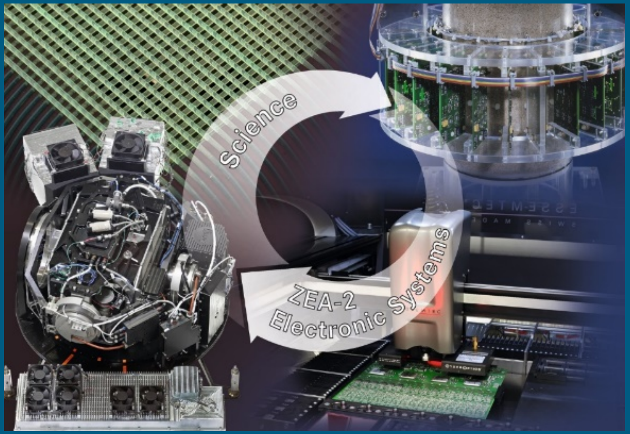
Silicon based photodetection in science

8th Electronics and Advanced Design Seminar



September 21, 2016 | Daniel Durini

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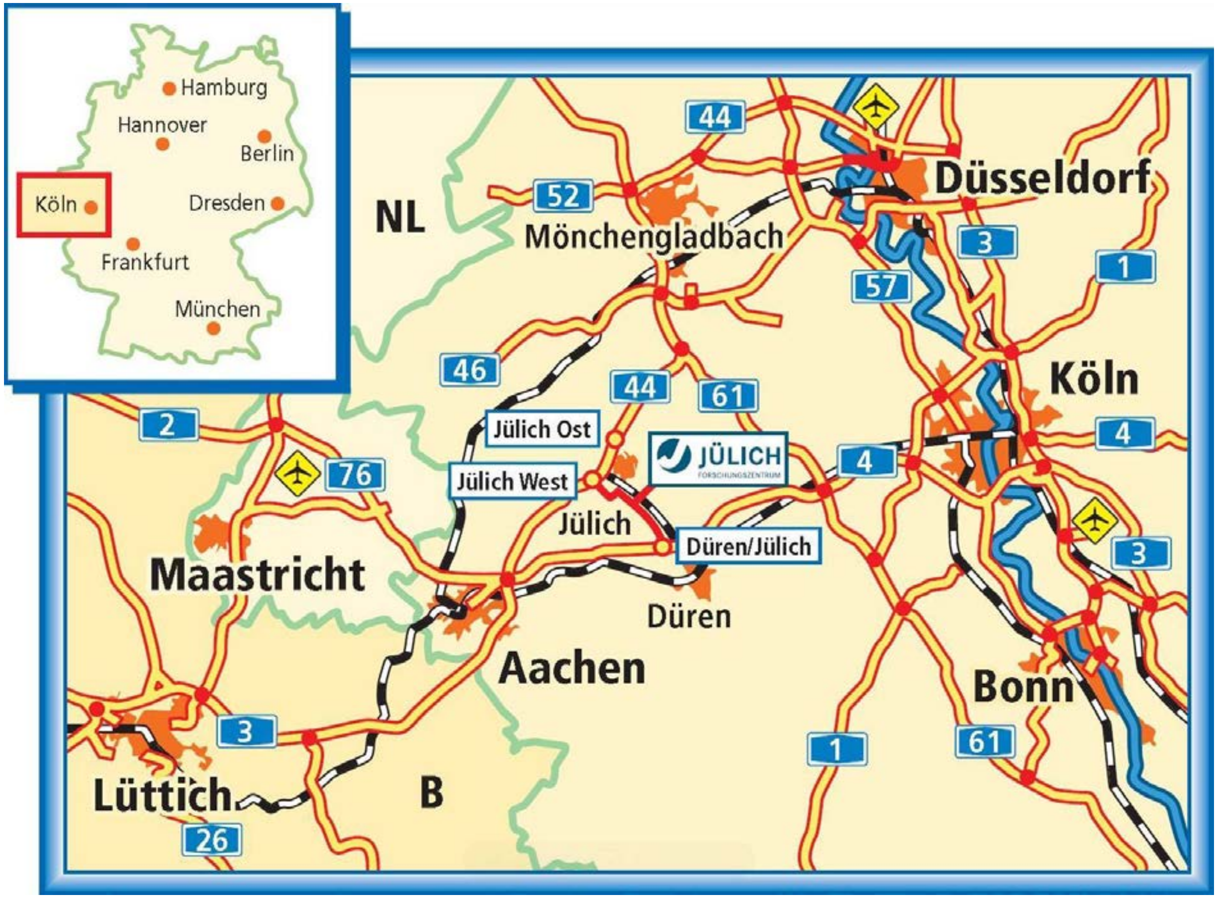
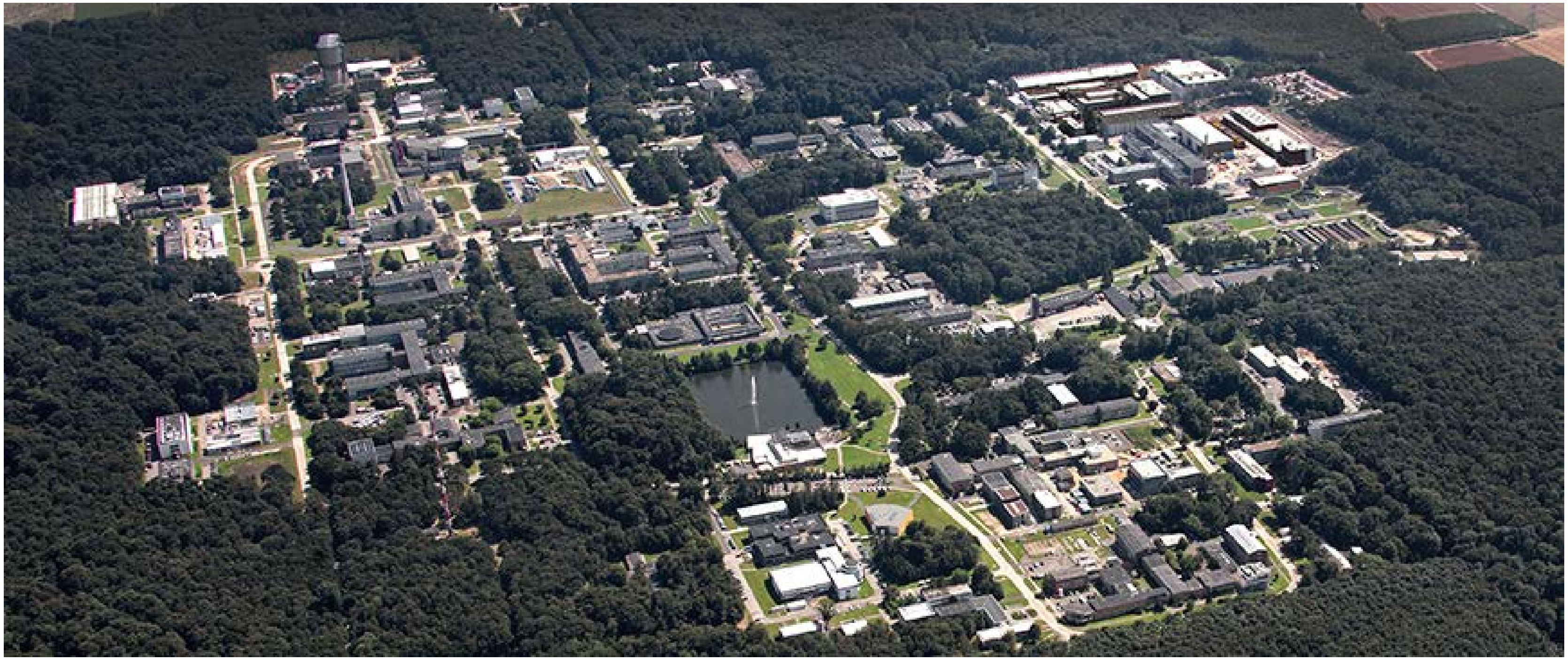
Where is Forschungszentrum Jülich?



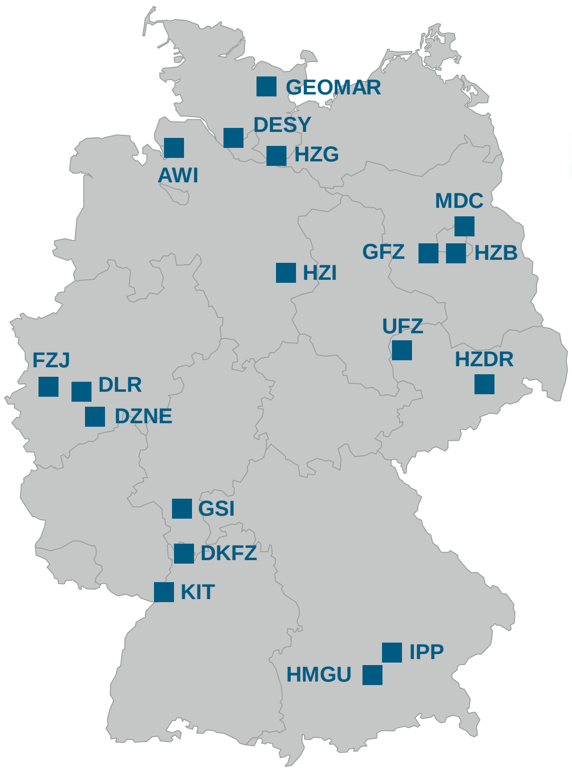
Science Campus Jülich



Future is Our Mission –
Research & development on 2.2 km^2

JÜLICH
FORSCHUNGSZENTRUM

Member of Helmholtz Association – Facts & Figures

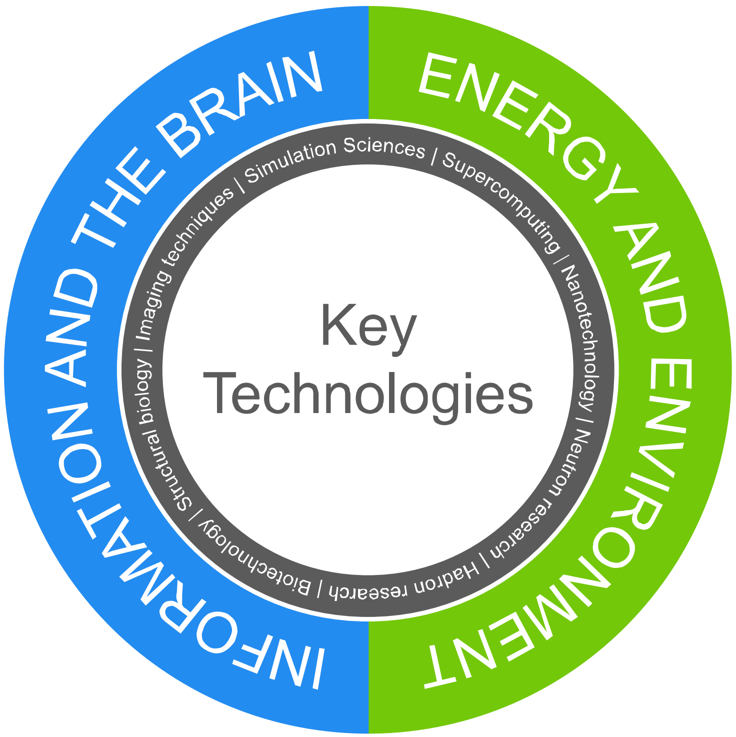


HELMHOLTZ
GEMEINSCHAFT

- Helmholtz Association of German Research Centres
  - 18 research centres
  - Employees: > 38000
    - approx. 14700 scientists
      - approx. 7400 PhD students
    - approx. 7400 guest scientists
    - approx. 1650 apprentices

Mitglied der Helmholtz-Gemeinschaft

Member of Helmholtz Association – Facts & Figures

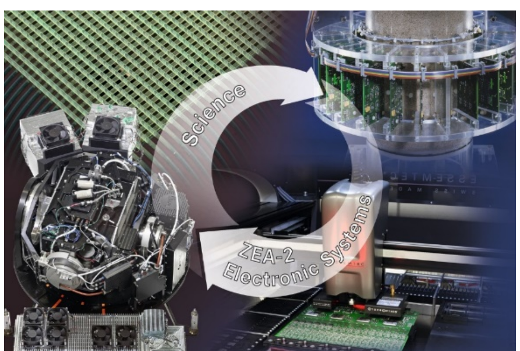


- Founded: 1956
- Employees: > 5700
  - approx. 2000 scientists
    - approx. 540 PhD students
  - approx. 900 guest scientists
  - approx. 360 apprentices and trainees
- Budget: 525 m. €
  - incl. 190 m. € third-party funding
- 1.8 bn. € project executing org.

