Low Noise Mix-Mode Integrated Circuits for Micro-sensor readout

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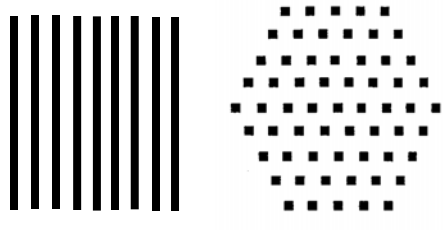
Outline

1. Introduction: multichannel low noise integrated circuit
2. Noise, crostalk and matching
3. Digital imaging system for diffractometry applications
4. Multichannel neurobiology experiments
5. Conclusions

Multichannel low noise ASIC

SET OF SENSORS (silicon strip detector, neuronal cells of retina)

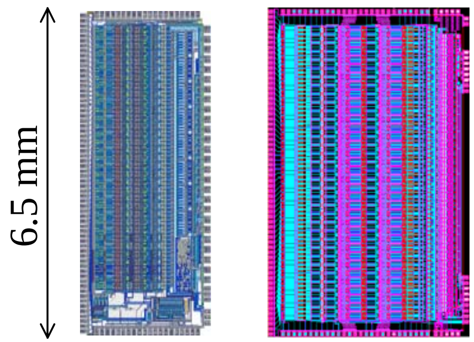


Microsensors
50-100 μm

Input signals

- small amplitude (Qin = 1400 el, Vin = 50 μV)
- stochastic character (amplitude, time)

MULTICHANNEL INTEGRATED CIRCUITS (analogue & digital blocks)



RX64 **NEURO64**

LIMITS: power & area

LOW LEVEL OF NOISE

UNIFORMITY OF PARAMETERS

CROSSTALK digital ⇔ analogue

Noise in MOS transistors

1. Thermal noise of channel

saturation

$$\frac{\overline{di_{th}^2}}{df} = \frac{8}{3} kTg_m$$

linear

$$\frac{\overline{di_{th}^2}}{df} = 4kTg_{ds}$$

Simulations (HSPICE)

NLEV=3
$$\frac{\overline{di_{th}^2}}{df} = \frac{8kT}{3} \mu C_{ox} \frac{W}{L} (V_{GS} - V_T) \frac{1+a+a^2}{1+a} GDSNIO$$

BSIM3v3 (NIMOD=2)
$$\frac{\overline{di_{th}^2}}{df} = \frac{4kT\mu_{eff}}{L_{eff}^2} |Q_{inv}|$$

Measurments – short channel effects (2-10x):

(velocity saturation, hot electrons)

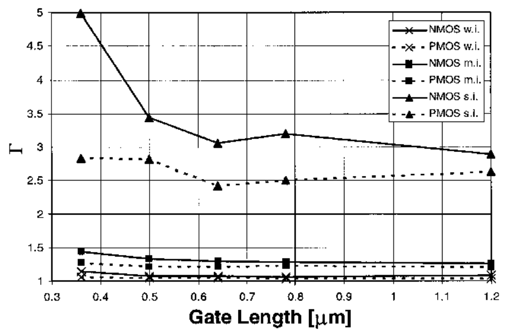
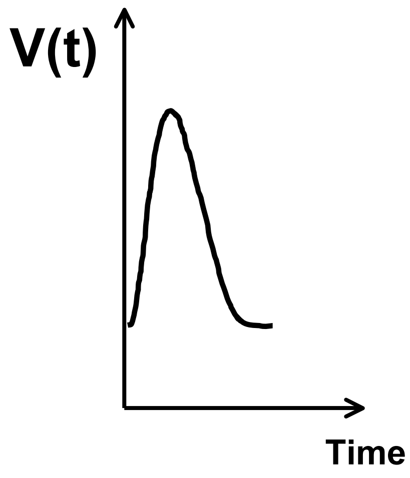
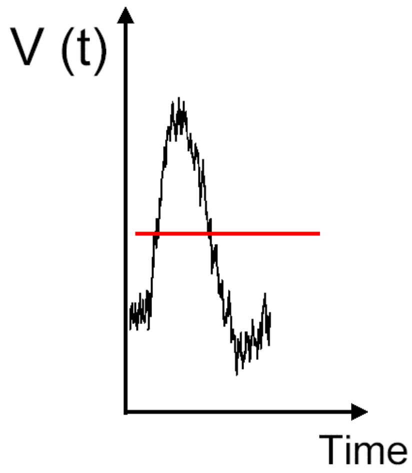


Fig. 4. White noise excess factor as a function of the device gate lengths for devices in weak (w.i.), moderate (m.i.) and strong (s.i.) inversion. The values are calculated as if the white noise measured came only from the channel thermal noise and the gate resistance thermal noise.



Signal



Signal+noise

2. Flicker noise

Simulations (HSPICE)

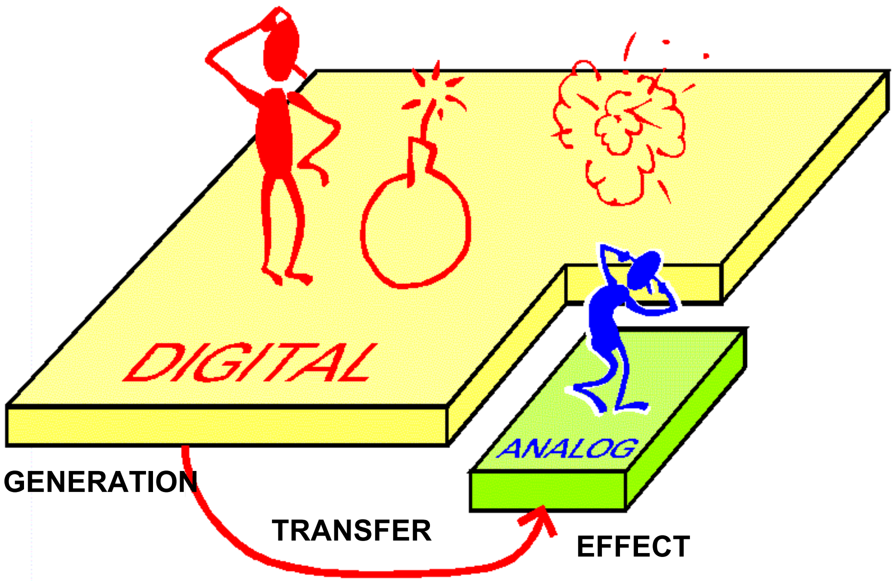
NLEV=2, 3
$$\frac{\overline{di_{1/f}^2}}{df} = \frac{KF}{C_{ox}} \frac{g_m^2}{W_{eff} L_{eff}} \frac{1}{f^{AF}}$$

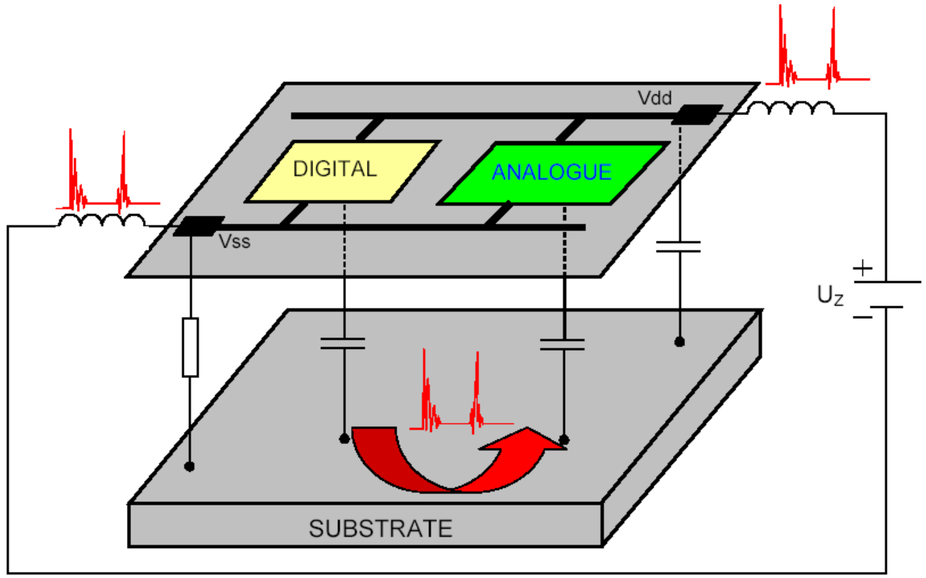
BSIM3v3 (NIMOD=2)

Measurments – short channel effects

(hot electrons, RST noise)

CROSSTALK





Transfer:
- common supply lines: parasitic inductance i resistance (V_{ind}=LdI/dt)
- common substrate: (substrate⇒epi, $V_T=f(V_{SB})$, g_{mb})

Effects for analogue blocks: switching noise, oscillation etc.

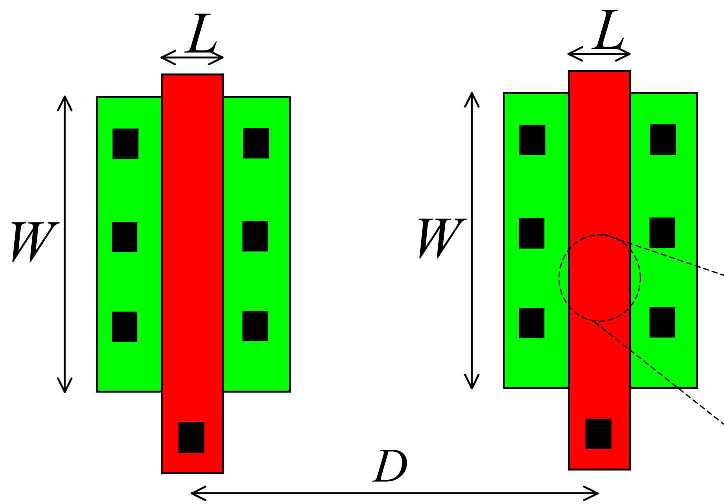
Minimisation:
- reducing the noise generation,
- increasing the immunity of analogue part,
- isolation techniques.

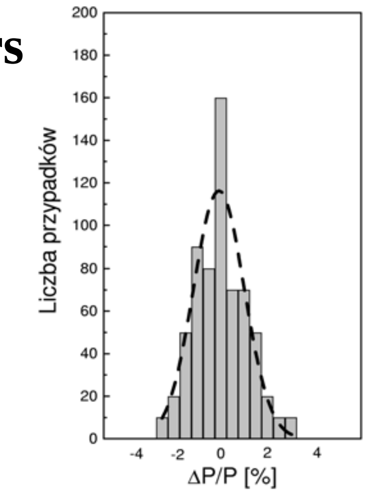
RANDOM MATCHING

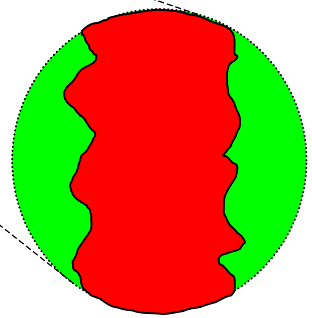
MATCHING - identically design devices have different parameters

$\Delta P = P_1 - P_2$ ($\Delta P/P$)

$$\sigma^2(\Delta P) = \frac{A_P^2}{WL} + S_P^2 D^2$$







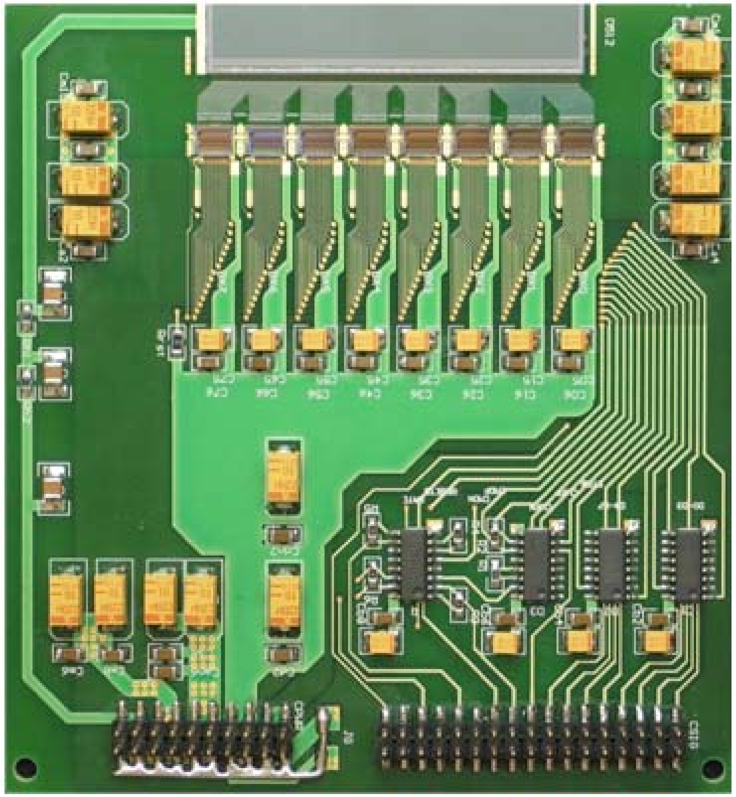
For MOS transistors: V_{T0}, β, γ

$$V_{T0} = \phi_{MS} + 2|\phi_F| - \frac{Q_{ox}}{C_{ox}} + \frac{\sqrt{4q\varepsilon_s|\phi_F|N_B}}{C_{ox}} \qquad \beta = \mu\, C_{ox}\frac{W}{L} \qquad \gamma = \frac{\sqrt{2q\varepsilon_s N_B}}{C_{ox}}$$

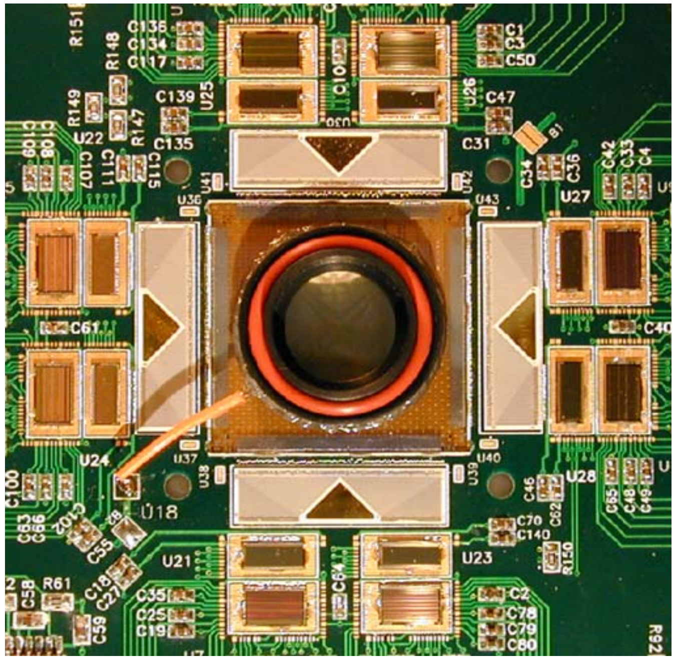
CMOS 0.7µm - $\sigma(V_{T0})$	NMOS	PMOS
W/L=2µm/0.7µm	9.72 mV	19.43 mV
W/L=1500µm/1.5µm	0.31 mV	0.63 mV

Two Examples of Low Noise Mix-Mode Integrated Circuits

Diffractometry



Neurobiology



Digital X-ray Imaging System

Digital Imaging System
(X-rays photon counting)

Position sensitive system with a good spatial resolution

MULTICHANNEL SYSTEM + ARRAY OF SENSOR

Energy window selection for X-ray photons

DISCRIMINATORS

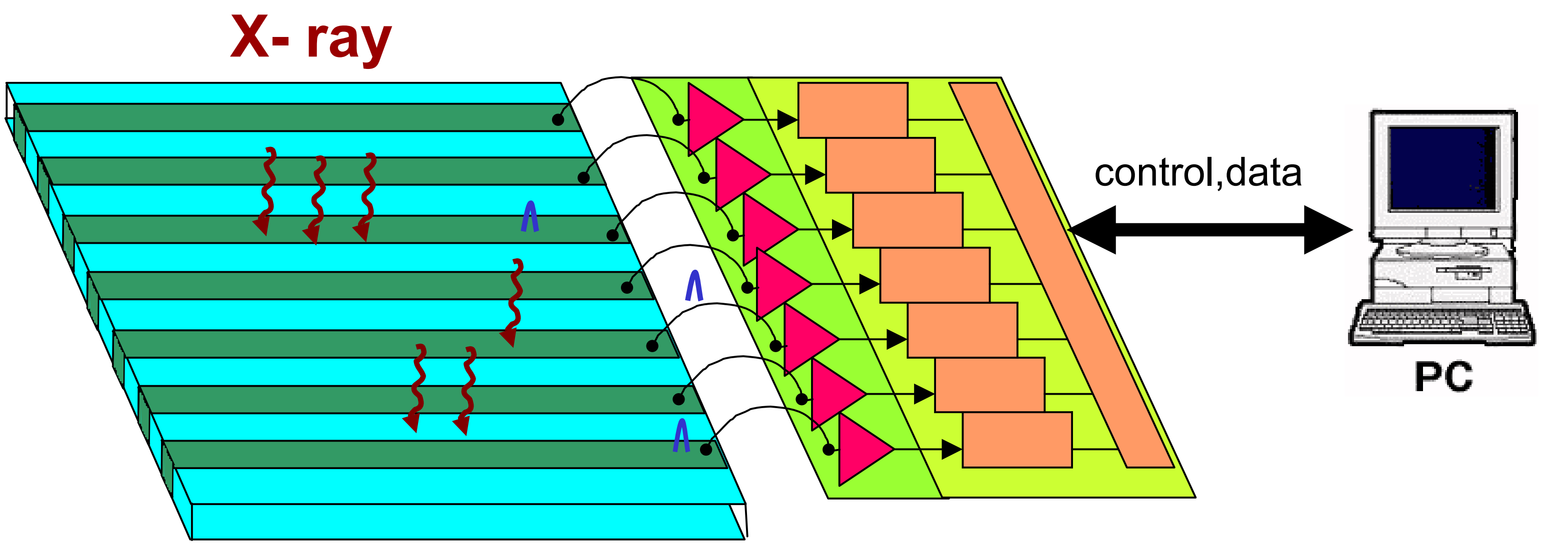
High dynamic range & relatively high X-ray intensity

SHORT TIME OF PULSE PROCESSING

Applications:

- clinical diagnostic: dual energy mammography & angiography
- material science - diffractometry

Scheme of imaging system



Silicon strip detector

⇓

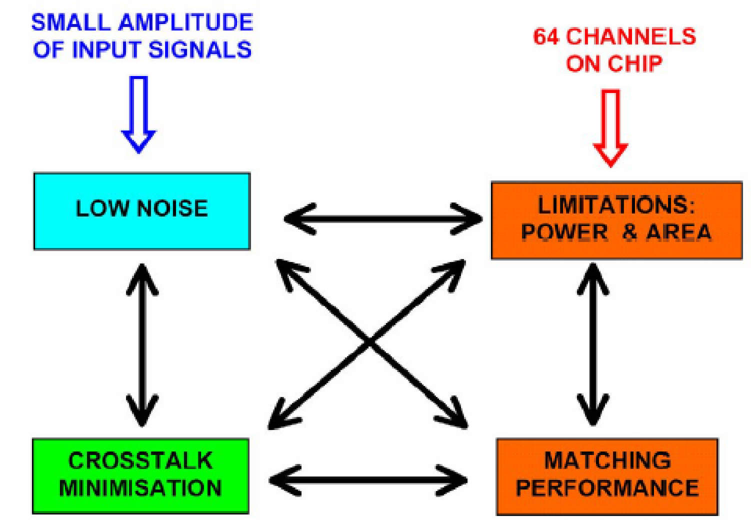
- good spatial resolution: tens of μm
- energy resolution: 3.67 eV/e-h
- single photon counting mode
- good efficiency

