

# How we wanted to revolutionize X-ray radiography, and how we then "accidentally" discovered single-photon CMOS imaging

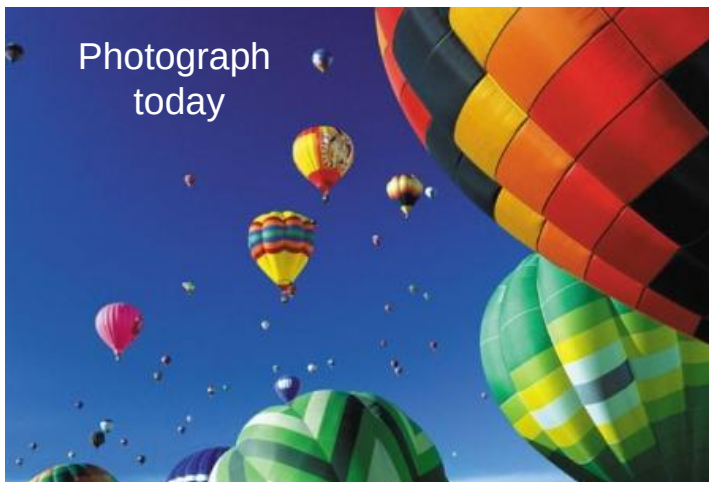
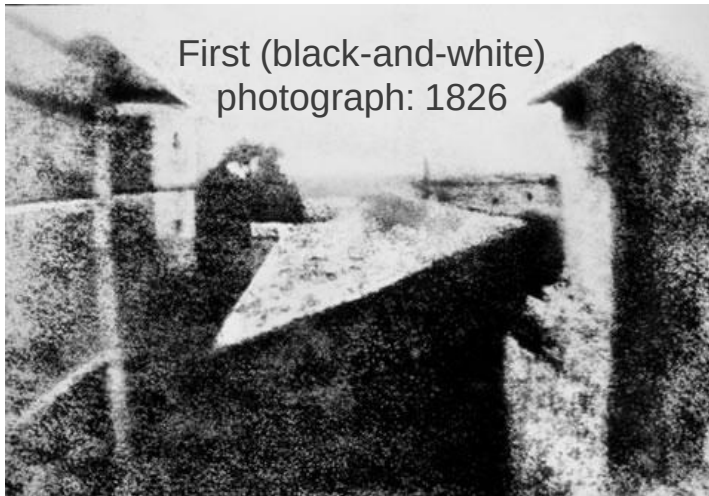
Stanford University EE Computer Systems Colloquium  
February 23<sup>rd</sup>, 2011 – EE380

Peter Seitz, Ph.D.

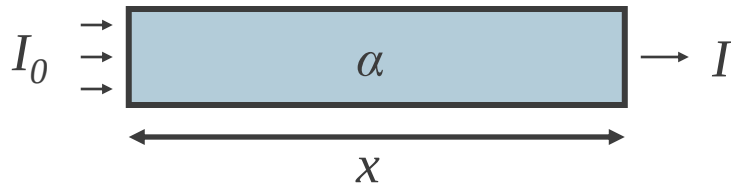
Vice President Nanomedicine, CSEM SA

Adjunct Professor, EPFL Institute of Microengineering

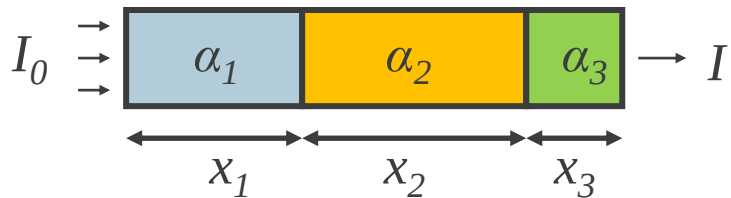
# Information Content: Photography and X-Ray Imagery



# Absorption Properties of X-Rays in Matter



$$I = I_0 e^{-\alpha x}$$



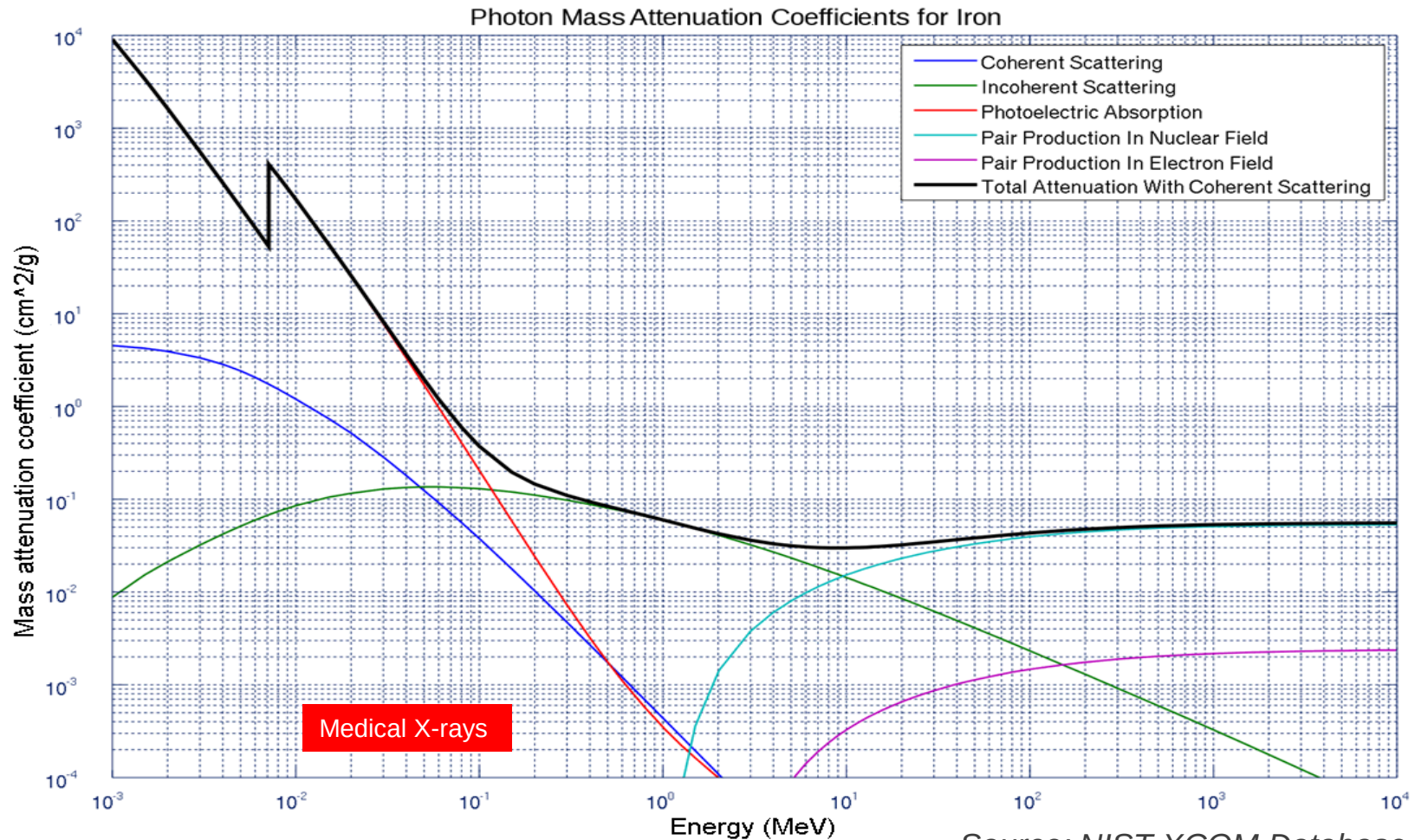
$$I = I_0 e^{-\sum_{i=1}^n \alpha_i x_i}$$

$$\mu = \frac{\alpha}{\rho}$$

$\alpha$  : linear attenuation coefficient (1/cm)  
 $\mu$  : mass attenuation coefficient (cm<sup>2</sup>/g)  
 $\rho$  : density (g/cm<sup>3</sup>)

$$\alpha_{tot} = \sum_{i=1}^n \alpha_i = \sum_{i=1}^n w_i \left( \frac{\mu}{\rho} \right)_i$$