ZEA-2 – Electronic Systems

Facts & Figures

- Approx. 90 employees
  - approx. 50 scientists, engineers und technicians
  - approx. 10 PhD students
  - approx. 13 students
  - 4 administrative staff members
  - approx. 15 apprentices
- Tasks inside Forschungszentrums Jülich
  - Development projects in all research areas
  - Third-party projects for pre-development
  - Supply of internal services
    - IT, prototype manufacturing, mechanical workshop

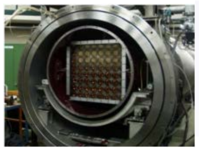
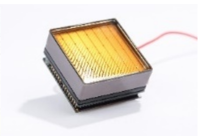
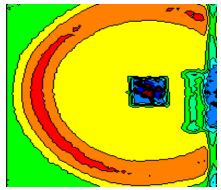
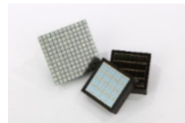


Capabilities

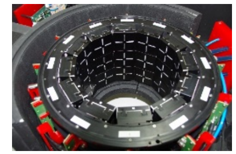
- Application Knowledge
  - Detector systems (From sensor to GUI)
  - Experimental systems (Control and measurement)
- Hardware Systems
  - Analog, Digital, Mixed signal, HF
  - Prototype lab, PCB design, SMD assembly
  - FPGA based readout electronics
  - Fast bus systems and optical links
- Software Systems
- Microelectronics
  - Chip design team
  - Prototype test facility
- Modelling and Simulation

ZEA-2 – Electronic Systems

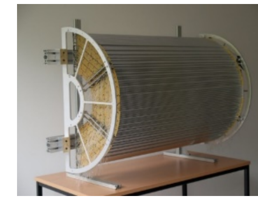
Neutron Detection

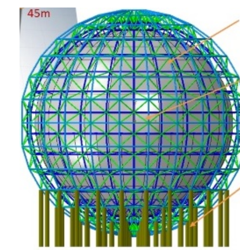





Detector Systems for Positron Emission Tomography (PET)

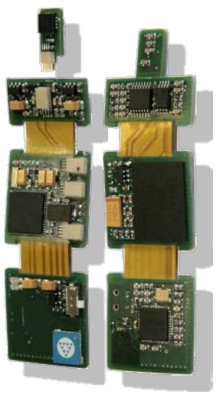


Detection Technology in Nuclear and Particle Physics






Environmental Imaging




- ZEA-2 develops complex, modular and large-scale networked detector systems using state-of-the-art implementation methods and generic approaches including silicon (semiconductor) based high integration (“System-on-Chip”) solutions
- Our systems include all the stages required by a scientific instrument, starting with the detection of the physical event and ending with the extraction of information and a digital user interface
- The great variety of applications and an interdisciplinary team are great assets that allow us getting the most out of designed experimental environments
- Our system solutions rely on commercially available technologies as well as on self-developed ones

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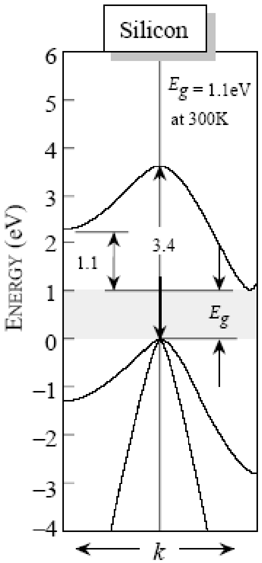
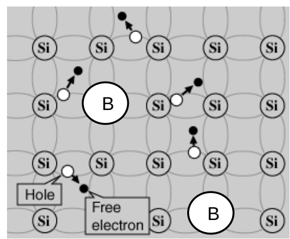
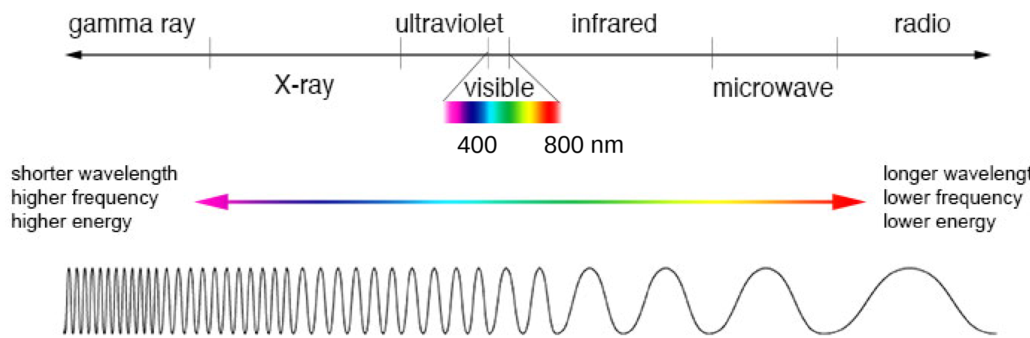
- Forschungszentrum Jülich GmbH and ZEA-2: Detector System Solutions for Science
- Silicon based phototransduction and imaging
- What about scientific applications?
- Challenges and perspectives

Silicon Based Phototransduction



Electron crystal momentum dependent band structure diagram of silicon (Si), an indirect semiconductor (Singh, 2003).

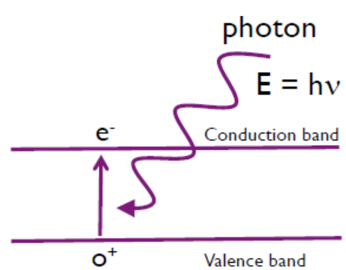




Source: http://imagine.gsfc.nasa.gov/Images/science/EM_spectrum_compare_level1_lg.jpg

1. Photon absorption in Silicon causes a generation of electron-hole pairs (Photon energy must be larger than E_g, and impurity doping helps!)

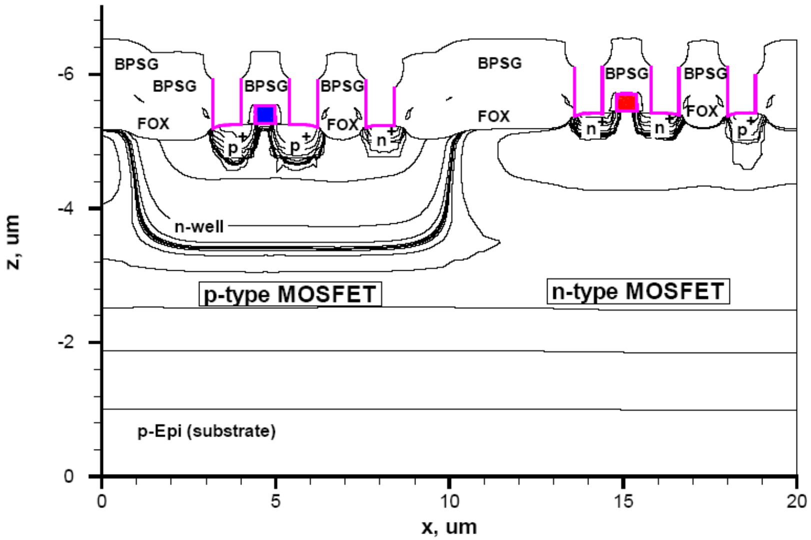
2. The electrons and holes must be separated to avoid their recombination (we need electrical fields for that: *p-n* junctions or reverse biased gates!)



3. Silicon has a combination of unique properties:
   - the best/most suited material for integrated circuits!
   - Right bandgap to detect visible light (and more)
   - Absorption of visible light in a few µm thickness

Silicon Based Phototransduction

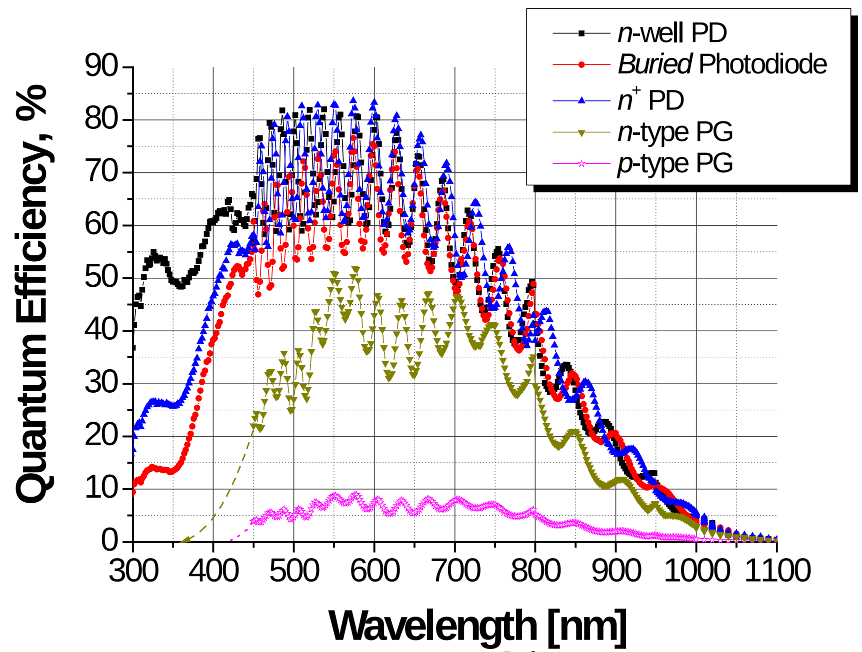
Choosing a proper photodetector is crucial!

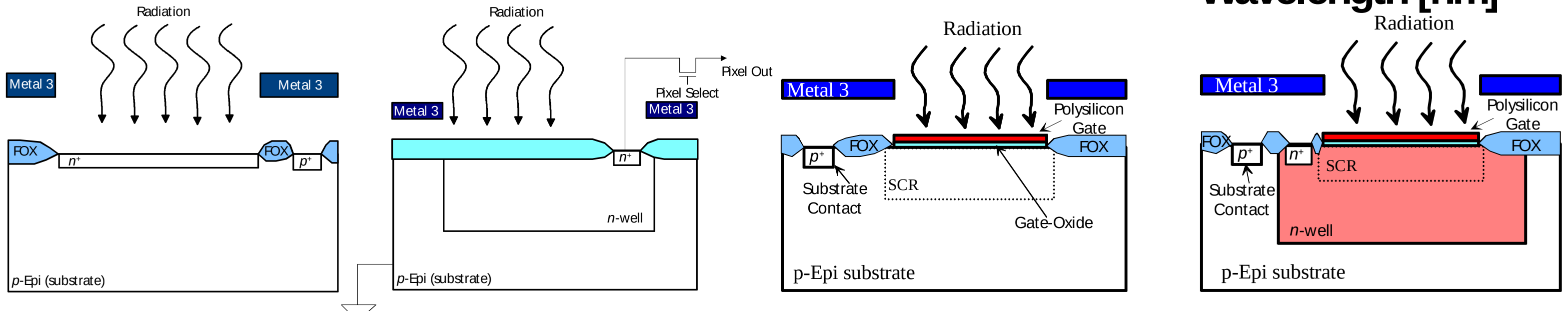


Typical technology cross-section of a CMOS process
-TCAD 2D process simulation- (D. Durini, 2008)