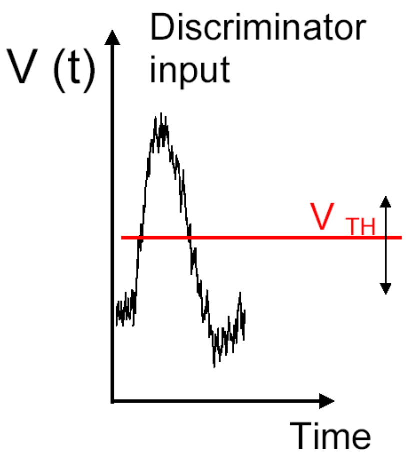
Multichannel ASIC
(analog processing + data storage)

⇓

- binary readout architecture to cope with **high X-ray intensity**
- **selection** of pulses according their amplitude

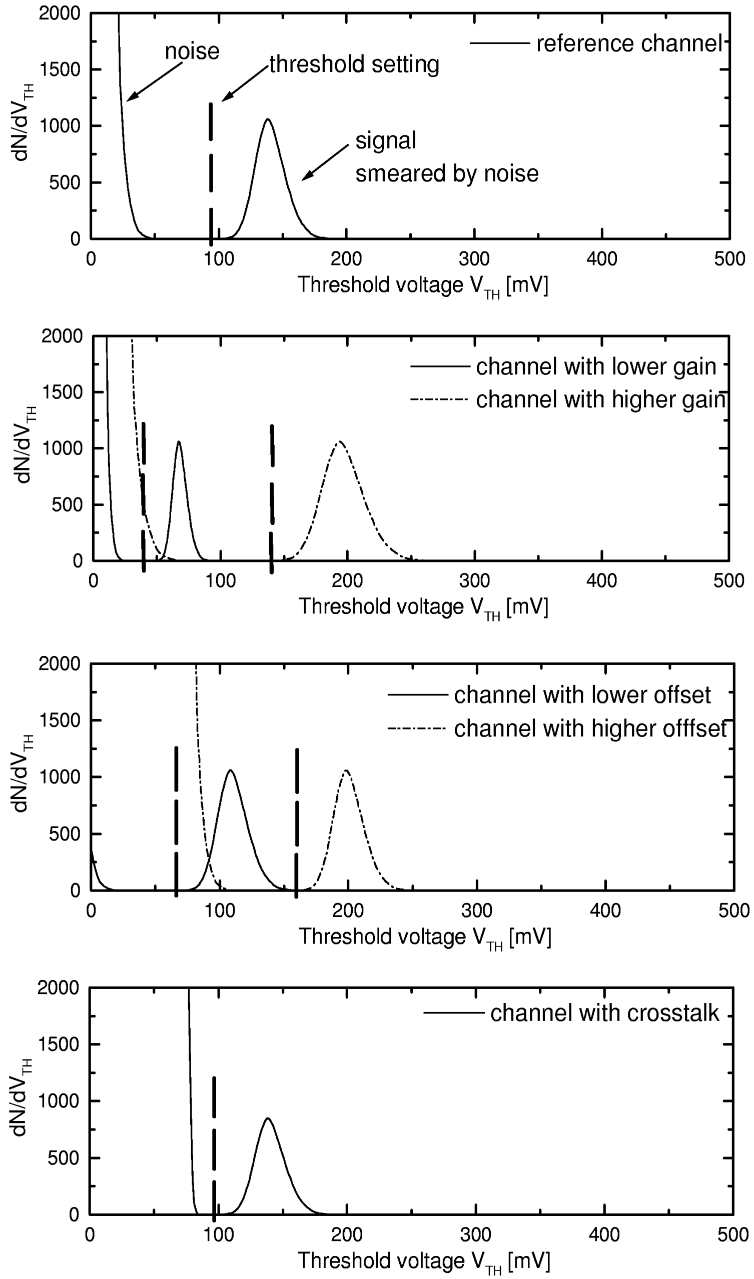
Problems with binary readout for X-ray applications





1) Counting pulses N

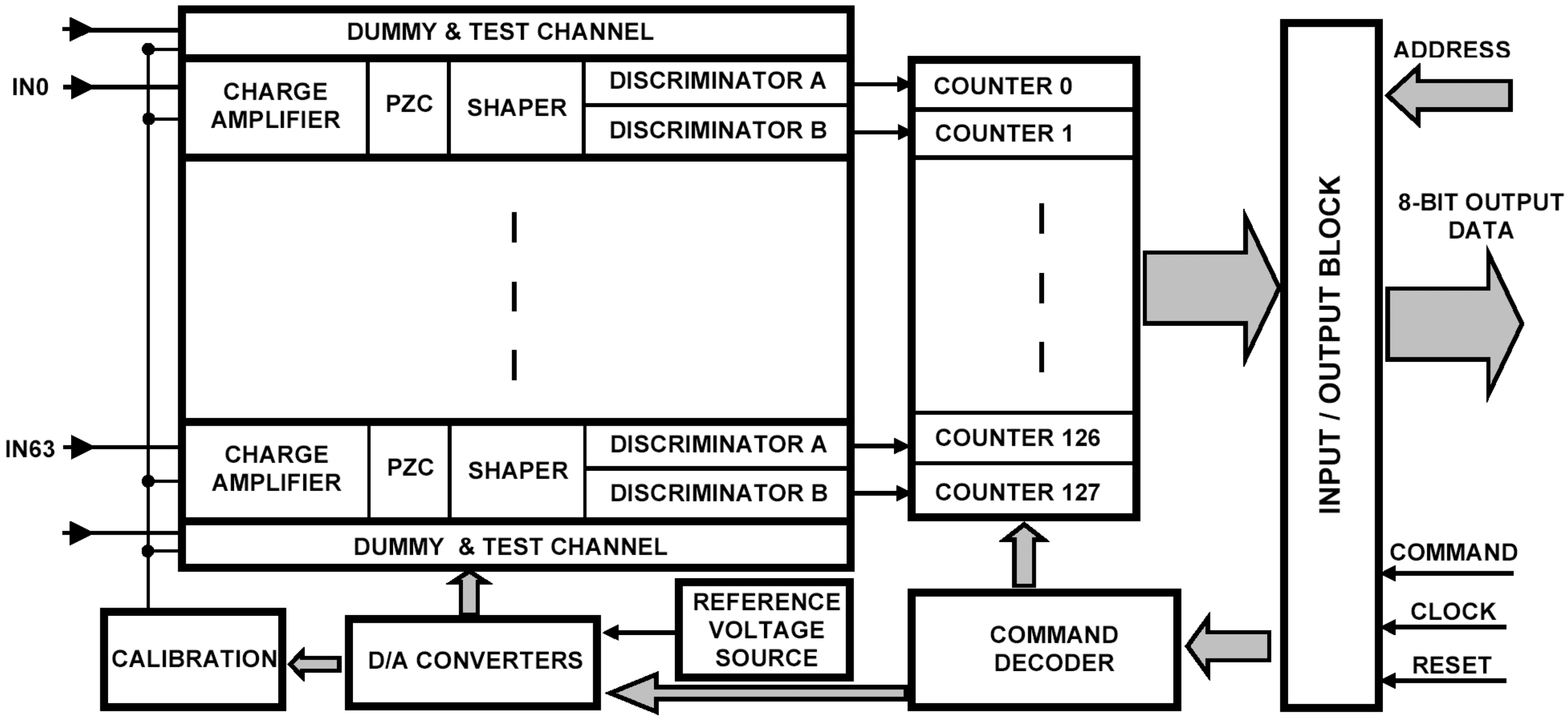
2) dN/dV_{TH}



Pulse height spectrum

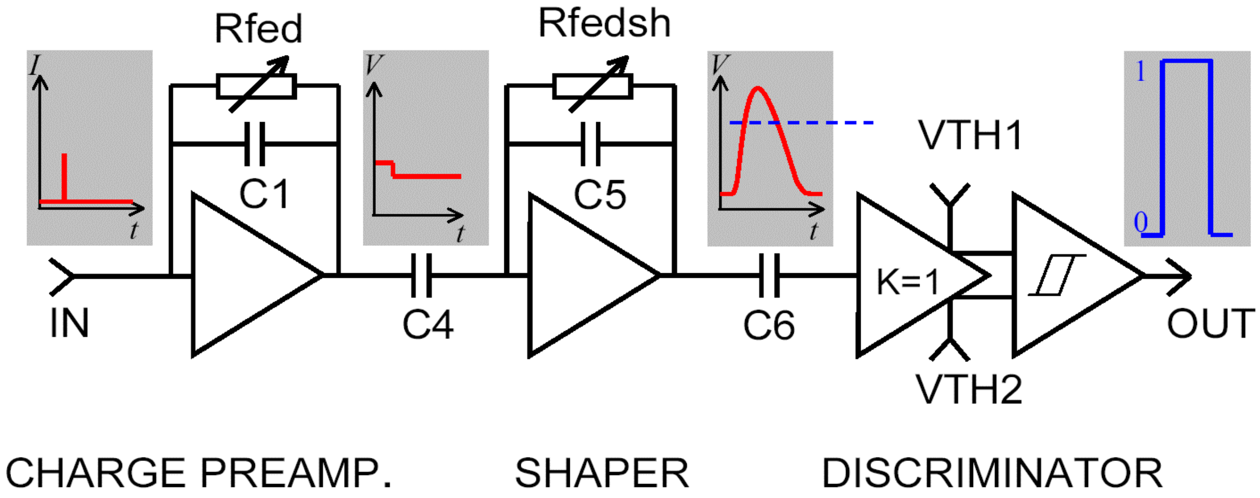
Multichannel ASIC architecture

DEDIX: Dual Energy Digital X-ray Imaging

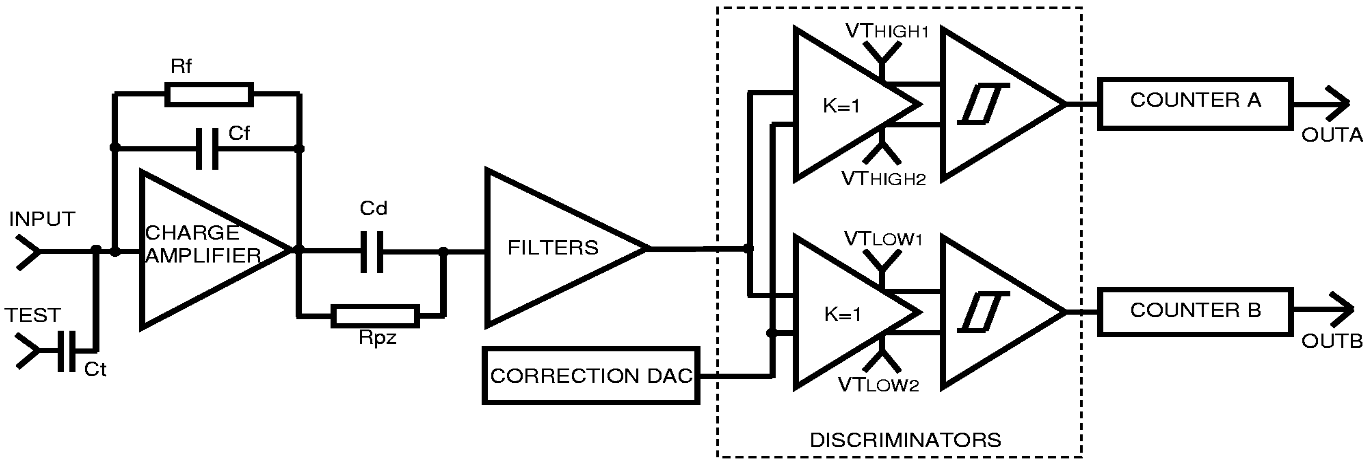


Single channel architecture (ASIC – 64 channels)

RX64:
CMOS 0.8 um
Tp=800 ns

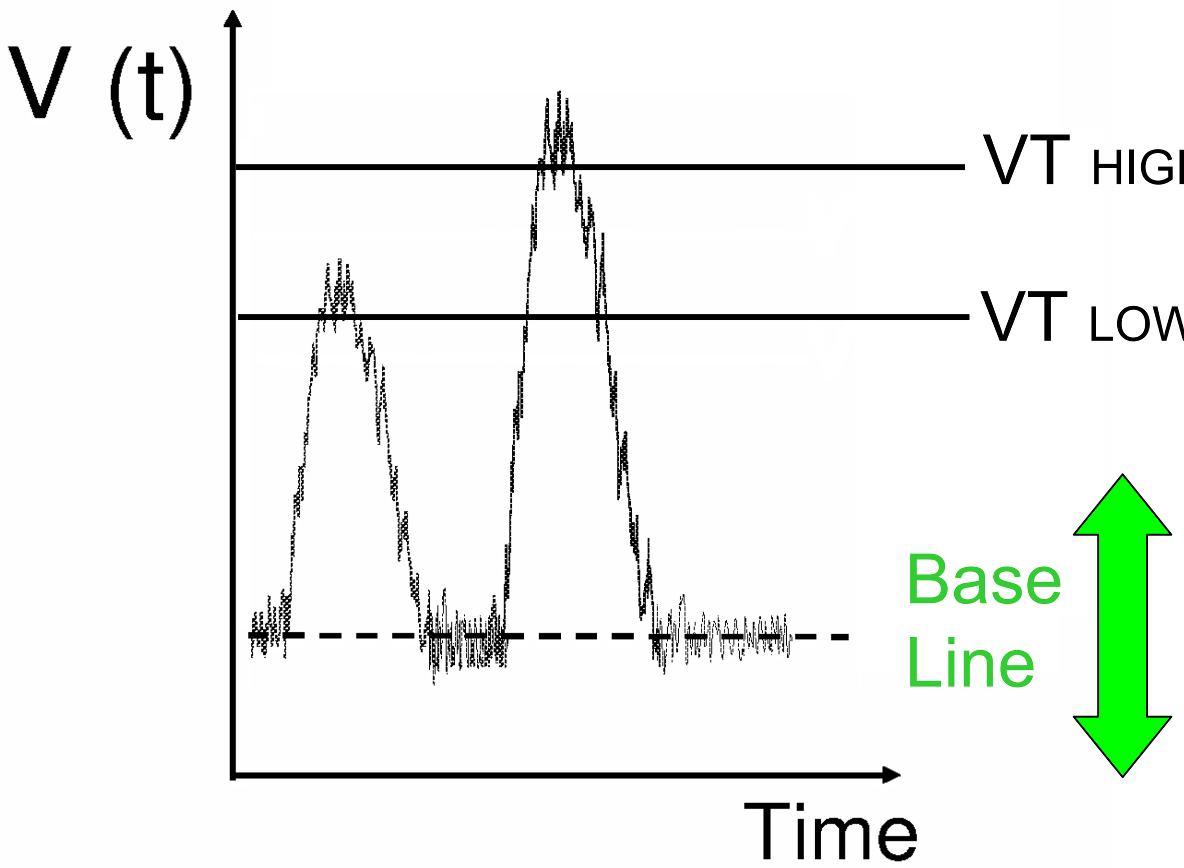


DEDIX :
CMOS 0.35 um
Tp = 160 ns

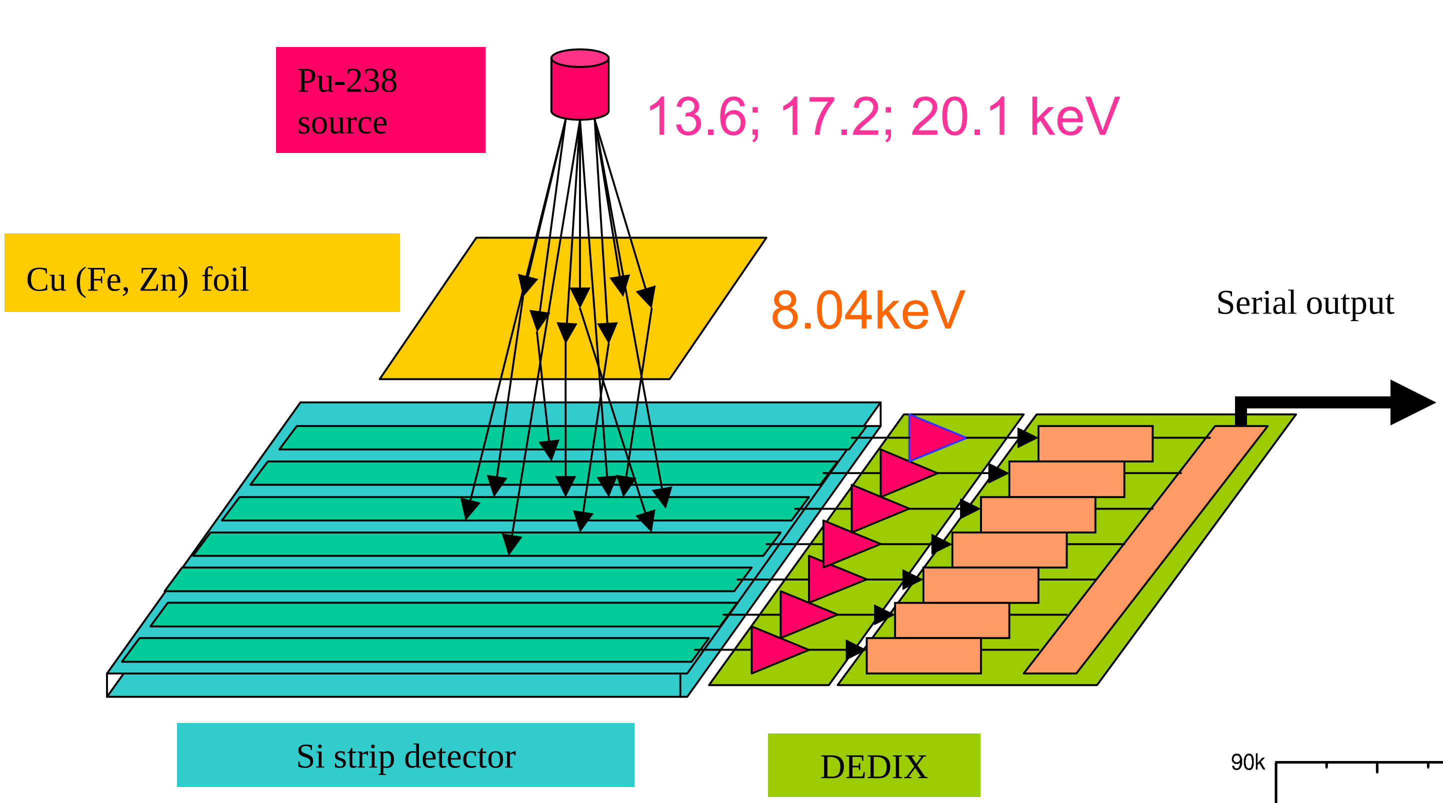


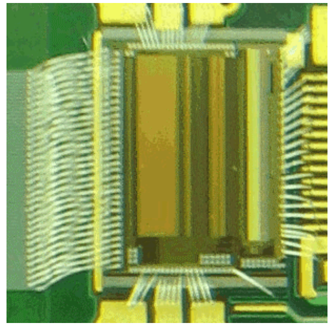
Why correction is necessary?