# Photon Energy Dependent X-Ray Absorption Spectra



## Functional Dependence of the Photoelectric Effect

Textbooks:

**Bragg-Pierce Law** for the photoelectric absorption of a homogeneous piece of elemental matter as a function of X-ray photon energy  $E$  and atomic number  $Z$  :

$$\alpha(Z, E) \propto Z^b E^a$$

$$b \cong 4.0 \quad ; \quad a \cong -3.0$$

End of slide show, click to exit.

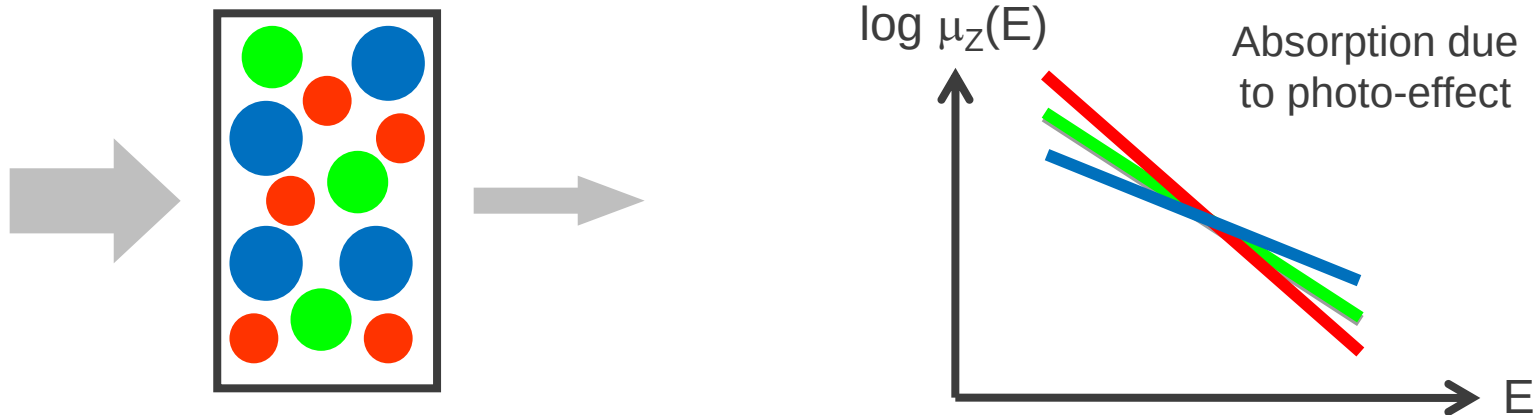
## Photoelectric Absorption Revisited ...

Assume “cross dependence”  $b(E)$  and  $a(Z)$  :

$$\mu_Z(E) = c Z^{b(E)} E^{a(Z)}$$

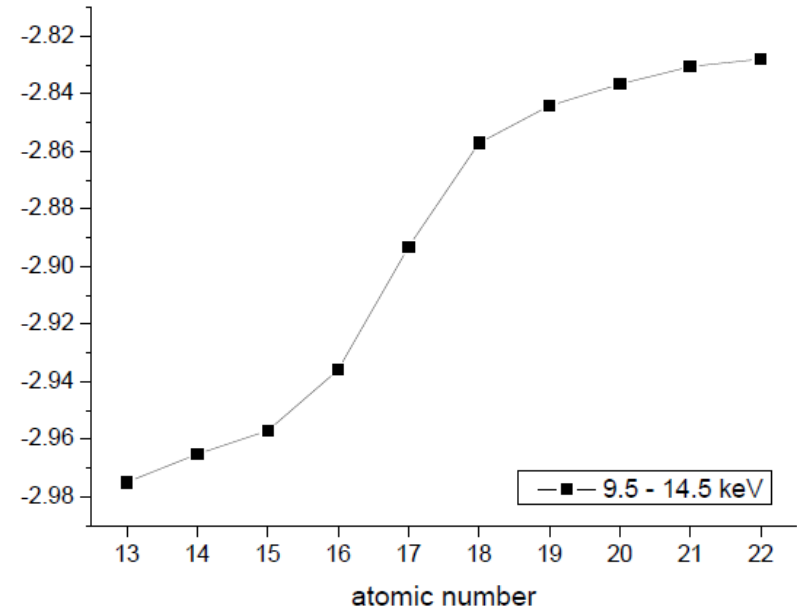
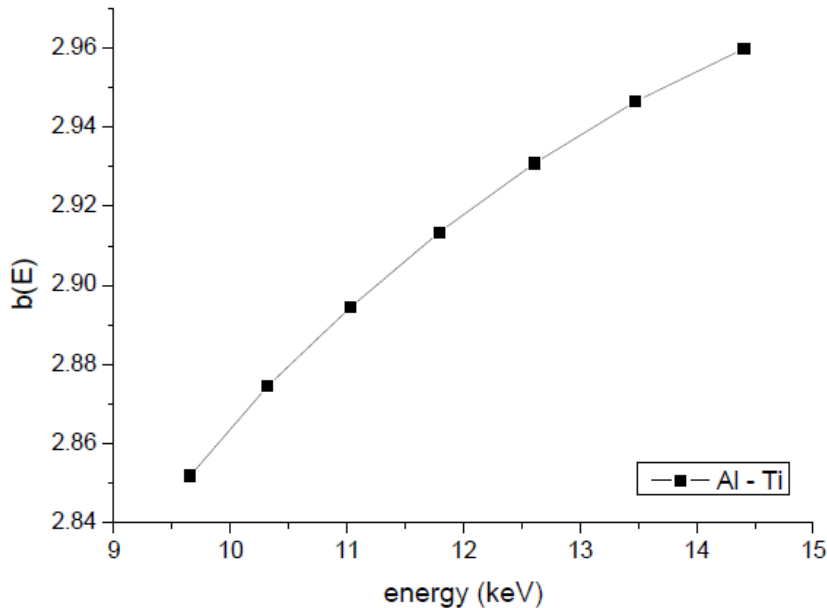
NIST Database : “Tables of X-Ray Mass Attenuation Coefficients and Mass-Energy Absorption Coefficients”

<http://www.physics.nist.gov/PhysRefData/XrayMassCoef/cover.html>



# Photoelectric Absorption : Monotonous Functions !

$$\mu_Z(E) = c Z^{b(E)} E^{a(Z)}$$



# Color X-Ray Imaging !

$$\alpha(E) = c \sum_{i=1}^n \rho_i Z_i^{b(E)} E^{a(Z_i)}$$

$i = 1, 2, \dots n$  constituting elements

$$\alpha_j = c \sum_{i=1}^n \rho_i Z_i^{b(E_j)} E_j^{a(Z_i)}$$

$j = 1, 2, \dots m$  energy sampling

$$\vec{\alpha} = B \vec{\rho} \quad B_{j,i} = c Z_i^{b_j} E_j^{a_i}$$

$$\vec{\omega} = B \vec{\sigma} \quad \omega_j = x \alpha_j \quad \sigma_i = x \rho_i$$