Possible Photodetector Devices

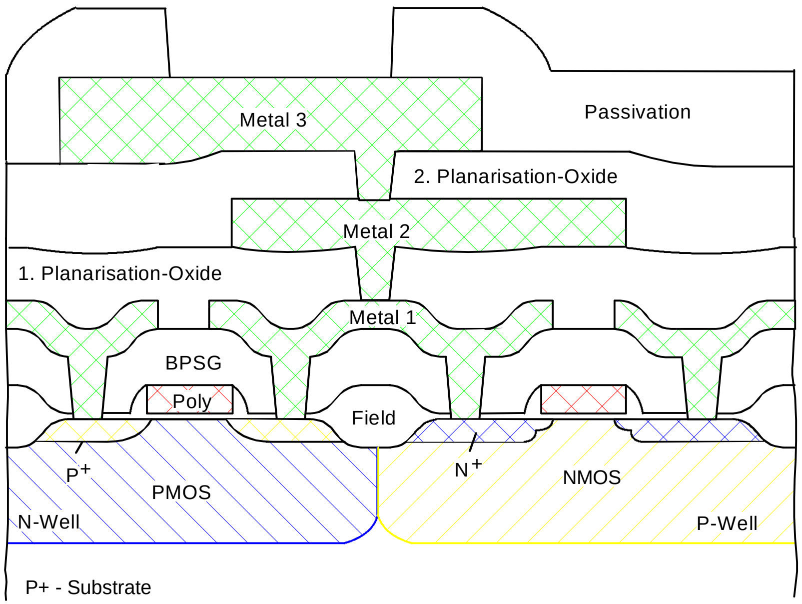
Optical Sensitivity:



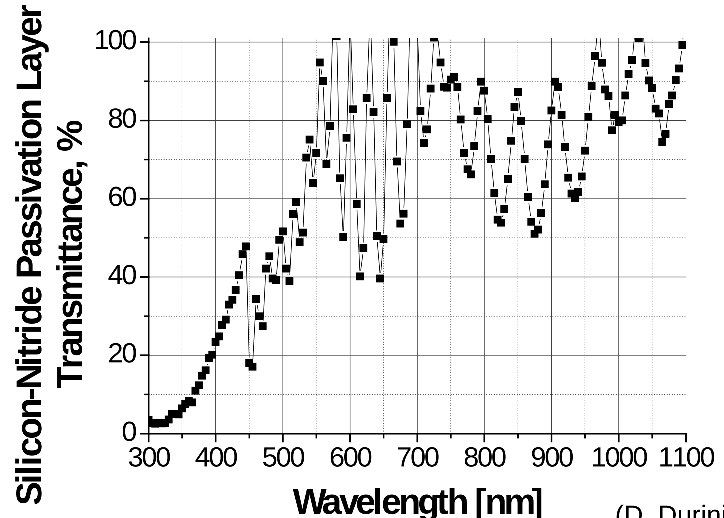


CMOS Imaging: Optical Sensitivity

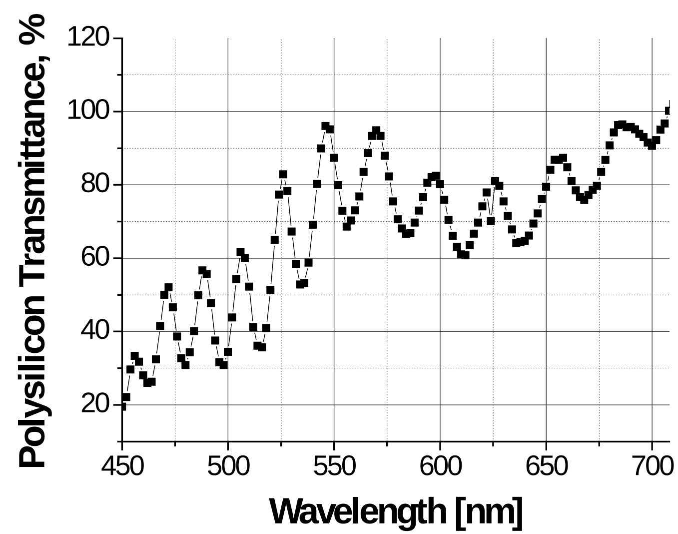
But it is **not** only Silicon what makes an imager!



Cross-section of the 0.5µm standard CMOS process (not to scale).
Courtesy of Fraunhofer IMS, Duisburg, Germany.



(D. Durini, 2007)



CMOS Imaging: Passive Pixel Sensors

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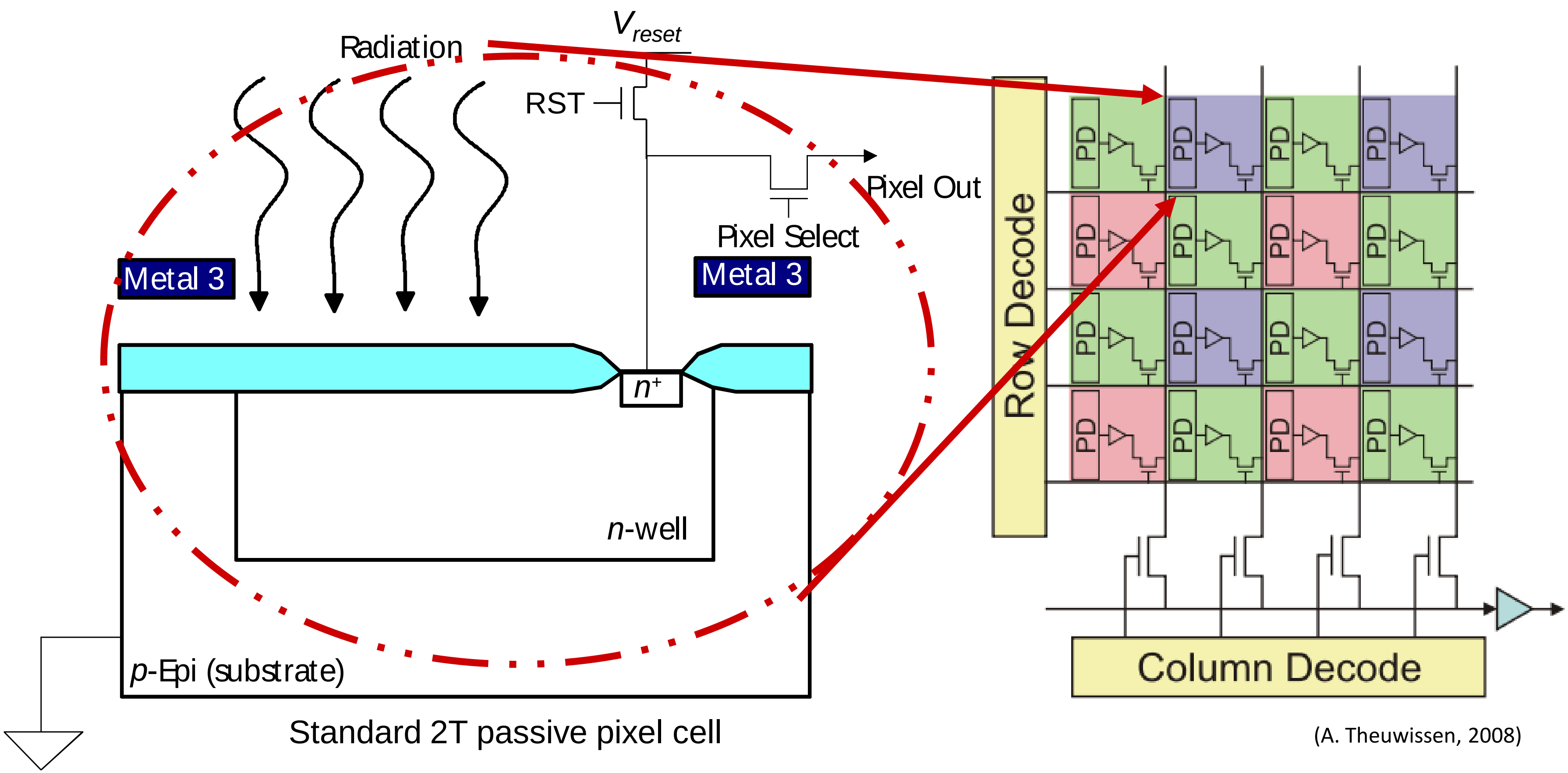
Separating the electrons from the holes, properly **collecting** the electrons from a well defined area for readout, and **sensing** the resulting output signal gives us the required information to define a “picture cell” (or **pixel**).

An array of pixels gives us an imager!

A CMOS pixel based on a reverse biased *p-n* Junction (**passive pixel** structures):

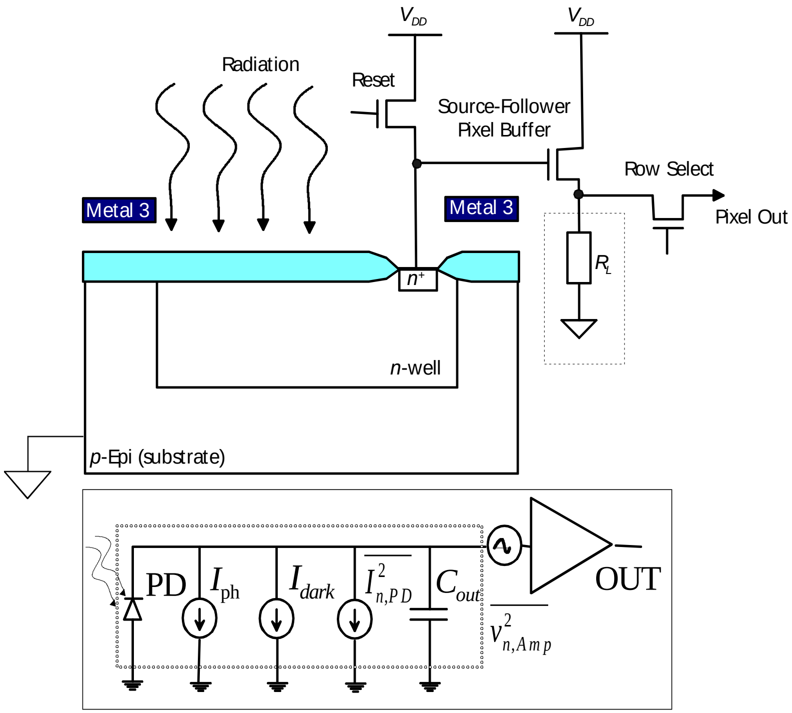


Standard 2T passive pixel cell

(A. Theuwissen, 2008)

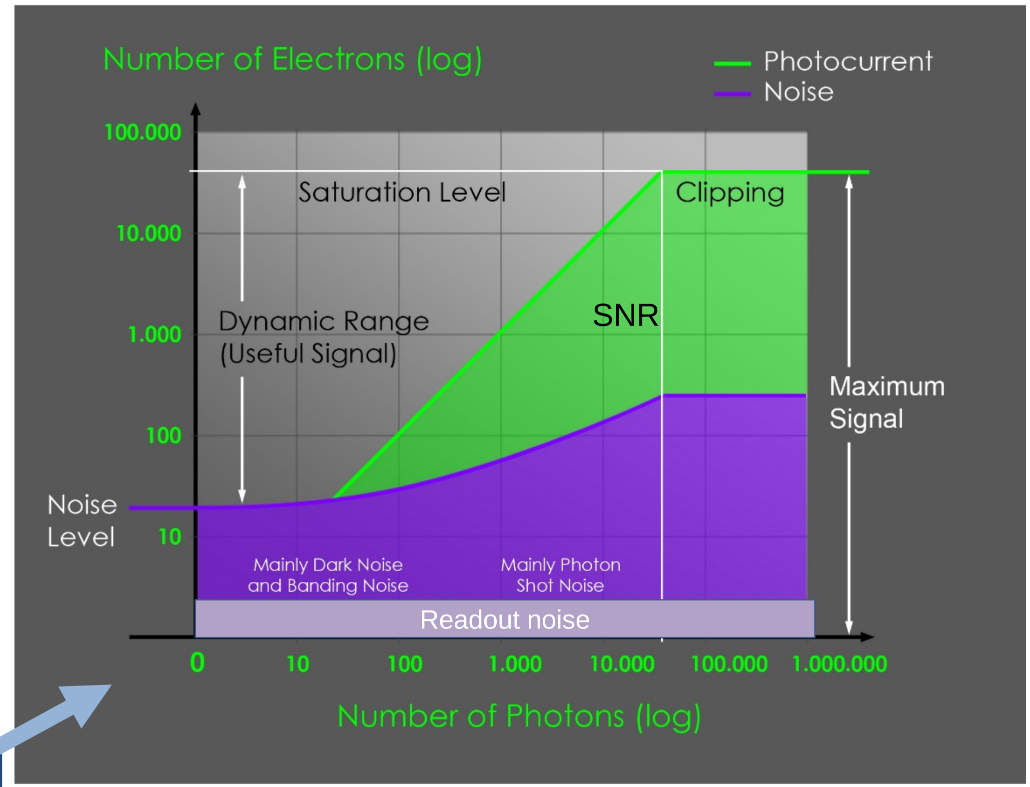
CMOS Imaging: Active Pixel Sensors

Dealing with the electric load produced by a column of several hundreds of thousands of pixels is not easy… we need some kind of signal buffering!



