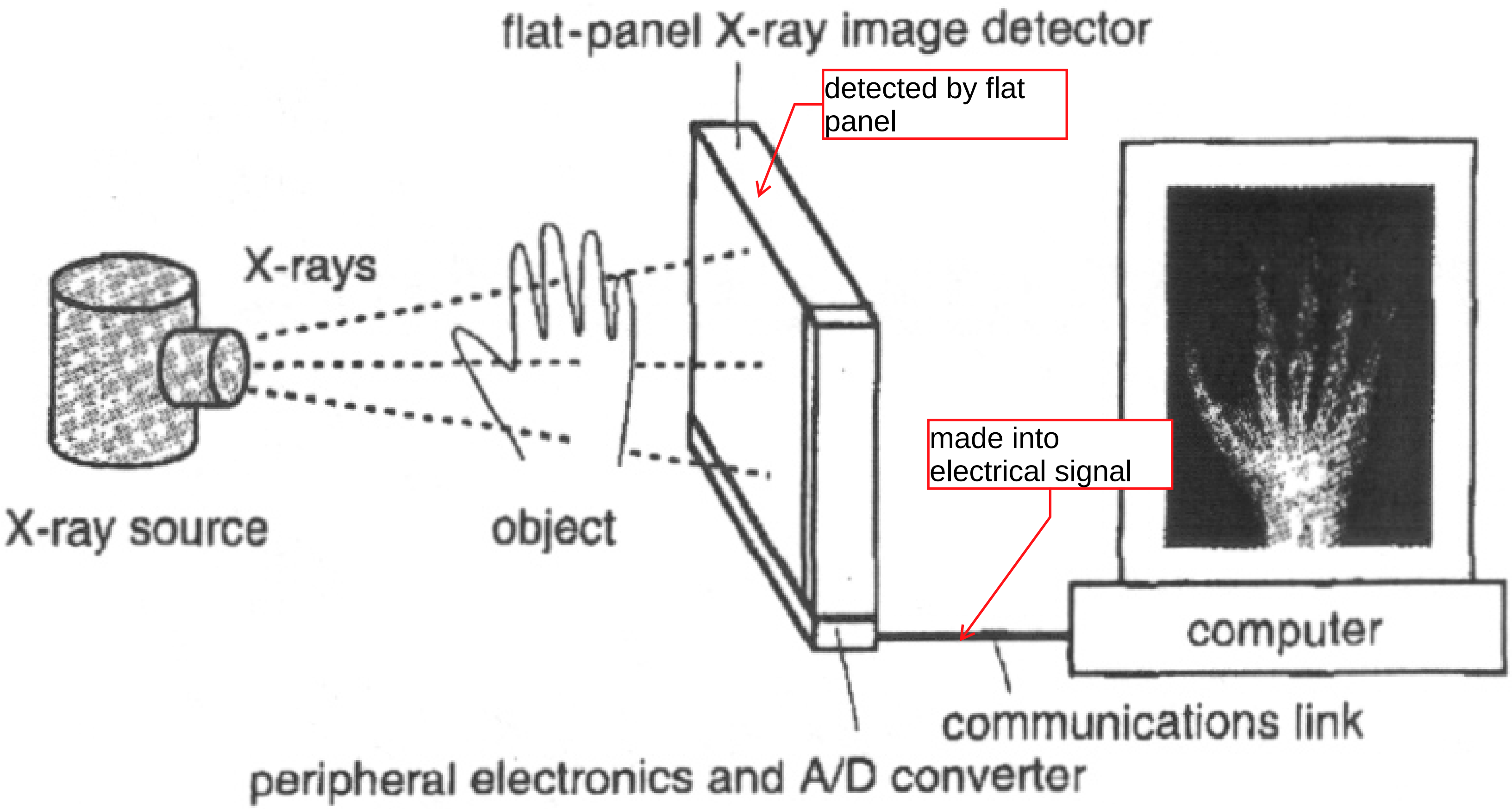
# Digital Radiography



"story time"

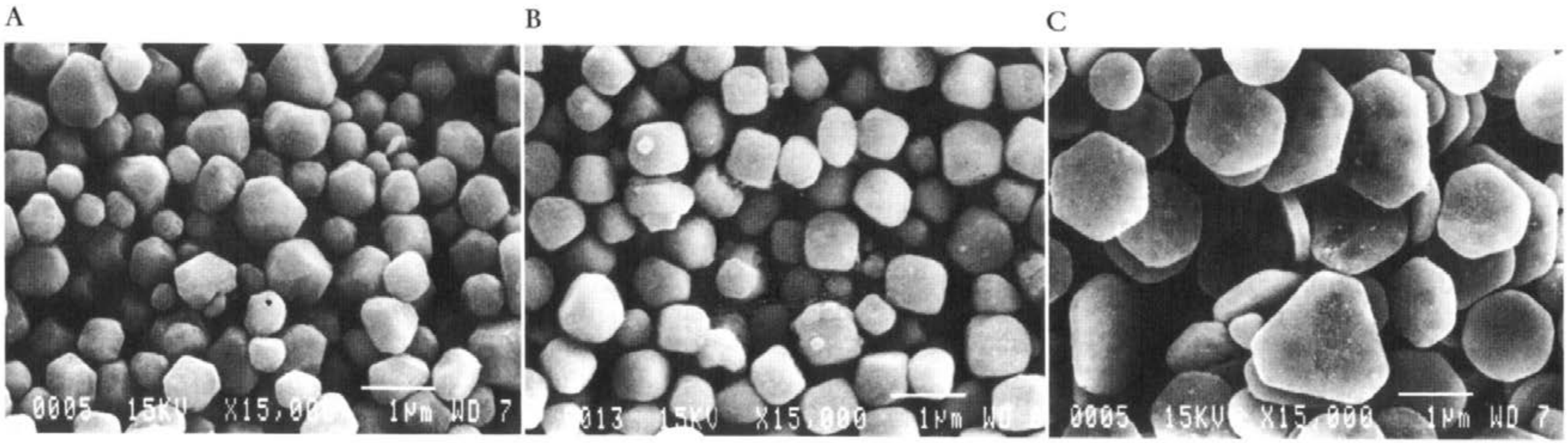
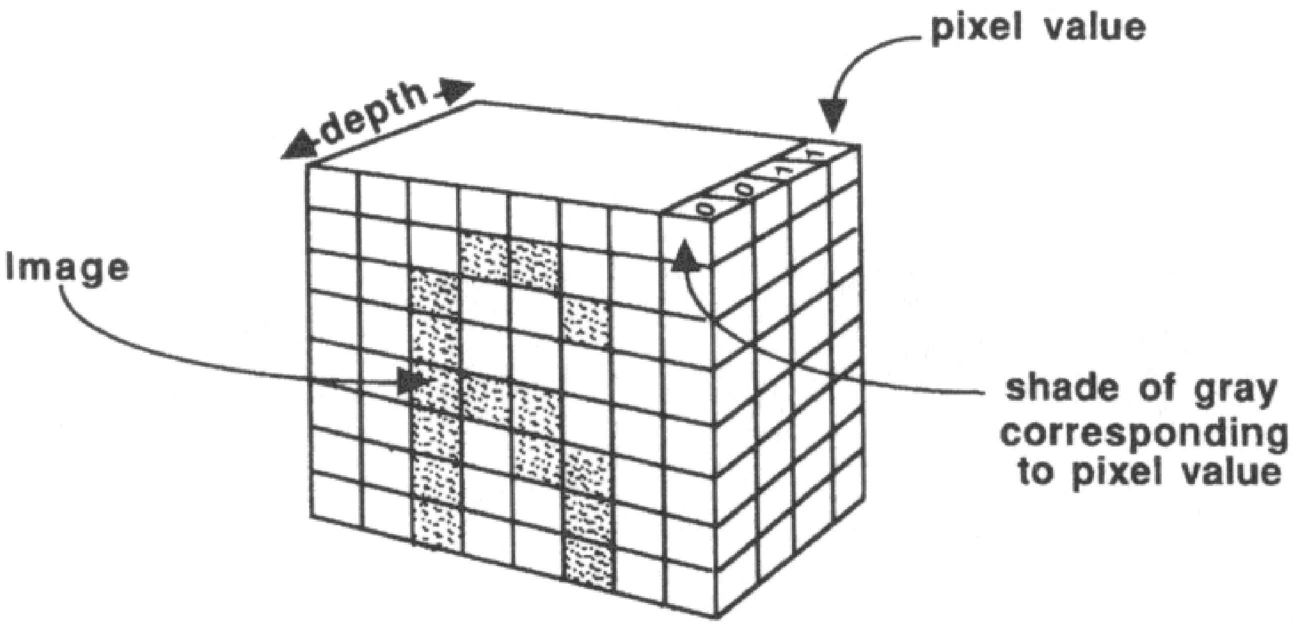



Fig. 18.2A-C – Tre microfotografie a pari ingrandimento di granuli di AgBr per emulsioni radiografiche:
A – granuli morfologicamente disomogenei
B – granuli cubici
C – granuli "laminari".

## Photographic emulsion for traditional radiography

Traditional: somehow also composed by pixels... small emulsion grains (high res., però stored su materiale fisico etc.)

# digital acquisition and registration of the image



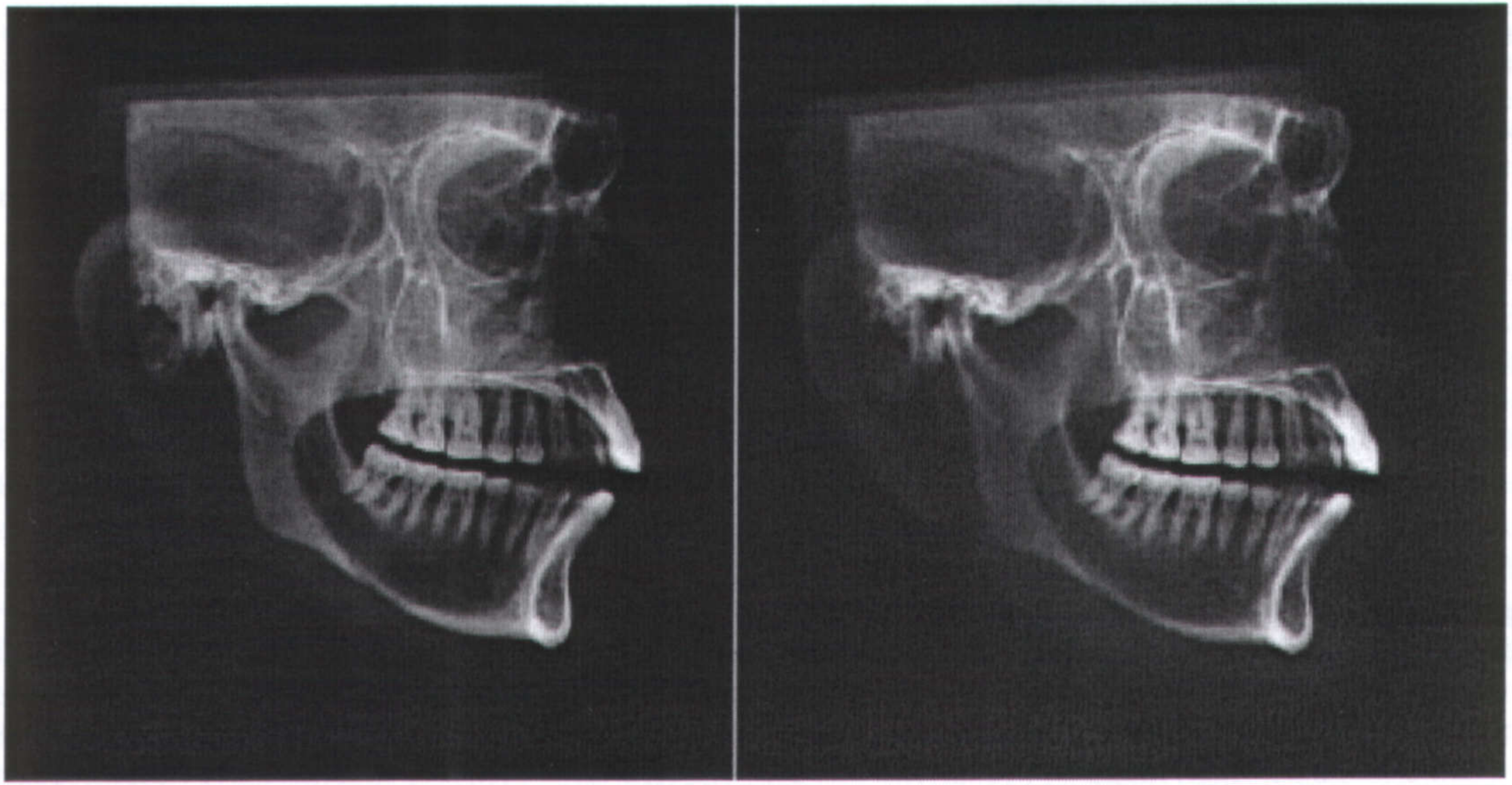

advantages vs. conventional radiography:

- it avoids emulsion-based slabs; simpler acquisition and storage of images
- digital processing of images
- it facilitates archive and communications of data

Pixelated camera. In each pixel photons are converted in el. signal. Collected and converted in digital format.

# Conventional vs. digital radiography

again: point NOT to improve res!



digital (Se amorphous, 100μm pixel) conventional (slab)

Res. of digital radiology obv. depends on pixel size.