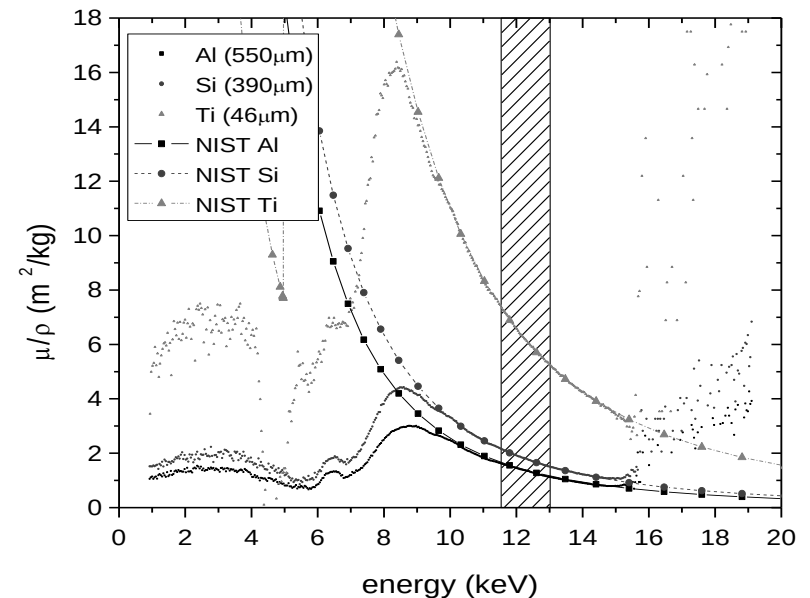
Simple linear problem: Find the elemental composition vector  $\rho_i$ , given the (tabulated/measured) matrix elements  $B_{i,j}$  and the measured attenuation vector data  $\alpha_j$

## Color X-Ray Imaging In Practice

$$\alpha_j = c \sum_{i=1}^n \rho_i Z_i^{b(E_j)} E_j^{a(Z_i)}$$

$j = 1, 2, \dots m$  energy sampling

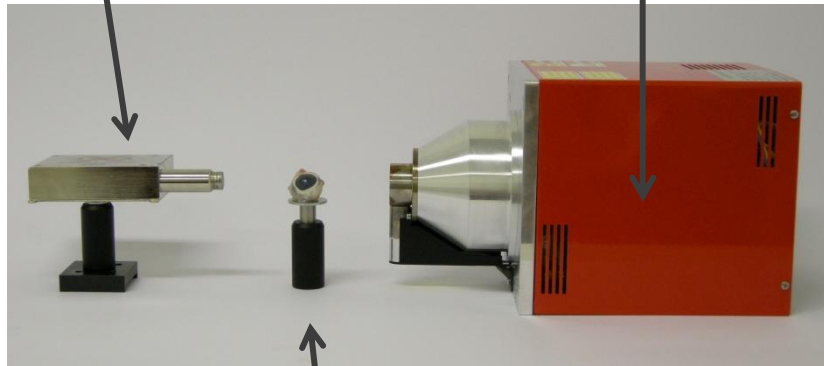
1. Measure reference absorption spectra for pure elements (basis) or use tabulated data
2. Measure absorption spectrum of unknown sample
3. Solve for linear combination of basis spectra which best fit the measured attenuation results



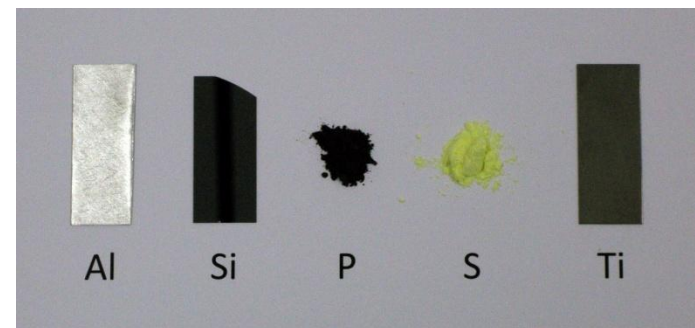
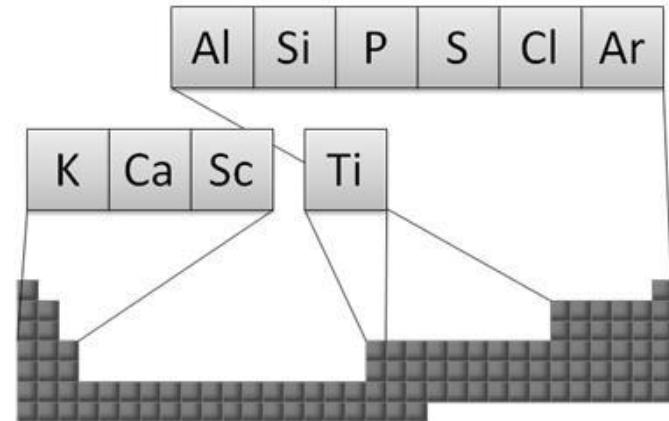
## Experimental Verification

X-ray spectrometer  
(Amptek X-123)