Standard 3T Active Pixel

Dynamic Range



But, transistors in the pixel:

- Introduce noise
- Reduce the photoactive area (fill-factor): diminish photosignal

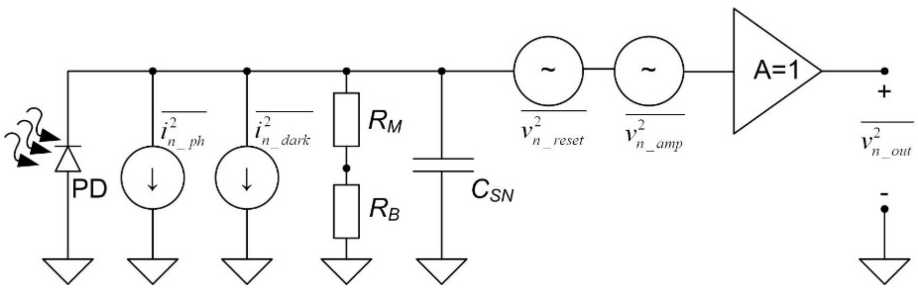
The useful signal is limited by the photodiode saturation and noise.

(Source: http://www.exclusivearchitecture.com/wp-content/uploads/2014/06/Dynamic_Range_01.jpg)

CMOS Imaging: Challenges

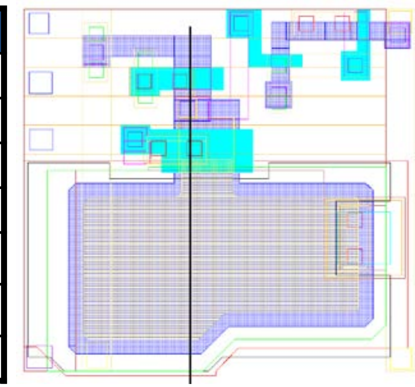
The CMOS industry evolved and specialized in **imaging enhanced processes**

Noise analysis for the CMOS 3T pixel



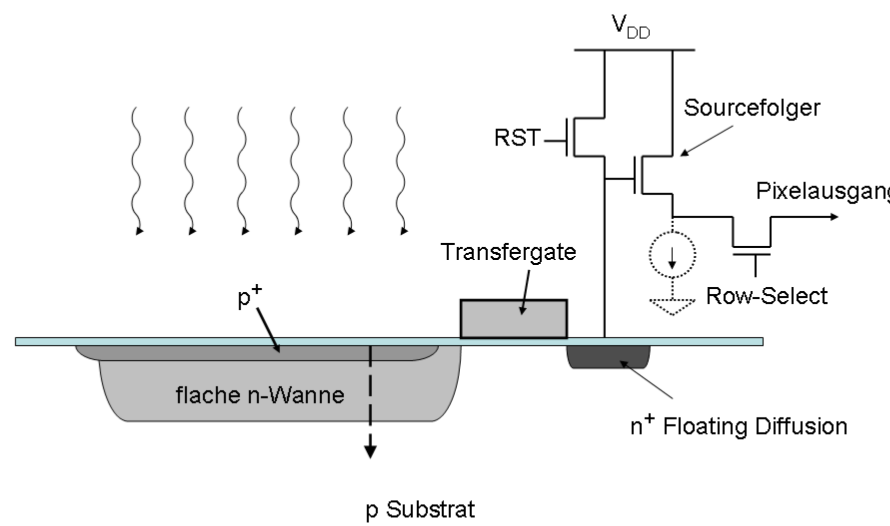
(Durini, 2014)

Parameter
Technology: 0.35 µm CMOS (Opto)
Pixel Size: 10 x 10 µm²
Fill-Factor: 50 %
Full-Well Capacity: 12,800 e⁻
Pixel Dark Current: < 20 e⁻ / s
SNR$_{max}$: 45 dB
DR: 48 dB



$$ENC = \sqrt{\overline{n_{dark}} + \overline{n_{ph}} + \frac{k_B T C_{PD}}{q^2} + \frac{2\alpha_{part} \cdot k_B T C_{G\_RST}}{\pi^2 q^2} + \frac{C_{PD}^2}{q^2} \cdot \overline{v_{n\_SF}^2}}$$

CMOS 4T pixel with a pinned photodiode



To improve the SNR of the *active pixel*, it is necessary to have:

- Higher Fill-Factors
- Lower dark currents
- Lower C_{PD}
- Reduce *kTC* and SF noise

!

Silicon Imaging: State-of-the-Art

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CCD-Based Imaging Offers:

- mature technology: high η and very low I_{dark}
- column-wise pixel readout: charge-transfer (low noise) and column FPT (TDI possible)
- single serial analog output with simple NMOS based amplification
- off-chip readout and biasing
- dedicated processes (variable substrates, full depletion possible, back-side illumination, high bias voltages etc.)

CMOS-Based Imaging Offers:

- random pixel access
- non-destructive pixel readout
- in-pixel amplification
- on-chip readout signal processing, control, and interfacing
- low-cost implementation in mass production CMOS
- imaging enhanced processes (BSI, microlenses, ARC, colour filters, etc.)

Downscaling of CMOS Processes Yields:

- smaller device area
- lower power consumption
- higher operation speed
- increased functionality

Good for Logic!

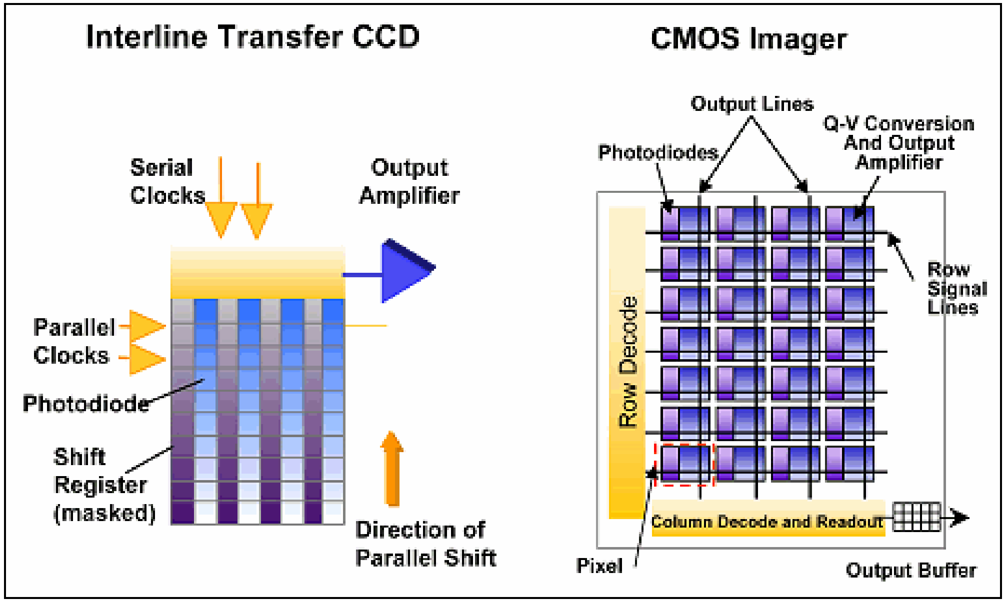
But

- higher doping concentrations
- lower operation voltages
- thinner oxides
- smaller space charge regions

Bad for Imaging!

Silicon Imaging: Perspectives

The two main Silicon based imaging technologies are:



Source: http://www.siliconimaging.com/ARTICLES/fig2.gif

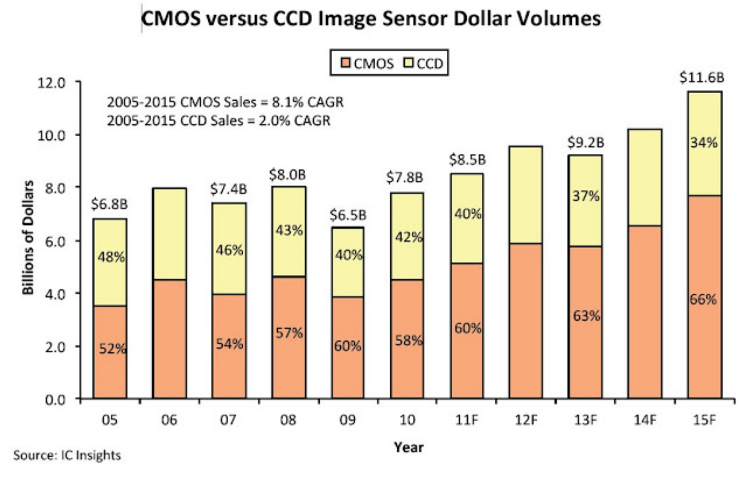
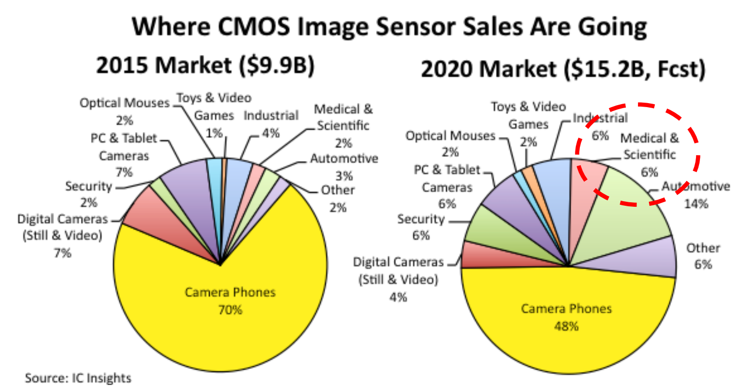


Figure 1



Source: http://www.icinsights.com

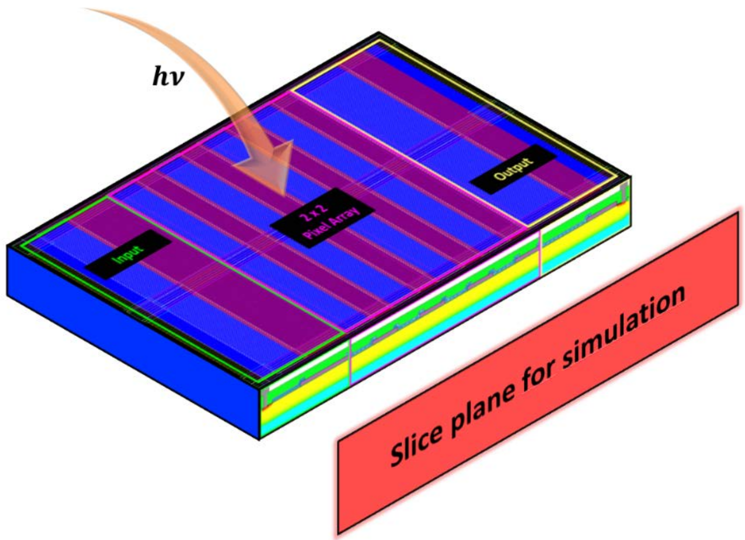
"CMOS imagers would benefit from further scaling after the 0.25 µm generation only in terms of increased fill-factor and/or increased signal processing functionality within a pixel"

(H. S. Wong, 1996)

Nowadays, the trend are

Imaging Enhanced CMOS Processes!

What about merging the best of both worlds: in CMOS embedded CCD line?