128 × 128 256 × 256

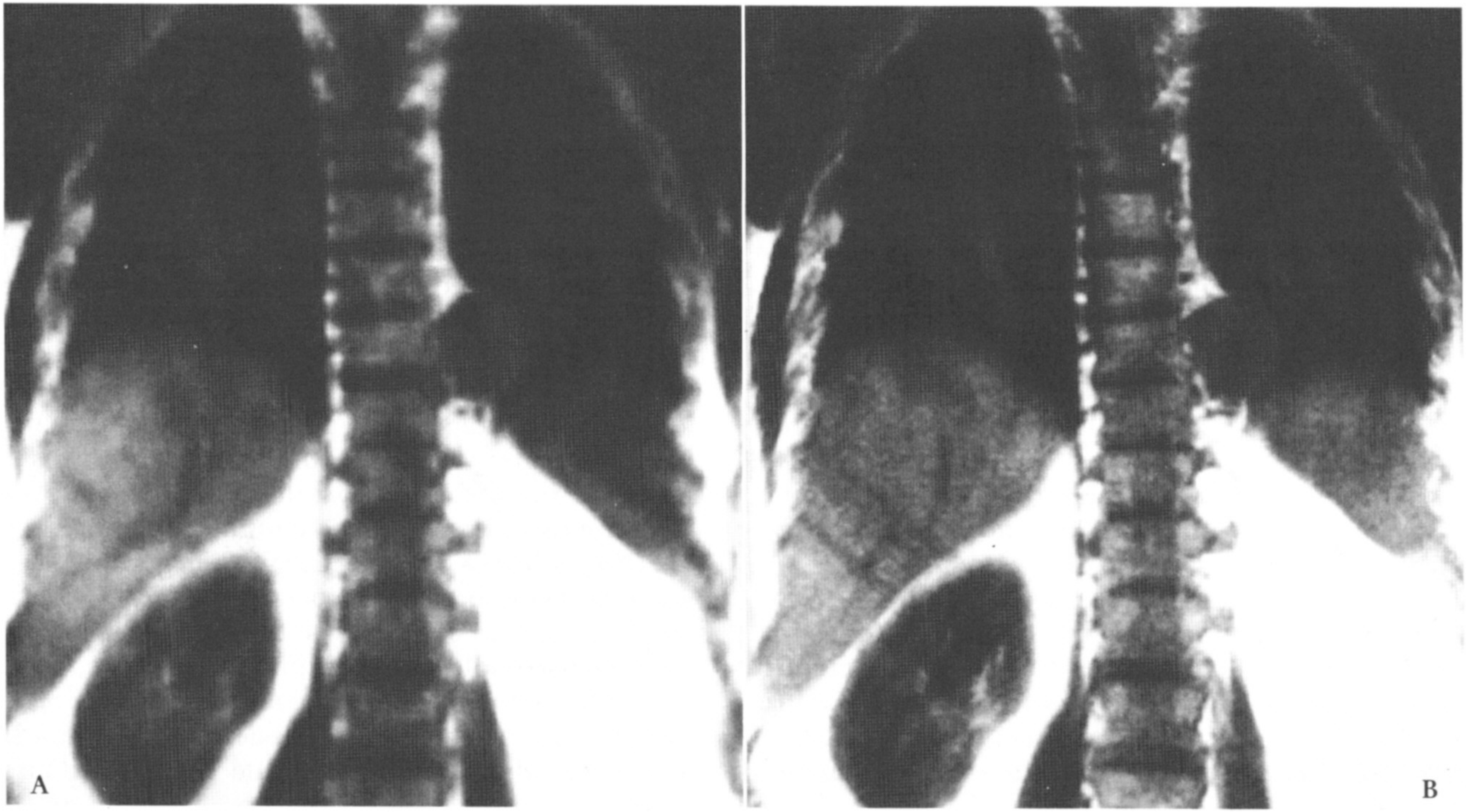



Fig. 26.2A-B – Incremento della risoluzione spaziale dell'immagine ottenuto diminuendo le dimensioni dei pixels. A: matrice 128 × 128; B: matrice 256 × 256.

just highlight main parameters (and order of magnitude)

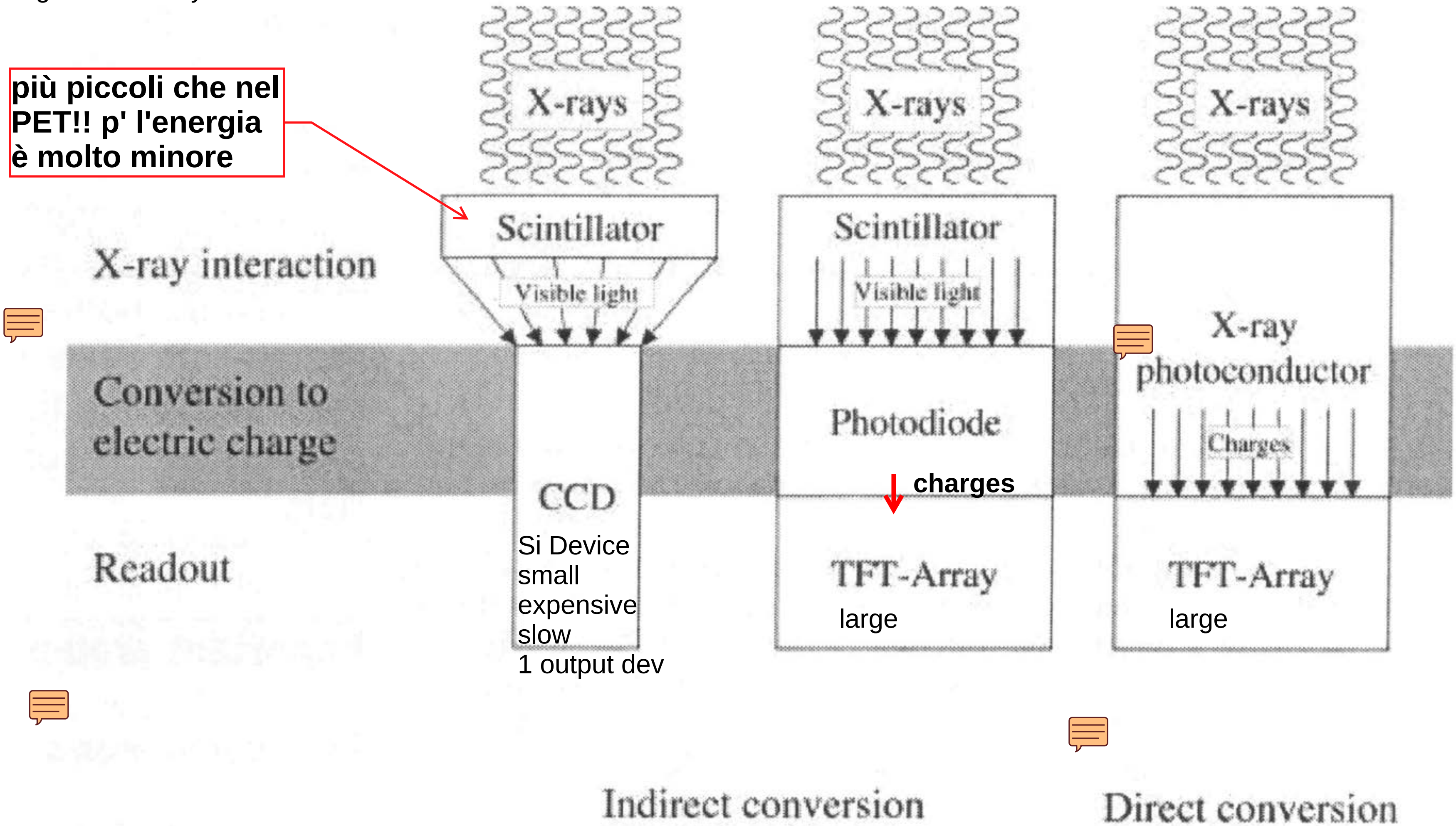
# Radiographic specifications

| | conv. rad. | specific for breast | same but movie |
|---|---|---|---|
| Clinical Task → | Chest radiology | Mammography | Fluoroscopy |
| Detector size | 35 cm × 43 cm | 18 cm × 24 cm | 25 cm × 25 cm |
| Pixel size | 200 μm × 200 μm | 50 μm × 50 μm | 250 μm × 250 μm |
| Number of pixels | 1750 × 2150 | 3600 × 4800 | 1000 × 1000 |
| Readout time | ~ 1 s | ~ 1 s | 1/30 s |
| X-ray spectrum | 120 kVp=keV | 30 kVp | 70 kVp |
| Mean exposure | 300 μR | 12 mR | 1 μR |
| Exposure range | 30 - 3000 μR | 0.6 – 240 mR | 0.1 - 10 μR |
| Radiation (quantum) noise | 6 μR | 60 μR | 0.1 μR |

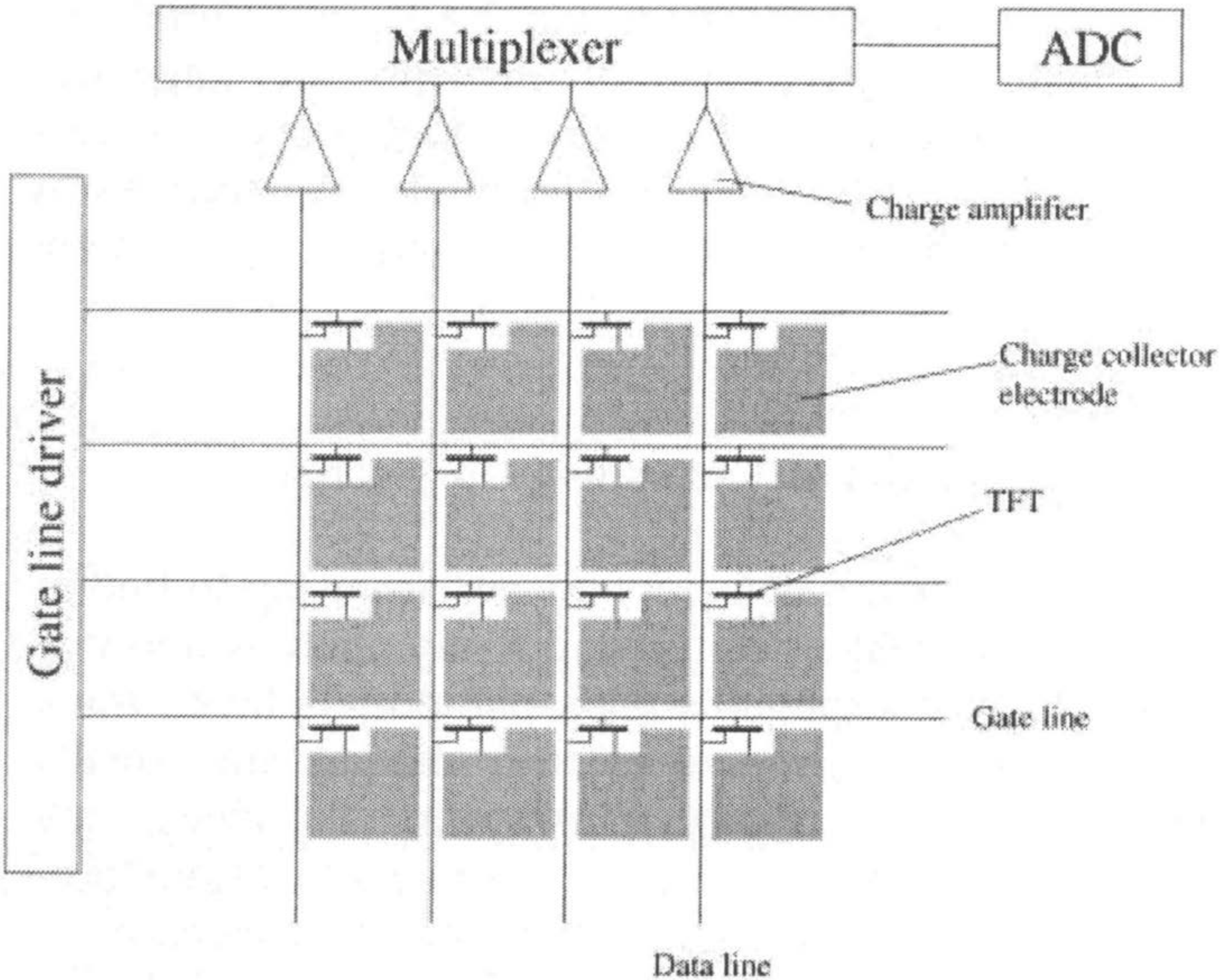
How PANELS are made, possibilities:

# Detectors for digital radiography

DIFF:
1. small scint
2. integration of xrays



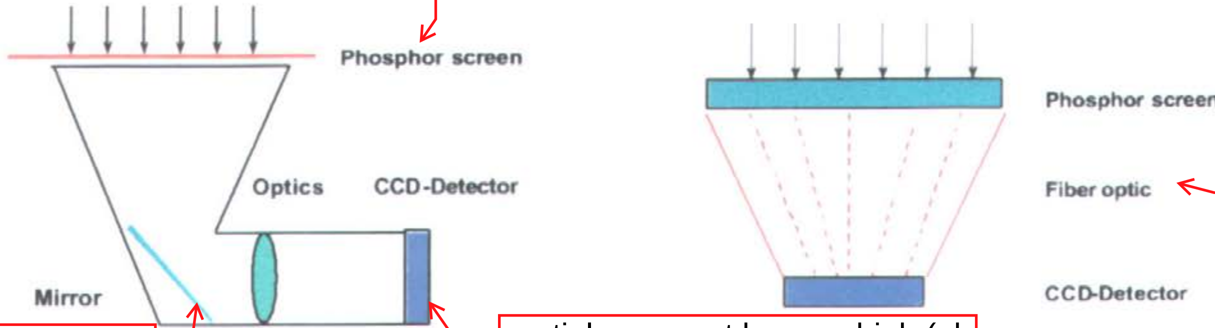

**[BTW Problem: cost/cm^2]** 2 based on indirect conv. (scintillator => visible light) and 1 direct (photoconductor). Readout TFT: THIN FILM TRANSISTOR. **DIFFERENCES WITH PET/SPECT** 1) The scintillator is not for PET! needs to stop low en. xrays, so we are talking about THIN scintillator coupled with P.D. [in PET we needed even up to 3cm!, here 1mm are enough] 2) PET/SPECT based on photocounting (we are measuring the individual g-ray). Here we **INTEGRATE** the xrays! (otteniamo l'immagine con tutti i sovrapposti) We lose the info on the single phenergy. (praticamente integriamo su tutto lo spettro di en.)not good, b/c absoprtion cap. of body depends! on this energy. modern: try to overcome the limitation with photcouting/energy sel. capability.. aka coloured xray radiography) no



Multiplexer
ADC
Charge amplifier
Gate line driver
Charge collector electrode
TFT
Gate line
Data line

# 1° METODO

similar to scint




alternative to focus

mirror optics to focus image into small fov

spatial res. must be very high (ok for ccd), b/c we are minifing

Figure 7. Collection of light from an X-ray absorbing phosphor or CsI(Tl) scintillator with optical lenses and mirrors (left) or with the use of fibre optic (right). (Figures supplied by Siemens).