DC coupling between stages
– base line changes from channel to channel



Spectrum of X-ray source – measurement set-up



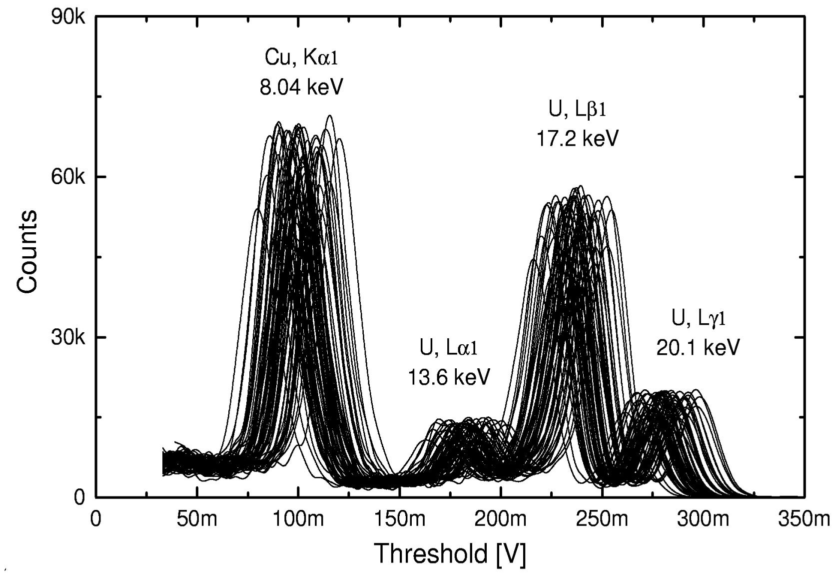


$$Q_1 = \frac{8.04\ keV}{3.67\ eV} = 2190\ \ el$$

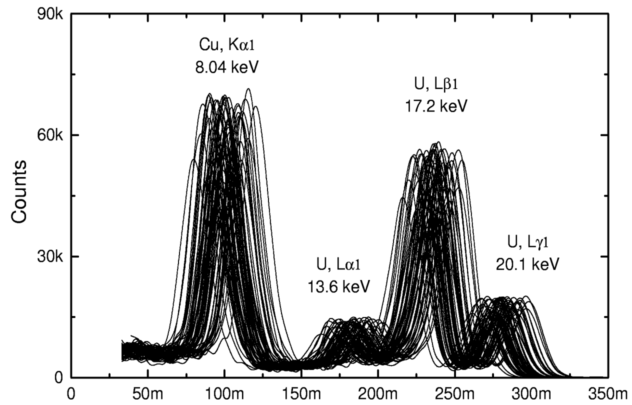
$$Q_2 = \frac{13.6\ keV}{3.67\ eV} = 3705\ \ el$$

$$Q_3 = \frac{17.2\ keV}{3.67\ eV} = 4686\ \ el$$

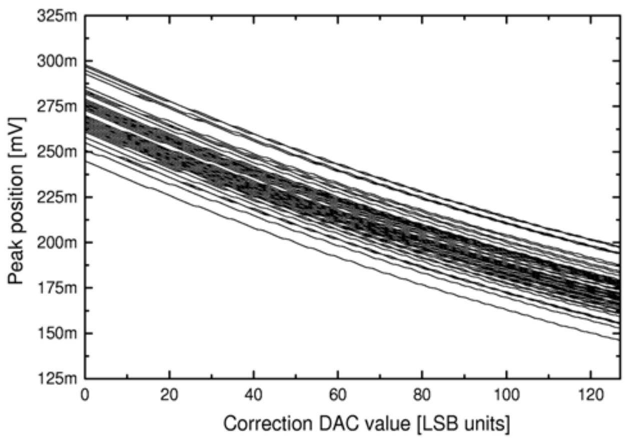
$$Q_4 = \frac{20.1\ keV}{3.67\ eV} = 5476\ \ el$$



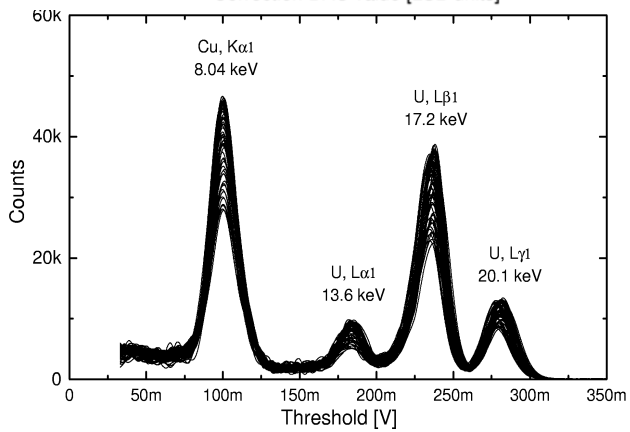
Correction procedure



1. Measurement with external X-ray source gives us effective voltage spread (constant correction)

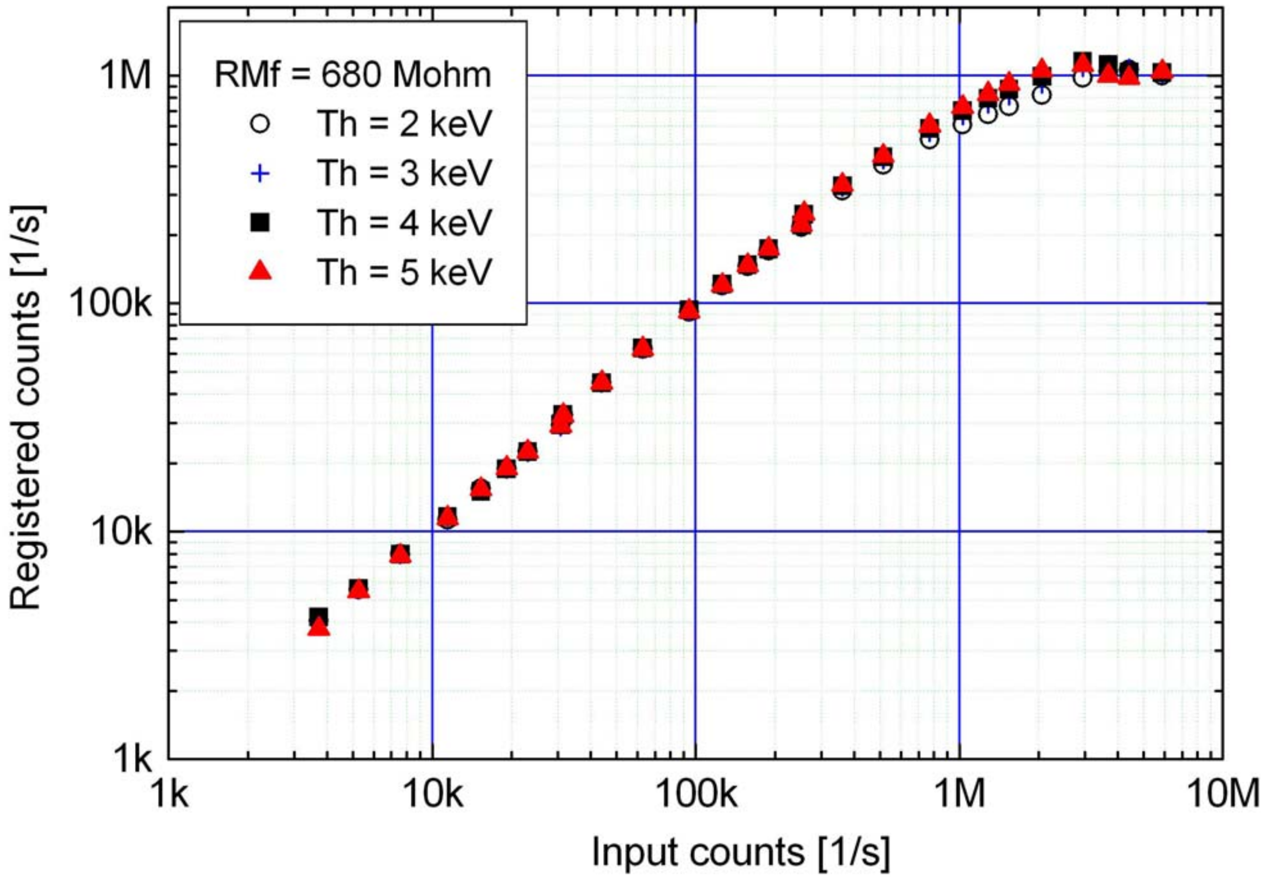


2. Measurements with internal generation circuit and different correction DAC's value gives us their nonlinear characterisation

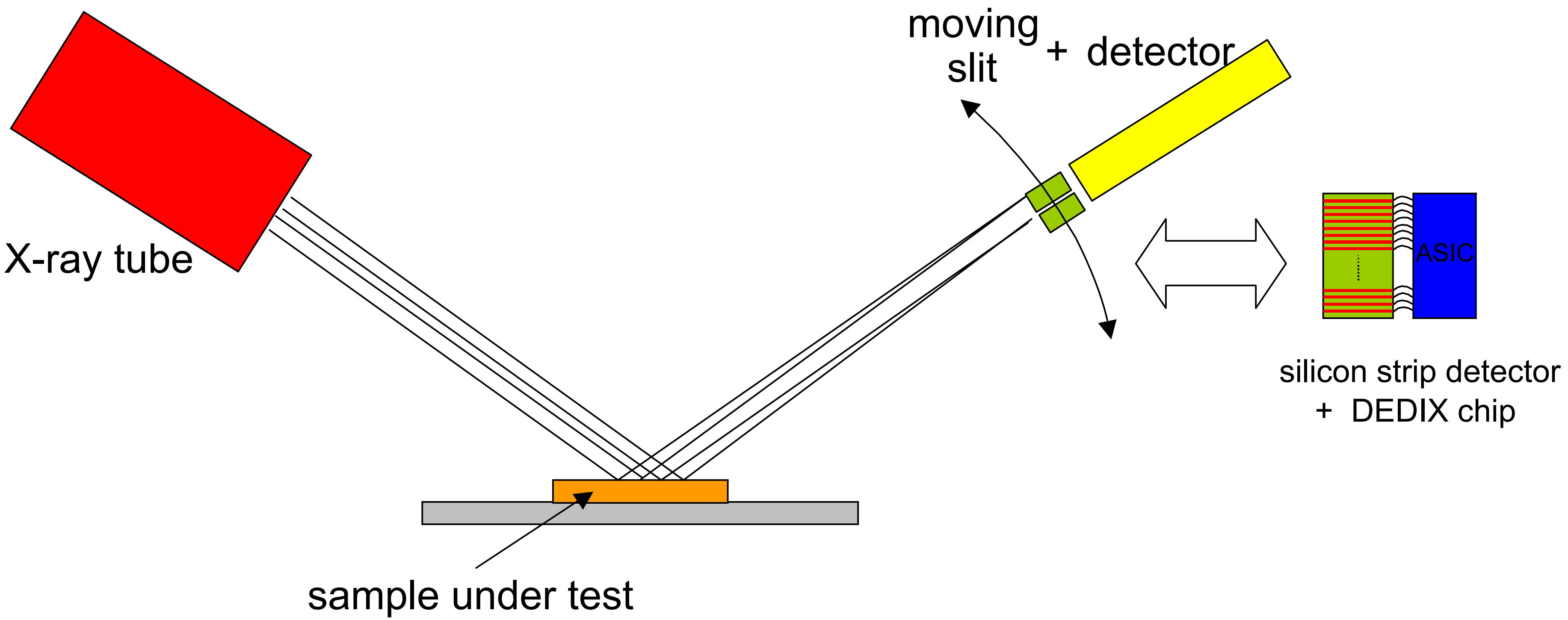


3. Calculation the value of correction DAC's – we know how much we want our threshold to be moved (1) and we know what DAC's value move the threshold to correct value (2)

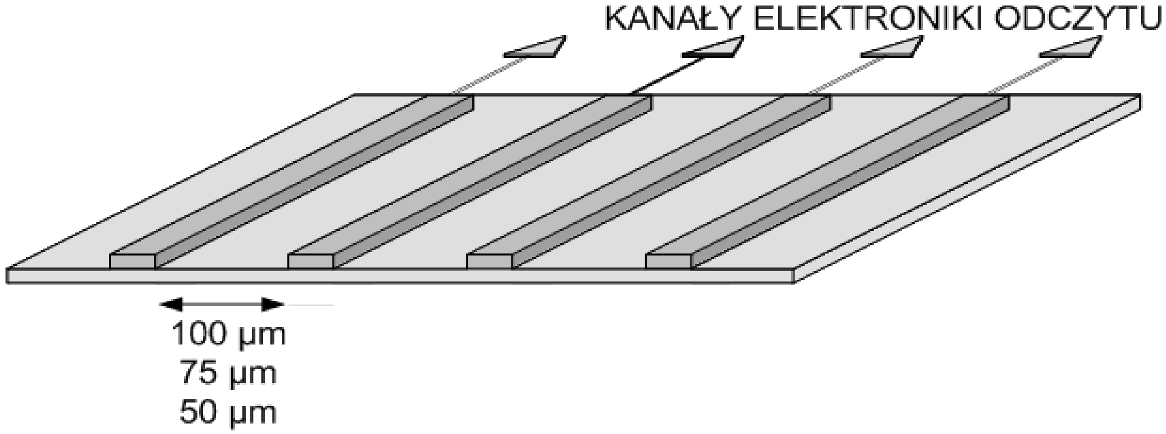
High count-rate measurement with X-ray tube