- 2P4M 0.35 µm CMOS (opto-) process by Fraunhofer IMS, Duisburg, Germany
- Horizontal Charge Transfer Efficiency (HCTE) > 99,996%
- Quantum efficiency > 60% (@625nm)
- Pixel size: 10 µm x 10 µm
- Array of 128 x 8 pixels

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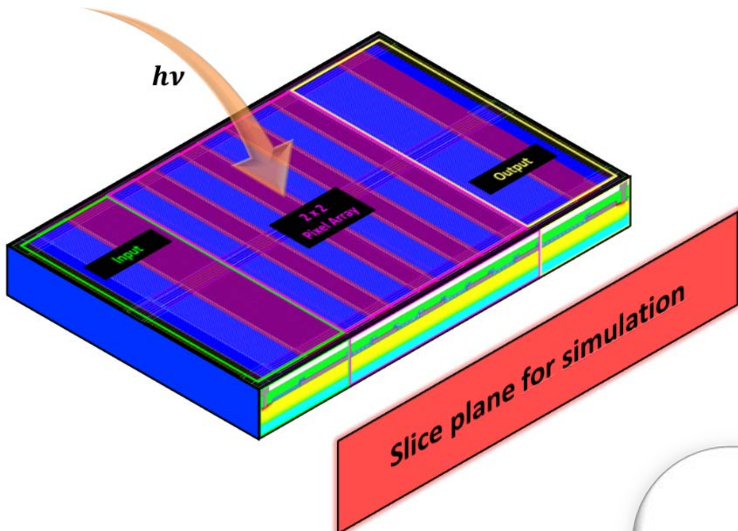

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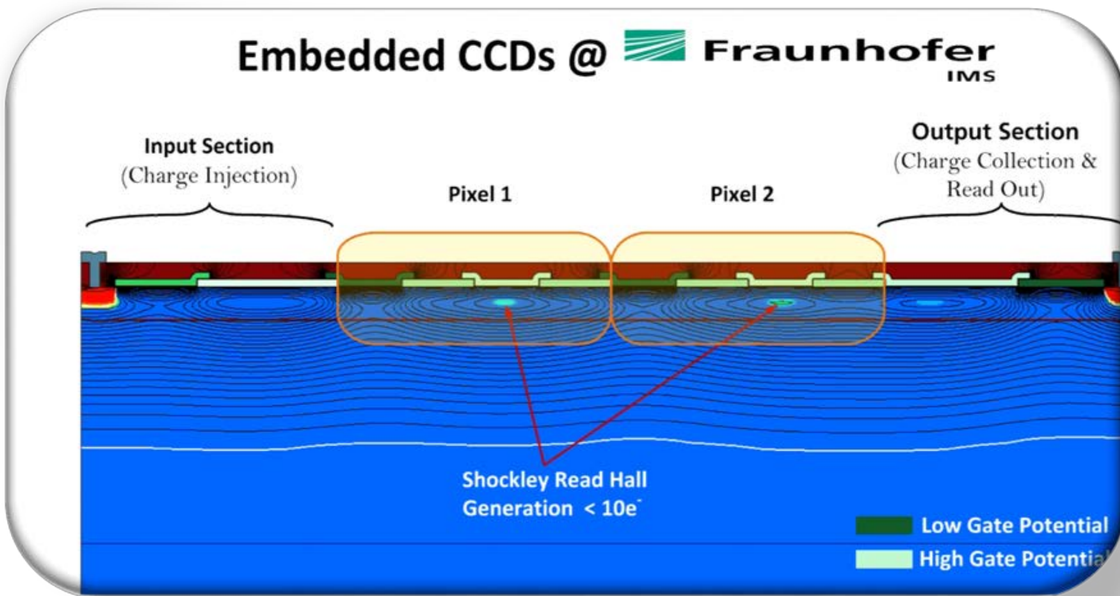
Time-Delayed Integration (TDI) just got available in **CMOS** technology: applications in Earth Observation tasks (partner: DLR).



Courtesy of S. Gläsener and W. Brockherde from the Fraunhofer IMS

What about single-photon counting and nanosecond time resolutions?

SINGLE-PHOTON DETECTION AND IMAGING APPLICATIONS:

- Time-resolved spectroscopy
- Fluorescence lifetime imaging
- Positron Emission Tomography
- Scintillation based photodetection
- …

DEMANDING REQUIREMENTS

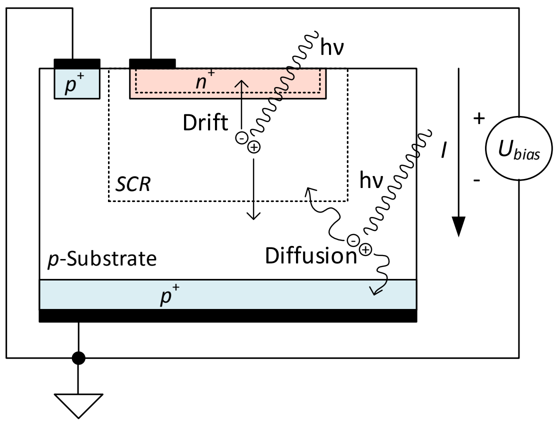
- High Photon Detection Efficiency
- Low Noise (low DCR, afterpulsing)
- Nano or even picosecond timing resolution, low quenching times
- Low Cross-Talk

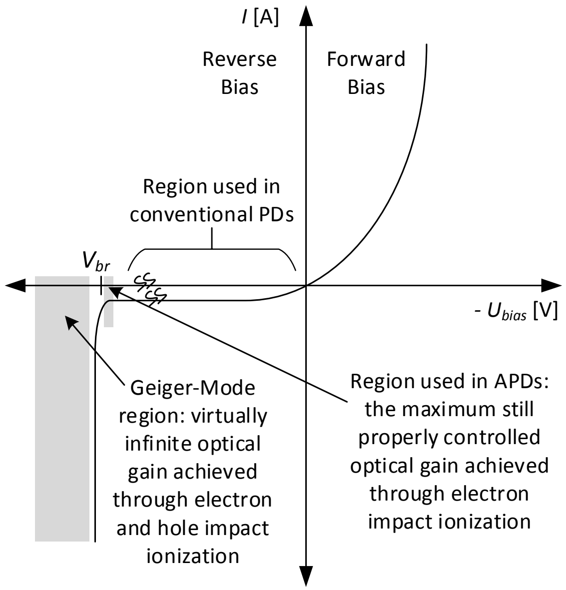
To obtain near single-photon counting capability in silicon, it is necessary to:

- Drastically **reduce noise** (maximize SNR)
- Add internal signal amplification (e.g. avalanche processes): APD, SPAD, EMCCD
- Have really fast readout

“Standard” silicon based imagers need long times (of at least hundreds of µs) for the reset, charge-collection and readout operations.

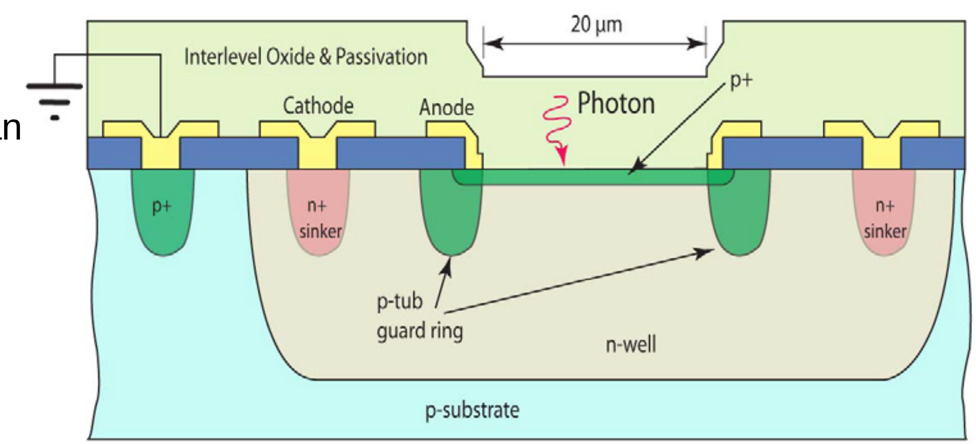
Single-Photon Avalanche Diodes (SPAD) and SiPM





Single-Photon Avalanche Diodes (SPAD) offer:

- Near single-photon counting with nanosecond time resolution: no need for charge collection (each impinging photon can be detected)
- Analog or digital readout
- Pixelated readout (SPAD-imagers) or single outputs (SiPM)
- Nevertheless (as always) there are issues:
  - DCR
  - After-Pulsing
  - Crosstalk…



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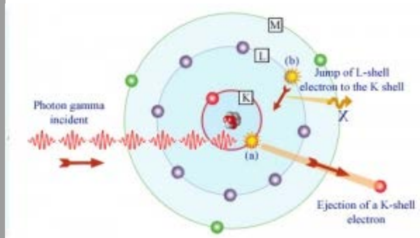
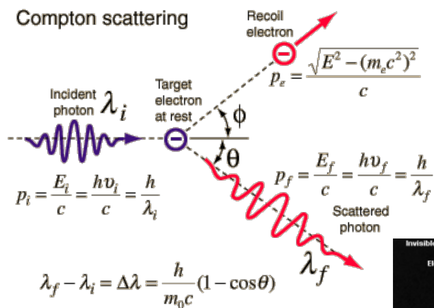
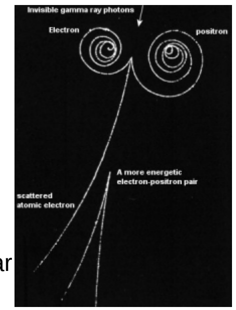
Electromagnetic radiation and Silicon



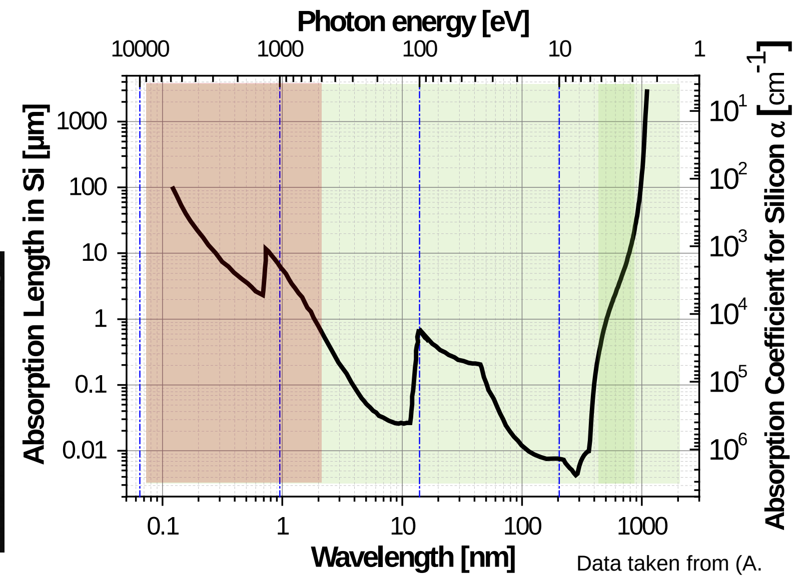
Photoelectric effect



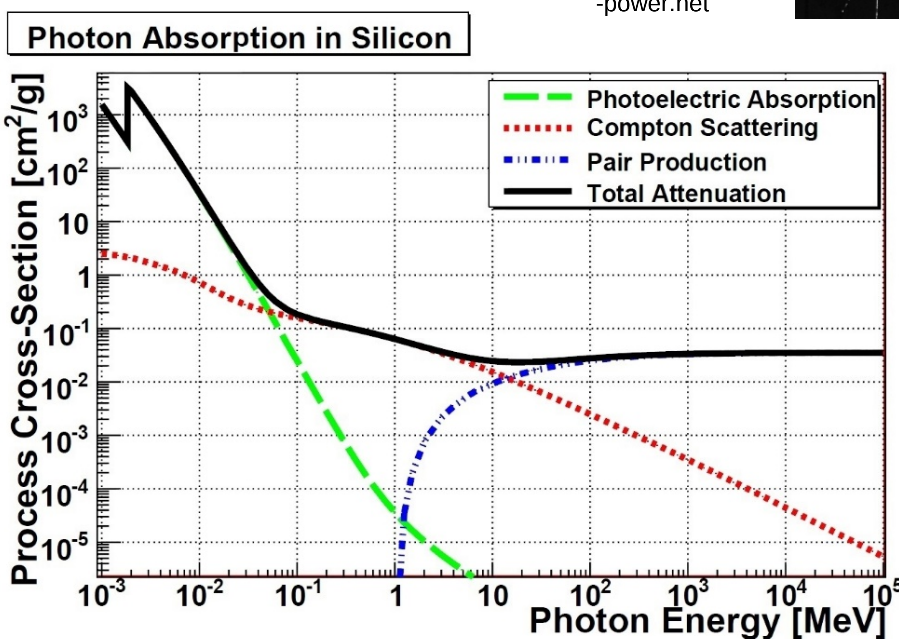


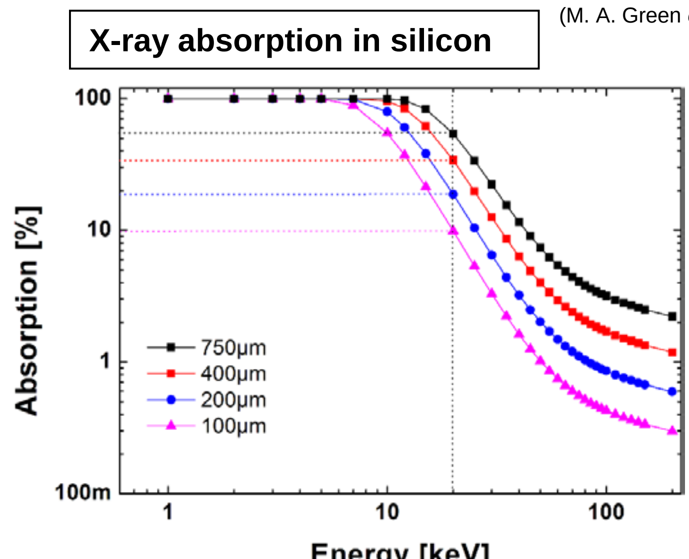
Pair production in chamber: electric field of a heavy atom is essential (conservation of momentum and energy) → a photon pair production in free space cannot occur.