for mammography: 1:1 coupling scint/det.
b/c ... audio

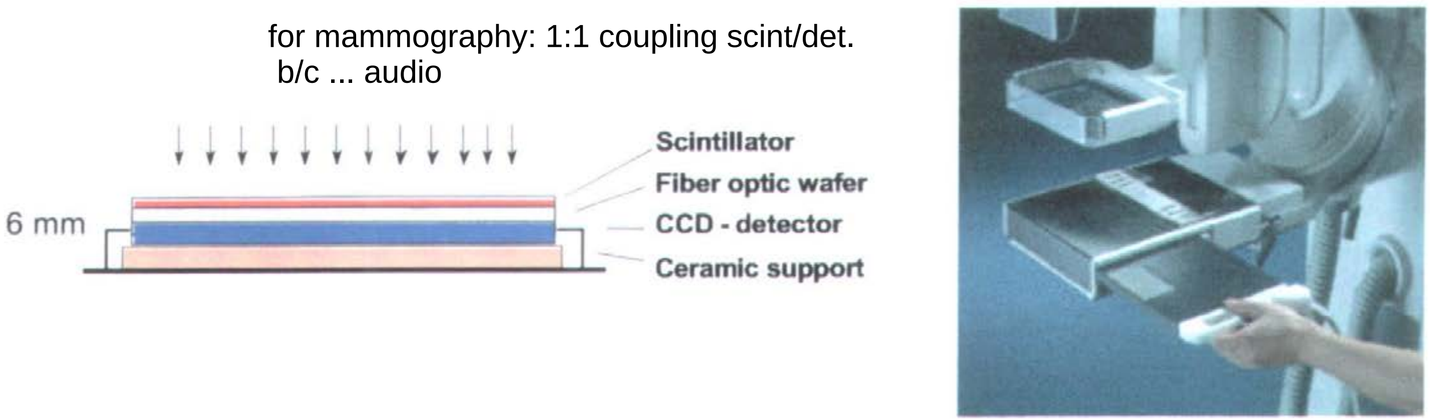
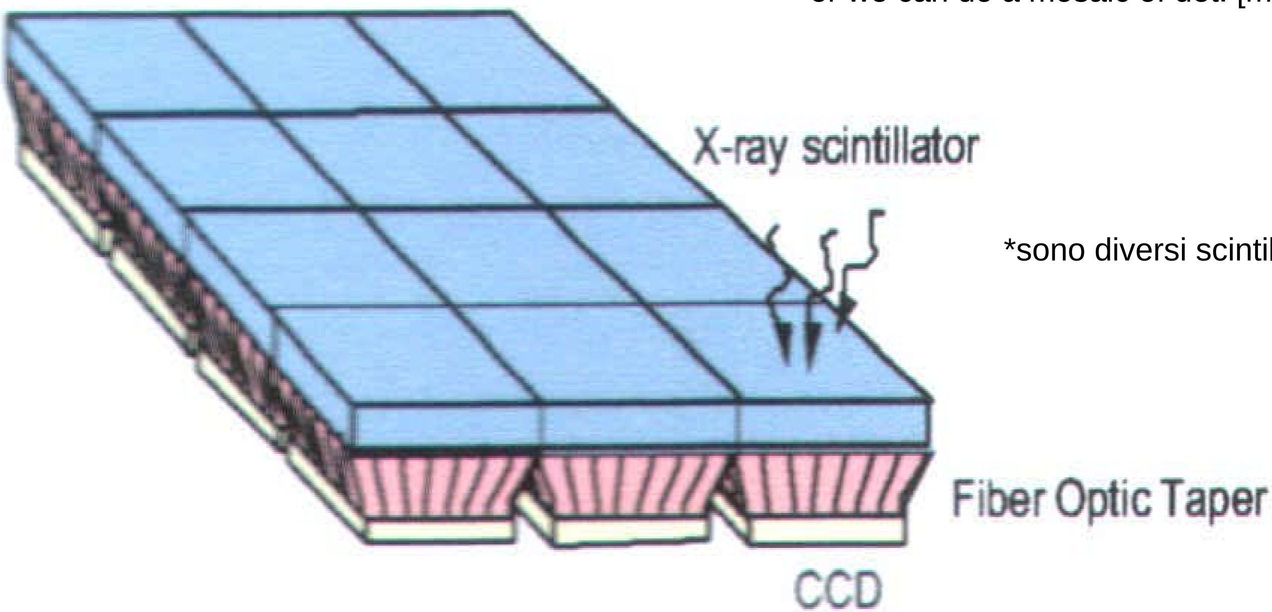



Figure 8. A CsI(Tl)-CCD detector with a 4.9 cm x 8.5 cm field of view. The principle of operation is shown (left) as well as the use of the detector in a cassette that can replace a film cassette in a mammography unit (right). (Figures supplied by Siemens).

or we can do a mosaic of det. [mammography?]




*sono diversi scintillators

Figure 9. A mosaic detector with 3 x 4 detectors of CsI(Tl), each coupled to a CCD with fibre optic.

# CCD

# Charge Coupled Device

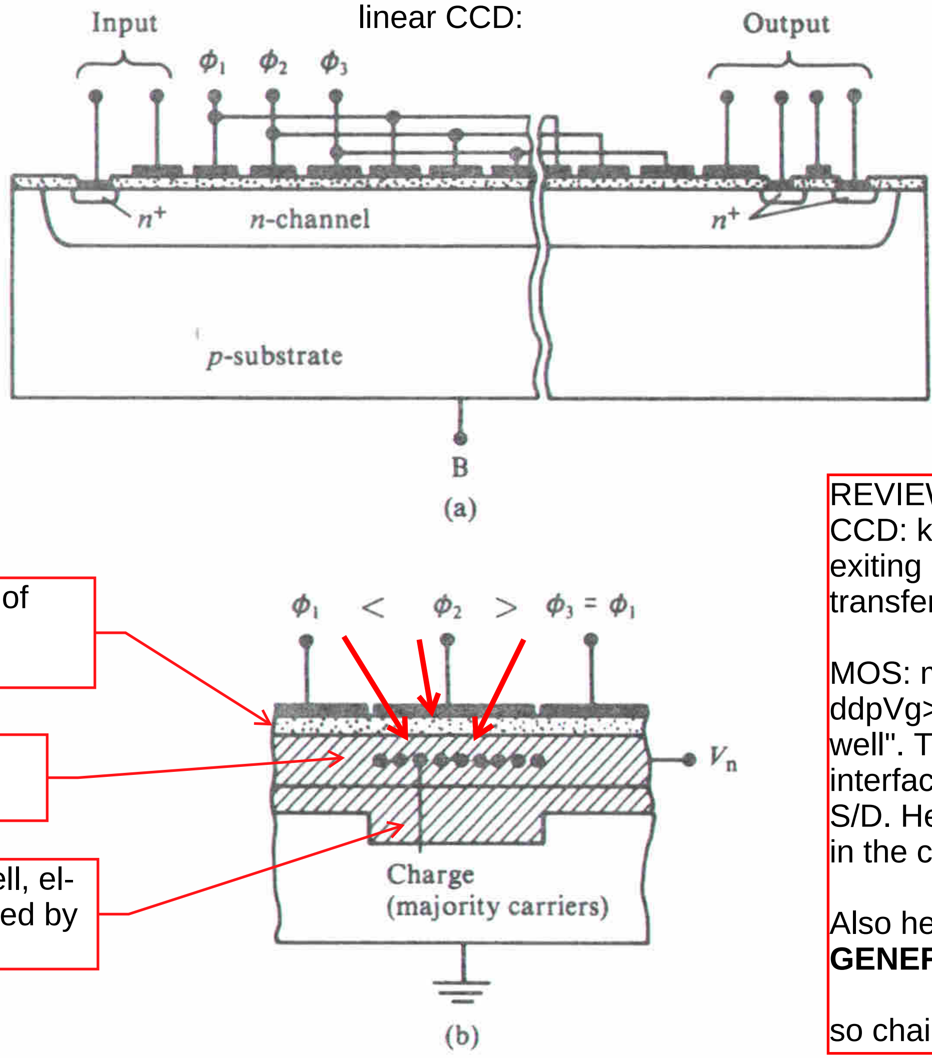



Fig. 3.3 Bulk-channel charge-coupled device (BCCD). The structure in (a) is a three-phase structure, showing the $n$-channel on a $p$-substrate; and (b) shows the charge stored in the $n$-channel as majority carriers. Reprinted after Ref. [4] with permission.

linear array of single MOS structures

**optical generation**

potential well, el- are generated by light here

REVIEW OF CCD.
CCD: key point: can cover large imaging area, with few exiting nodes. It's a pixelated sensor with a smart way to transfer charges into a common exit node.

MOS: metal oxide semiconductor M [ox][Si p] => apply ddpVg>0, depleate holes in the region creating a "potential well". Then Vg is so high that accumulates el- in the interface Si/Ox. These electrons in the channel comes from S/D. Here we dont have D and Source, and thus electrons in the channel. But we have a **potential well**.

Also here in the well el- are stored, but by **OPTICAL GENERATION**

so chain of MOS, in each one we create a well.

# Charge storage in the pixel

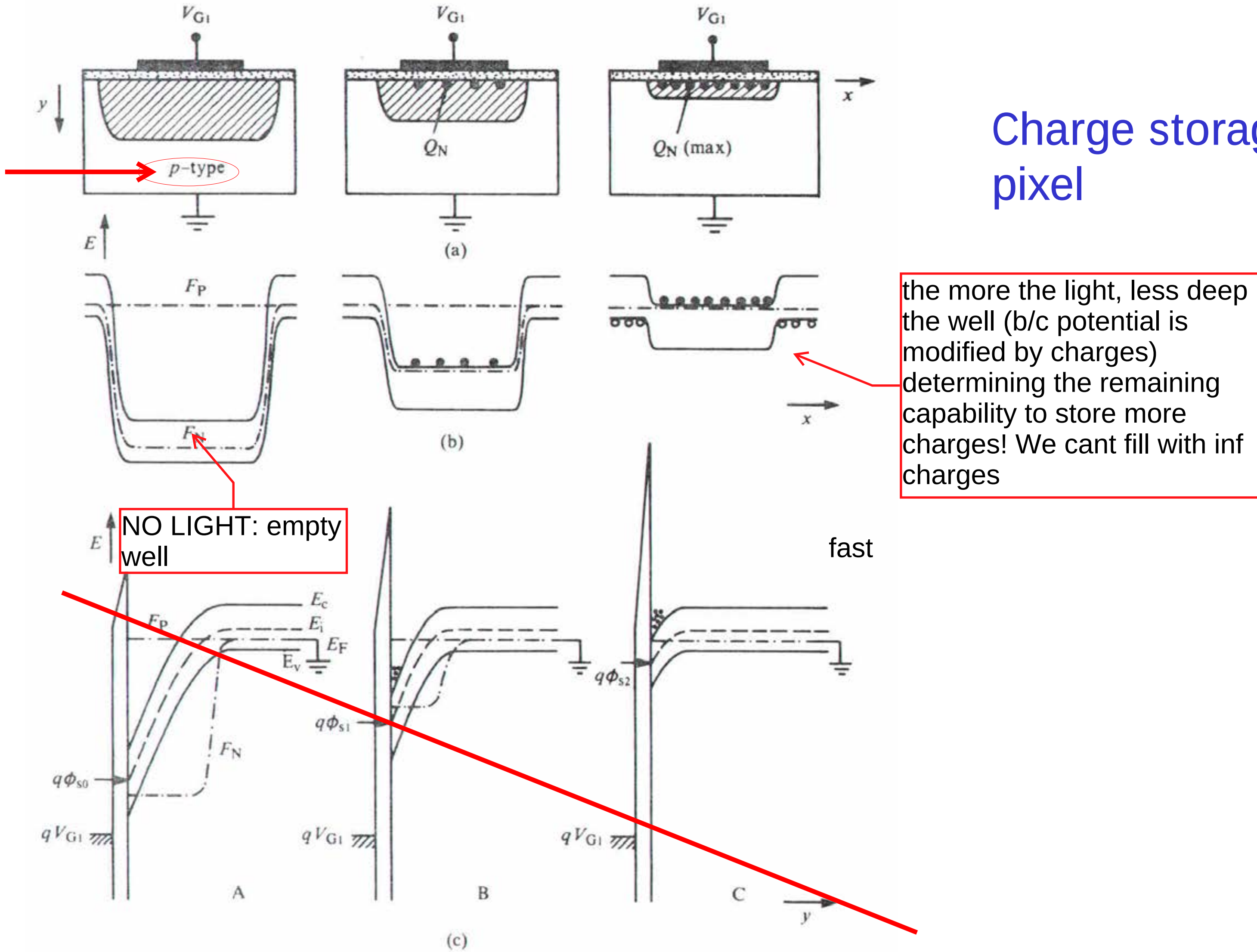



**Fig. 3.6** MOS-C of Fig. 3.5 for points A, B, and C. (a) shows the space-charge regions, (b) shows the potential diagrams along $x$ for $y = 0$, and (c) shows the potential diagrams along $y$ into the semiconductor. The inversion charge is indicated by the solid circles.