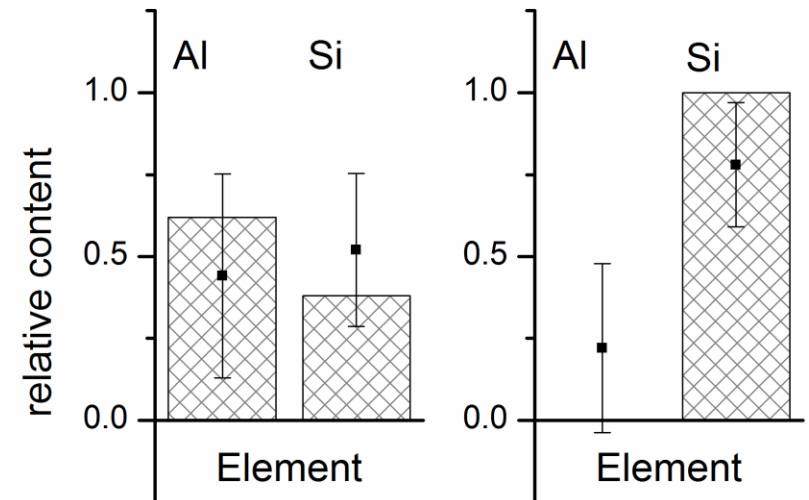
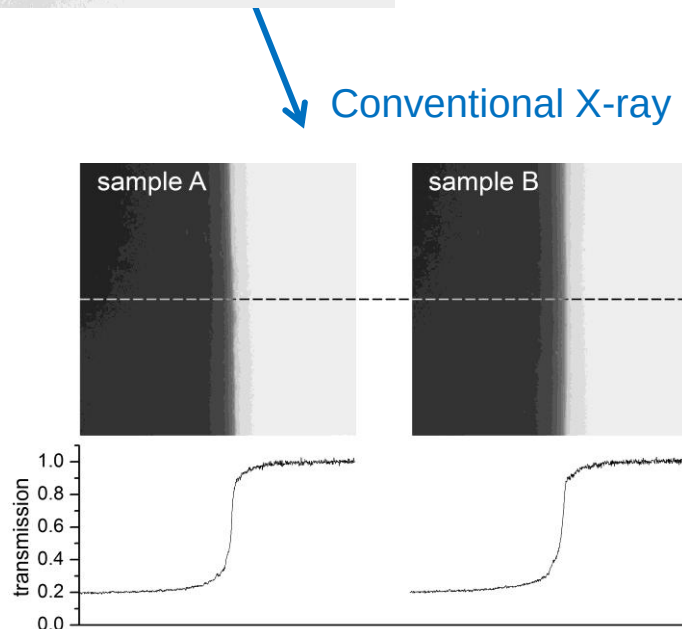
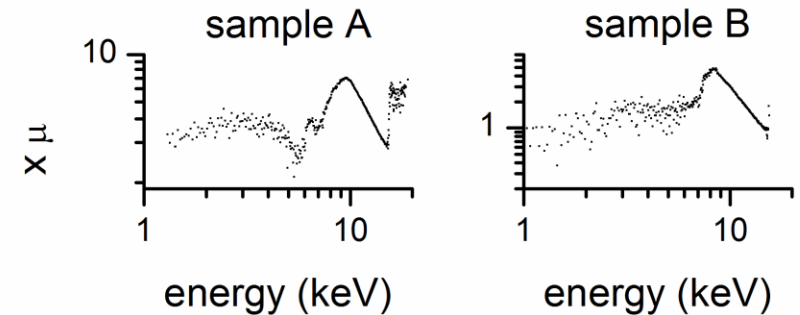
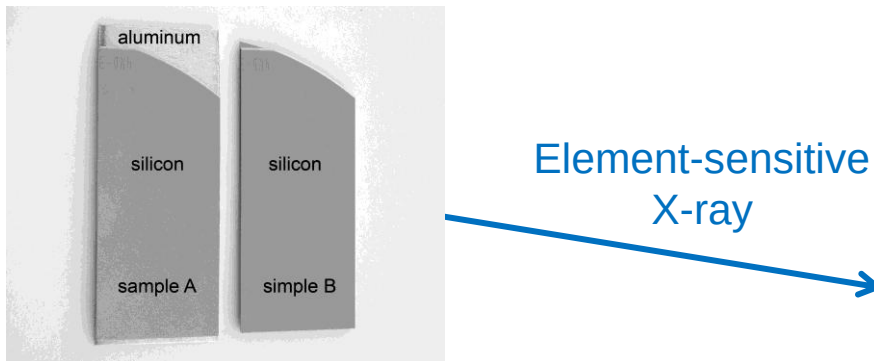
Microfocus X-ray source  
(Hamamatsu L1010101)



Sample



# Element-Sensitive X-Ray Imaging Demonstrated !



$E = 11.6 \dots 13.1 \text{ keV}$

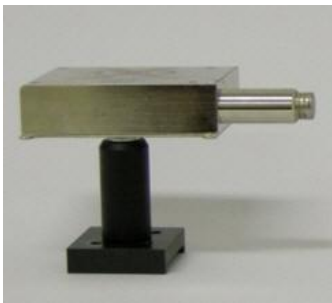
## Color X-Ray Imaging Around the Corner ?

$$\vec{\alpha} = B \vec{\rho} \quad B_{j,i} = c Z_i^{b_j} E_j^{a_i}$$

### Ill-conditioned inversion problem !

Example:  $\text{cond}(B) \sim 200 \dots 600$  for the combination Al and Si with the limited single energy interval of around 11 – 14 keV

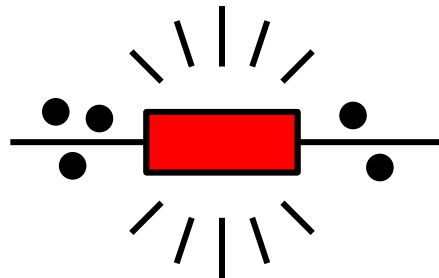
Possible way out: Multiple energy intervals for reduced  $\text{cond}(B)$



**Large, expensive, power-hungry, high-resolution X-ray spectrometer**

Wanted: Affordable Megapixel 2D array of  $<100 \times 100 \mu\text{m}$  X-ray pixels with  $\Delta E < 50 \text{ eV}$

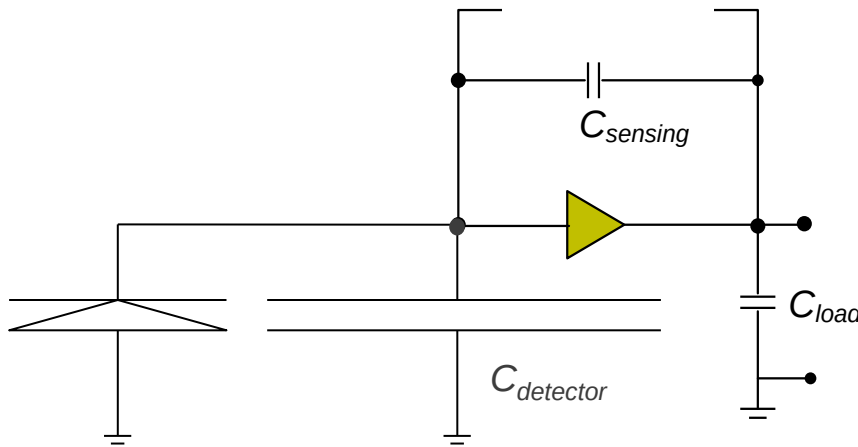
## Fundamental Noise Source: Johnson Noise in Resistor



$$\sigma_V = \sqrt{4kT R B}$$

$\sigma_V$  : noise voltage;  $k$  : Boltzmann's constant;  $T$  : temperature;  
 $R$  : resistance;  $B$  : bandwidth

# Energy-Selective Single X-Ray-Photon Detector Pixel



$$q_{noise} \approx \sqrt{kTC_{sensing} \frac{C_{detector} + C_{sensing}}{C_{load}}}$$

$$\sigma_V = \sqrt{4kT R B} \quad ; \quad B \propto \frac{1}{RC}$$

**Problem:** Large X-ray pixels (area of several  $1000 \mu\text{m}^2$ ) can have capacitances of pF and more

# Lateral Drift-Field Pixels !

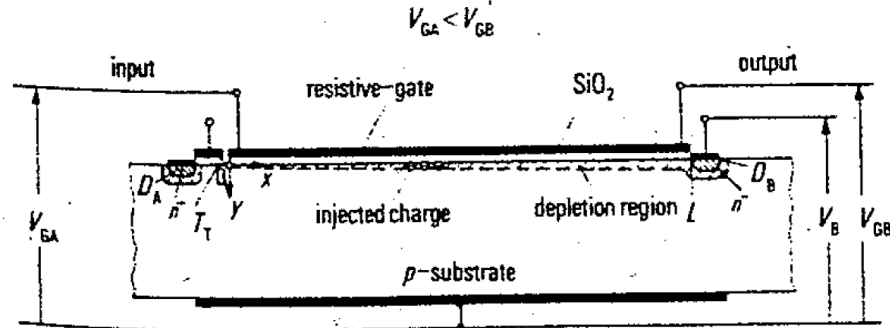
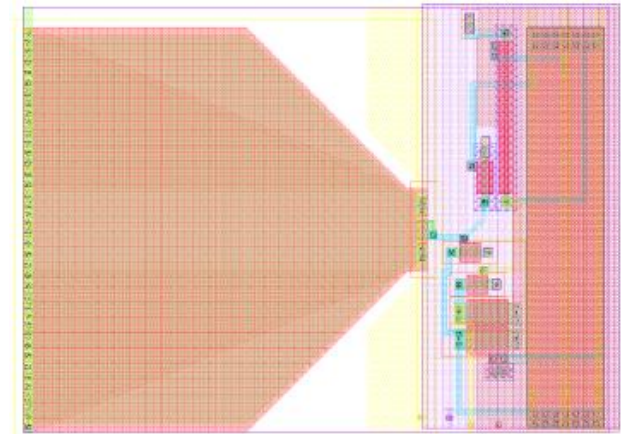