http://www.nuclear-power.net



Data taken from (A. Theuwissen, 1996) and (M. A. Green *et al.*, 1995)

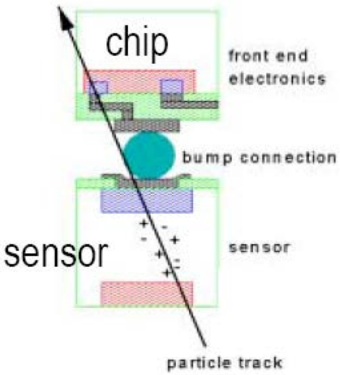




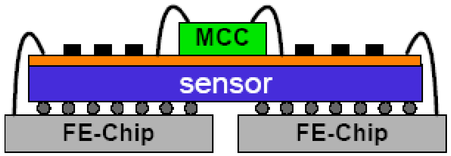
Source: Spieler H. (1998) Lecture Notes – Physics 198, UC Berkeley

What about scientific applications?

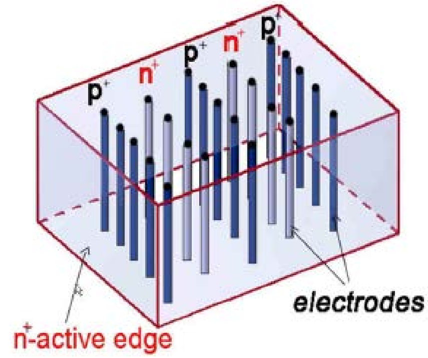
Particle Detection: all LHC detectors like the ones built for ALICE, ATLAS, CMS at CERN and other experiments employ hybrid pixel technique to build large scale (m^2) pixel detectors



(Wermes, 2004)



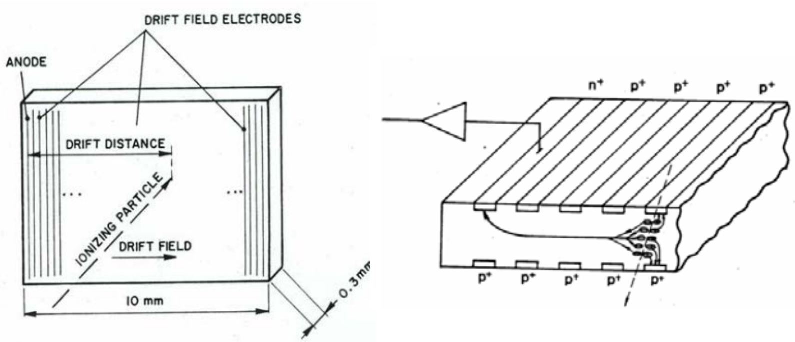
The present hybrid-pixel modules of the LHC experiments use an additional flex-kapton fine-print layer on top of the silicon sensor, to provide power and signal distribution to- and from- the module front-end chips, or as an alternative, the so called Multi-Chip-Module Technology deposited on silicon substrate (MCM-D)



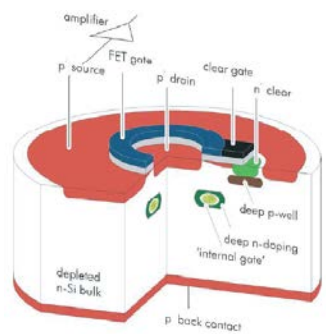
The main advantages of the 3-D silicon detectors: electrode distance is short in comparison to the conventional planar devices at the same total charge, resulting in a fast (1-2 ns) collection time, low (<10V) depletion voltage and a large active/inactive area ratio of the device

(Kenney, 1999)

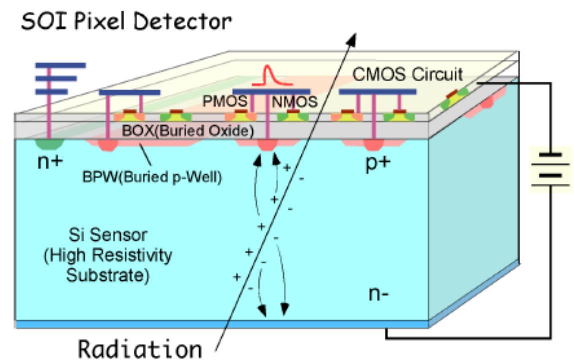
Semiconductor Drift Chamber **(nowadays, *Semiconductor Drift Detector*, SDD): ultra-low capacitance, large area semiconductor X-ray spectrometers and PD structures, and fully depleted thick CCDs**



(Gatti, Rehak, 1983)

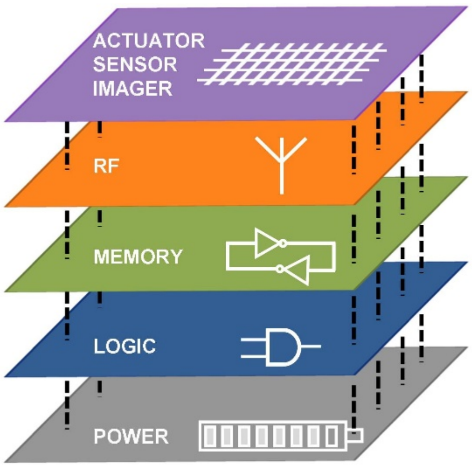


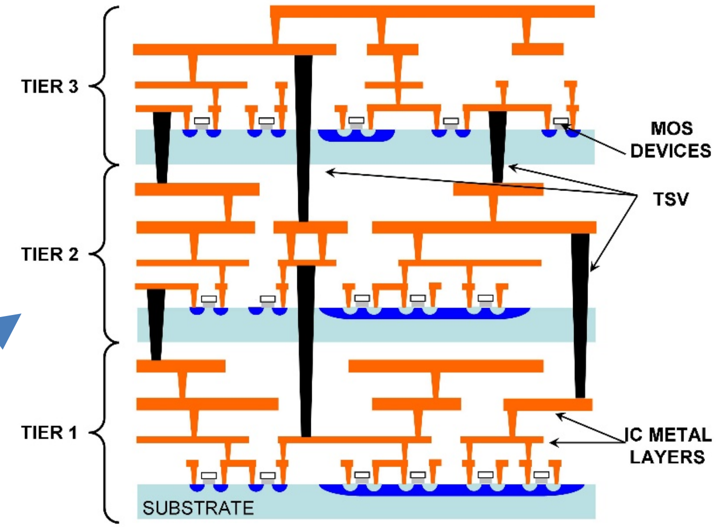
Schematic view of a circular DEPFET pixel; X-ray photons enter through the *p* back-contact (P. Holl *et all.*, 2003)



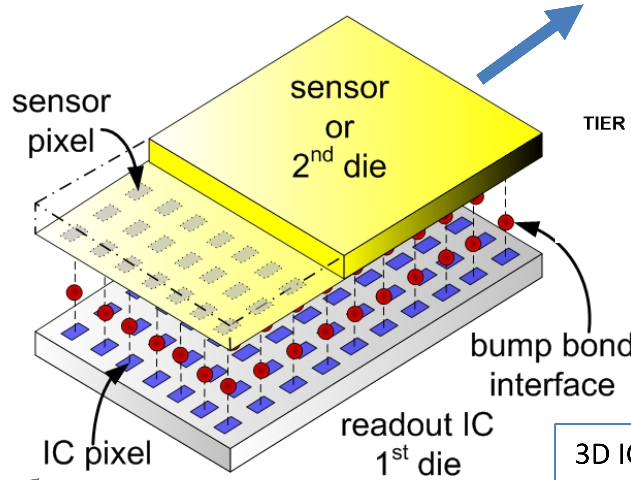
The SOI pixel detectors fabricated by OKI Semiconductor Ltd. 0.2 µm fully depleted (FD-) SOI process. (Onuki, 2011)

Evolution of 3D integrated sensors

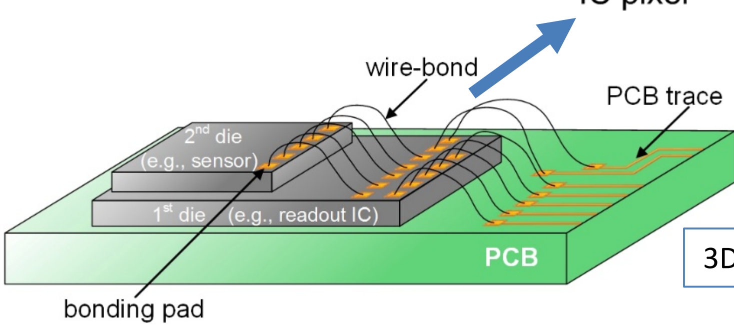




3D IC stacking using TSV



3D IC stacking using bump-bonding



3D wire-bonded IC

(D. Durini, D. Arutinov, 2014)

Silicon Radiation Hardness

Impinging particles
(e.g. electrons, protons, photons, heavy ions)

Ionisation

Displacement of lattice atoms

1–100 MeV protons

Total ionising dose

Co-60, X-rays, electrons

Single event effects (SEE)

Heavy ions, Cf-252

Single event upset (SEU)

Latch-up

Transient or permanent degradation due to an accumulation of a certain total ionizing dose.

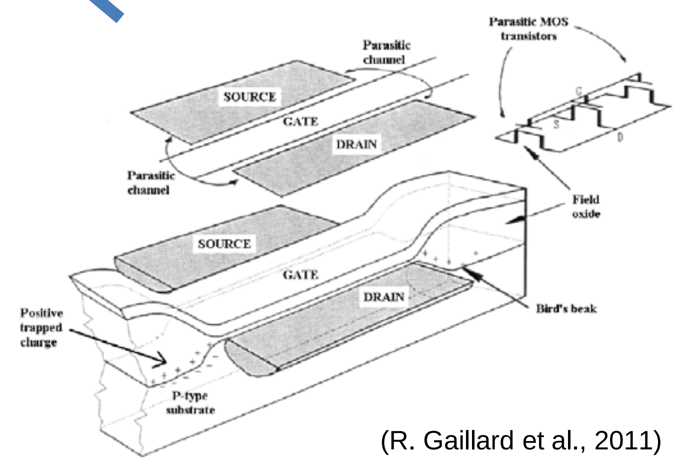
Also, single heavy ions can generate enough electron-hole pairs to cause single event effects (SEEs).

May exceed the critical charge that is required to change the logic state of a circuit.

Energetic photons and charged particles make an energy transfer to the target nuclei and cause displacement of atoms. The atom that is displaced can in turn interact with other atoms and produce a displacement cascade.