# Charge transfer (3 phases)

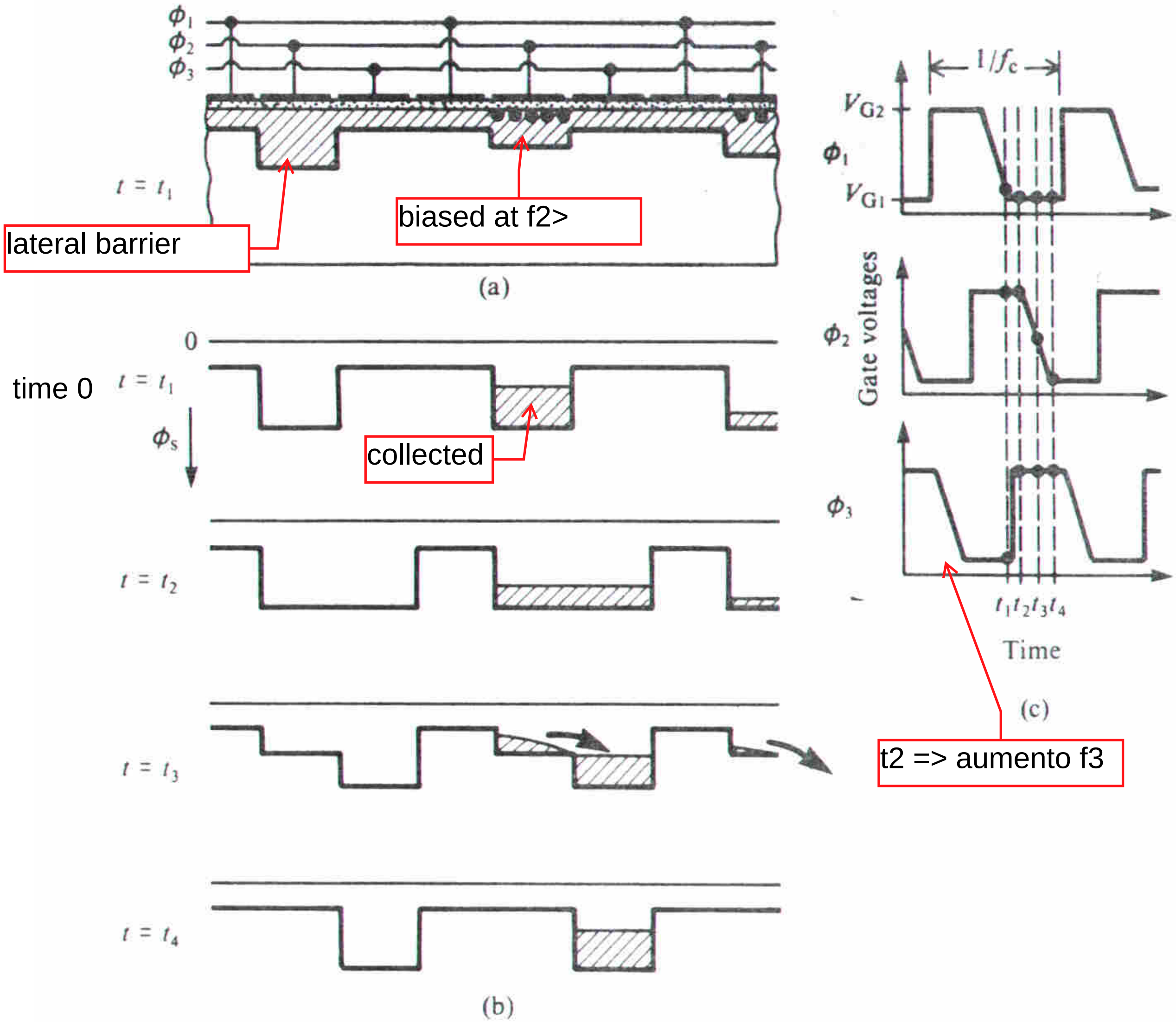


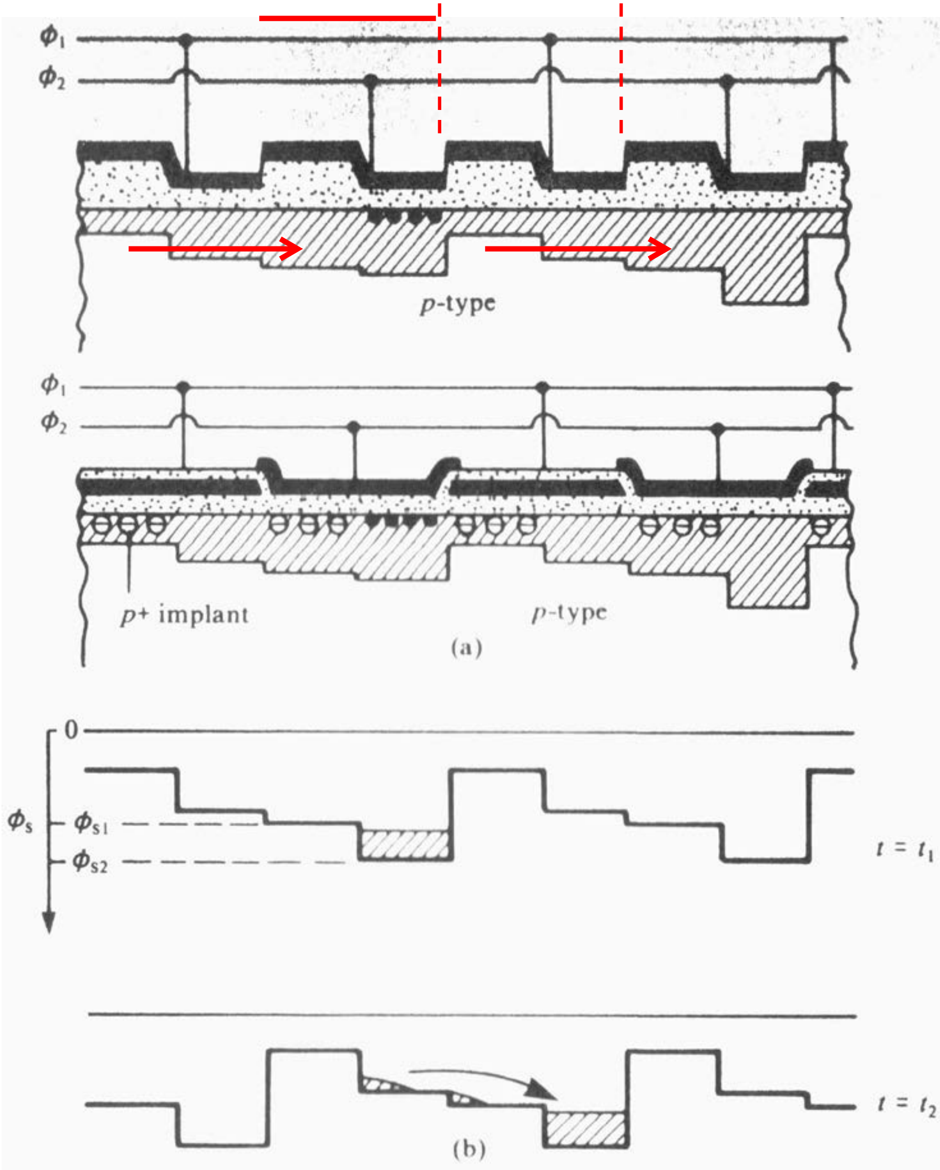

**Fig. 3.11** (a) Device cross section, and (b) surface potential diagrams for times $t_1$, $t_2$, $t_3$, and $t_4$ shown on the clock-voltage waveform diagram in (c).

In CCD we have many, se applico a tutti la stessa ddp ho una "vasca" e non riesco a fare imaging. So: out of 3 only 1 is biased to accept charge. The other 2 neighbour are kept at low voltage, so we dont have potential well, they are **barriers** so the collected wont overflow.

Transfer charge: we lower the barrier of the pixel on the right, creating potential well, charge spread among the two pixels, but we also decrease the voltage on the one before, so we have a complete transfer. **peristaltic transfer mechanism** [clocked changes of ddp]. It's actually a **slow** device!!

pixel attivo

pixel

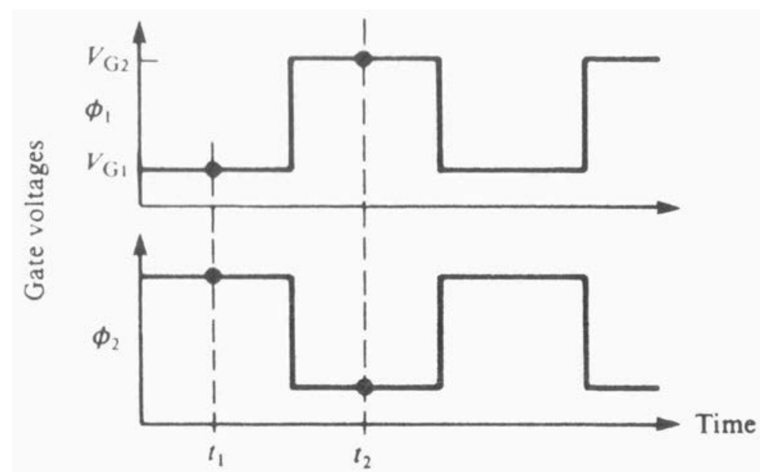



fast

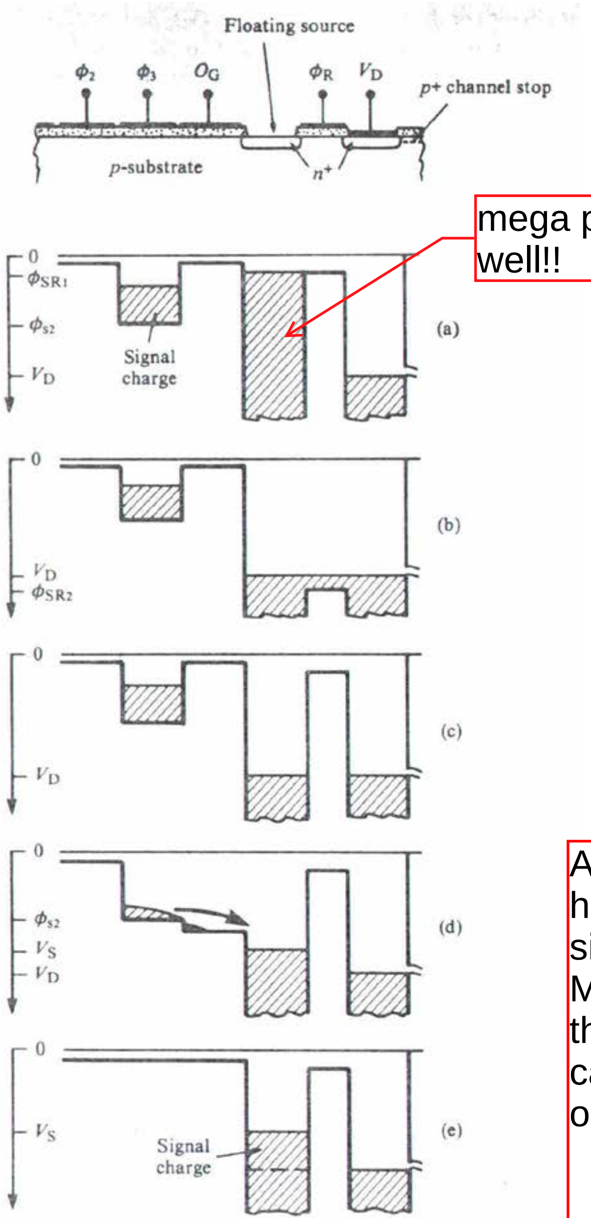
## Charge transfer (2 phases)

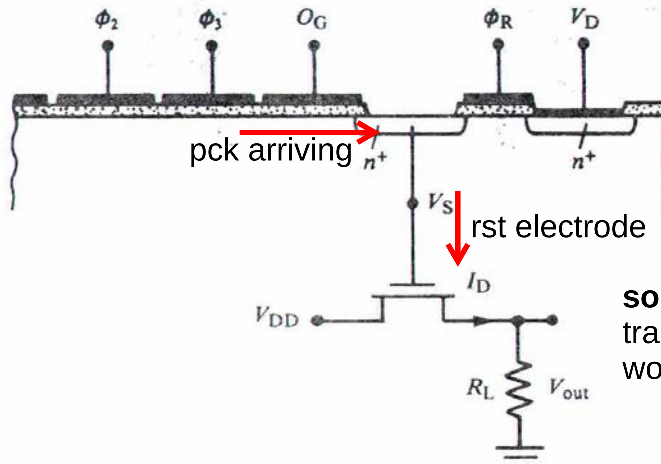
the steps in the potential well of each phase are obtained with an additional implantation or with a different oxide thickness

only 2 clock lines needed




Drawback of 3 phase: only 1 is available for imaging, so filling ratio = 1/3 :(.  => 2 phase CCD, inside the pixel we create a local minimum, CHANGING THE OXIDE THICKNESS. Dove è piccolo abbiamo un well, dove è alto no. Se il pixel dopo va giù viene trasferito e funziona.




**source follower** to transfer to outside world

Fig. 3.14 The complete output circuit, showing the floating diffusion connected to the gate of a source-follower MOSFET on-chip amplifier.

## signal readout

At the end they arrive to a **floating electrode** [n dop for eg.] (which has cap to respect surrounding Si). Arrives the packet, creates the signal, we need to reset the electrode every time.. so we have a MOSFET that just acts as a switch. Why dont we read directly from the electrode [n+]? b/c we'd have a load capacitance (even the cable, or of the amp...), so we'd have the parallel of two cap, obtaining a voltage signal very small!

## 1D CCD

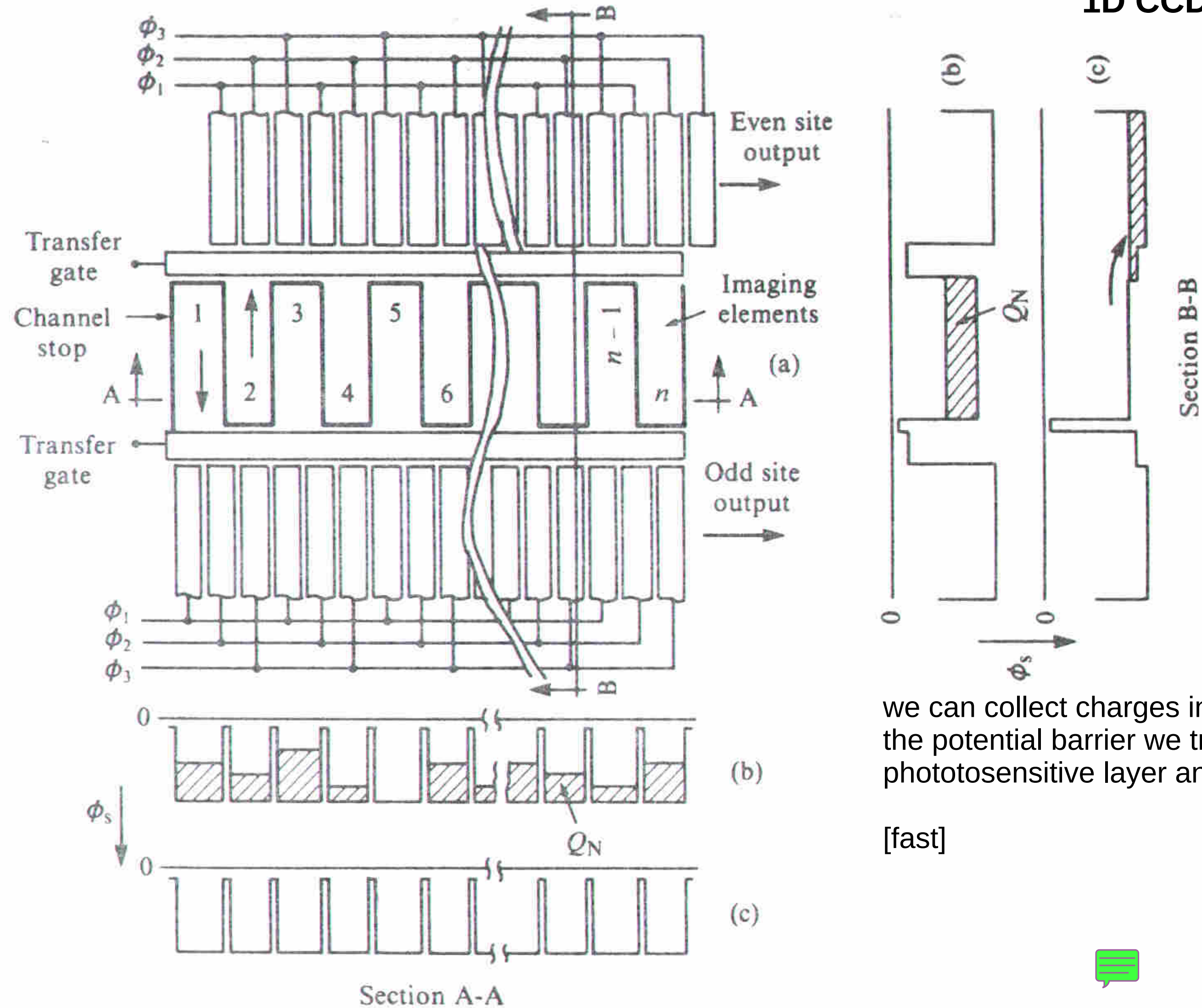



Fig. 4.11 (a) A CCD imaging line array. Two surface potential cross sections show the charge (b) during integration and (c) after transfer into the read-out registers.

linear matrix of CCD

we can collect charges in real photodiodeds, then by lowering the potential barrier we transfer the charge. Central phototosensitive layer and 2 transfer up/down.