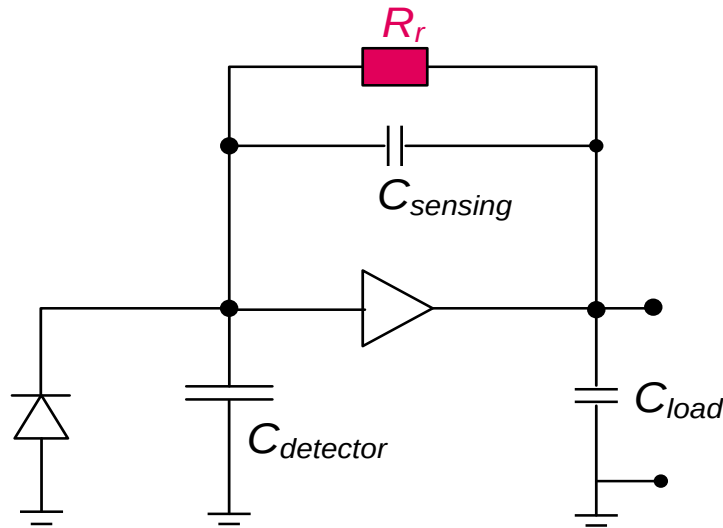
Fig. 1. Cross section through an  $n$ -channel MOS-transmission-line.

K. Hoffmann: "Surface charge transport with an MOS-transmission line", *Solid State Electronics* Vol. 20, 177 (1977)



Note: Lateral drift-field pixels have recently been adopted by industry (Hamamatsu, Mesa Imaging, Espros Photonics, etc.)

## Fundamental Noise Limit : Recharge Resistor !



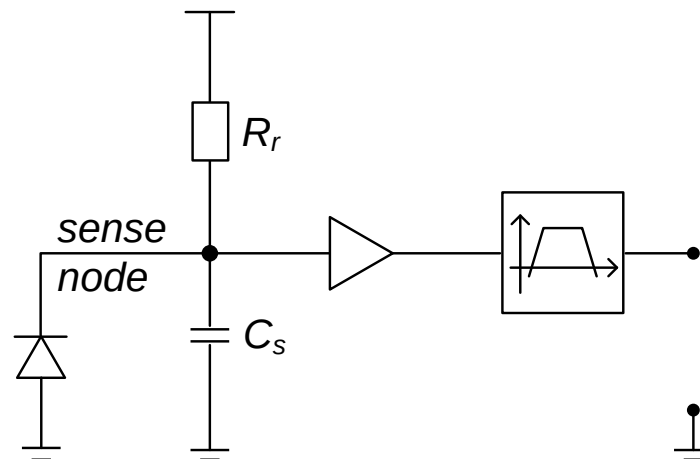
$$q_{noise} = \sqrt{kTC_{sensing}}$$

**Note:** Johnson (resistor) noise is RC-filtered: Independent of R !

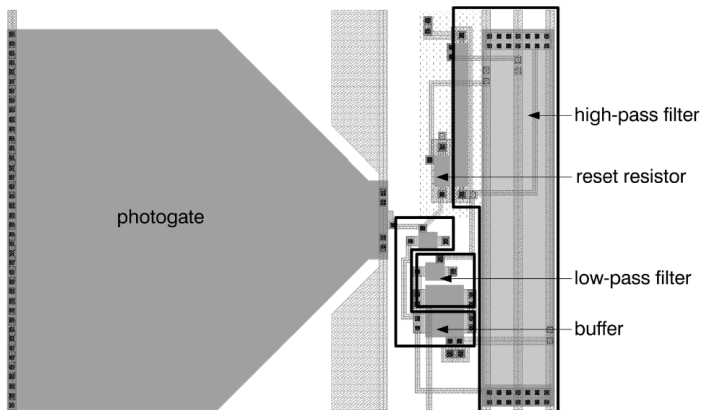
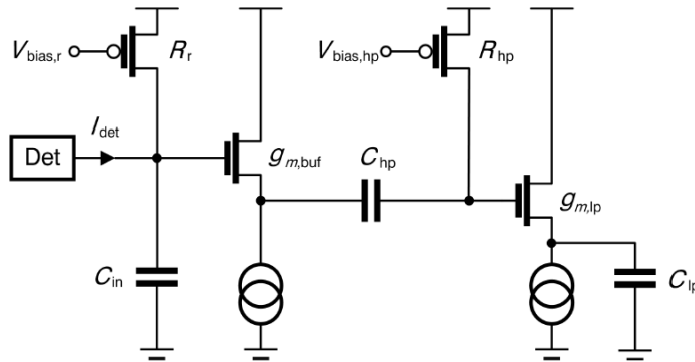
**Typical value:**  $C_{sensing} = 50 \text{ fF}$ ,  $T = 300 \text{ K}$  :  $q_{noise} = 90 \text{ electrons}$

## Energy-Selective Single-Particle (X-Ray) Detection

- Integration on (small) capacitance on sensor side
- Continuous “reset” on sensor side
- Continuous-time **high-pass filtering** of reset noise
- **Narrow bandwidth shaping** of recharge noise: High  $R_r$  ( $G\Omega$ ) implementation difficult when connected as feedback resistor

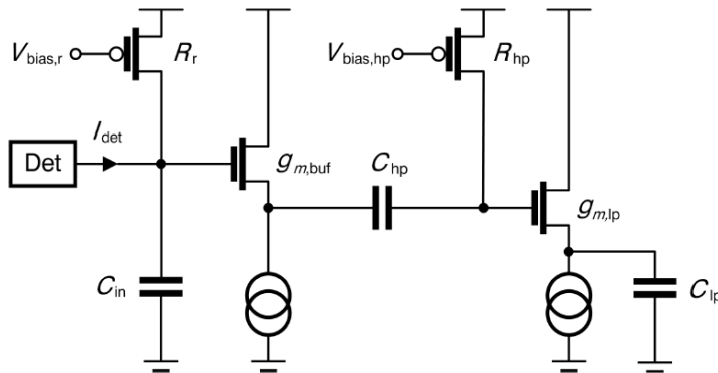


# Energy-Selective Single-Particle (X-Ray) Detection



| Parameter                  | Value                     |
|----------------------------|---------------------------|
| detected pulse width       | 150 ns – 1.5 $\mu$ s      |
| conversion factor          | 27 $\mu$ V/e <sup>-</sup> |
| recharge time constant     | 10 $\mu$ s                |
| high-pass time constant    | 2 $\mu$ s                 |
| pixel area                 | 30 x 20 $\mu$ m           |
| fill factor                | 56 %                      |
| Hi-pass filter capacitance | 200 fF                    |
| Overall noise (r.m.s.)     | 13.5 e <sup>-</sup>       |