(Bogaerts, 2014)

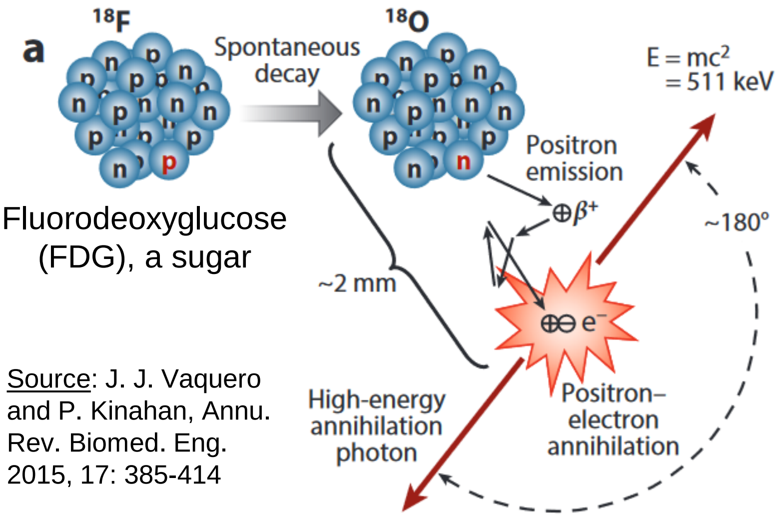
- Transistor threshold shift
  - Ionizing radiation creates immobile charges inside gate oxide and at Si-SiO_2 boundary
  - Transistor threshold is influenced by these charges
- Leakage current increase
  - Oxide charges in LOCOS or STI create parasitic transistors along edges
  - Shallower subthreshold slope



(R. Gaillard et al., 2011)

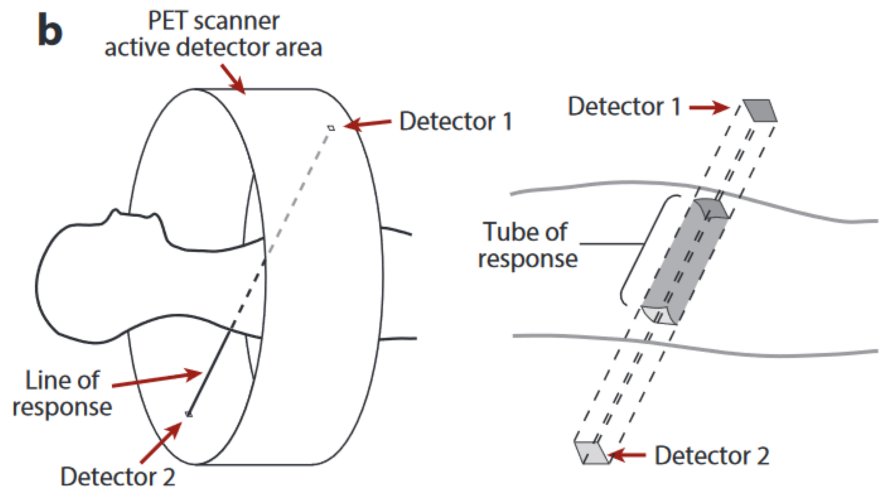
Positron Emission Tomography (PET)

PET is used to observe metabolic processes in a human body (clinical applications), a body of small animals (pre-clinical), or in plants.



Fluorodeoxyglucose (FDG), a sugar

Source: J. J. Vaquero and P. Kinahan, Annu. Rev. Biomed. Eng. 2015, 17: 385-414



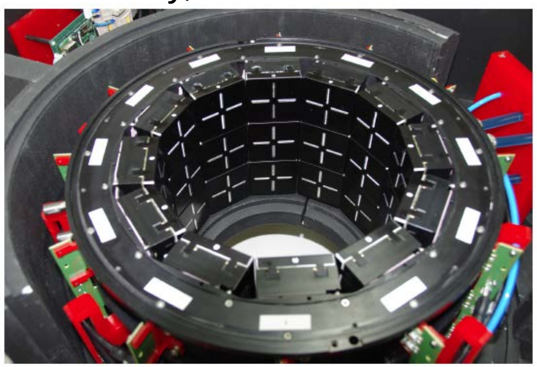
For **time resolutions** of the photodetector **< 500 ps**, it is possible to localize the event (the position of the radionuclide or radiotracer flowing inside the blood vessels) with **space resolution < 2 mm**. As the timing resolution improves, the SNR of the image will improve, requiring fewer events to achieve the same image quality.

At the Jülich Institute of Neurosciences and Medicine (INM-4), a Siemens **MRI device with a PET-insert** began operation in 2014 at 3T. For higher MR resolution, higher magnetic field are required (7T, or even 9.4 T). To use them in parallel, the PET system has to be optimized to operate in **high magnetic fields**.

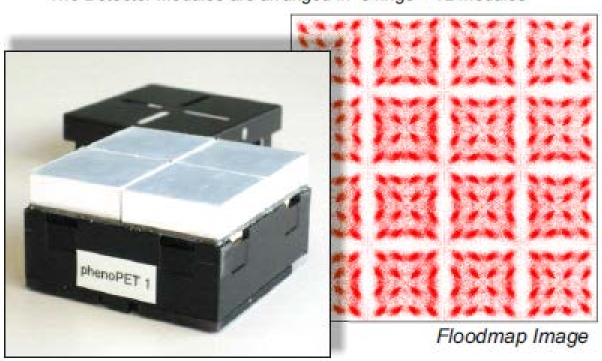
What photodetector can have near single-photon counting capabilities, acceptable space resolutions, time resolutions < 500 ps, and still be insensitive to high magnetic fields?

PhenoPET Project at FZJ

- **Radiotracer**: (half-life time 20 min) **carbon isotope ^{11}C** which can be administered to a plant as $^{11}CO_2$
- **Photodetector:** Philips DPC-3200-22-44. Three 12-module detector rings cover a transverse field of view (FOV) of 18 cm in diameter and 20 cm axial height.
- **Scintillator:** matrix of 16x16 individual **LYSO scintillator crystals** (1.85x1.85x10 mm³)
- **DAQ:** is performed on **FPGAs** within the detector module. For **further processing and coincidence sorting**: central Concentrator Board based on Kintex-7 FPGA Mini-Modules (*Xilinx*), 12 sector boards connect 3 modules and route the data via HDMI cables using one LVDS pair per module for 50 MB/s data rate. Finally, a USB 3.0 connection sends the data with up to 300 MB/s to the PC.



The Detector Modules are arranged in 3 rings × 12 modules



Floodmap Image

Opened detector module showing the four scintillator matrices.

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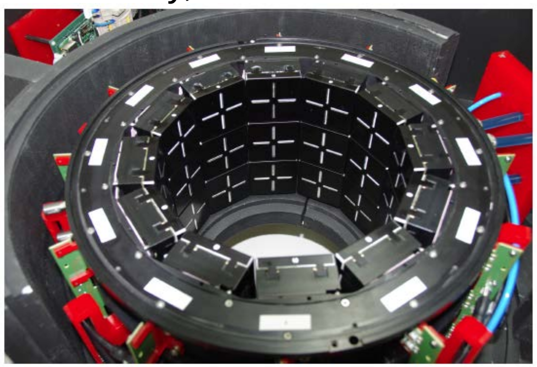

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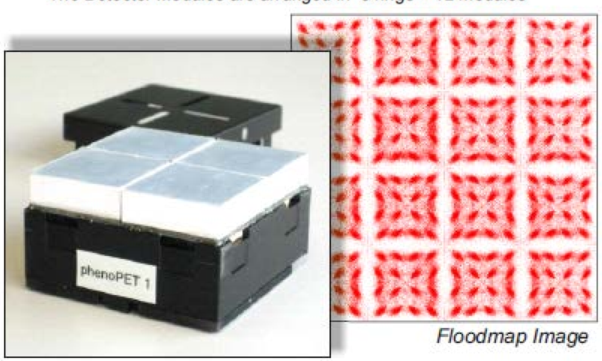
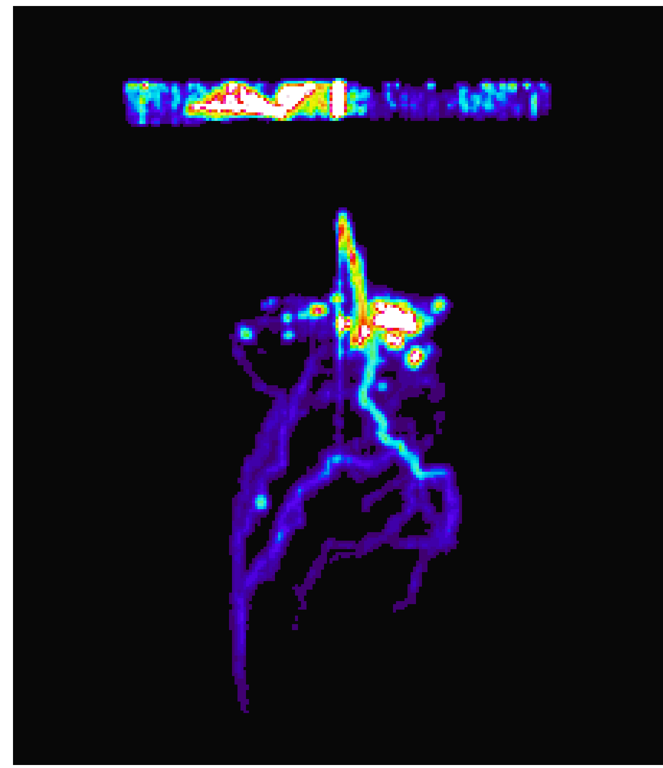


Floodmap Image

Opened detector module showing the four scintillator matrices.

A PET image obtained using the PhenoPET system of the roots of a green bean plant.



Courtesy of Dr. Siegfried Jahnke IBG-2, and Dr. Jürgen Scheins INM-4, Forschungszentrum Jülich GmbH

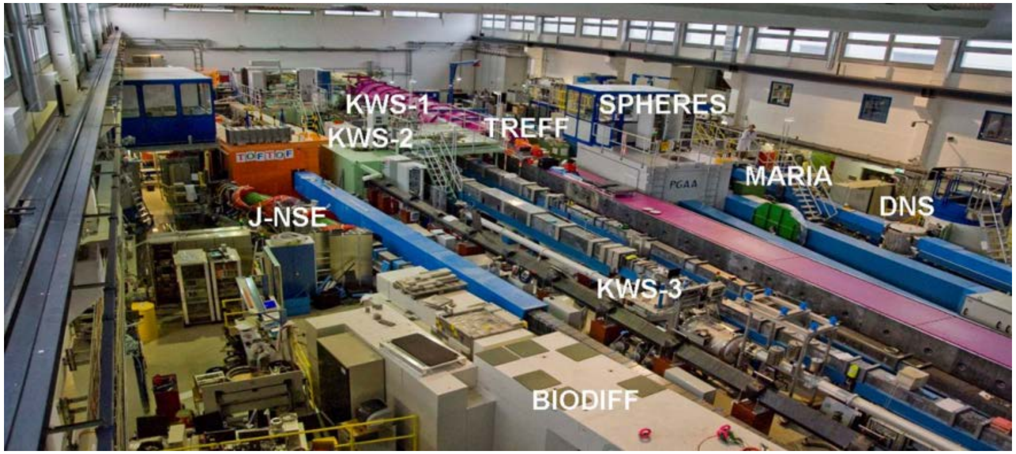
SiPM based detectors for Small Angle Neutron Scattering (SANS) Experiments

Small-angle neutron scattering (SANS) experiments:

- Are used for soft and condensed matter investigations
- Neutrons have no electric charge → can penetrate deep
- Neutron magnetic moment enables investigation of magnetic properties of matter
- Thermal and cold neutrons do not significantly change the properties of the investigated sample → they deposit only minimum amounts of energy into it
- The world-wide shortage of the preferred ^{3}He gas triggered novel approaches for neutron detection → e.g. **scintillation based detectors**

Since 1969: Development of detector systems for neutron and gamma detection

- 11 systems operational at FRM-II; 2 in construction
- Systems at ILL Grenoble and SNS Oakridge
- Upcoming experiments at ESS Lund