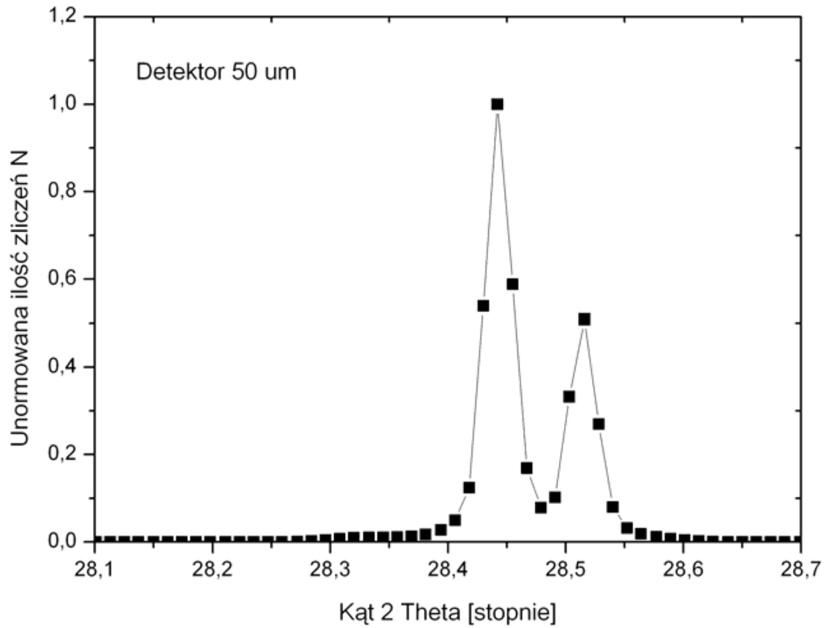


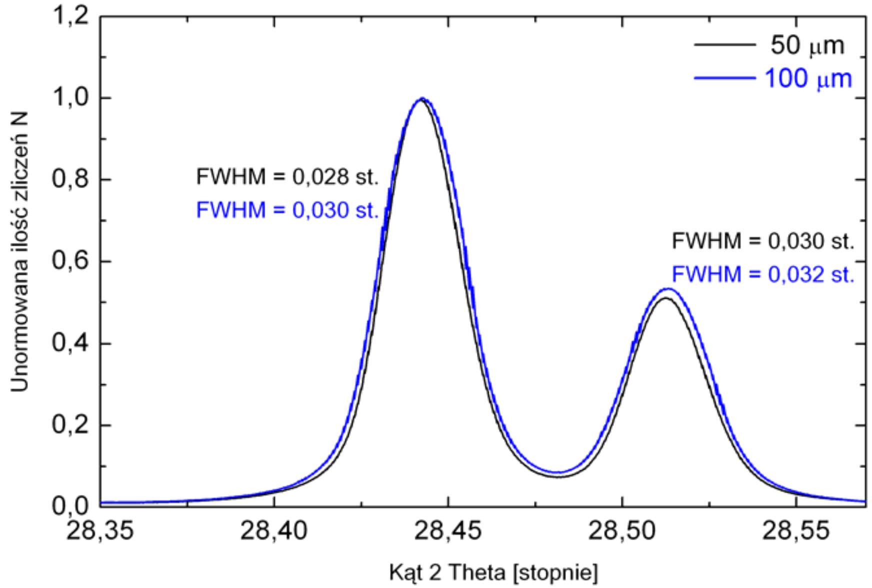
SSD in diffractometry

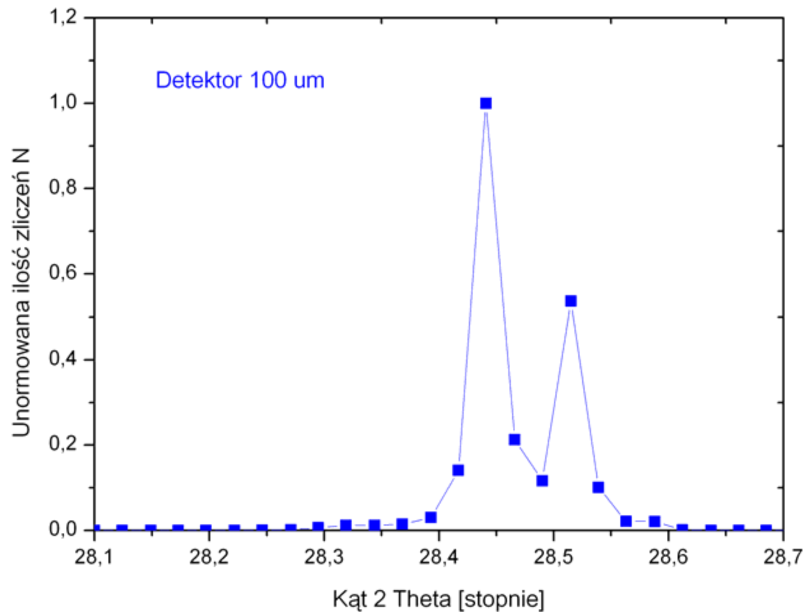


Detectors with different pitch

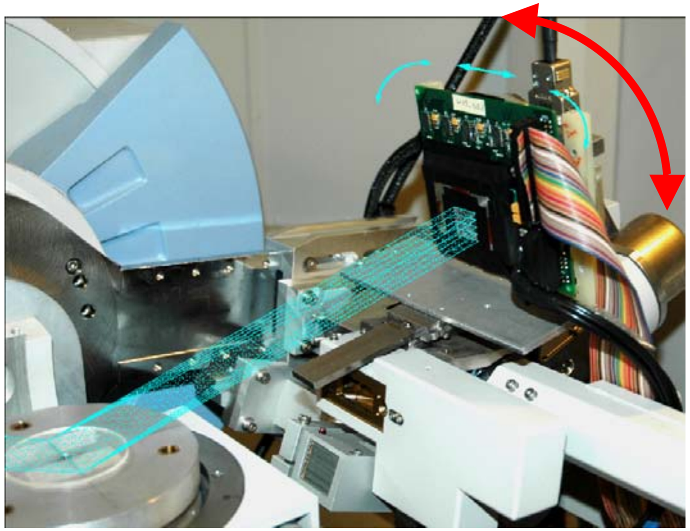


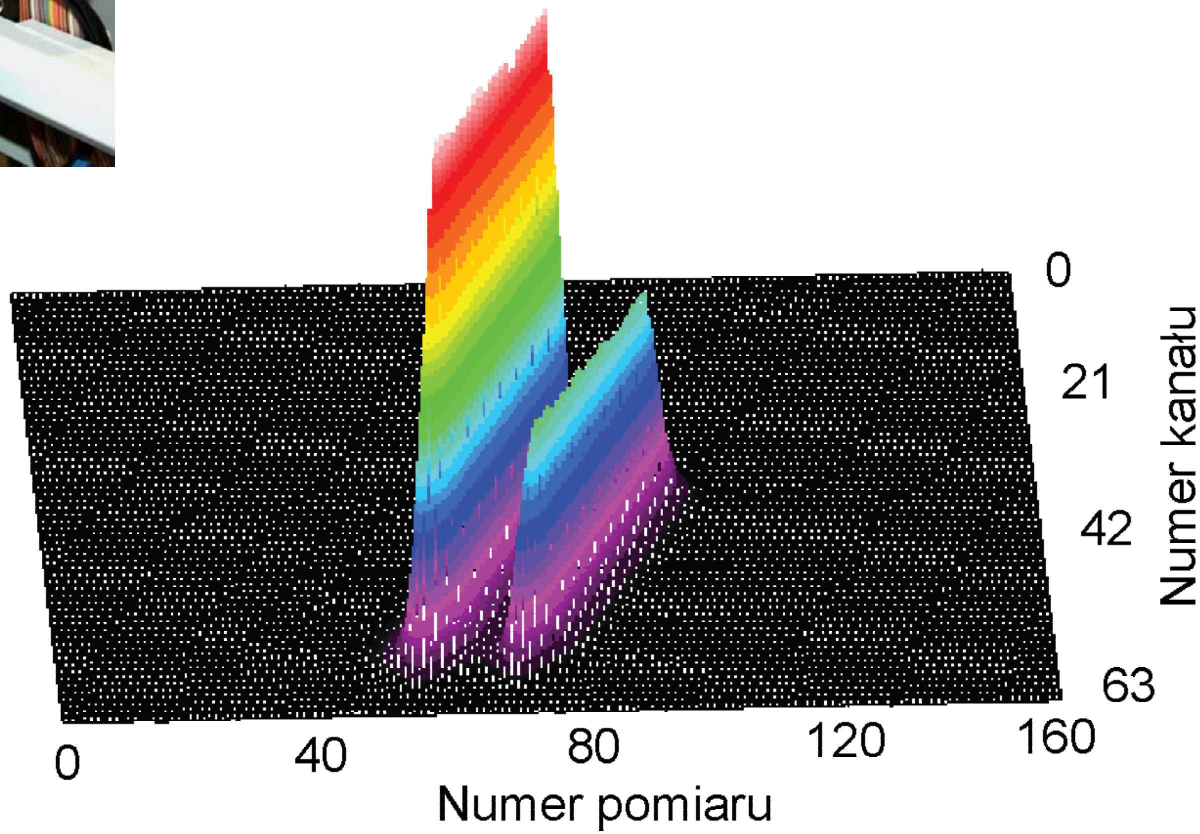




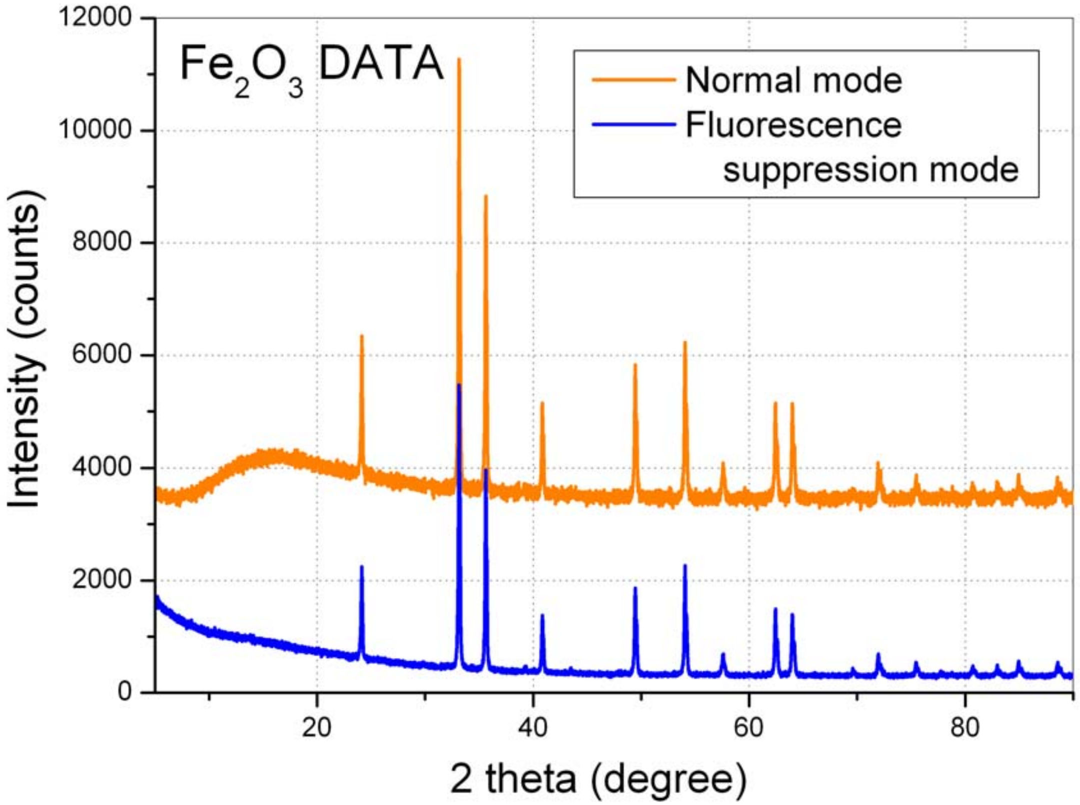


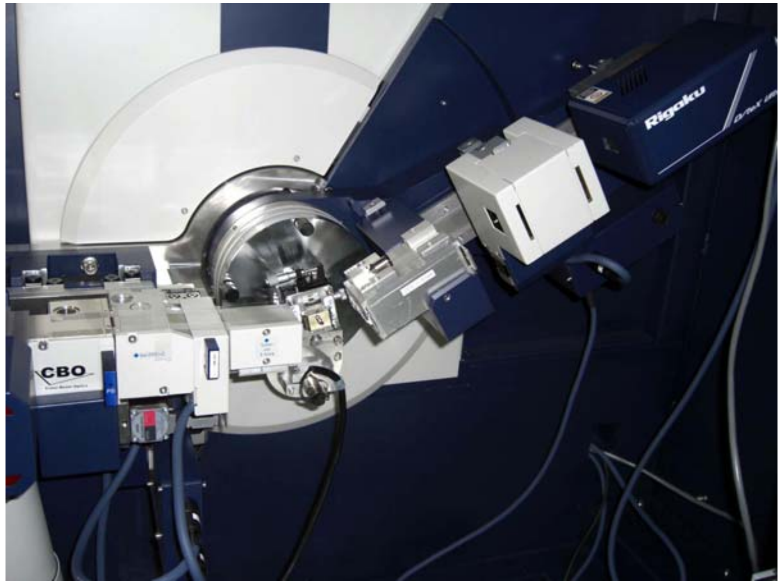
Continous scan (prof. T. Stobiecki laboratory)

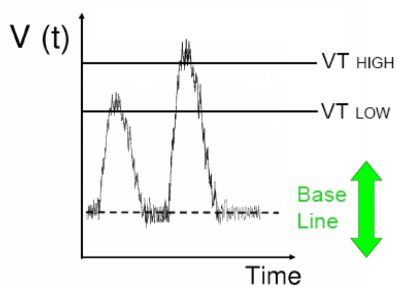




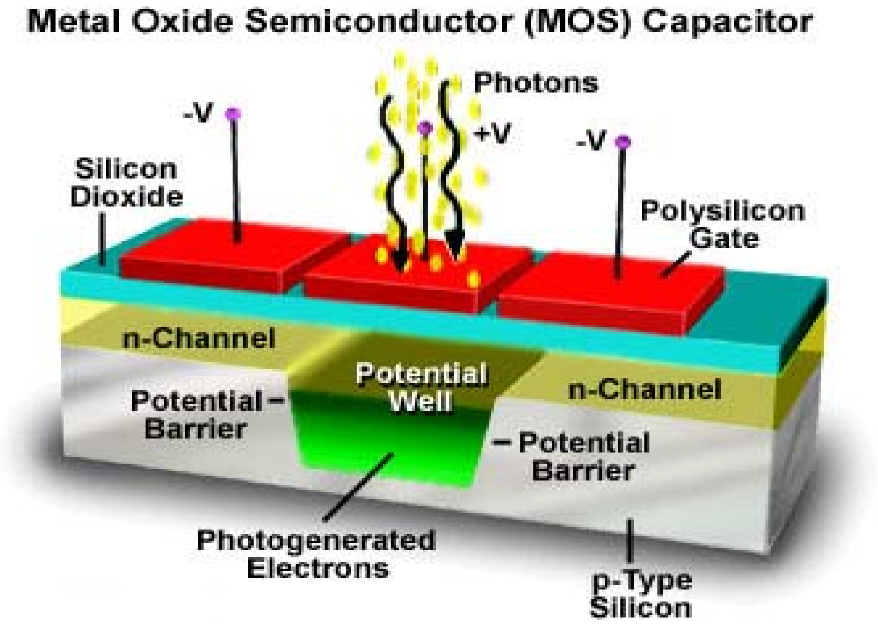
Fluorescence suppression - Rigaku, Japan