## Low-Noise Charge Detection : Noise Sources



| Noise contribution            | Value                     |
|-------------------------------|---------------------------|
| Buffer (first transistor)     | 1.6 e <sup>-</sup>        |
| High-pass filter resistor     | 3.9 e <sup>-</sup>        |
| Active low-pass filter        | 1.4 e <sup>-</sup>        |
| Reset resistor ( $R_r$ )      | 12.7 e <sup>-</sup>       |
| <b>Overall noise (r.m.s.)</b> | <b>13.5 e<sup>-</sup></b> |

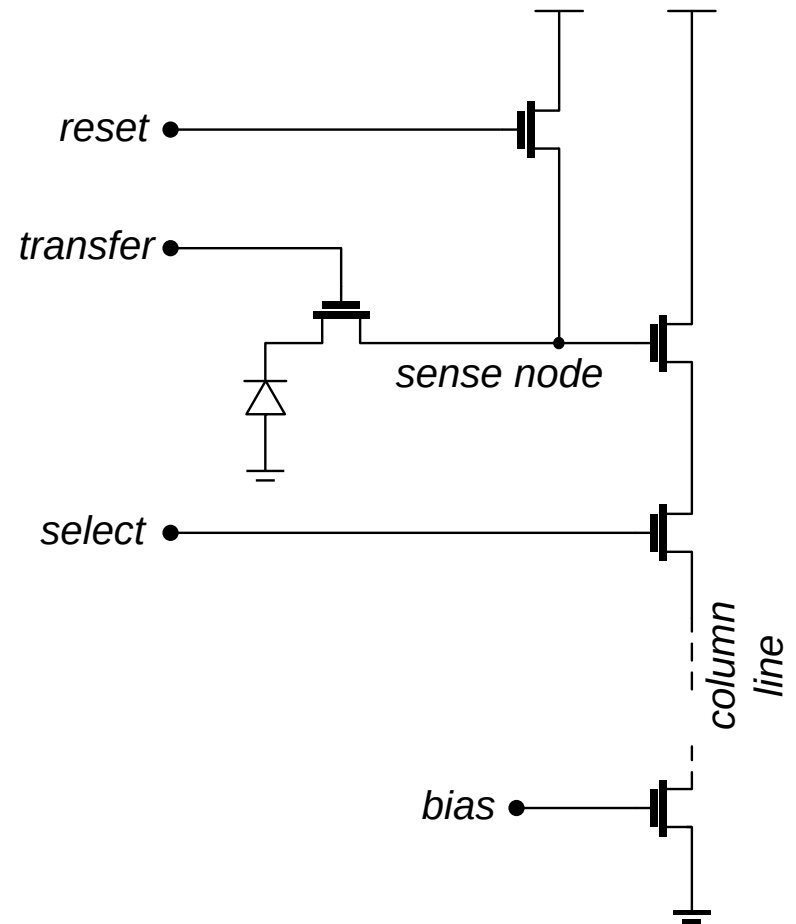
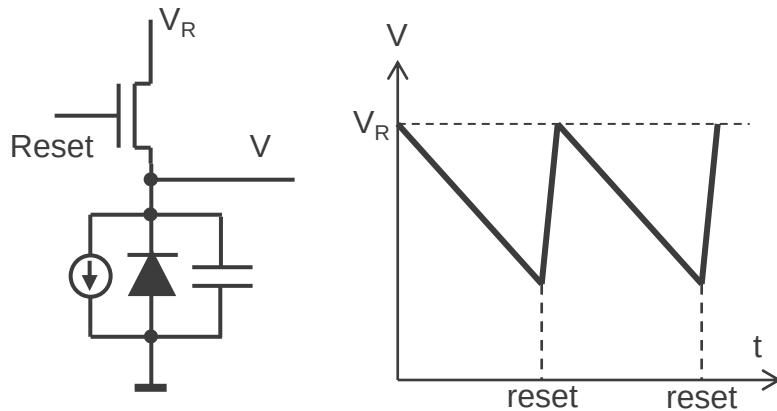
- Reduce noise substantially (to less than 5 electrons) by changing from “continuous” (asynchronous) reset to “switched” (synchronous) reset !
- Input stage resembles a CMOS active pixel (APS). Is it possible to employ the same ideas (bandwidth engineering, in-pixel amp, input capacitance reduction, synchronous reset) to ultra-low-noise CMOS image sensing?