[fast]

1ST TYPE of 2D CCD

# frame-transfer CCD [50% filling factor]

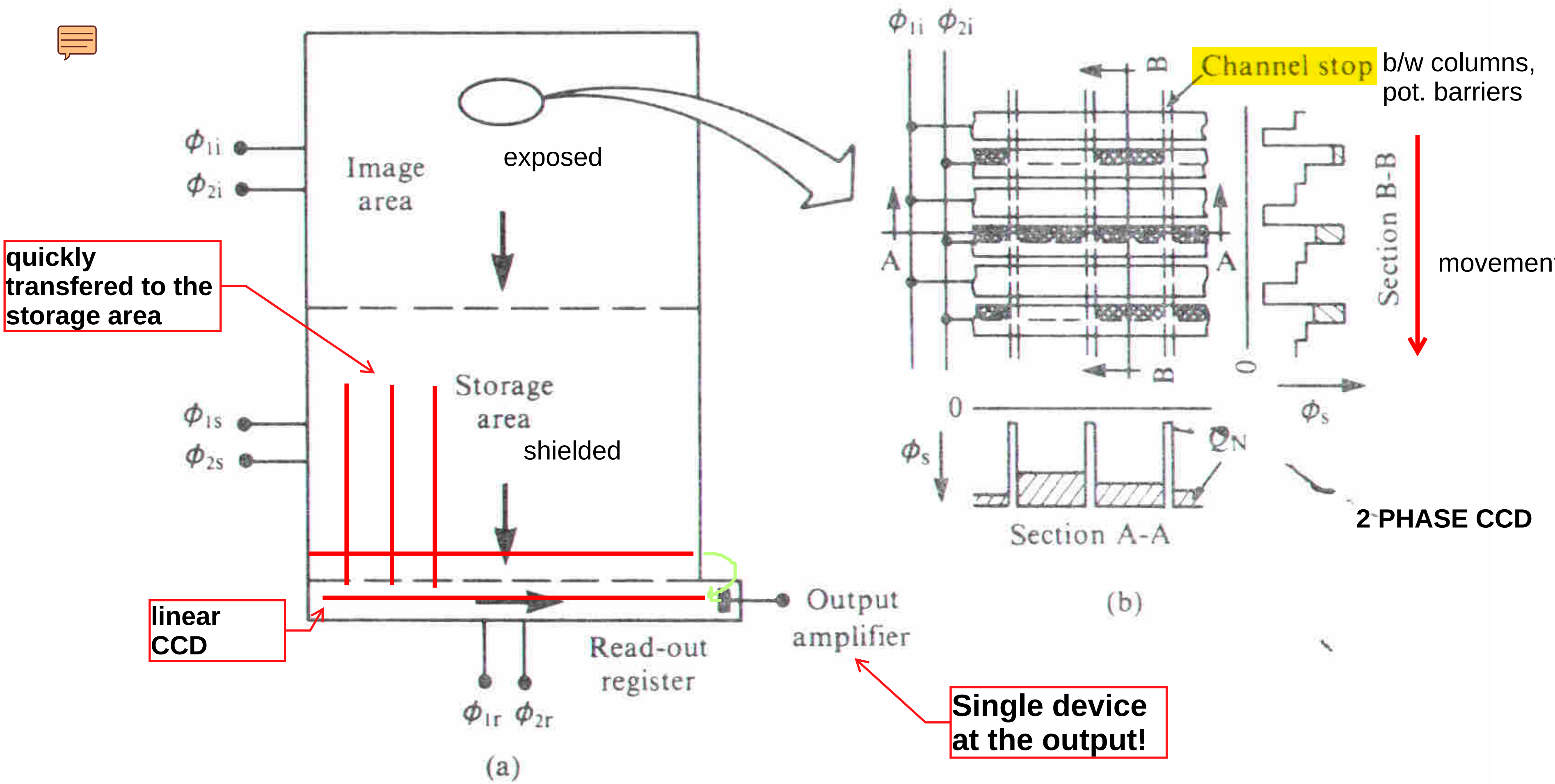



**Fig. 4.12** (a) Schematic of a frame-transfer CCD imager, and (b) an enlarged section of the image area, showing the gate structure and surface potential profiles. A two-phase CCD is used.

based on 2 phase transfer CCD. We have two separate areas (image/storage). First exposed to imaging, the second is SHIELDED (prevents light). 1. acquire image 2. quickcly transfered to storage 3. image area ready to collect new img.; storage area is "digesting": it's connected to a linear CCD (single output) (each line of the storage area goes down to CCD, which reads one "parallel" line at time). Freq of linear CCD must be m time larger than the freq. of storage area that puts down the lines. (again, CCD is slow :(). ADV: just one single device at the output!

**2nd type 2D**, to avoid 50% filling factor.. we'd like100% filling factor! won't happen, but we'll be able to do 1:1 coupling

# interline-transfer CCD

**charge collected in photodiode, e CCD usato solo x trasporto**

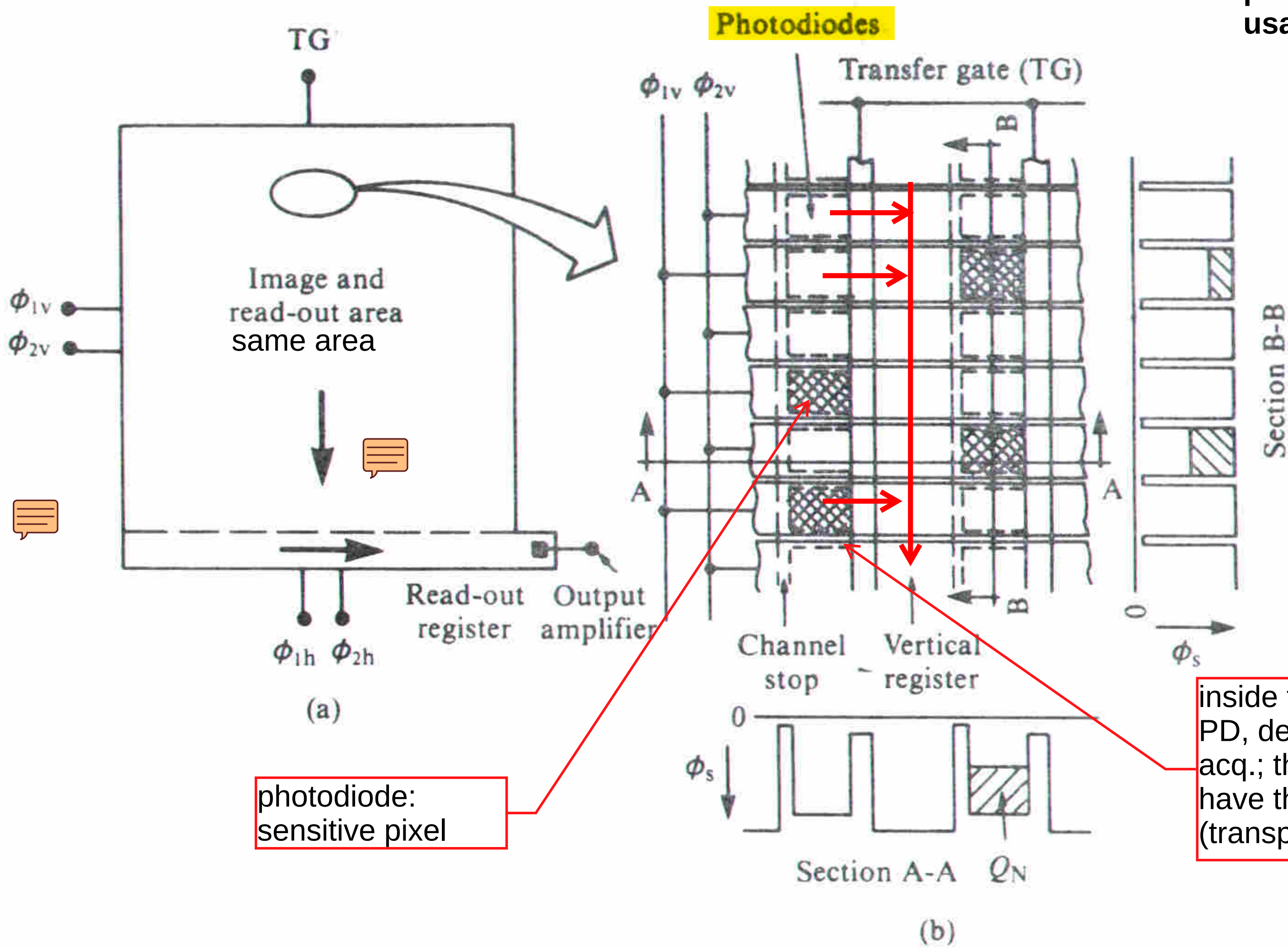
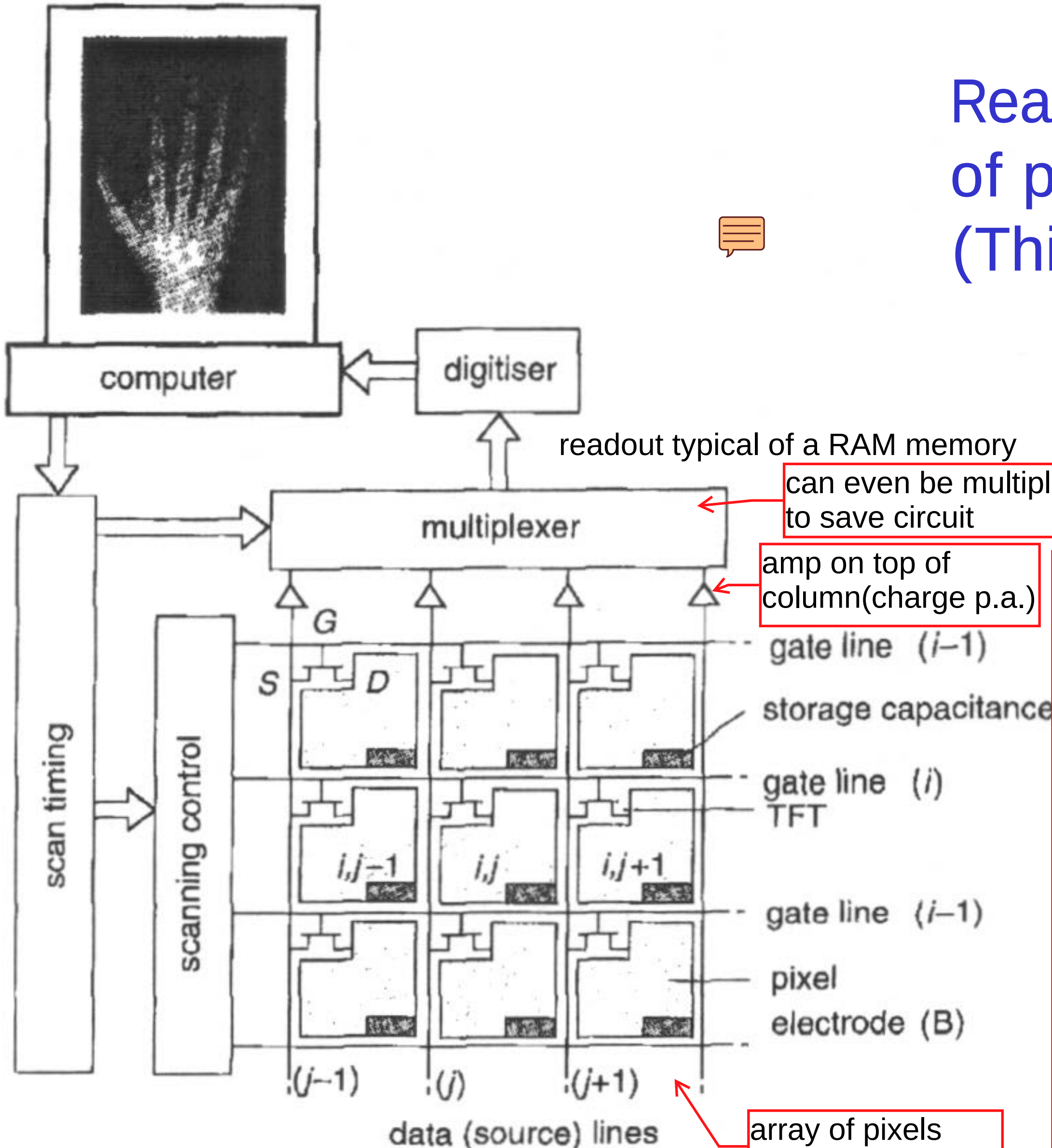



**Fig. 4.13** (a) Schematic of an interline-transfer CCD imager, and (b) an enlarged section of the image area, showing the gate structure and surface potential profiles. A two-phase CCD is used.

# Readout scheme of pixels with TFT (Thin-film transistor)




readout typical of a RAM memory

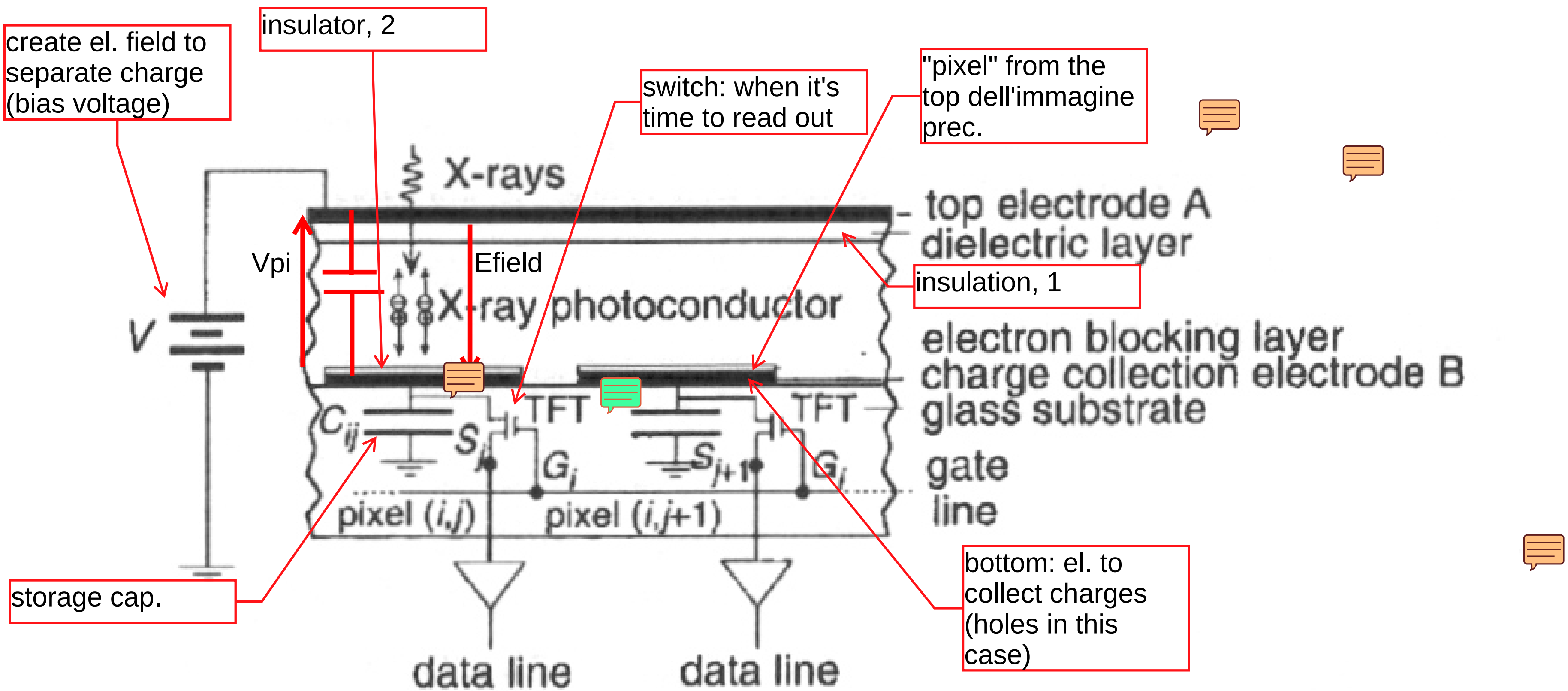
can even be multiplexed to save circuit

amp on top of column(charge p.a.)

array of pixels made of TFT

We scan row by row. Each pixel is collected by the amp of its column. I can activate a row, and only these pixels will have the switch connecting them to the individual column amplifier. Then I pass to the next row etc. IN 1 sec=> charges collected into a cap. inside the pixel. During readout rows are scanned row by row, and each individual column is sent to the amp.