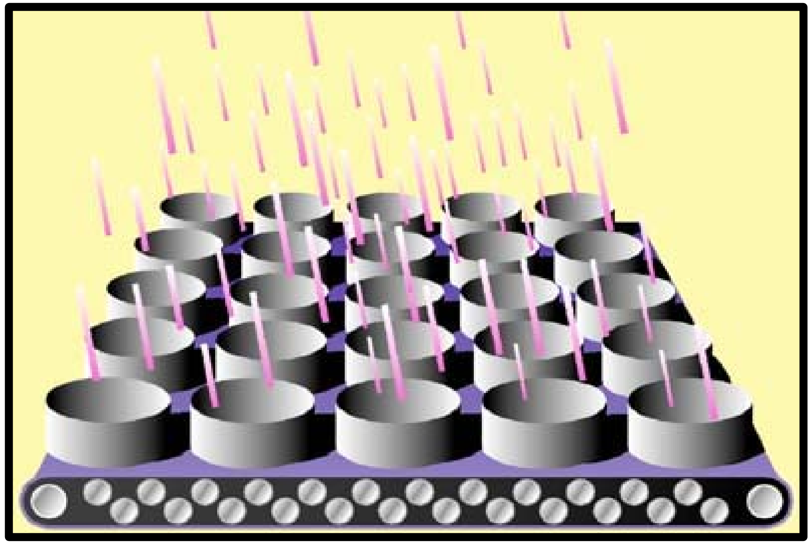


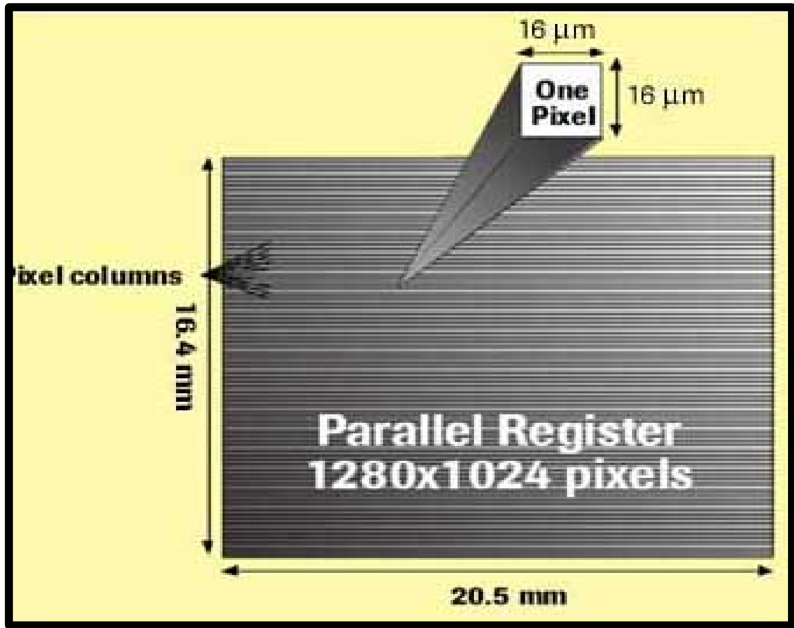




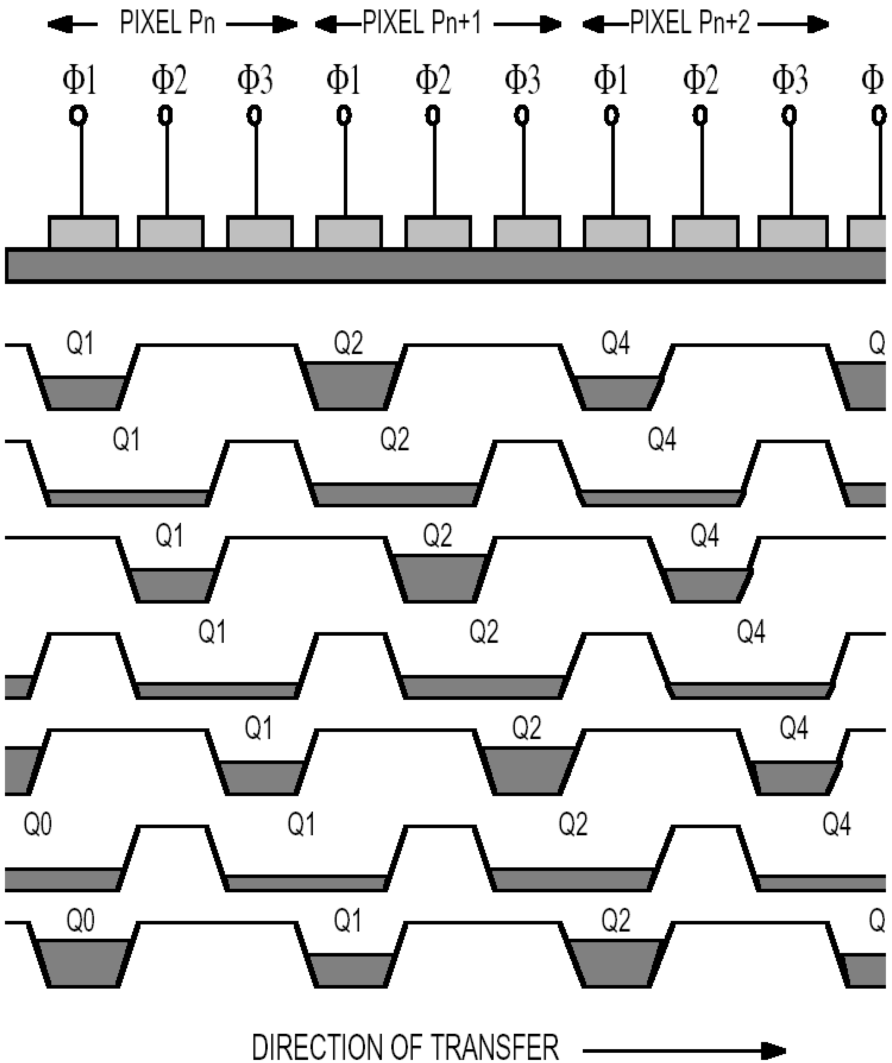
CCD detector

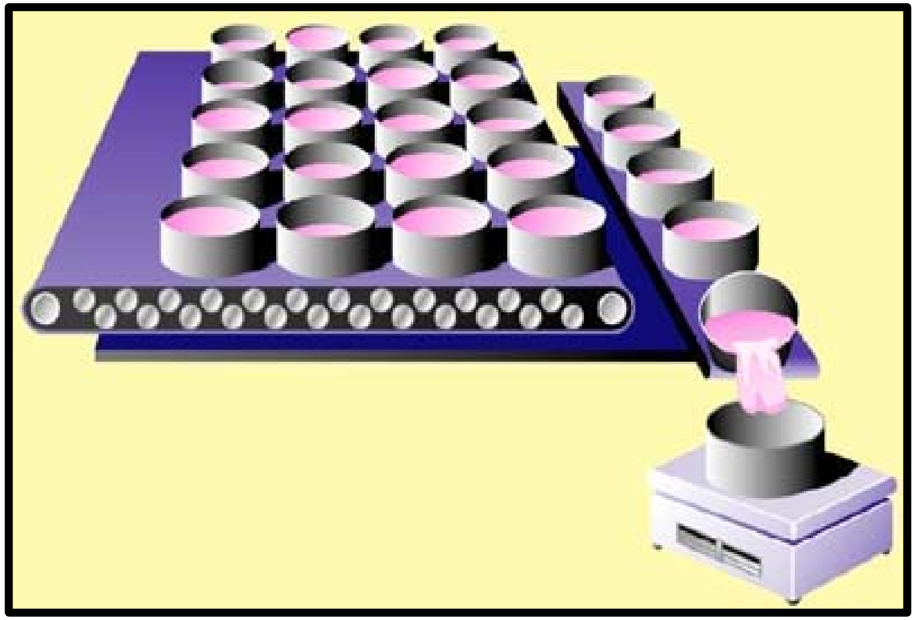




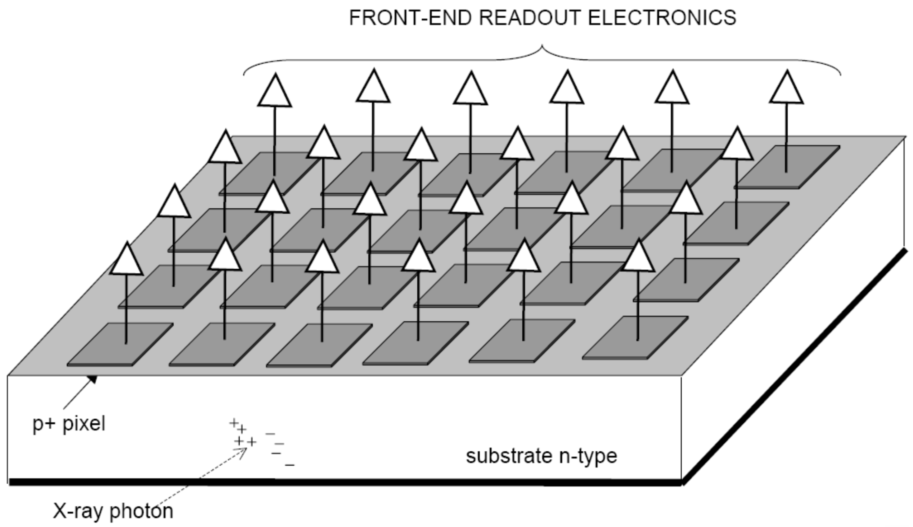


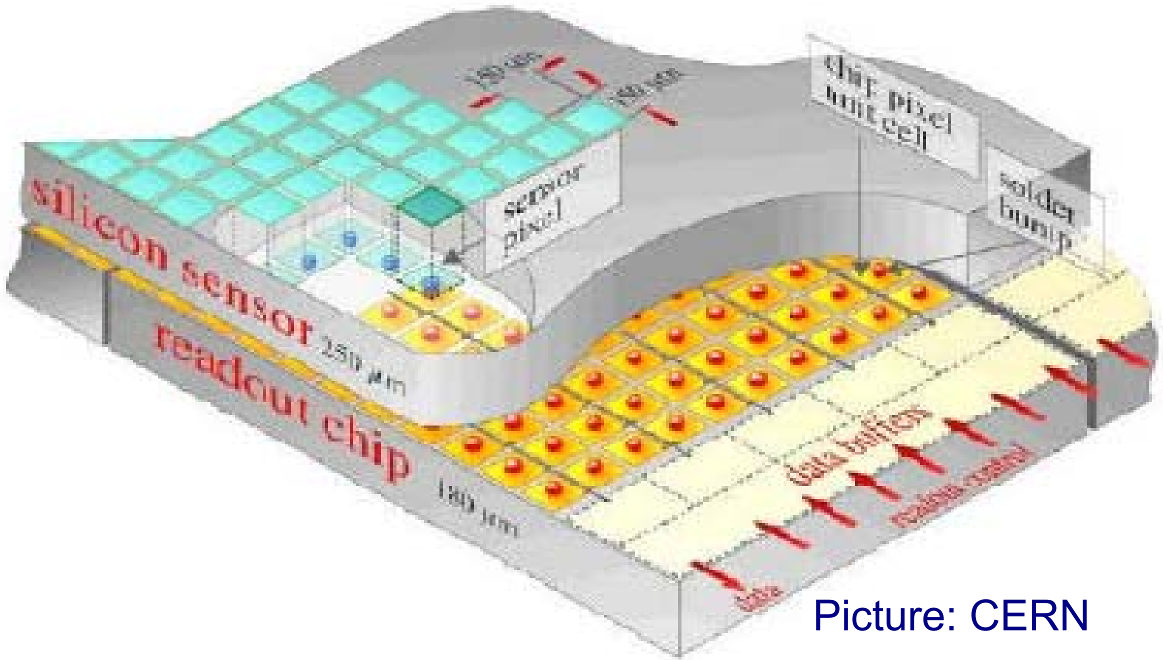
Readout of CCD





Pixel detector Si/GaAs

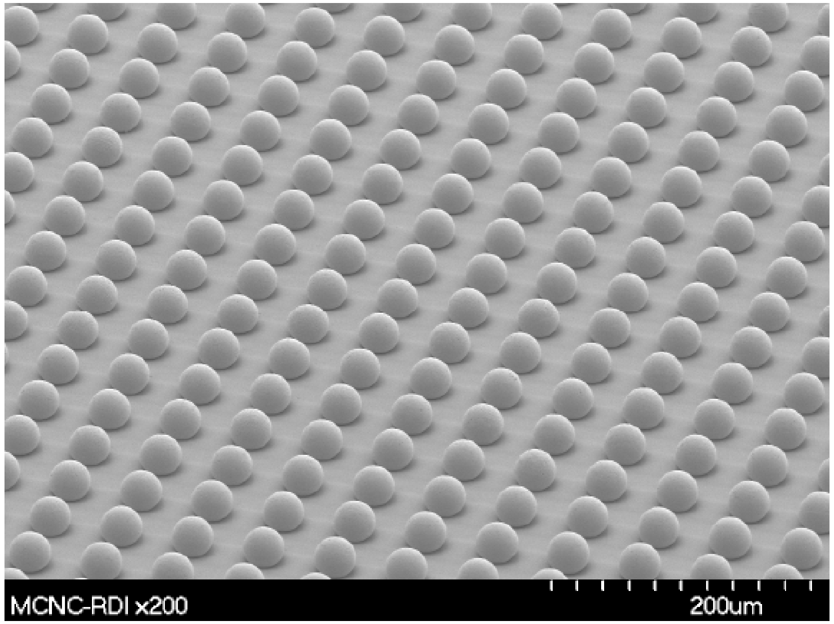




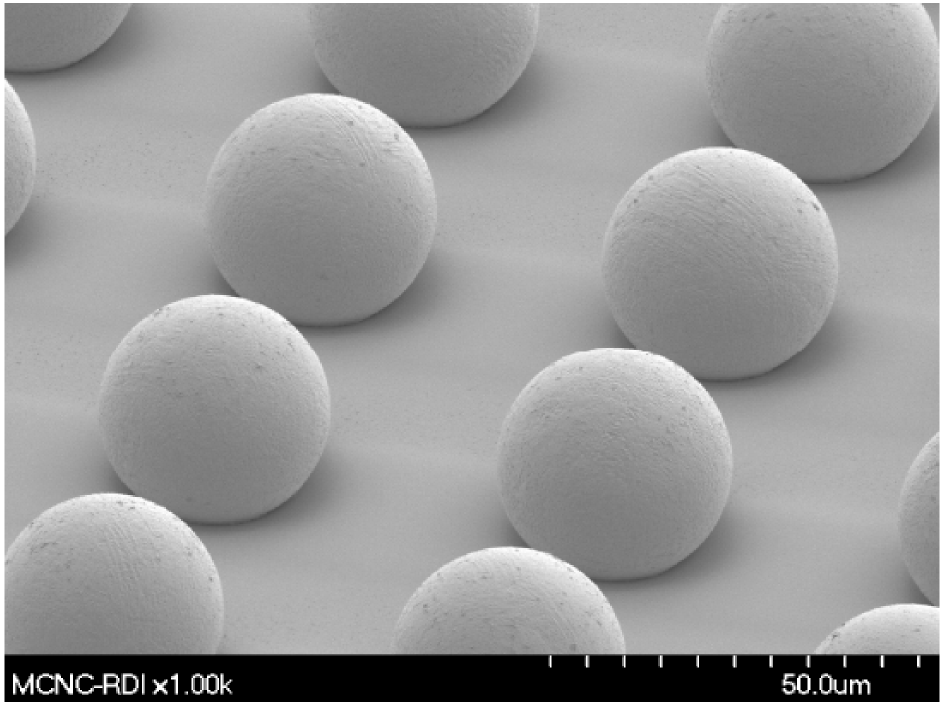
Picture: CERN

Bump Bonding

Bumps on the readout side

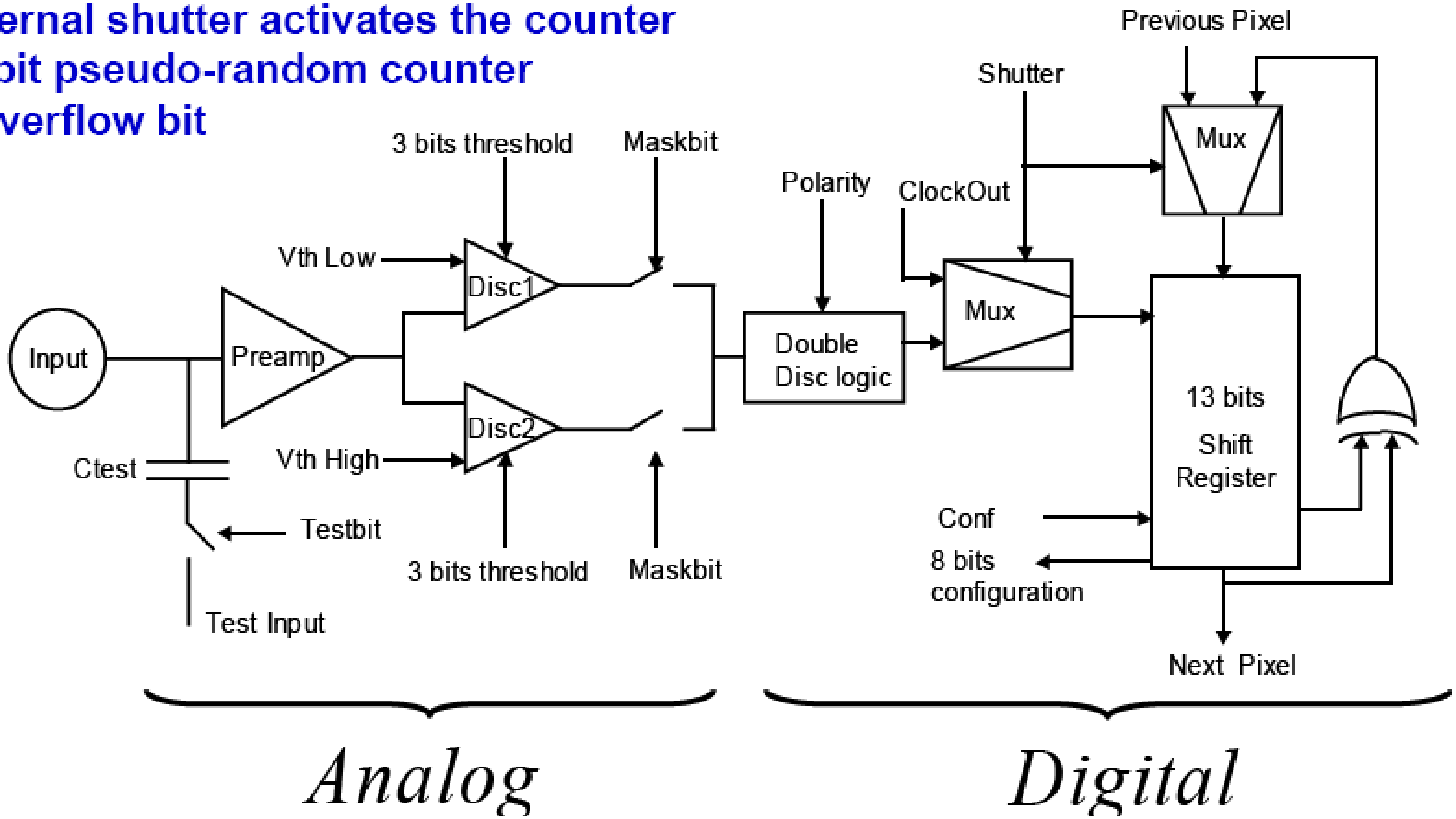


Bumps on the readout side – close up



Medipix -CERN

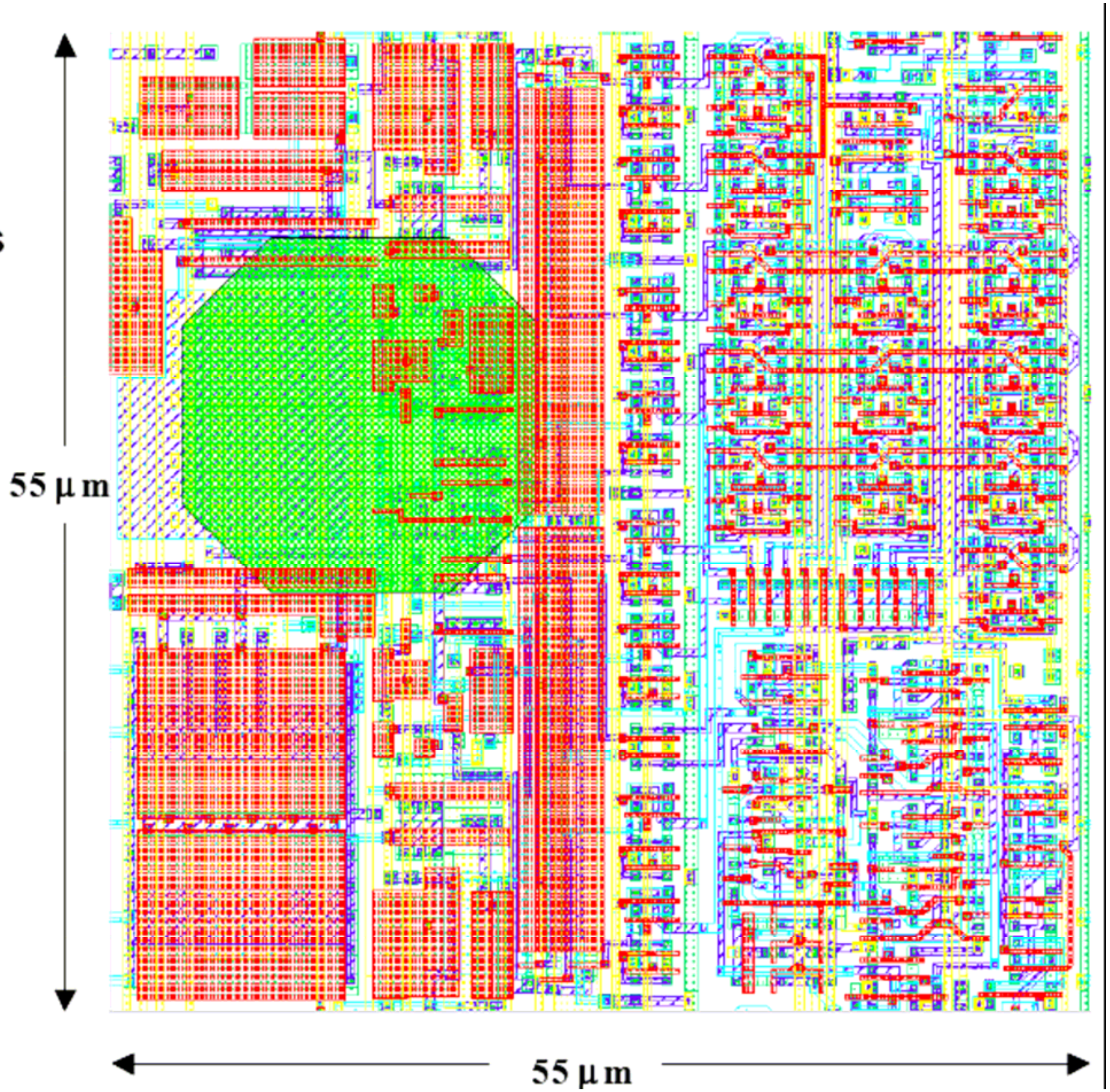
Charge sensitive preamplifier with individual leakage current compensation
2 discriminators with globally adjustable thresholds
3-bit local fine tuning of the threshold per discriminator
1 test and1 mask bit
External shutter activates the counter
13-bit pseudo-random counter
1 Overflow bit



Medipix -CERN

503 transistors per pixel

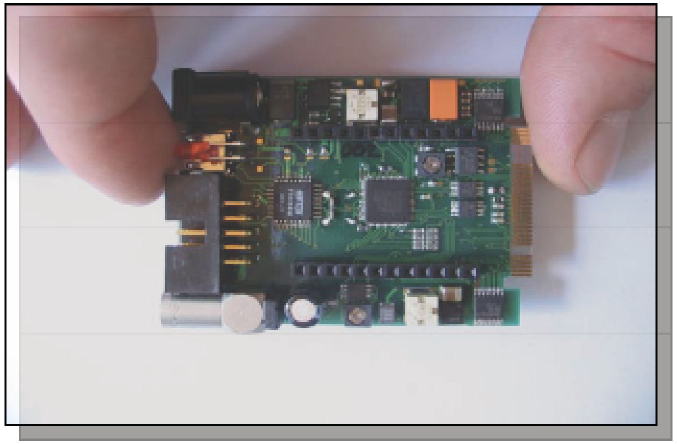
33M per Chip



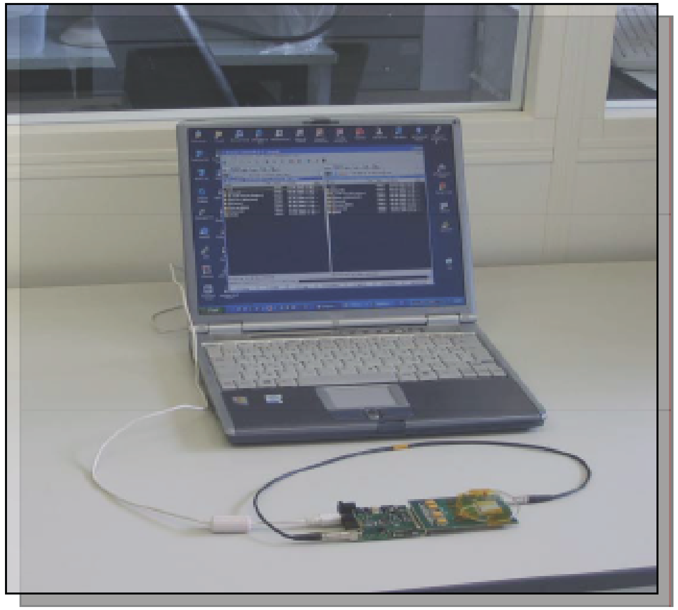
Medipix -CERN

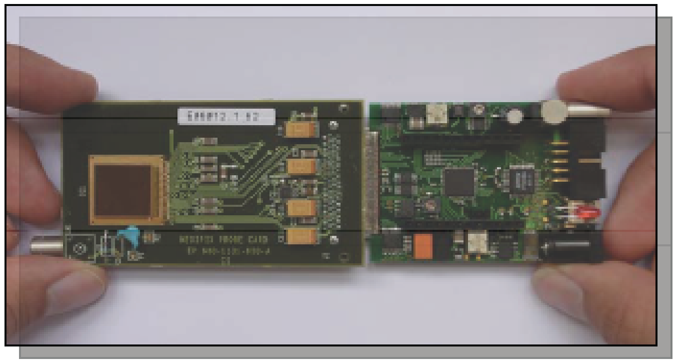
Medipix2 Si Assembly

A new USB based Medipix2 Readout System

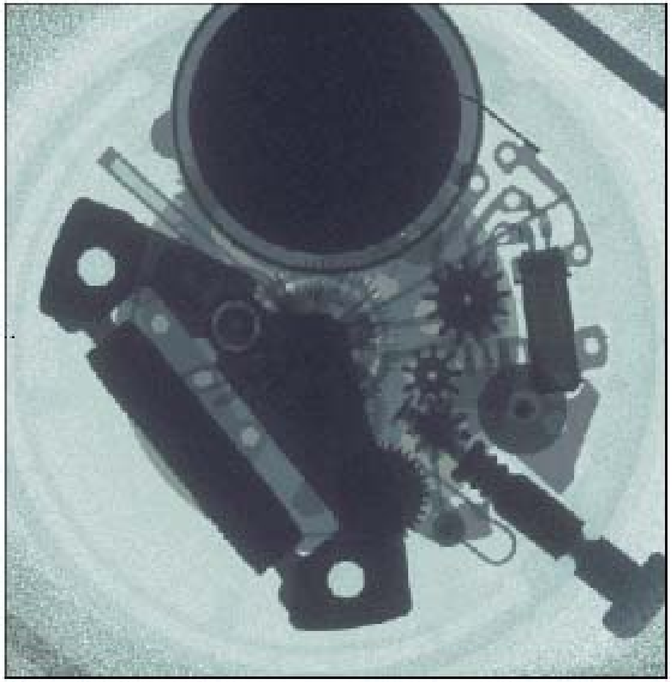


USB1 compatible
Developed by S. Pospisil et al.
CTU, Prague



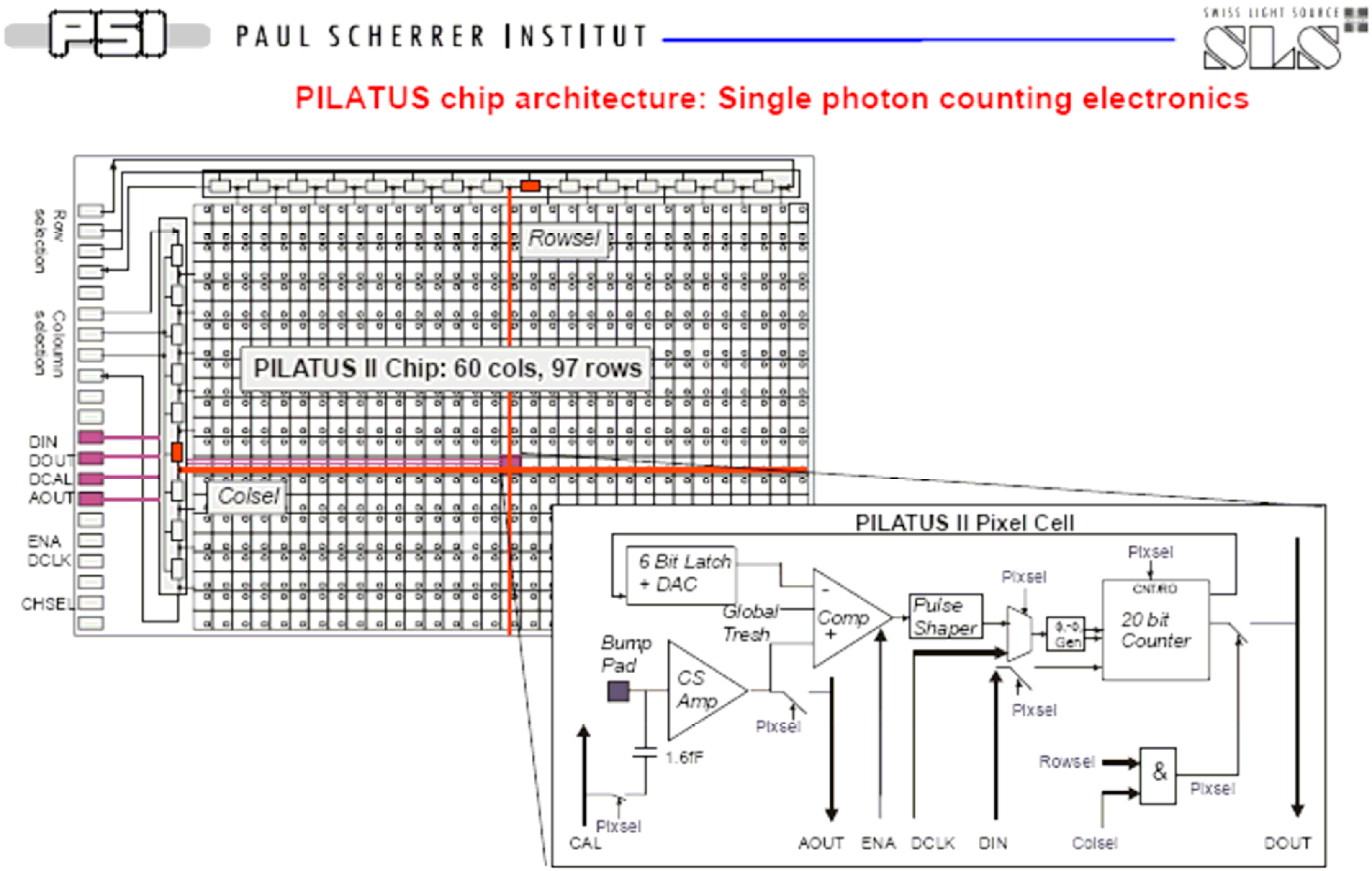


Medipix -CERN



X-Ray movie at 5.5fps 512x512 pixels
Uses 4-chip Quad detector

PILATUS - PSI


PAUL SCHERRER INSTITUT
SWISS LIGHT SOURCE
SLS
PILATUS chip architecture: Single photon counting electronics
Row selection
Coloumn selection
DIN
DOUT
DCAL
AOUT
ENA
DCLK
CHSEL
Rowsel
Colsel
PILATUS II Chip: 60 cols, 97 rows
PILATUS II Pixel Cell
6 Bit Latch
+ DAC
Global
Tresh
Comp
Pulse
Shaper
20 bit
Counter
CNTRO
Gen
Bump
Pad
CS
Amp
1.6fF
Pixsel
&
CAL
AOUT
ENA
DCLK
DIN
Colsel
DOUT