## The Holy Grail : Single-Electron/Photon Detection !



# CMOS/APS Image Sensing

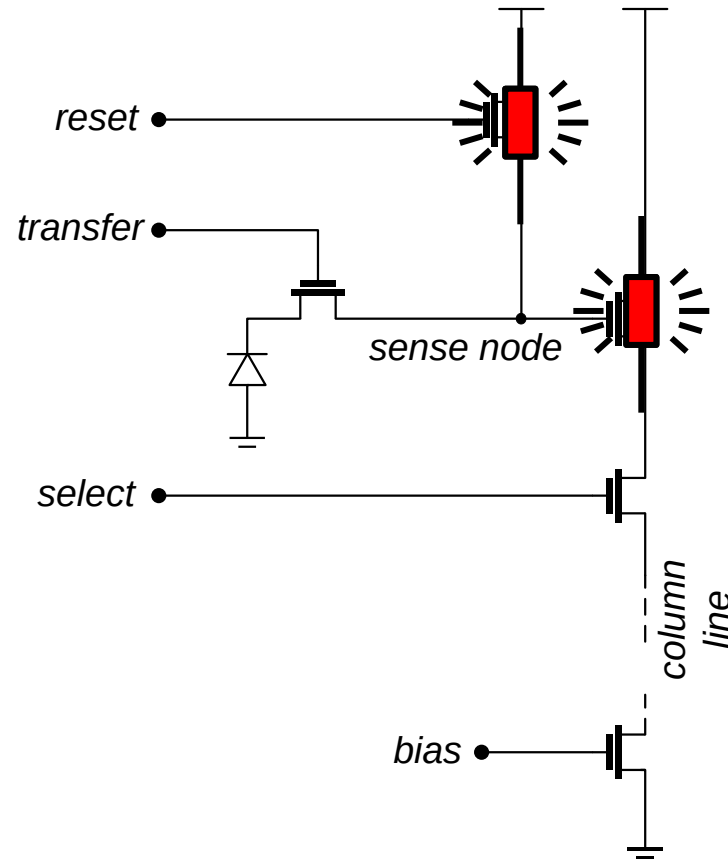
## Conventional CMOS pixel



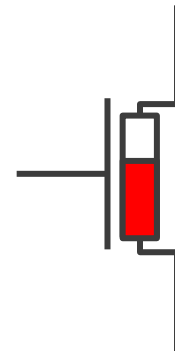
## Noise Sources in CMOS/APS Pixels

**Reset noise  
(kTC noise)**

**Solution:**  
Correlated  
Double  
Sampling  
(CDS)



**MOS-FET  
channel noise  
(input-referred  
Johnson noise)**



$$\sigma_Q = C_s \sqrt{\frac{4kTB\alpha}{g_m}}$$

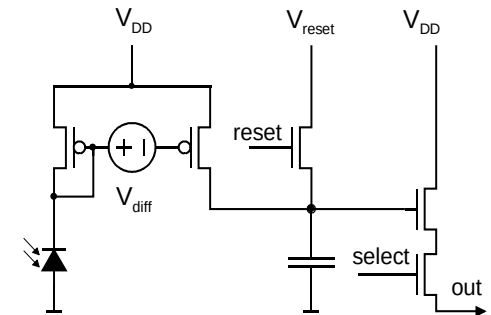
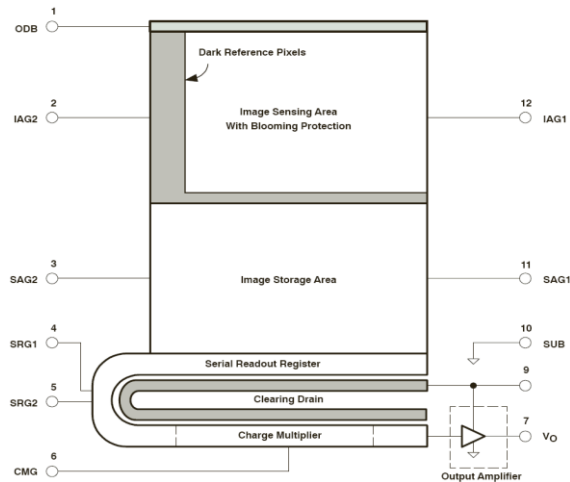
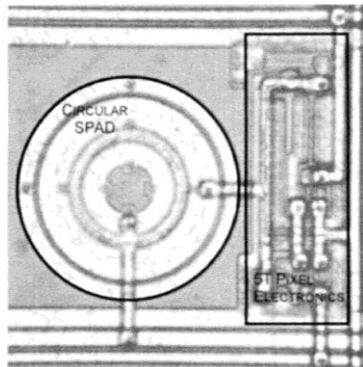
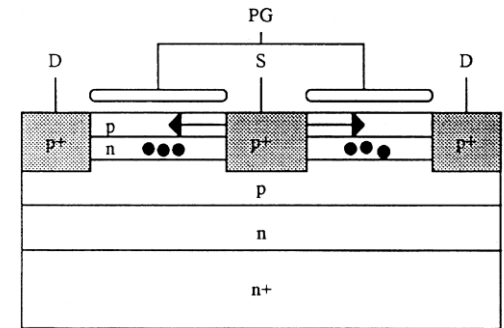
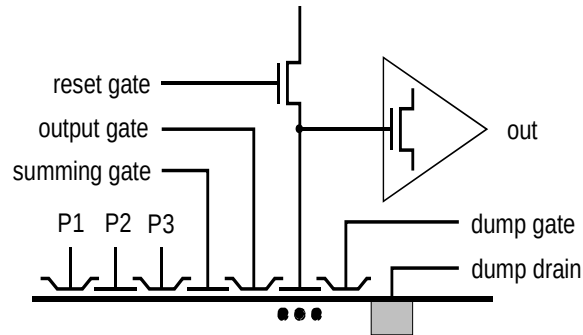
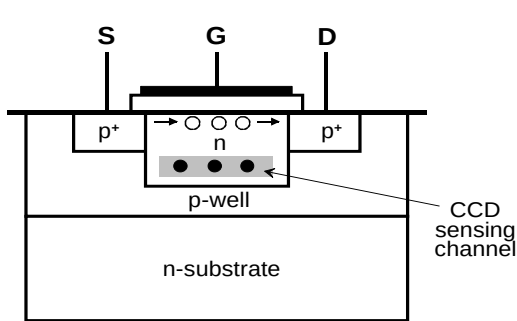
## State of the Art: MOS-FET Channel Noise

$$\sigma_Q = C_S \sqrt{\frac{4kTB\alpha}{g_m}}$$

$$C_S = 10 \text{ fF} ; T = 300 \text{ K} ; B = 20 \text{ MHz} ; \alpha = 1 ; g_m = 50 \text{ } \mu\text{S}$$

$$\sigma_Q = 5.1 \text{ electrons}$$

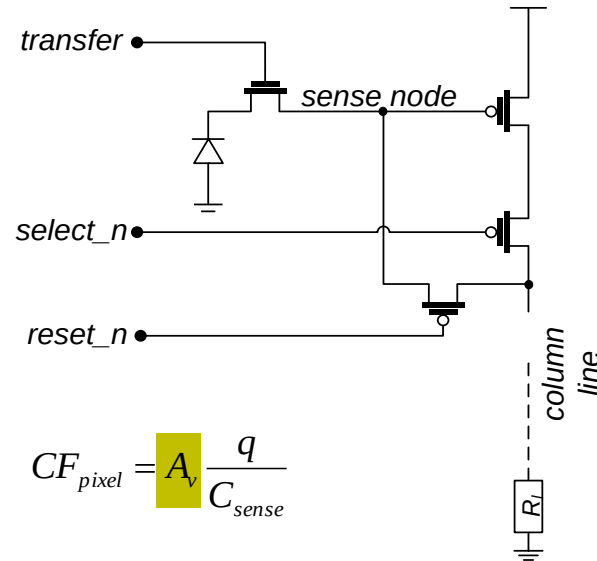
# The Long Quest for Single-Electron/Photon Detection



## Novel CMOS/APS Pixel With In-Pixel Gain

- In-pixel amplification for reduced bandwidth and reduced impact of downstream circuit noise → *very low readout noise*

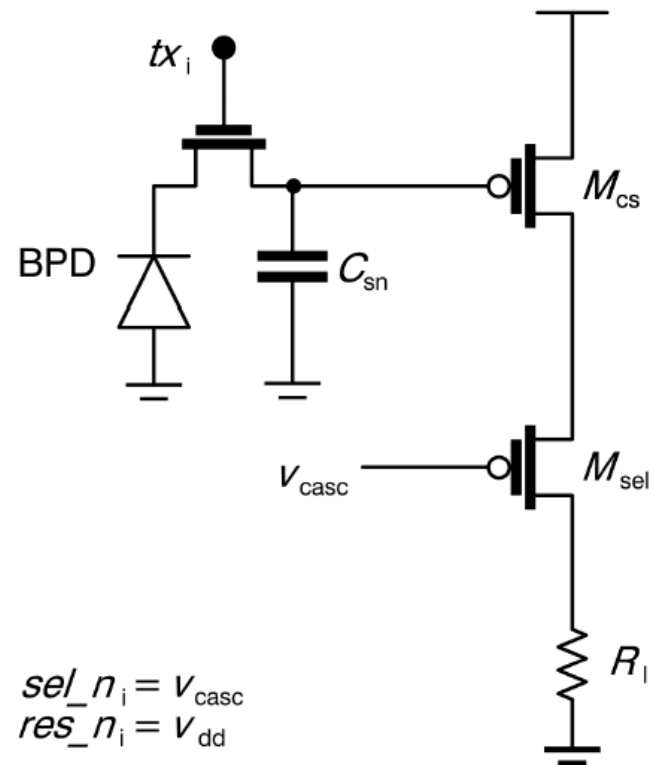
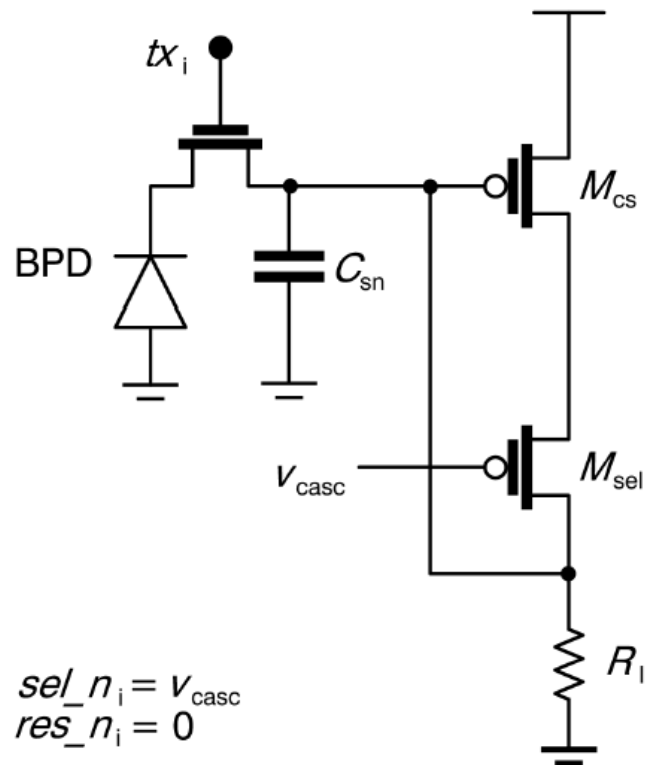
**Amplifying pixel**  
(common-source  
connected p-MOS  
amplifier pixel)