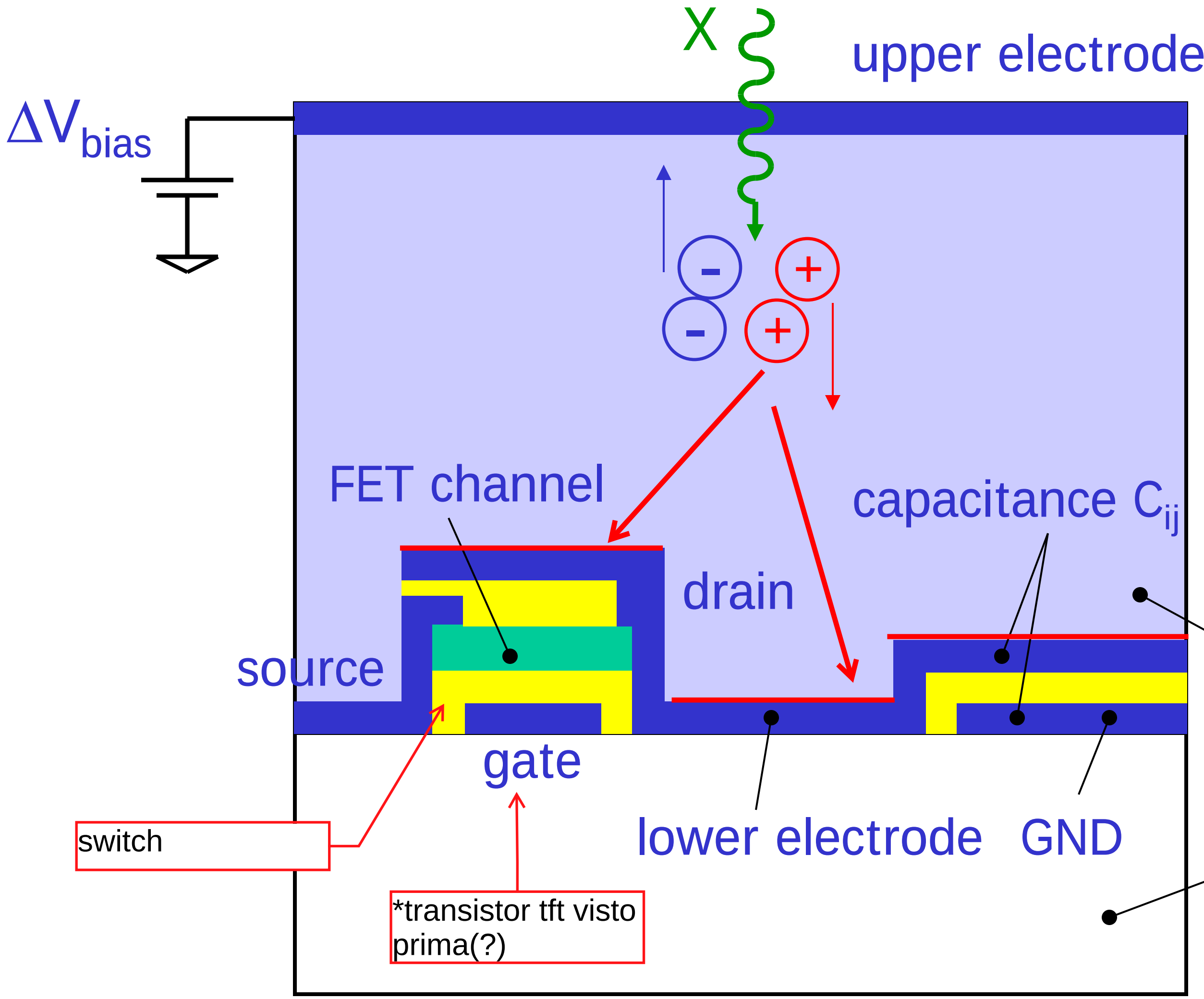
# Direct-conversion X-ray *Imager* (with photoconductors)




photoconductor: [generally speaking, material where charge created by optical abs. change conducibility of material. light => change of conductance]. Our case: we dont use the material for the change in cond., but simply as a traditional ionizing radiation material. **FOR OUR PURPOSES, PHOTOCONDUCTOR IS AN IONIZATION DETECTOR.** xray=> couple of el-/holes. We apply a ddp across, to separe them. DRAMATIC DIFFERENCE WITH PN JUNCITON DEPLEATED: the pndiode is deplated, and the charge is just created by optical photons. In photoconductor it's not depleated! it has its own mobile charges!! So the challenge is that we have also el/holes everywhere in the material. If we collect for e.g. holes, it should not **recombine** with electrons existing and survive. It's not hopeless: we choose p.c. with **lowest doping** so that we reduce number of carriers... plus we are dealing with xrays, so we dont need a thick device, to make abs. effective [**1mm is ok**]. This gives "hopes" not to have **recombination** by the mobile charges. BTW we use this and not PN junction, because the photoconductor material **deposition** is **compatible** with the **TFT** technology! so it adapts well with the tech we use to implement the matrix.

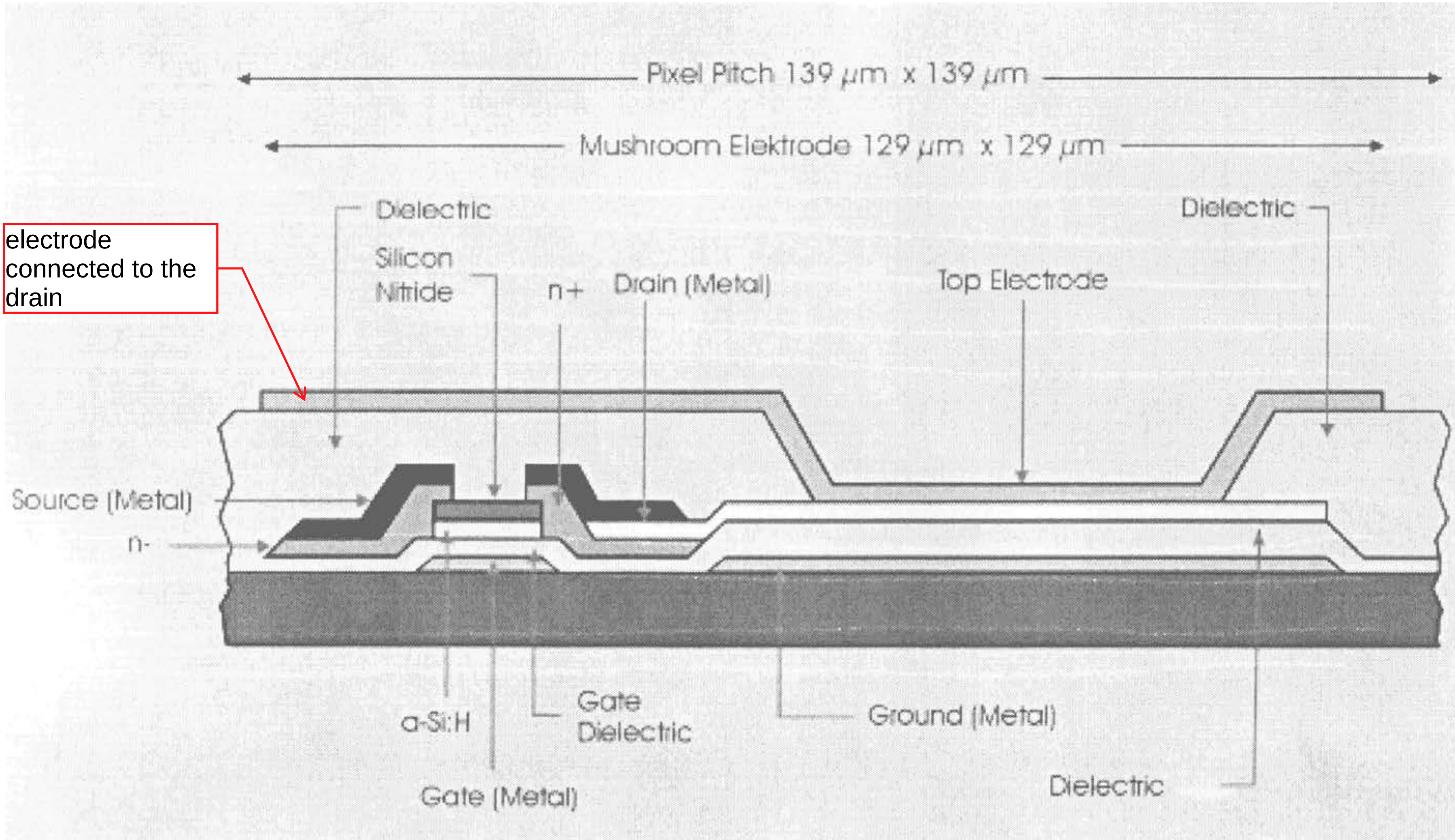
all these things are deposited on a TFT. It's a layer by layer amorphous deposition (that's why it's cheap).

# photoconductor + TFT (structure)

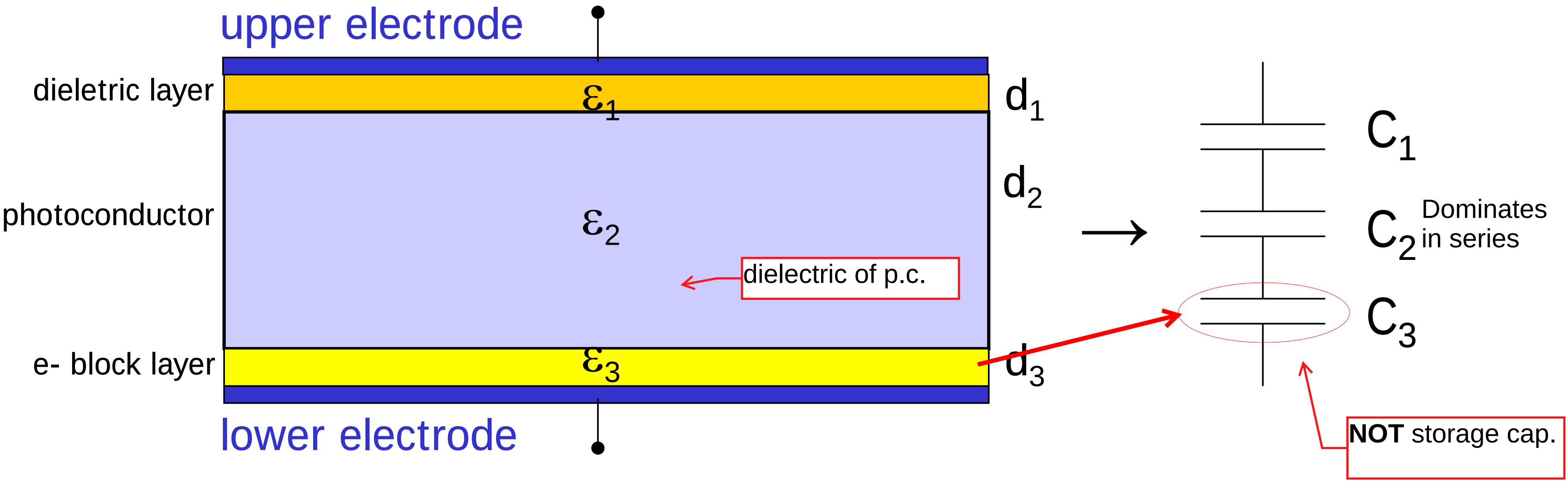



All these layers are deposited over a substrate of glass. Not expensive as building a Si device

TFT technology: Si amorphous hydrogenate (a-Si:H), semiconductor deposited as thin layer from silane gas ($SiH_4$) in a plasma chamber electrode connected to the drain



**...with also insulator layer:** doesnt change the capacity value! 3 insulator in series. We have Conservation of dielectric vector, this result that the stack is like 3 cap. in series, each one with classic formula




somma in serie, la più piccola domina, è sicuramente quella con d più grande, cioè C2

$$1/C_P = 1/C_1 + 1/C_2 + 1/C_3$$

surface, dielectric constant, distance

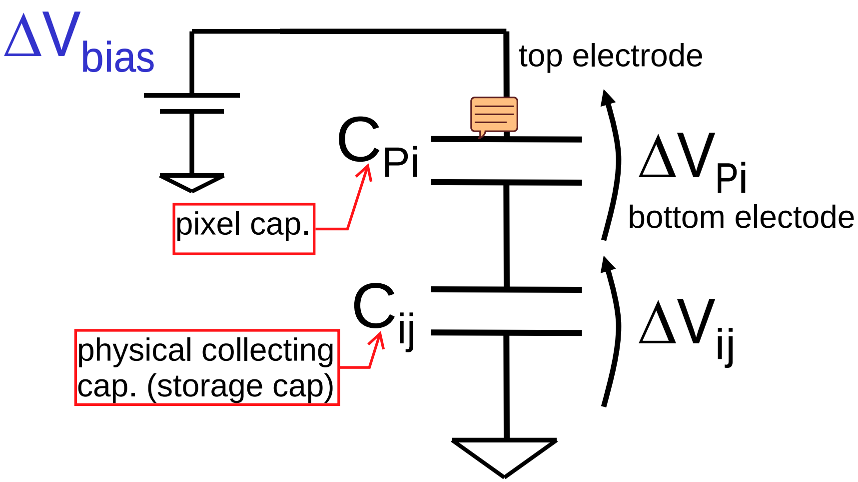
$$C_X = e_X S/d_X$$

$$\Rightarrow C_1, C_3 >> C_2$$

$$\Rightarrow \boxed{C_P \sim C_2}$$

Conclusion: despite the addition, the resulting cap. from pin to pin is still the cap. of the photoconductor!! All the conclusion are the same we have said!!!!