PILATUS- PSI

Bump-Bonded Multi-Chip-Module (PILATUS I)

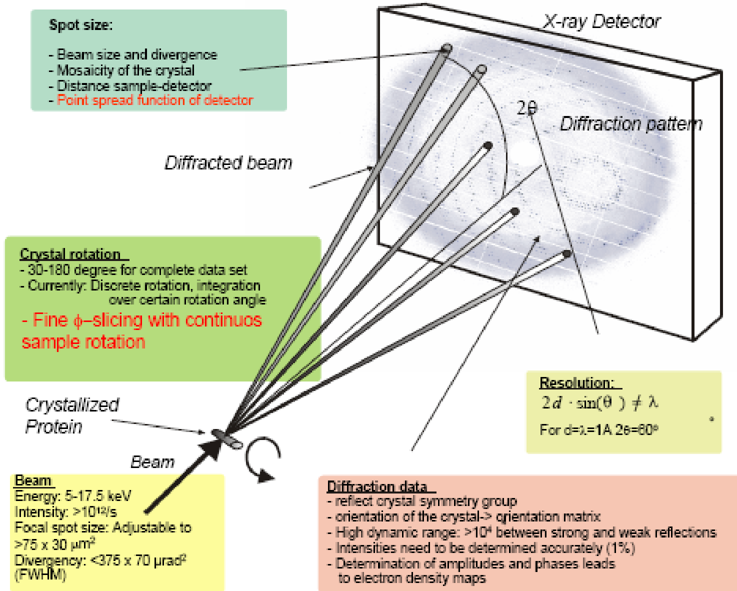
- Pixel size 0.217 x 0.217 mm^2
- Chip has 44 x 78 pixels
- 16 chips bump-bonded to 1 Silicon Sensor
- Module has 366 x 157 pixels
- Active Area is 79.4 x 34.1 mm^2

The PILATUS 1M Detector for Protein Crystallography

- Finished in Fall 2003
- First large area pixel detector for Protein Crystallography (Prototype)
- 6 banks a 3 modules, 1120 x 967 pixels
- Area: 21 x 24 cm^2
- Readout time: 6.7ms
- 2 frames/ s
- Fine-ϕ slicing with continuous sample rotation
- Active area: 85%
- Moderate count rates (<10kHz/pixel)
- PX Data processing difficult due to limitations of PILATUS I chip
- Extremely important for further development of pixel detectors for PX

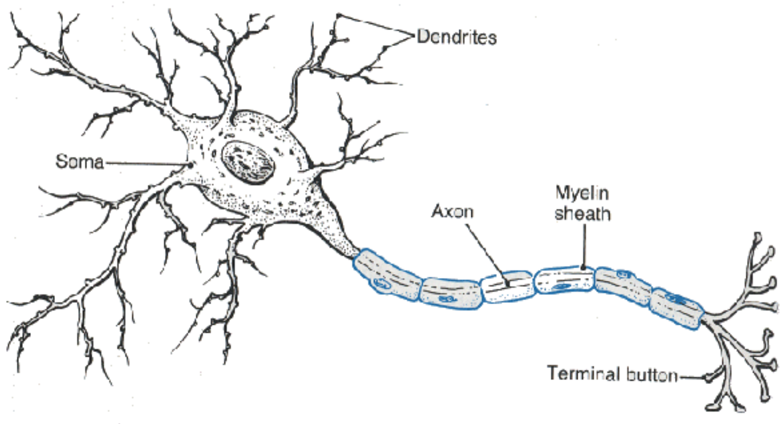
Brönnimann et al., J. Synchrotron Rad., 13, 2005,120-130.
The Pilatus 1M Detector.

Pixel Detectors for Protein Crystallography



Low Noise Mix-Mode Integrated Circuits for Neurobiology Applications

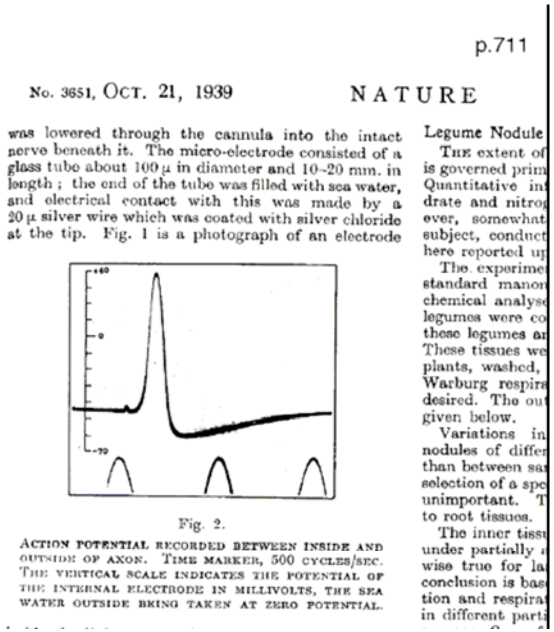
History – single channel recording



First Recording of Action Potentials

JZ Young, 1937 - Anatomical Description of Squid Giant Axons

Hodgkin & Huxley, 1939 - record AP using Squid Giant Axon



p.711

No. 3651, Oct. 21, 1939 NATURE

was lowered through the cannula into the intact nerve beneath it. The micro-electrode consisted of a glass tube about 100 μ in diameter and 10–20 mm. in length; the end of the tube was filled with sea water, and electrical contact with this was made by a 20 μ silver wire which was coated with silver chloride at the tip. Fig. 1 is a photograph of an electrode

Fig. 2.

ACTION POTENTIAL RECORDED BETWEEN INSIDE AND OUTSIDE OF AXON. TIME MARKER, 500 CYCLES/SEC. THE VERTICAL SCALE INDICATES THE POTENTIAL OF THE INTERNAL ELECTRODE IN MILLIVOLTS, THE SEA WATER OUTSIDE BEING TAKEN AT ZERO POTENTIAL.

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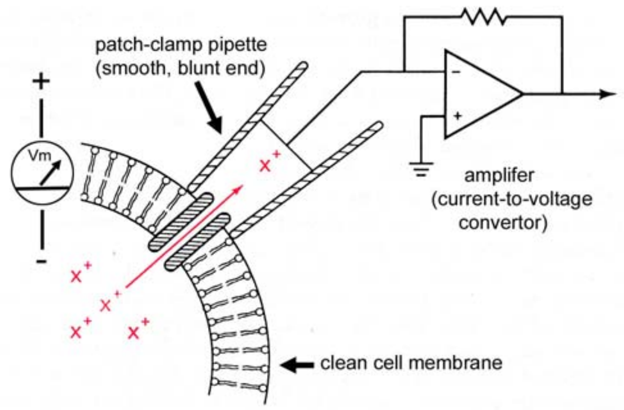
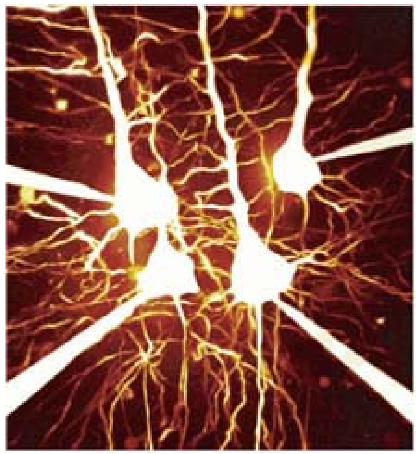
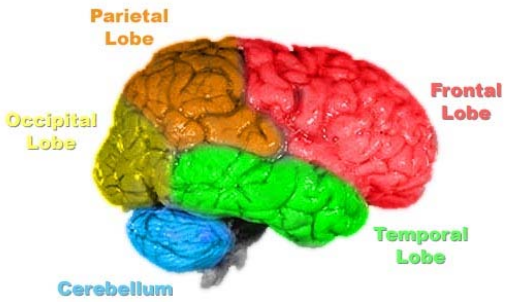




'Patch-clamp' technique :
Neher & Sakmann, 1976, (Nobel Prize1991)

Neural systems

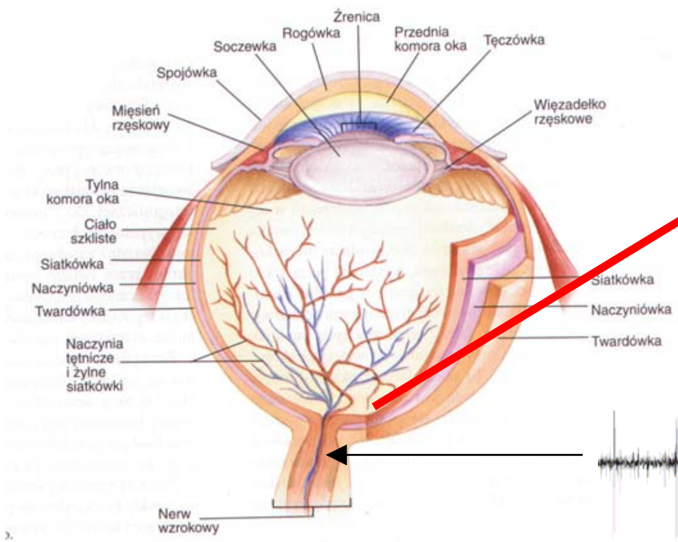
BRAIN

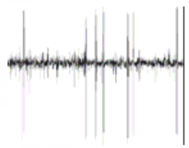


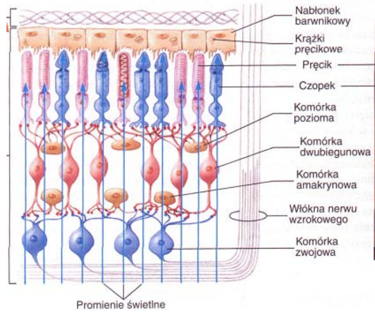
Single neuron

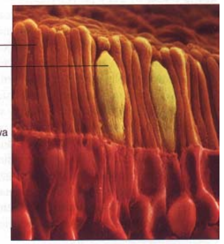
Bibliographic Entry	Result (w/surrounding text)	Standardized Result
Glencoe Health 2nd Edition. Mission Hills: Glencoe Inc., 1989: 252.	"Weighing around three pounds (1.35kg), the brain contains nearly 100 billion cells."	100 billion
World Book 2001. Chicago: World Book Inc., 2001: 551.	"The human brain has from 10 billion to 100 billion neurons."	10 - 100 billion
Magill's Medical Guide Revised Edition. Salem Press, 1998: 221.	"It has been estimated that the adult brain has around one hundred billion neurons and an even larger number of glial cells."	100 billion
The Science Times Book of the brain. New York: The Lyons Press, 1987: 150.	"The human brain holds about 100 billion nerve cells."	100 billion
The Scientific American Book of the Brain. New York: Scientific American, 1999: 3.	"An adult human brain has more than 100 billion neurons"	> 100 billion

RETINA









Cones: 6.5 x 10^6 (colours)
Rods: 125 x 10^6 (move, shape)
Optical nerve: 1 x 10^6 fibers

Photo: Biologia, PWN

AIM: to build an electronic interface

for recording/stimulation of neuronal system comprising several hundreds or thousands of electrodes

Motivation

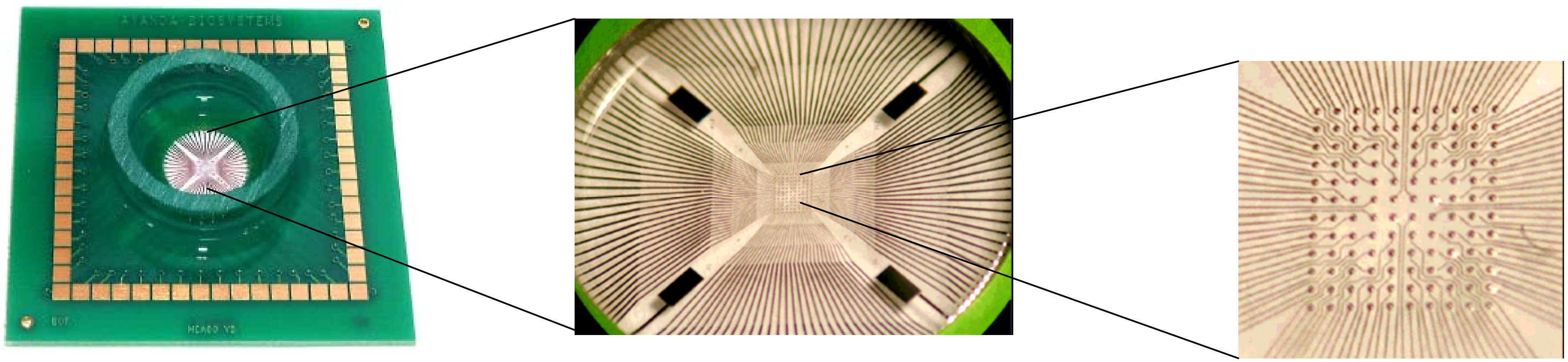
1. Understand neuronal coding,
2. Biosensors
3. Neuronal prostheses

Components

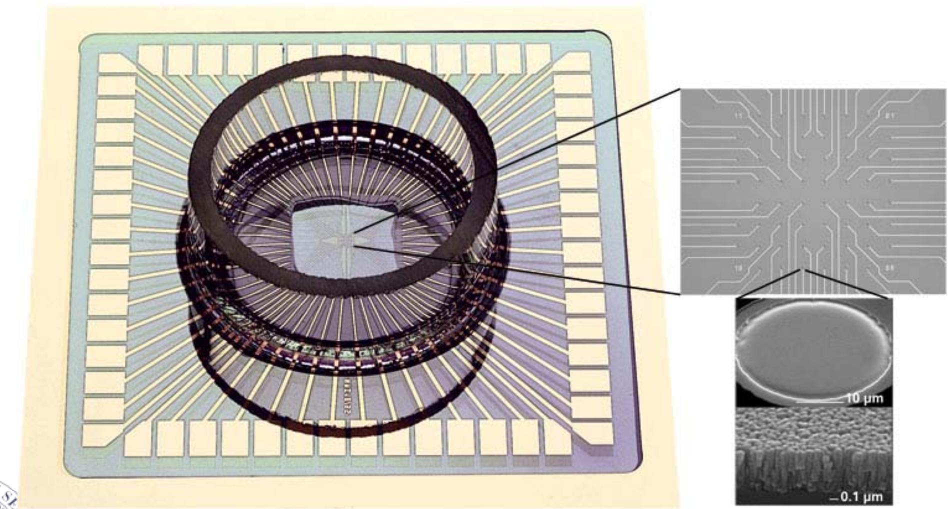
1. Microelectrode array
2. Multichannel electronics

Microelectrode arrays I – planar microelectrodes

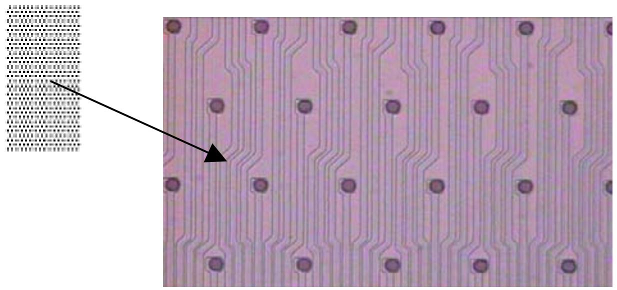
Ayanda Biosystems



Multi Channel Systems



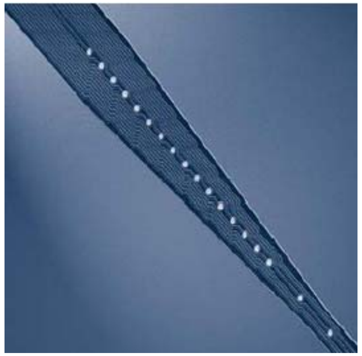
University of Glasgow

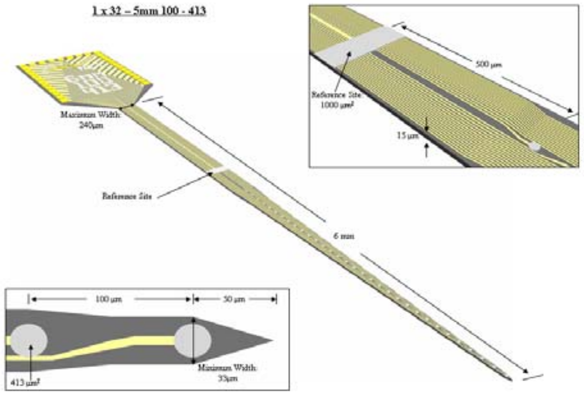


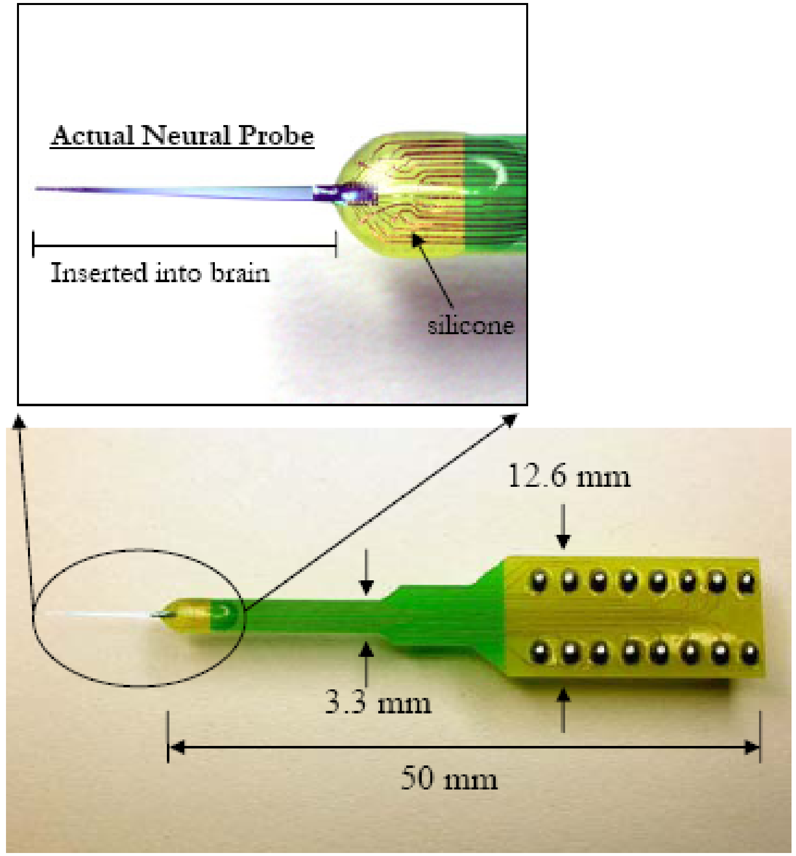
512-electrode array 32x16:
spacing = 60 um diameter = 5 um