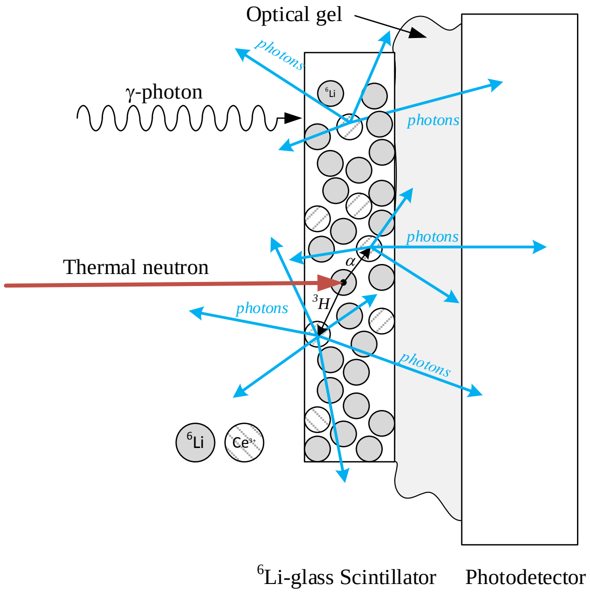


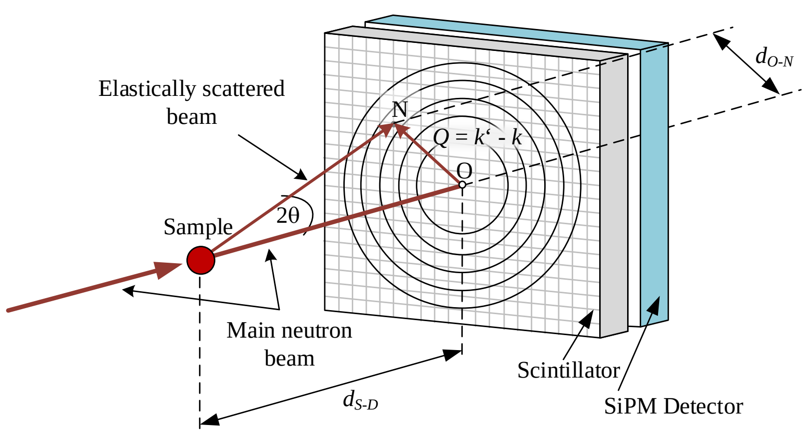
Experimental hall at FRM-II Garching, Munich

SiPM based detectors for Small Angle Neutron Scattering (SANS) Experiments

We propose using a 1 mm thick Ce-doped ^{6}Li-glass scintillator (GS20) and an array of SiPM photodetectors:

- Near single photon counting
- Low bias voltages (27-70 V) and power consumption
- Acceptable space resolution (< 2 mm sq.)
- Neutron counting rates much higher than those achieved by current ^{3}He based detectors (1 m²), and
- Insensitivity to magnetic fields up to several Tesla





SiPM based detectors for Small Angle Neutron Scattering (SANS) Experiments

In the 1950's it was demonstrated that impurity atoms can be introduced into semiconductor materials by **nuclear transmutation** processes initiated by **thermal neutron (*n*) capture** following a nuclear reaction**:**

$$^{30}\mathrm{Si} + n \rightarrow {}^{31}\mathrm{Si} \rightarrow {}^{31}\mathrm{P} + \beta^{-}$$

The experiments shown that the **damage introduced into silicon by thermal/cold neutrons is primarily in form of point defects**, approximately **2-5 defects per absorbed neutron** remaining at room temperature.

$$\left|I_{dark}\right| = \alpha_p \left\{ q A_n \left(\frac{n_i^2}{N_D}\sqrt{\frac{D_p}{\tau_{r\_p}}} + N_{def} W_{SCR} \sigma_n c_n T^2 e^{\left(-\frac{E_c - E_T}{k_B T}\right)} \right) \right\}$$

Increase in the dark signal of the SiPMs!

So, **we investigated the dark signal performances** of 3 SiPM technologies under irradiation with cold neutrons, both with and without a scintillator material covering the following photodetector arrays:

	SensL Series-C ArrayC-30035-144P-PCB	*Hamamatsu* 8 × 8 MPPC array S12642-0808PB-50	*Philips DPC3200-22-44*
Array format	12 × 12	8 × 8	8 × 8
Pitch of each individual detector, mm	4.2	3.2	4.0
Array package size (4-side tileable), mm²	50.2 × 50.2	22.4 × 25.8	32.6 × 32.6
Active area of each individual sensor (pixel), mm²	3 × 3	3 × 3	3.2 × 3.8
Microcell size, µm	35	50	59.4 × 32
No. of micro-cells	4774	3584	3200
Micro-cell fill-factor, %	64	62	74
Detector fill-factor, %	51	87.9	76

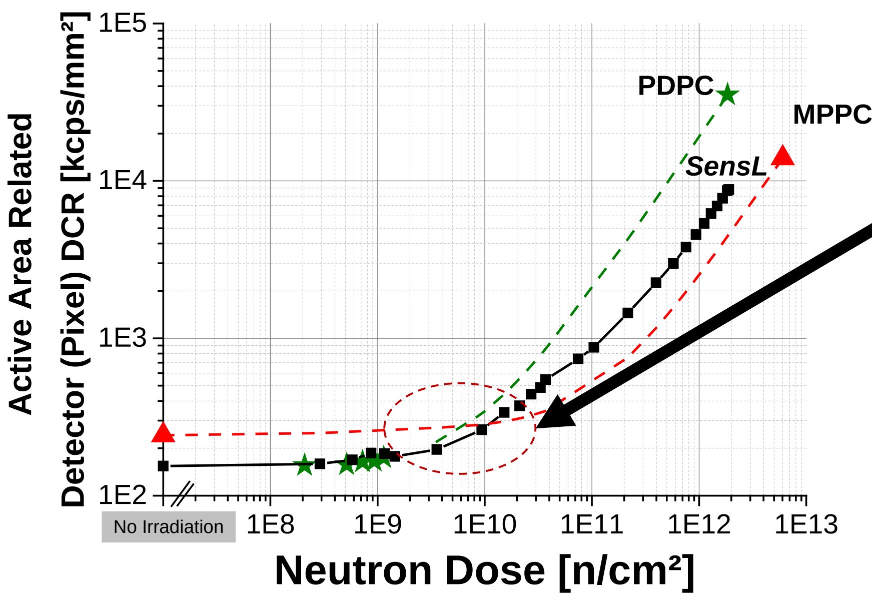
SiPM based detectors for Small Angle Neutron Scattering (SANS) Experiments

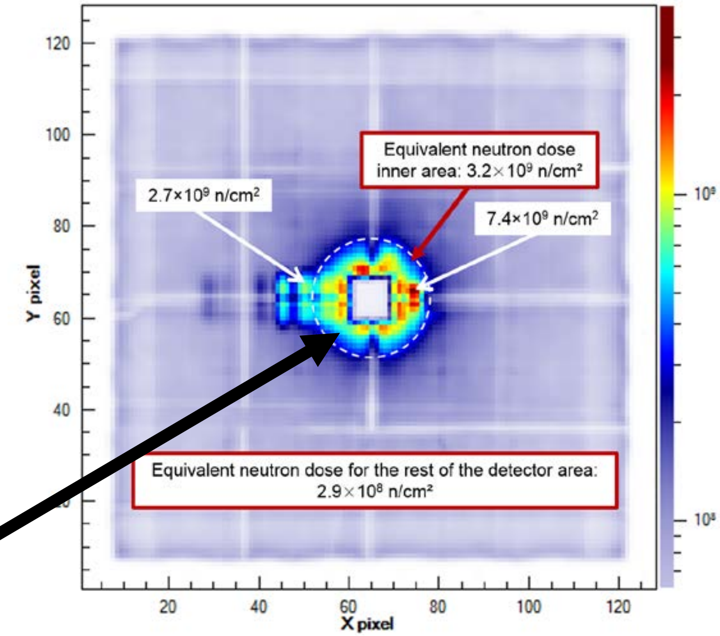
<u>**To compare the 3 technologies**</u>

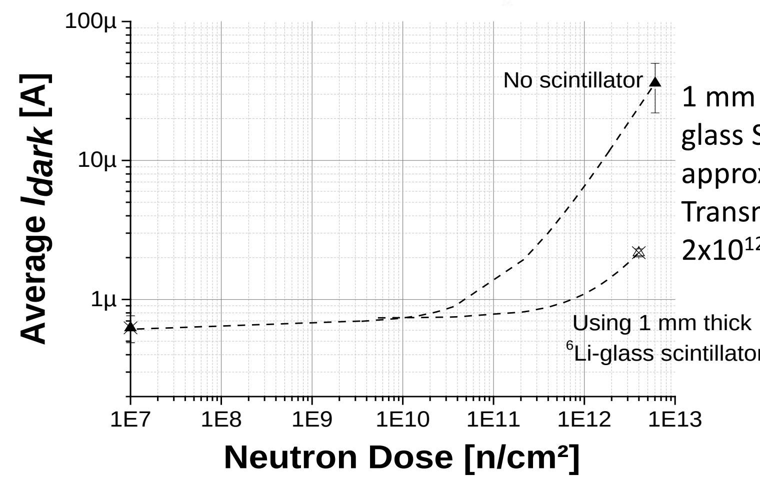
Results obtained for ***SensL* and *Hamamatsu* MPPC** detectors were used to calculate their DCRs:

$$DCR = (I_{dark} / q \cdot G \cdot A_{active})(1\text{-}XT\text{-}AP)$$

For PDPC: $DCR_{pixel} = DCR_{single\text{-}cell} \times (0.9 \times 3200) / A_{active}$, where $A_{active} = 3.2 \times 3.8\ mm^2$.







1 mm Ce-doped ^{6}Li-glass Scintillator approx. Transmission @ 2×10^{12} n/cm²: 12%

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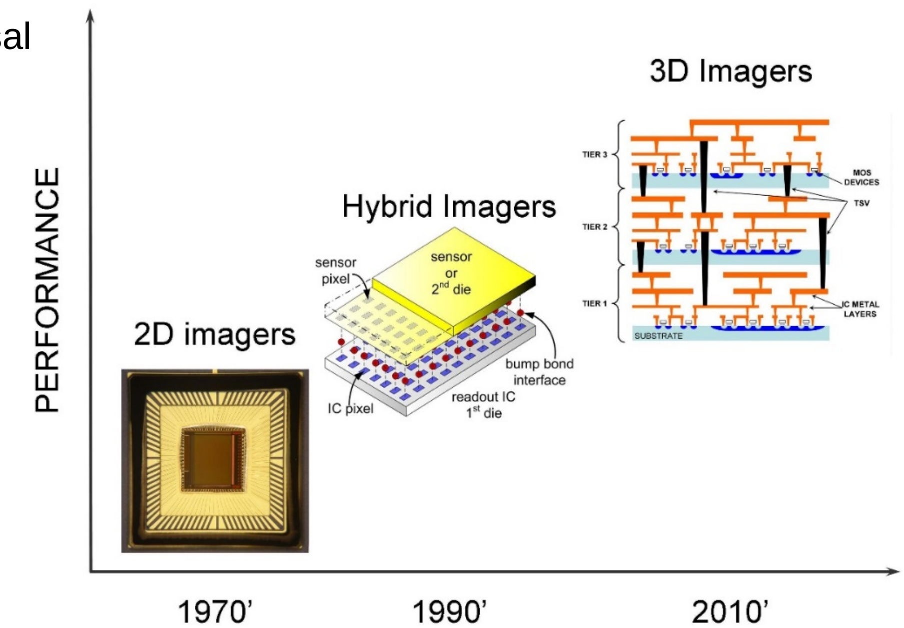
- Forschungszentrum Jülich GmbH and ZEA-2: Detector System Solutions for Science
- Silicon based photodetectors
- What about scientific applications?
- Challenges and perspectives

Challenges and Perspectives

- Dark signals have to be further minimized on the photodetector level (single photon capability)
- SNR and DR must be further improved (direct signal processing and ADC at the detector level)
- Timing resolution has to be improved (picoseconds)
- Special attention has to be put on the 3D-integration technology: integrating the best from all possible worlds (detector front-end, analogue signal processing, digital signal processing) → this is the new present!
- Nevertheless, there are huge issues still to be solved regarding radiation hardness (ionization radiation and/or sub-atomic particles) on the detectors as well as on the readout circuits for scientific, space and medical applications
- Unfortunately, there is no magical universal formula that suits every application → we must use synergies and learn from different applications, but cannot escape individual sets of solutions for scientific experiments.



Thank you for your attention!
Any questions?