# Biasing




[*1]

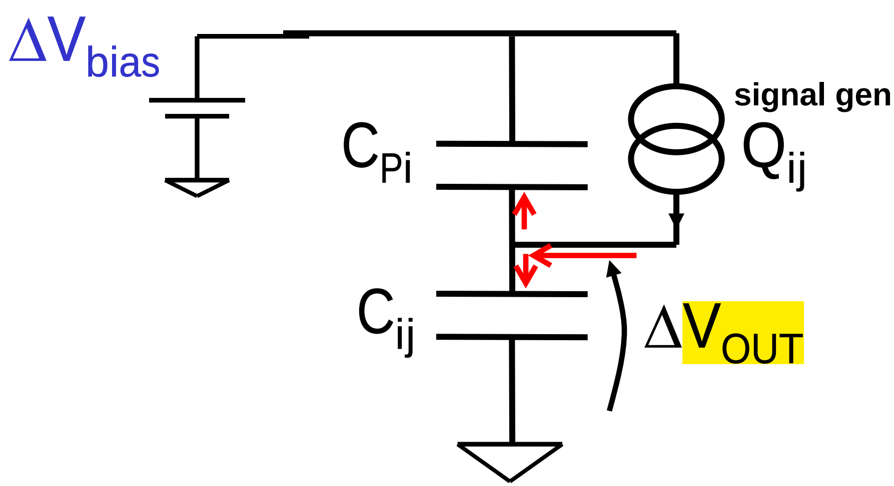
$$\Delta V_{Pi} = \Delta V_{bias}\, C_{ij}/(C_{ij}+C_{Pi})$$

$$C_{ij} >> C_{Pi} \qquad (C_{ij} \sim 1\text{pF})$$

$$\Rightarrow \boxed{\Delta V_{Pi} \sim \Delta V_{bias}} \qquad (\sim\text{kV})$$

# Signal integration

## (signal produced by X-ray absorption in the exposure time)




supplied in the parallel of the two cap

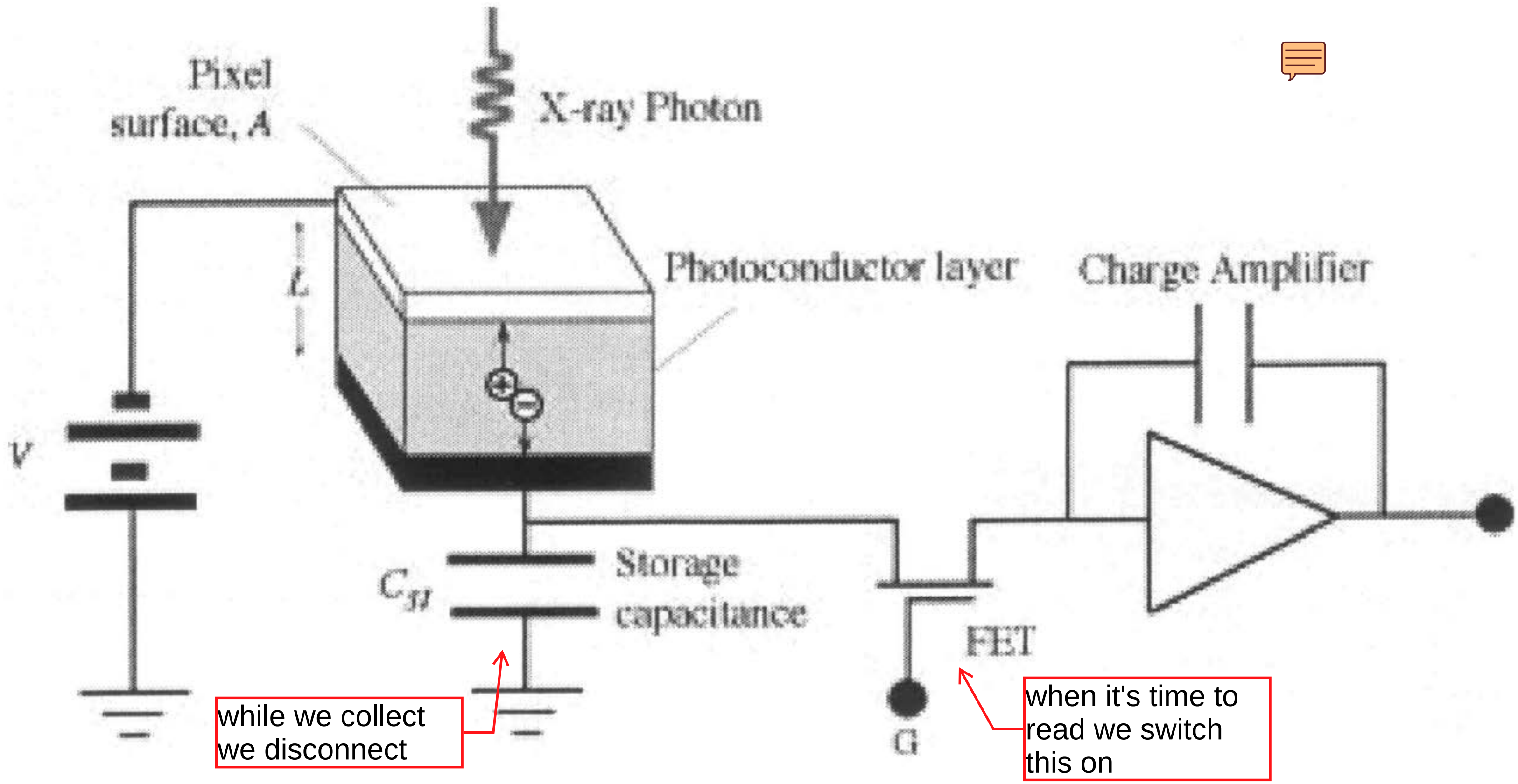
$$\Delta V_{OUT} = Q_{ij}/(C_{ij}+C_{Pi})$$

$$C_{ij} >> C_{Pi} \qquad (C_{ij} << C_3)$$

$$\Rightarrow \boxed{\Delta V_{OUT} \sim Q_{ij}/C_{ij}}$$

*si passa dal parallelo ad una approx.

storage cap! dominates




when a pixel is connected by switching on the FET to the common output line connected to the preamplifier:

$$V_{OUTpre} = Q_{ij}/C_F$$

# Solutions to protect the pixel from over-voltages due to $I_{dark}$:

1) inversion of the bias voltage (TFT turns on when over-voltage occurs)
2) electric field lowering due to trapped electrons
3) protection devices

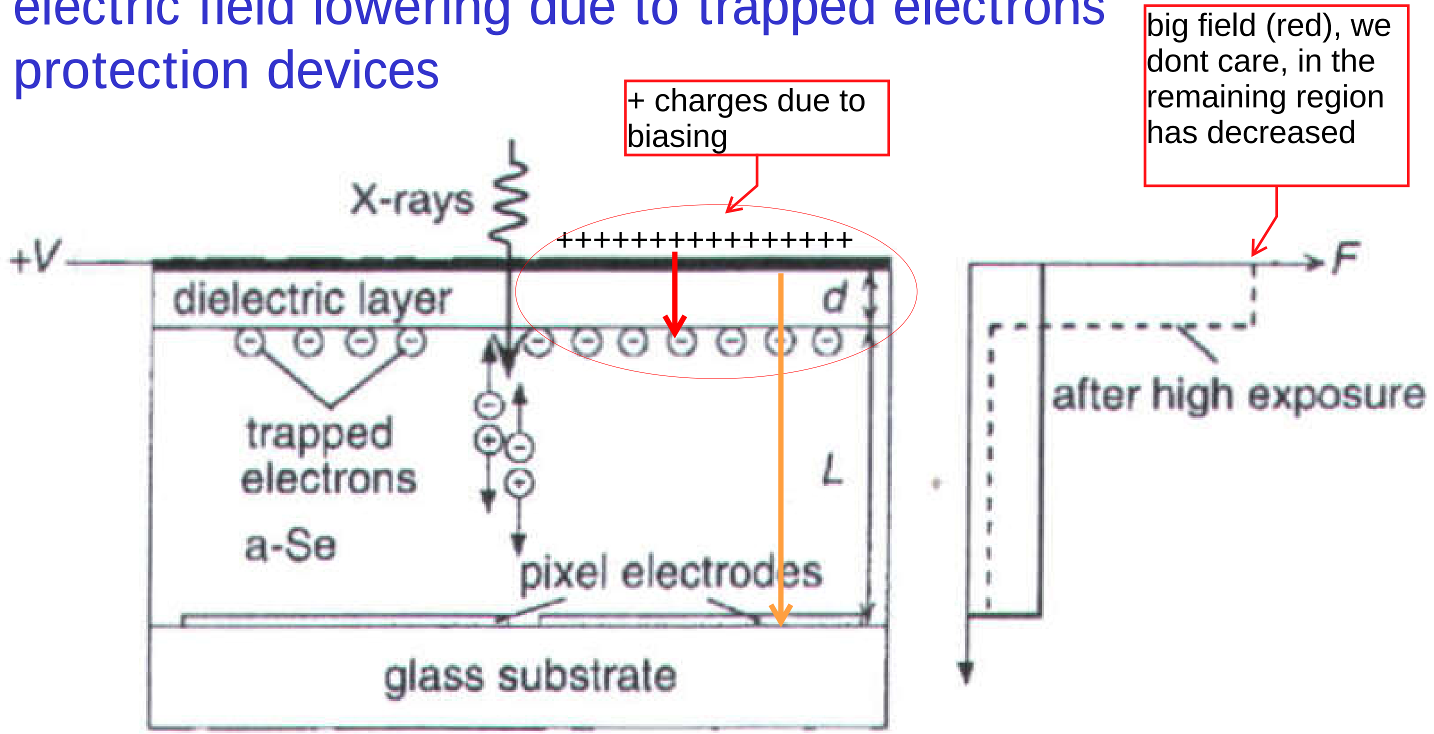
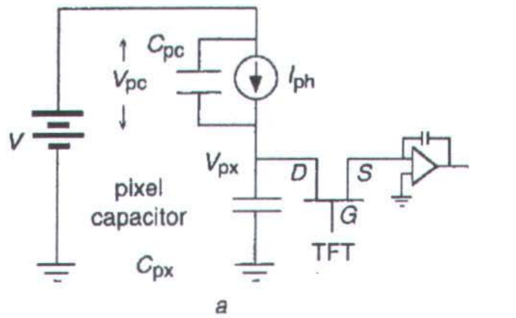
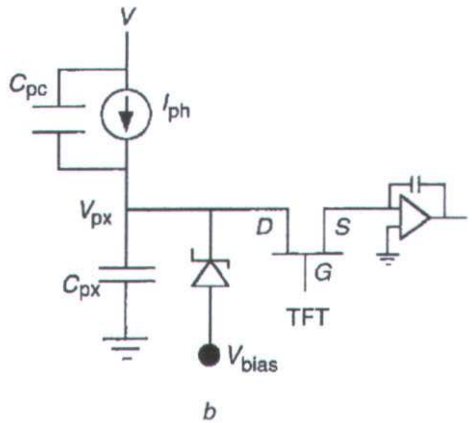



**Fig. 5** *Trapped electrons at interface between dielectric layer and photoconductor collapse field in photoconductor so that no further charge can accumulate on pixel electrodes; thus TFT is prevented from breakdown under high exposure*

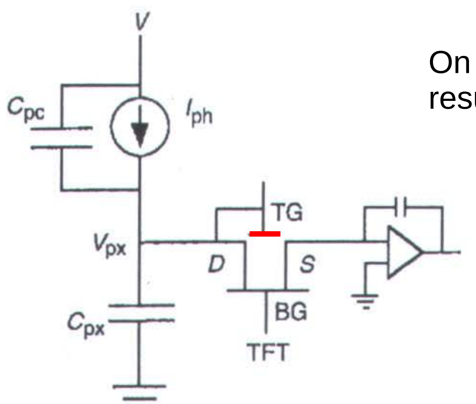



conventional readout




Zener protection

would mean apply a zener in the Si region, maybe not easy




On same transistor we add an additional top gate, and connect it to the drain.. resulting in a "parallel" TRANSDIODE. If D (=G) goes high it turns on!

protection with a Top gate
in a ‘transdiode’ configuration

dont learn the table.. meaning of figure of merit

**Table 1: Densities, attenuation depths ($\delta = 1/\alpha$) at photon energy of 20 and 60 keV and energy bandgaps ($E_g$) of selected potential X-ray photoconductor materials**

| Photoconductor | TlBr | PbO | $PbI_2$ | $HgI_2$ | Ge | GaAs | a-Se | GaSe | ZnTe | CdS | CdSe | CdTe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Density ($g\,cm^{-3}$) | 7.5 | 9.8 | 6.1 | 6.3 | 5.32 | 5.31 | 4.3 | 4.6 | 6.34 | 4.82 | 5.81 | 6.06 |
| $\delta$ ($\mu m$) at 20 keV | 18 | 11.8 | 28 | 32 | 44 | 44 | 48 | 49 | 58 | 127 | 56 | 77 |
| $\delta$ ($\mu m$) at 60 keV | 317 | 218 | 259 | 252 | 929 | 926 | 976 | 1026 | 300 | 439 | 385 | 250 |
| $E_g$ (eV) | 2.7 | 1.9 | 2.3 | 2.1 | 0.7 | 1.42 | 2.3 | 2.0 | 2.26 | 2.3 | 1.8 | 1.5 |
| $W_\pm$ (eV) | 6.5 | 8–20 | 5 | 4–7 | 1.5 | 6.3 | $45^*$, $20^\dagger$ | 6.3 | 7 | 7.2 | 5 | 4.65 |

*at $F = 10\,V/\mu m$
$^\dagger$at $F = 30\,V/\mu m$
X-ray mass attenuation coefficients data from http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html

# Figures of merit:

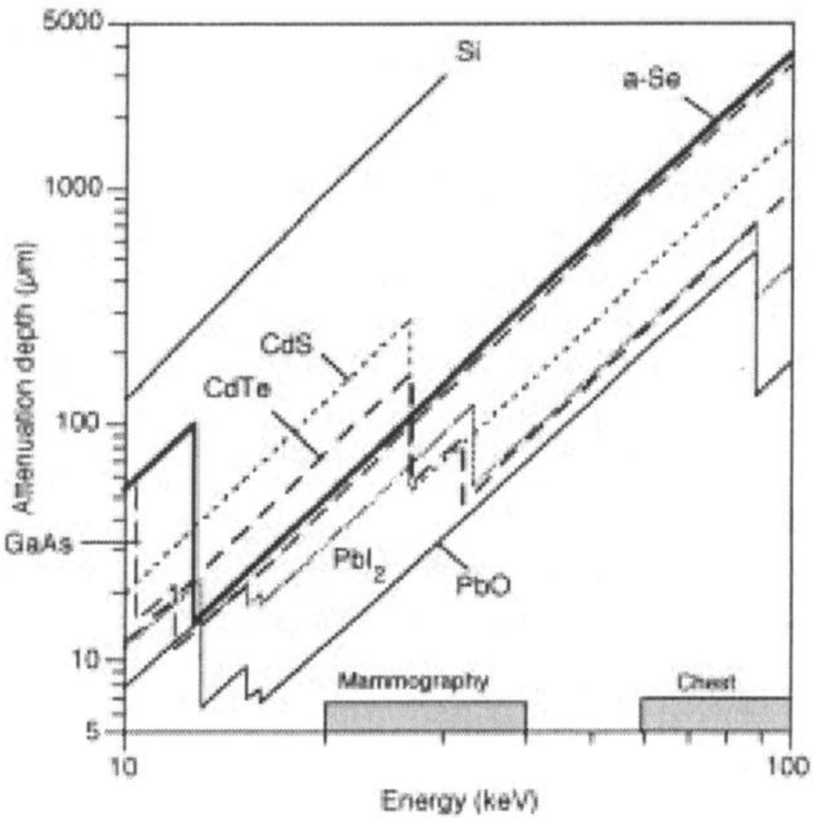
- low absorption length $\delta$ of the material at the energy E of interest
- high sensitivity of the photoconductor: $Q=qE/\varepsilon$ $\quad \varepsilon \sim 2.8E_{gap}$
- low carriers recombination in the bulk during drift and
  low trapping (large carrier mean path : $\mu\tau F >> L$
  $\mu$ = mobility, $\tau$ = carrier life time, F = electric field, L = thickness)
- low dark current (not-injecting contacts, low thermal generation)
  (note: thermal generation $\div\ 1/E_{gap}$ in conflict with sensitivity)
- polycrystalline photoconductor material of easy grow on large areas