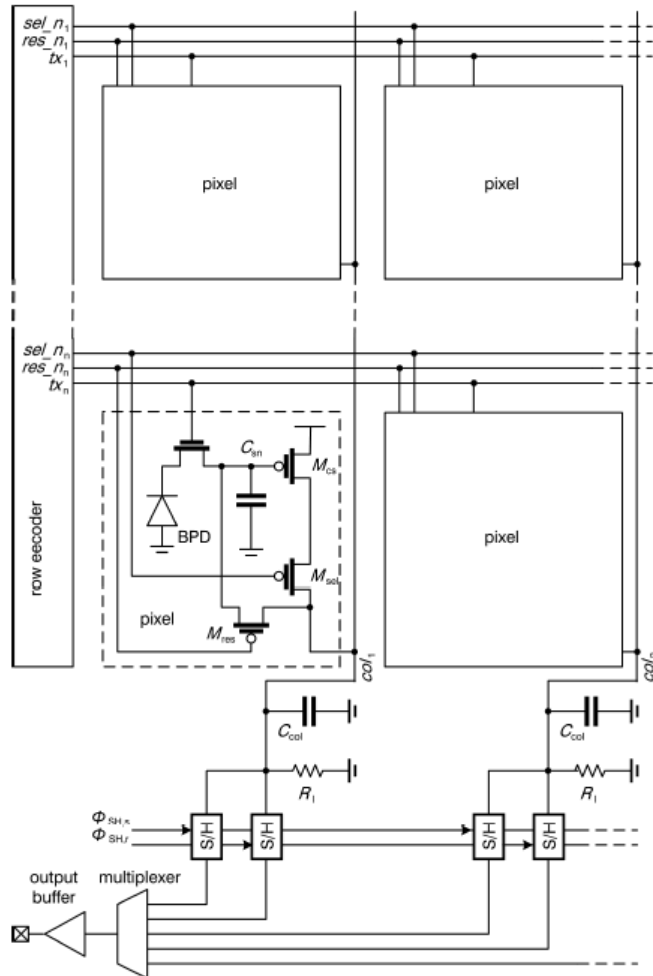
$$CF_{pixel} = A_v \frac{q}{C_{sense}}$$

$$v_{n,thermal} \cong \sqrt{\gamma kT A_v C_{column}}$$

## Gain Pixel : Reset and Amplifying State



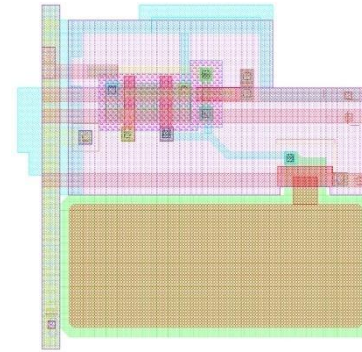
# Gain Pixel : Column-Level Bandwidth Engineering



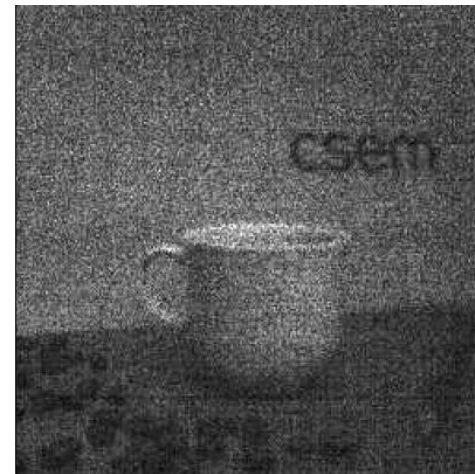
| Specified Parameter  | Value                 | Calculated Parameter | Value                 |
|----------------------|-----------------------|----------------------|-----------------------|
| $A_{\text{pix}}$     | 10                    | $\beta R_l$          | $14.8 \text{ V}^{-1}$ |
| $C_{\text{col,tot}}$ | 3.3 pF                |                      |                       |
| $T_{\text{cds}}$     | $8 \mu\text{s}$       | $R_l$                | 303 k $\Omega$        |
| $n_\tau$             | 8                     | $\beta$              | $48.9 \mu\text{F/Vs}$ |
| $\mu C_{\text{ox}}$  | $16.4 \mu\text{F/Vs}$ | $W/L$                | 2.98                  |

# Single Electron/Photon Detection With CMOS Imagers !

| Parameter                                        | Value                                   |
|--------------------------------------------------|-----------------------------------------|
| pixel pitch                                      | 11 $\mu\text{m}$                        |
| fill factor                                      | 50%                                     |
| transistor count                                 | 4                                       |
| sense node capacitance                           | 5.3 fF                                  |
| voltage gain (linear)                            | 9.9                                     |
| pixel conversion factor (lin.)                   | 300 $\mu\text{V}/\text{e}^-$            |
| linear range                                     | 4 $\text{ke}^-$                         |
| full well capacity                               | 29 $\text{ke}^-$                        |
| readout noise (60 fps, 300K)                     | <b>0.86 <math>\text{e}^-</math> rms</b> |
| dynamic range ( $t_{\text{exp}} = 17\text{ms}$ ) | <b>90.4 dB</b>                          |



11x11  $\mu\text{m}$   
CMOS pixel  
with 50% fill  
factor



Sample  
picture of  
256x256  
imager.  
Average:  
6 photo-  
electrons  
per pixel

# Summary

- 105 years after Röntgen's discovery, it has been shown that “color” X-ray imagery (element-sensitive radiography) is possible, in principle.
- Determination of elemental composition from spectral measurements is an ill-posed problem. Only decomposition into a few components seems practical. Relevance of “color radiography”? Too early to tell !
- Spectral measurements require integrated (monolithic) energy-resolved single-photon X-ray detectors. State of the art ( $\Delta E = 50\text{-}100\text{ eV}$ ) can be improved by an order of magnitude ( $\Delta E = 5\text{-}15\text{ eV}$ ), using bandwidth optimization, in-pixel amplif., input capacitance reduction, synchronous reset
- The same techniques can be applied to CMOS/APS image sensors, resulting in sub-electron (photo-) charge detection at room temperature and at video rates. Night vision for everybody is around the corner!