Microelectrode arrays II - Microprobes

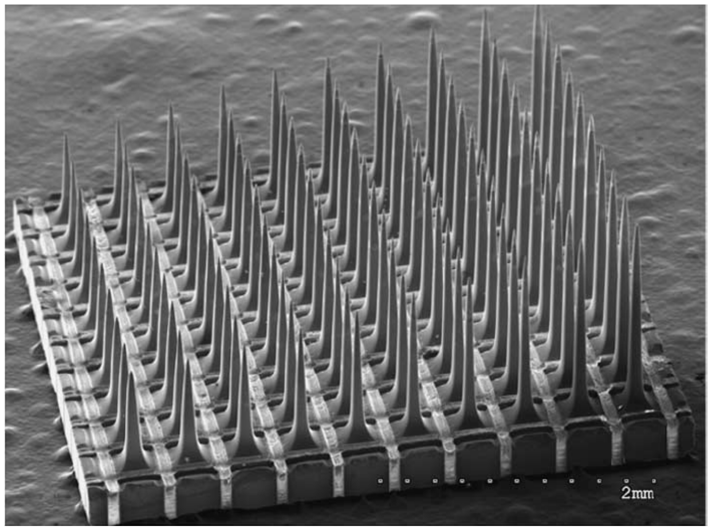
NeuroNexus Technologies







Utah Microelectrode Array



Recording/stimulation electronics – standart solutions

BROWNLEE PRECISION

4-channel recording amplifier

multichannel systems

8-channel stimulus generator

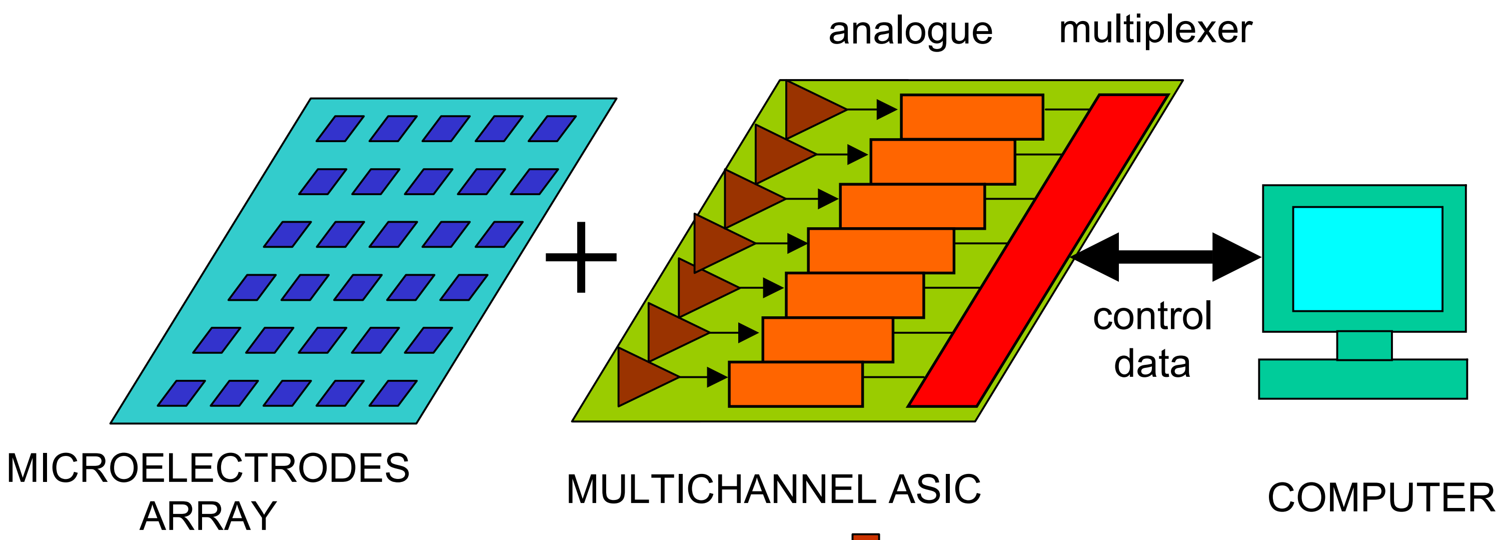
60-channel recording system

multichannel systems

Limits:

- number of channels
- large volume and weight
- high costs

Multichannel neuribiological recording based on ASIC

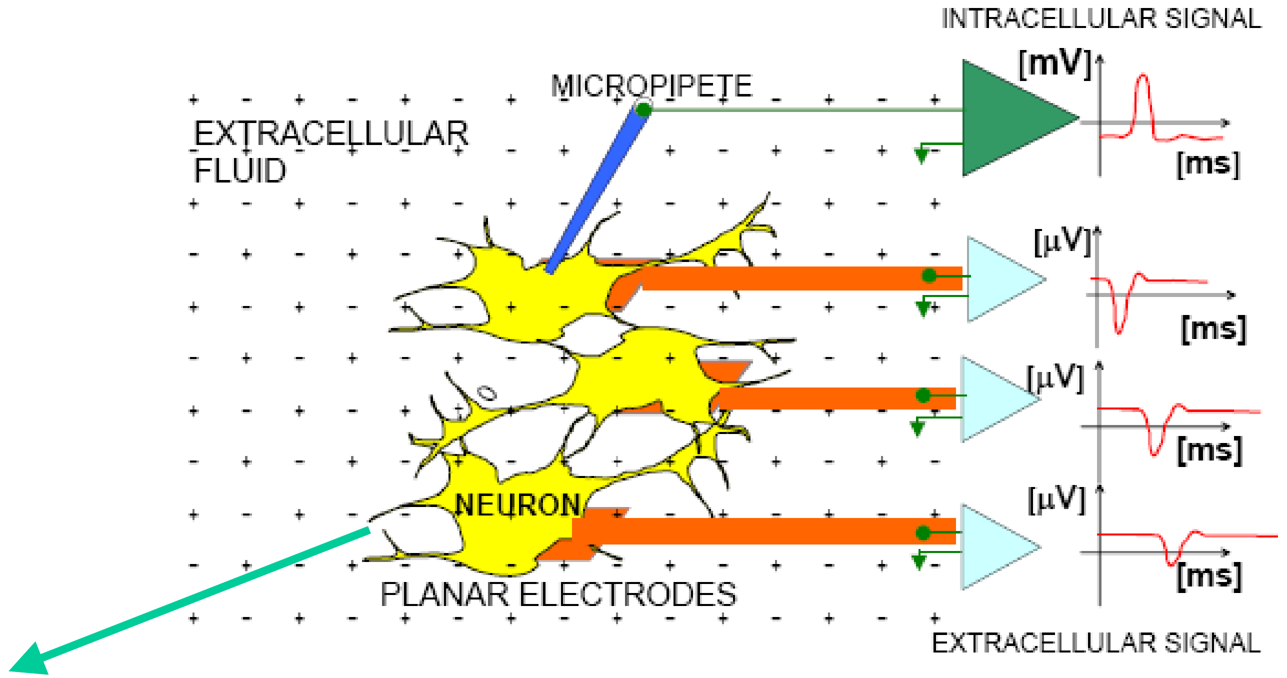


To design a multichannel
APPLICATION SPECIFIC INTEGRATED CIRCUIT (ASIC),
which is able to cope with extracellular neuronal recording

system

- **to built recording system comprising several hundreds or thousands of electrodes**
- **miniaturization**

Extracellular recording – requirements for electronics



Signal source (e.g. retina tissue): V_{amp} = 50-500 μV, DC offsets,
$t_w \approx$ 1-2 ms, band: 20 -2000 Hz,

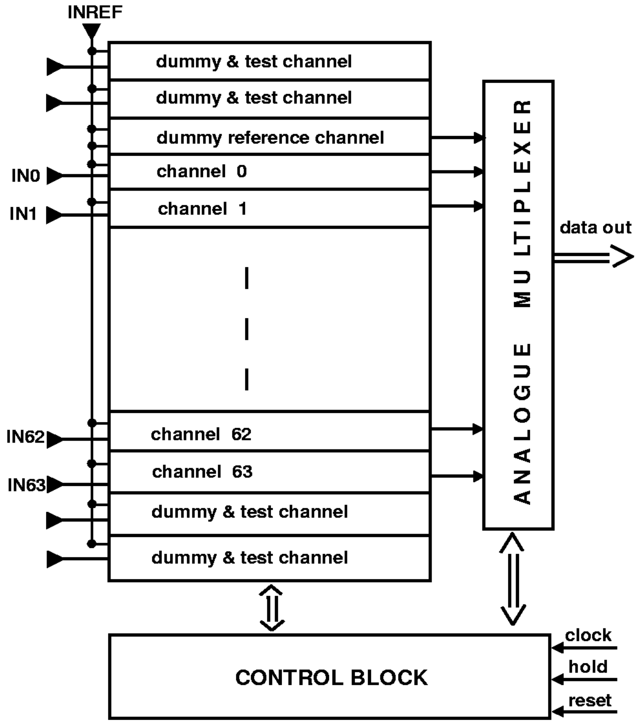
Requirements:

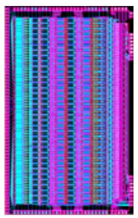
Low noise ~ 5 μV rms
Frequency band pass 20 Hz to 2000 Hz
AC coupled input cut-off frequency < 20 Hz

→ **MULTICHANNEL ARCHITECTURE**

Multichannel architecture

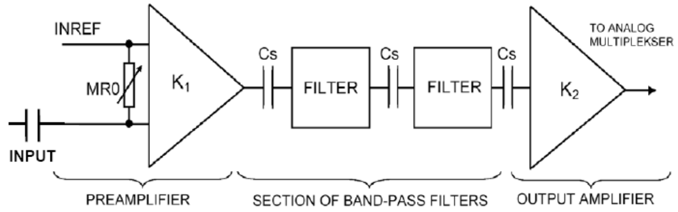
64 channel ASIC - NEURO64

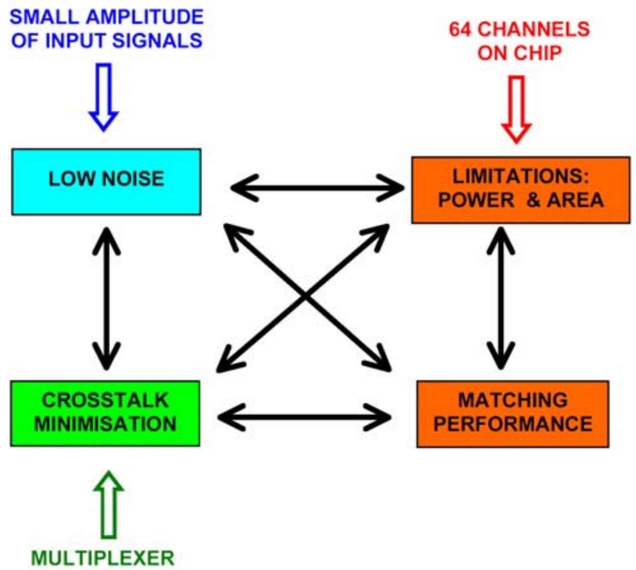




CMOS technology 0.7 um
4 mm x 6 mm

Single channel architecture



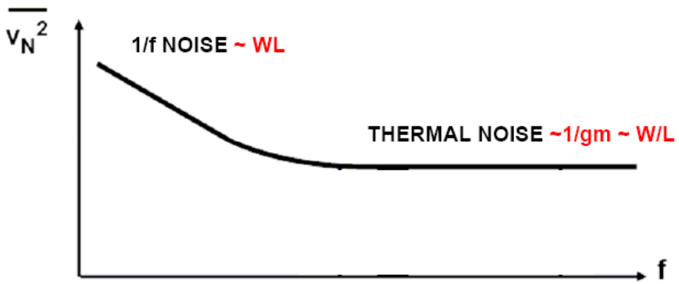


LIMITATION OF CMOS TECHNOLOGY

CMOS technology - noise

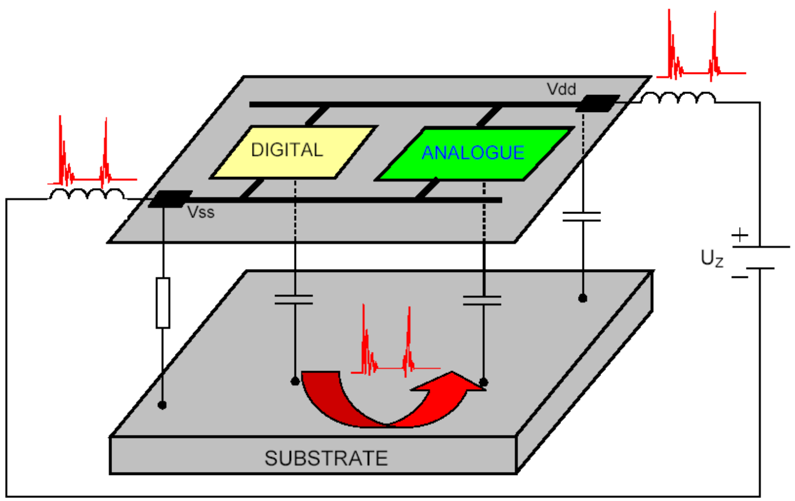
MOS transistors:

- flicker noise ⇐ low frequency,
- thermal noise ⇐ power limitation



Crosstalk:

- supply bounce,
- substrate noise



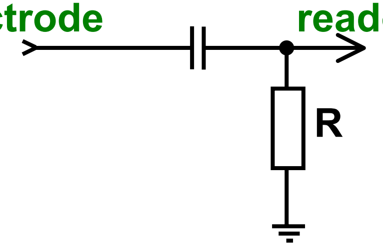
AC-coupling -kT/C noise:

- small capacitors ⇐ area limitation

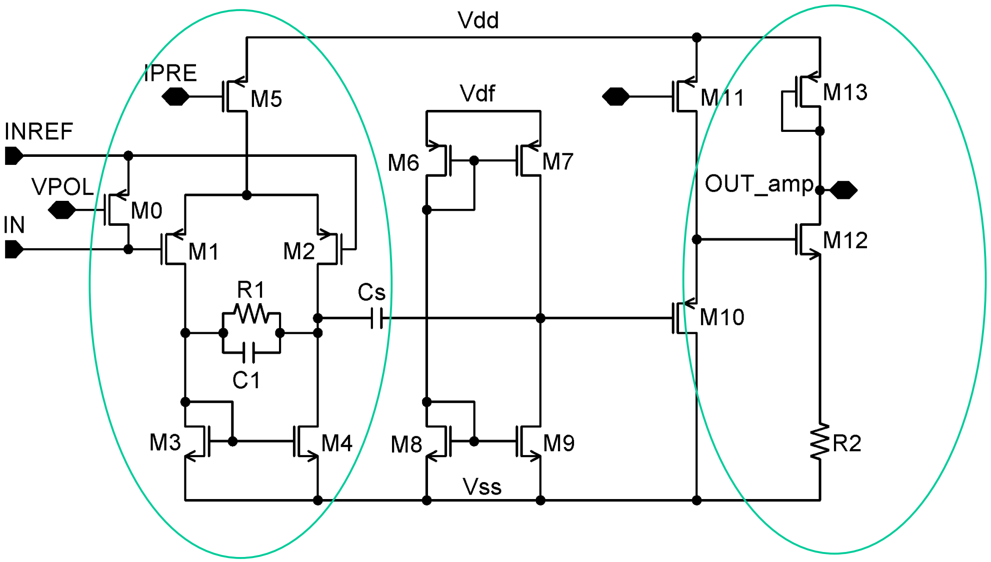
CMOS technology: C= 1pF ⇒ 64μV rms

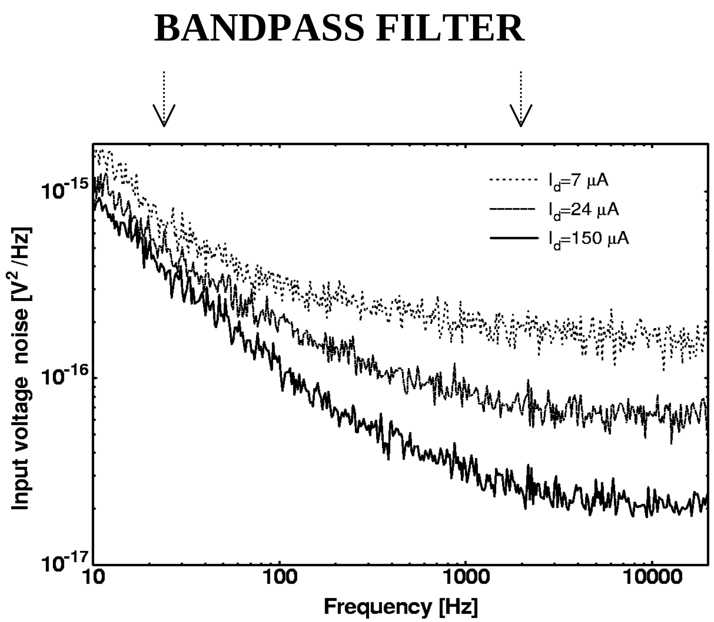
C= 100pF ⇒ 6.4μV rms

SMD technology: C= 10nF ⇒ 0.64μV rms



Low noise preamplifier





NOISE

POWER

Power: < 2 mW/channel

Noise: 2 µV rms (10Hz-20kHz)

Flicker noise

$$\frac{\overline{dv^2_{1/f\_dif}}}{df} = \frac{2K_{fp}}{C_{ox}W_1L_1}\left(1+\frac{\mu_n K_{fn} L_1^2}{\mu_p K_{fp} L_3^2}\right)\frac{1}{f}$$

MINIMUM: ⇒ $\frac{L_1}{L_3}=\sqrt{\frac{K_{fp}\mu_p}{K_{fn}\mu_n}}$

+ Thermal noise → HSPICE → PRODUCTION MEASUREMENT

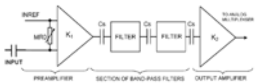
M1: 1500/2

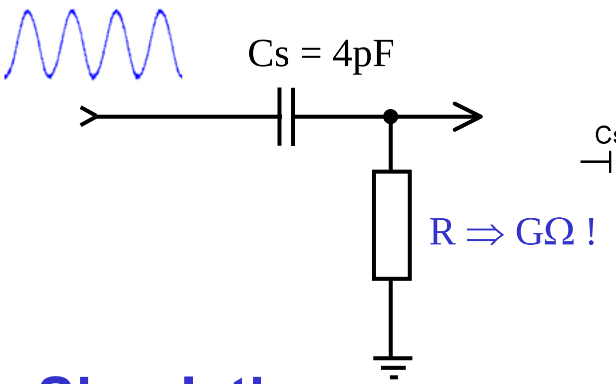
M3: 100/24

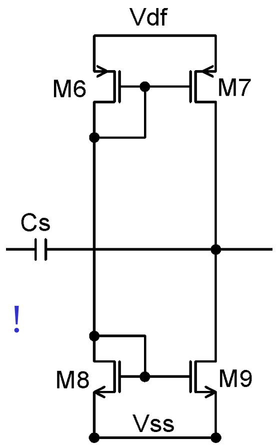
.....