# Absorption efficiency

$$\eta_{assorb.} = 1 - \exp(-\mu L)$$

L : sensor thickness
$\delta=1/\mu$ : absorption length

($L=\delta$ absorbs 63% of the radiation)
is it good to have at least $L=2\delta$
ex. a-Se: 20keV 100$\mu$m, 60keV 2000$\mu$m

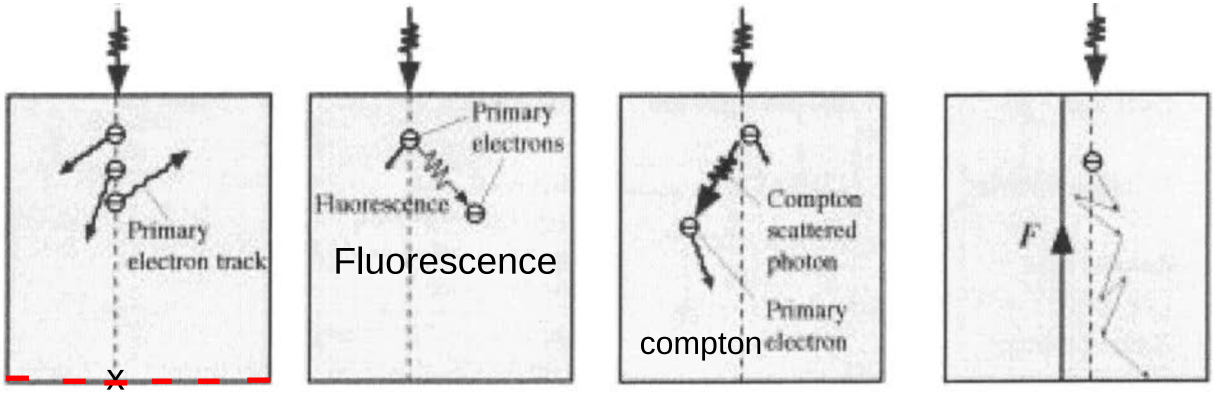



L not too large (thick) because:
- it increases the probability of trapping/recombination of the charge
- difficult to grow on extended areas with large thickness without defects
- the bias voltage to apply to reach a given F increases with L

"things that can go wrong"... asked if you are doing a really good exam

causes of loss of spatial resolution

initial spread of cloud of charges

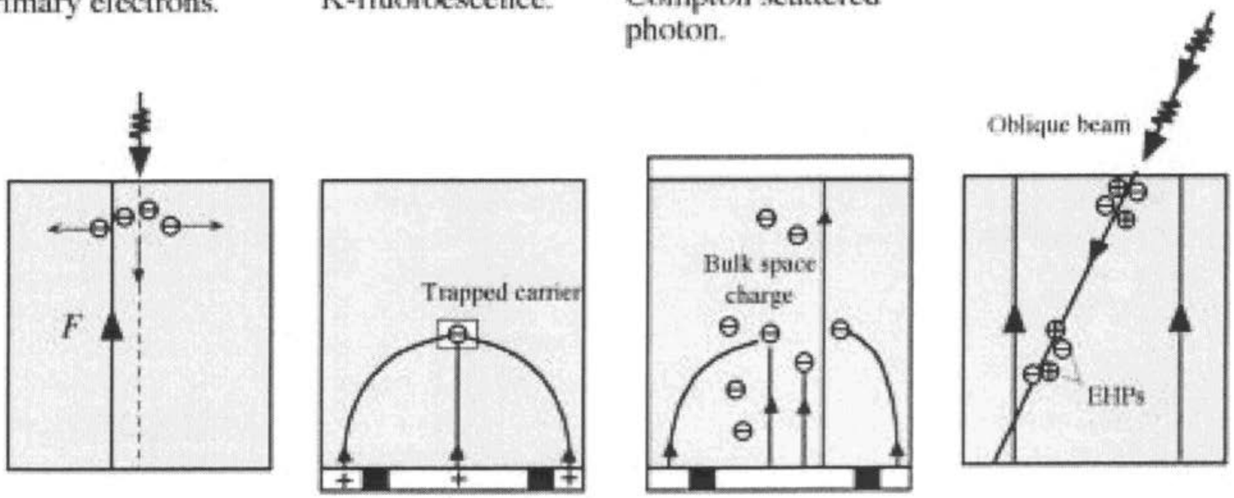



(a) Lateral spreading due to the range of the primary electrons.

(b) Lateral spreading due to the reabsorption of K-fluoroescence.

(c) Lateral spreading due to reabsorption of a Compton scattered photon.

(d) Lateral carrier diffusion during drift.




(e) Lateral spreading due to space charge effects (Coulombic repulsion)

(f) Lateral spreading due to bulk trapped carriers (the average filed is relatively unaffected)

(g) Lateral spreading due to bulk space charge modifying the field.

(h) Lateral spreading due to oblique incidence.

diff tra e ed g?

# CsI(Tl) - photodiode – TFT

fast

not commented

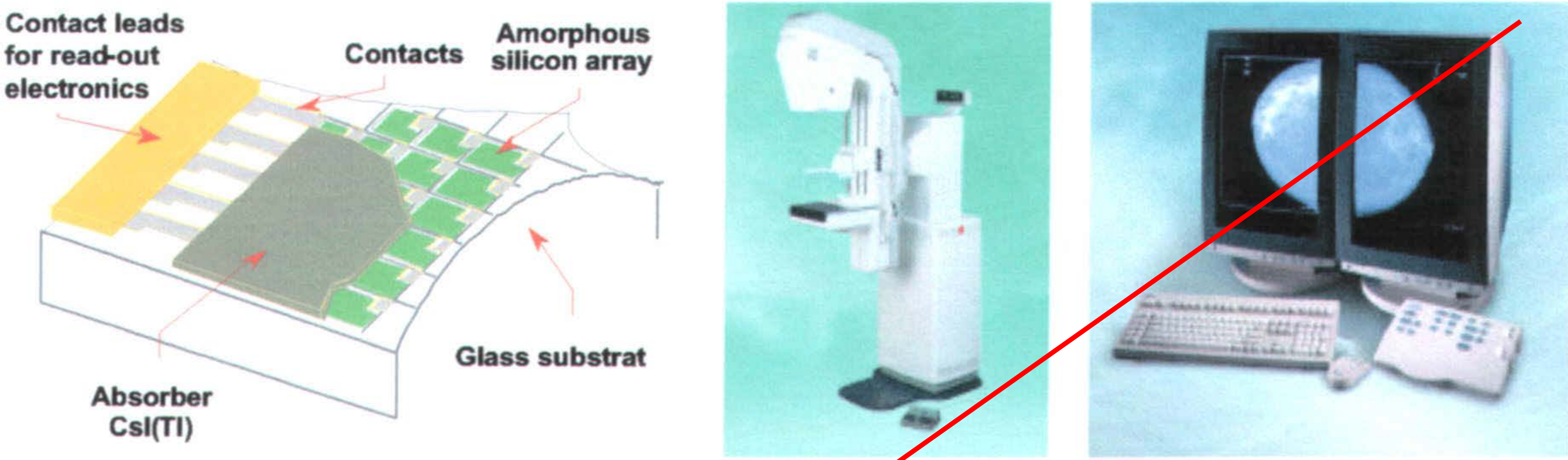
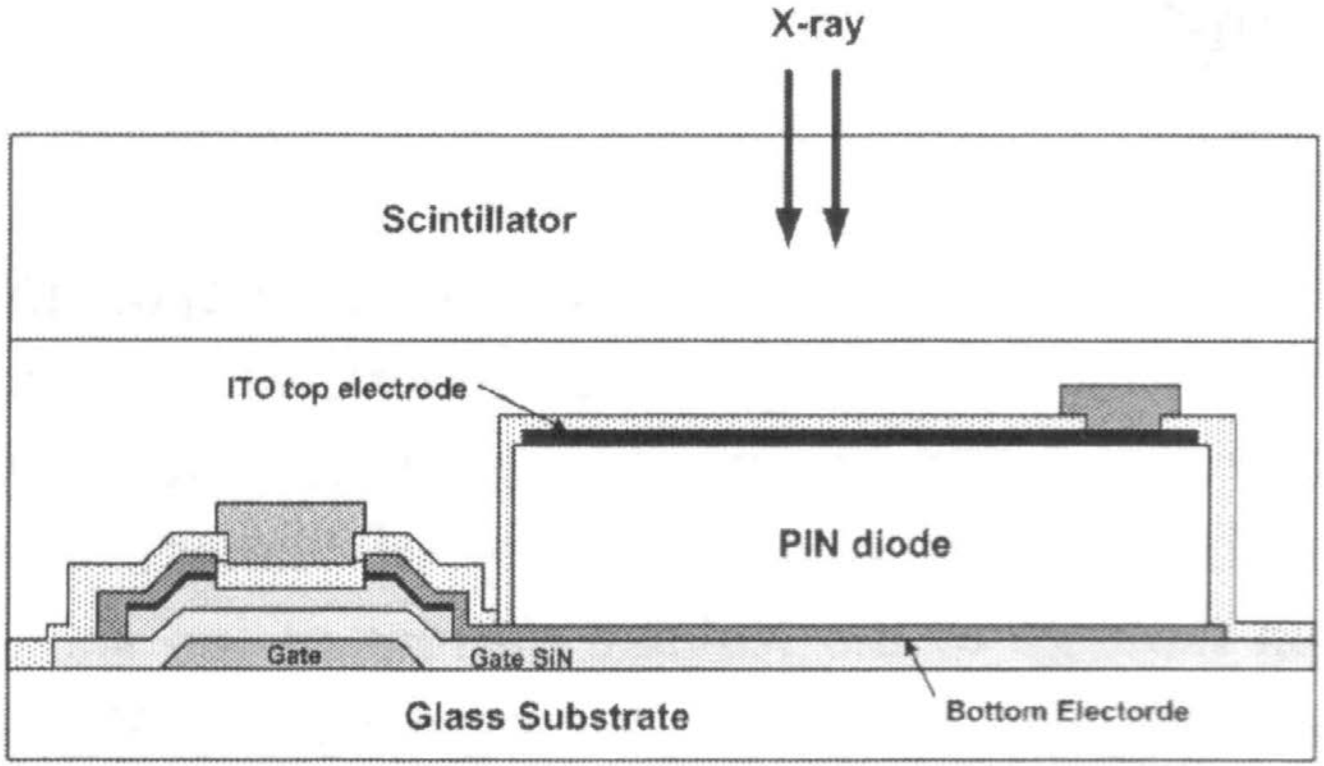



**Figure 11. A CsI(Tl)-aSi detector, with the construction shown (left). The FFDM system GE Senographe 2000D with this detector is seen (middle) as well as the GE review workstation (right). (Figures supplied by General Electric).**

TFT can be used also to readout scintillators

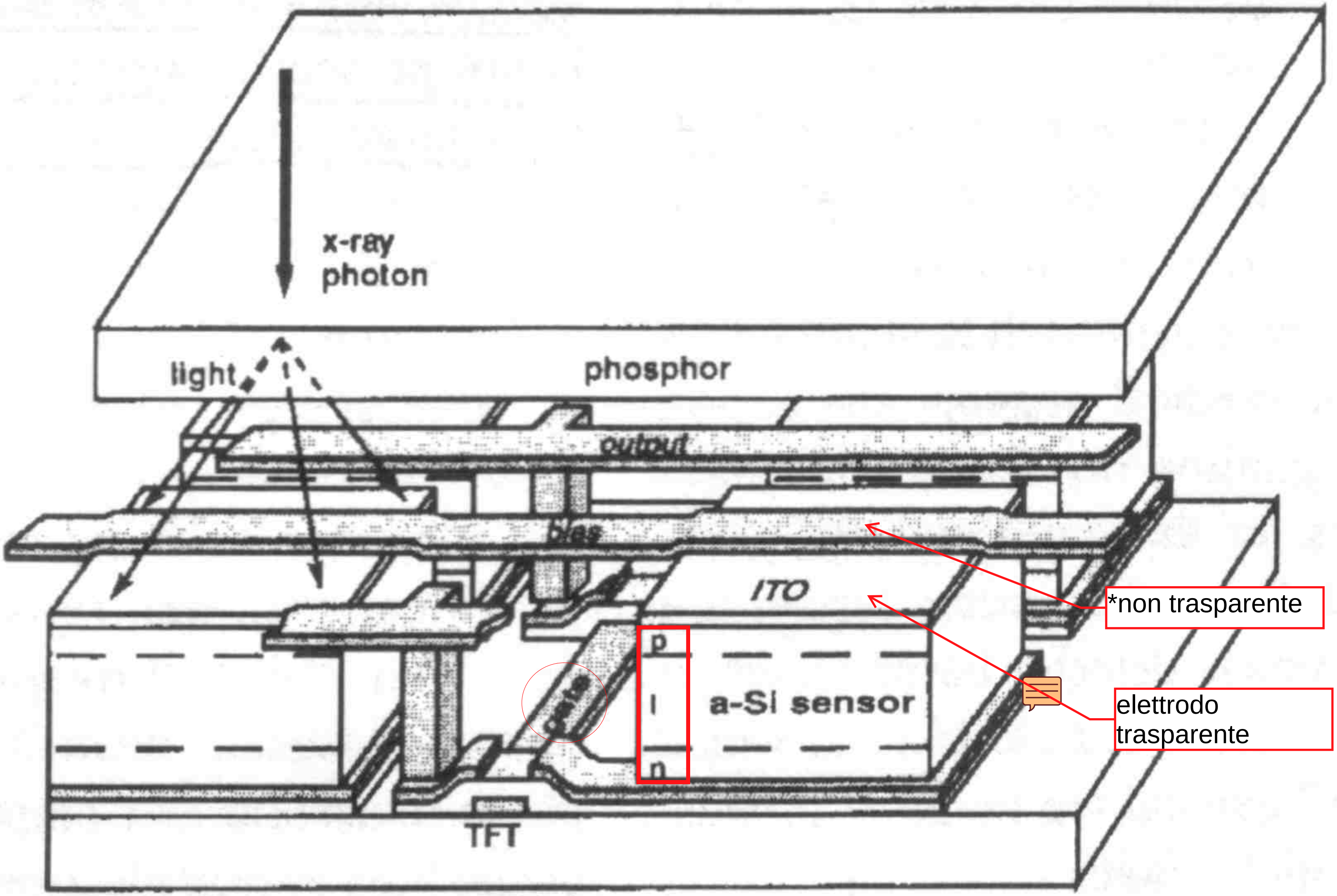



PIN diode in amorphous Si (same material used in solar cells), slightly reverse-biased or not biased

example of pixel dimension = 139μm with 57% of sensitive area

No more photoconductor, we have a scintillator that converts the xray into visible light, which then enter into a PIN diode => charges => collected at bottom electrode. At the end again charge stored on a cap., but it's not generated in a photoconductor, instead a PIN diode, which absorbs light.

# 3D view


x-ray
photon
light
phosphor
output
bias
ITO
*non trasparente
elettrodo
trasparente
p
I
n
a-Si sensor
gate
TFT