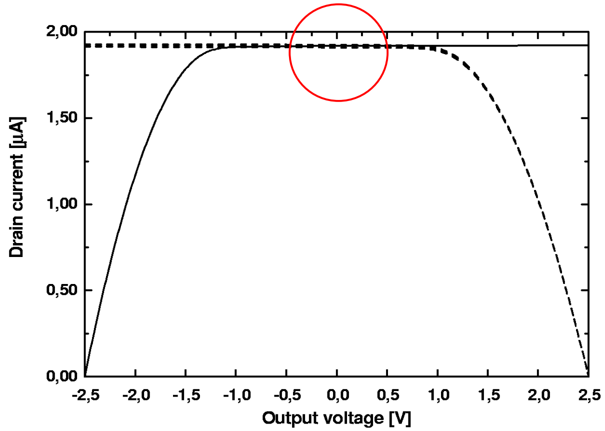
Technology (Alcatel-Mietec CMOS 0.7µm): KF_{NMOS} = 3e-28 V^2F, KF_{PMOS} = 5e-30 V^2F

AC coupling – NEURO64



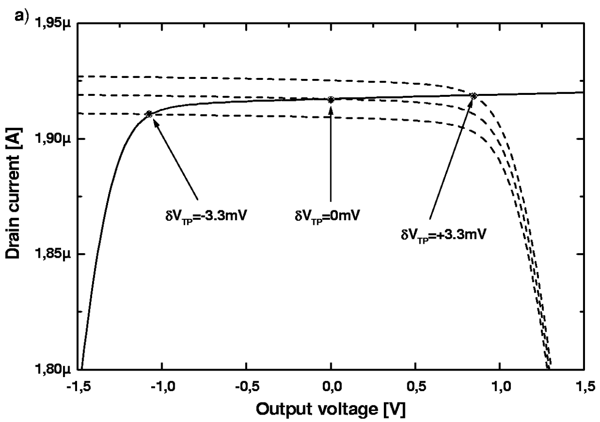




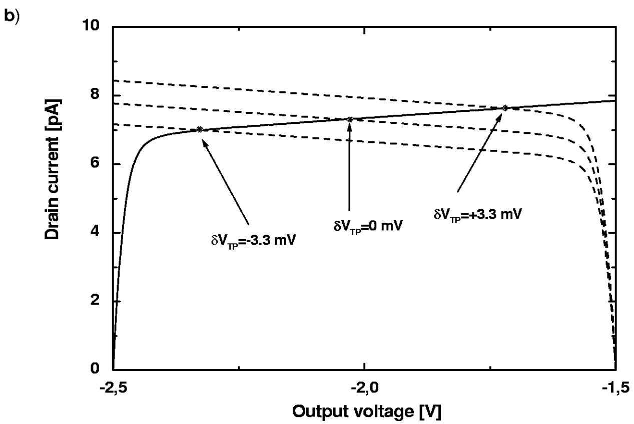


Simulations

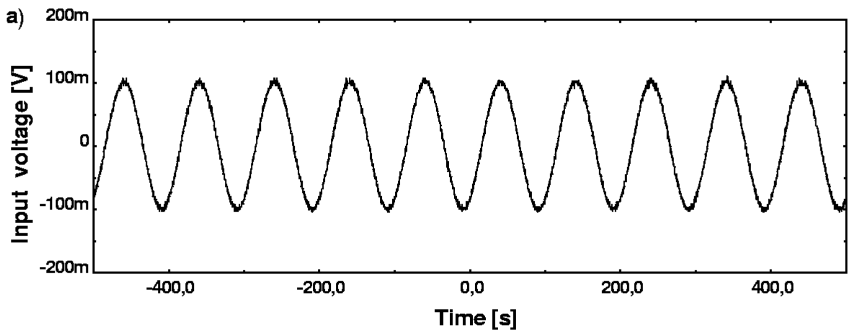
WEAK INVERSION

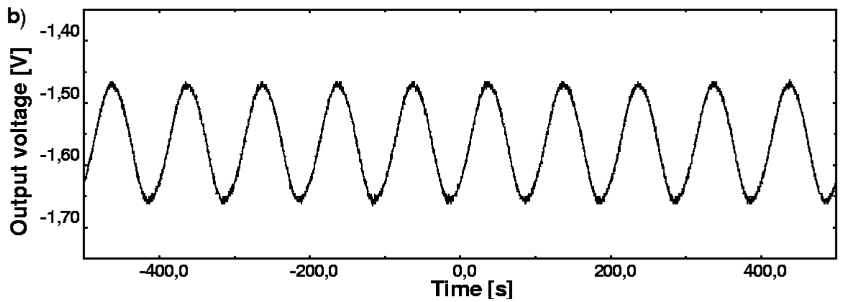


STRONG INVERSION

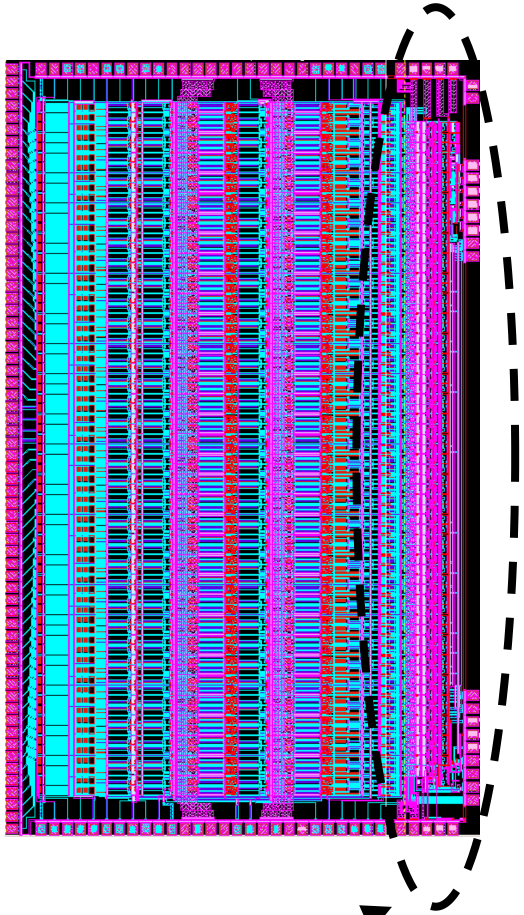


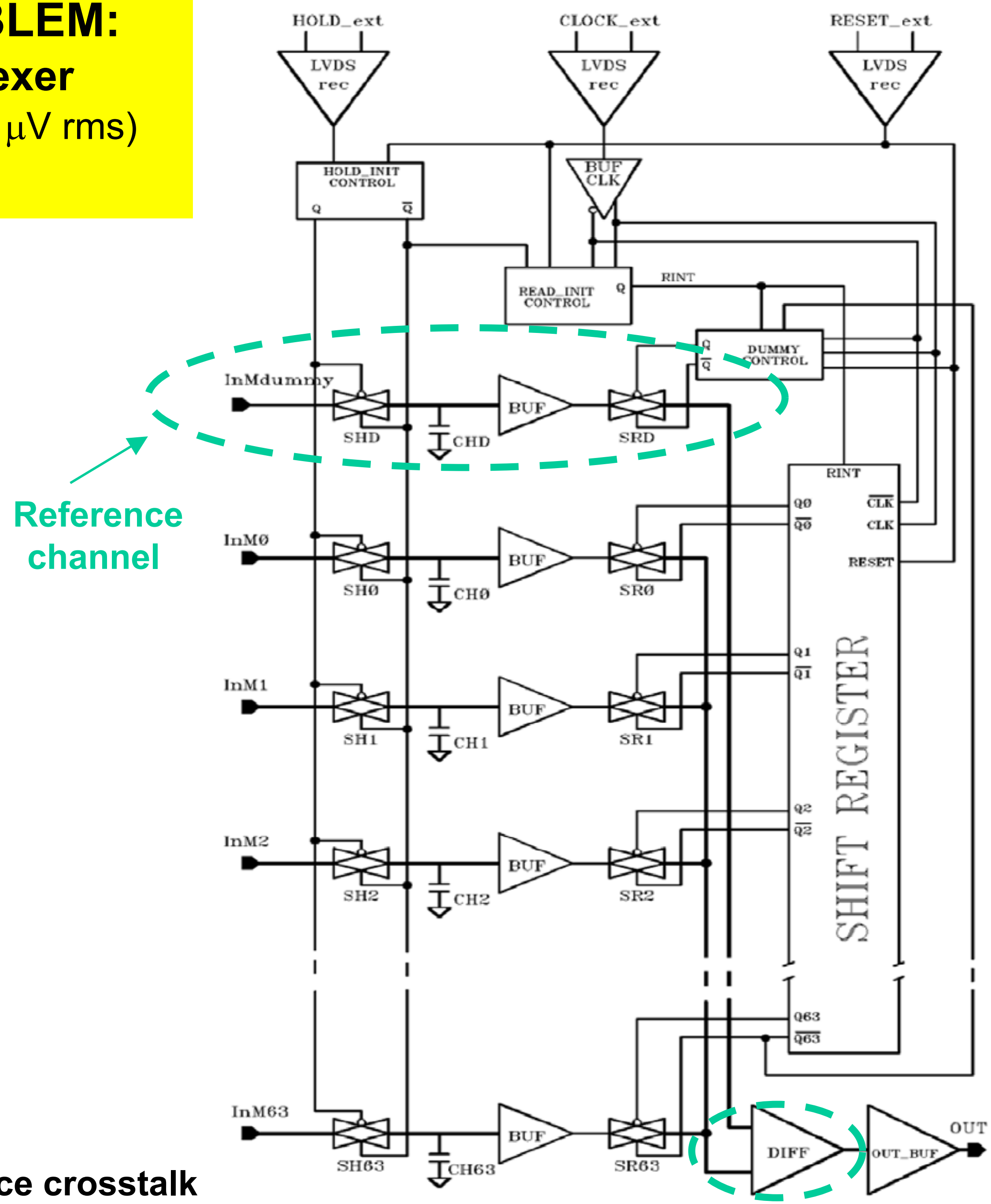
Measurements f=10 mHz





CROSSTALK PROBLEM:
analogue multiplexer
(input noise VIN-rms < 5 µV rms)



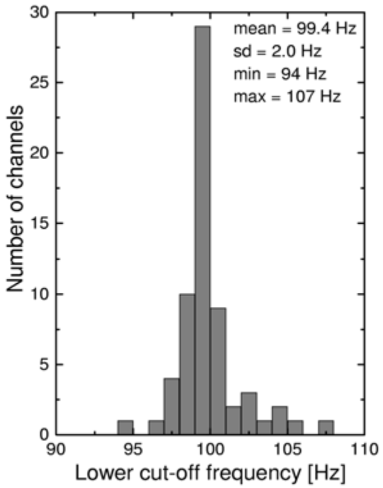


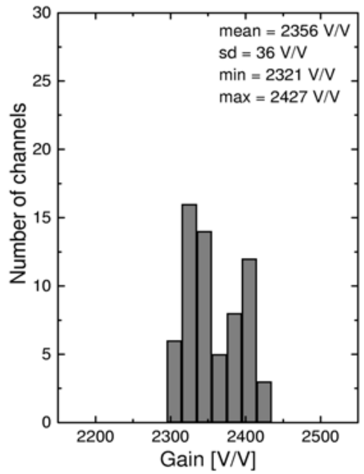
Multiplexer in NEURO64 ⇒ to reduce crosstalk

Measure parameters

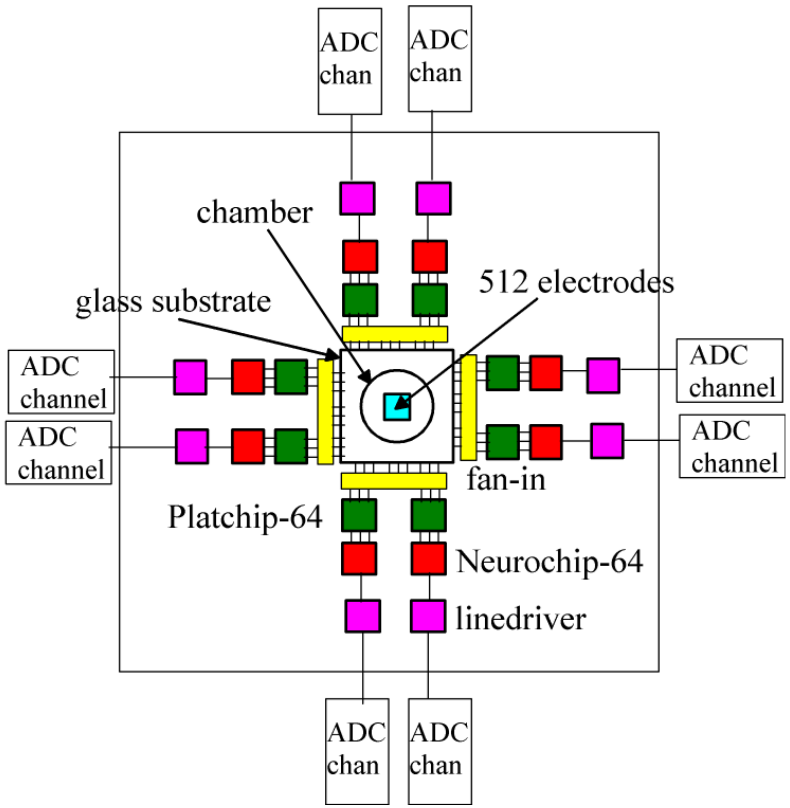
Parameter	Measured value
Bandwidth	30 to 1400 Hz
Total equivalent input noise	3 µV rms
Input signal linear range	960 μV_{pp}
Tolerance to the input offset	−8 mV, +11 mV
Gain	1000 V/V
Spread of the gain channel to channel (std)	< 1.3%
Input signal common mode range	+/−300 mV
Power dissipation per channel	1.7 mW
Power supplies	−2.5 V, +2.5 V
Single channel area	100 µm × 3500 µm

Matching

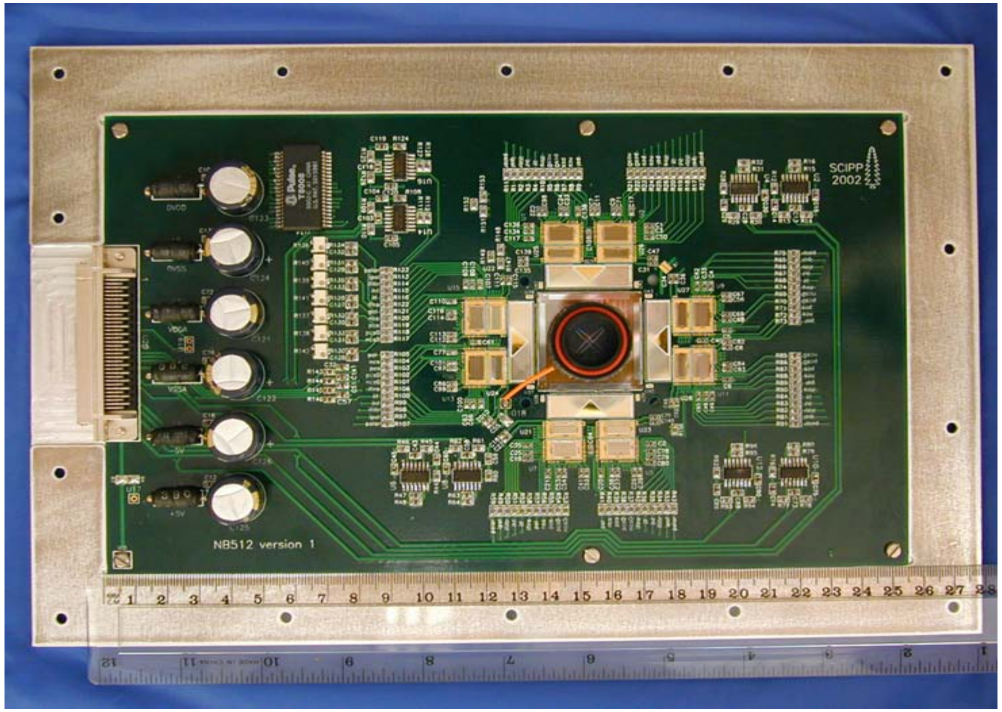




Example of practical application:
RETINAL READOUT SYSTEM

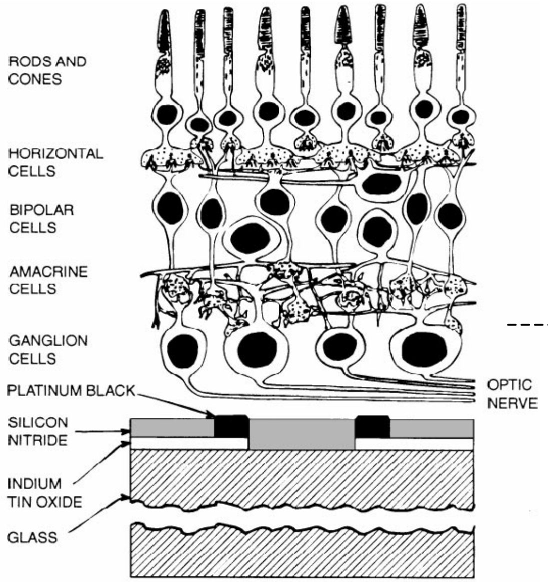


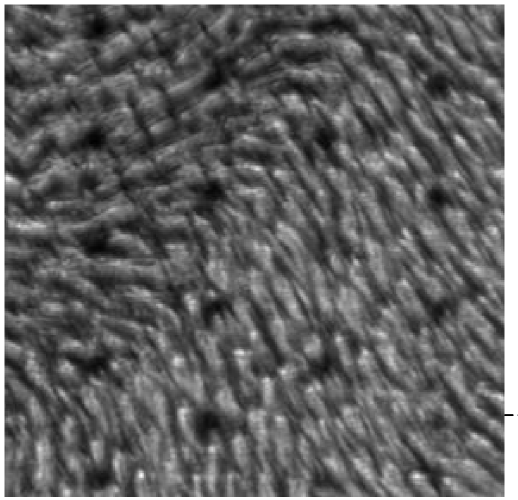
Four group of people from:
UC - Santa Cruz: data acquisition system & analysis
AGH UST - Krakow: IC design and testing
Univ. Glasgow – UK: microelectrode fabrication
Salk Institute - San Diego: neurobiology

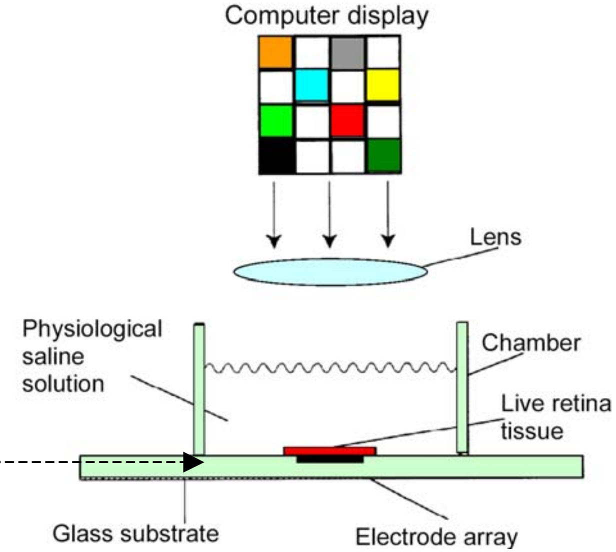


Experimental set-up
RETINAL READOUT SYSTEM

Experiments have been done in:
Salk Institute, San Diego
http://www.snl-e.salk.edu





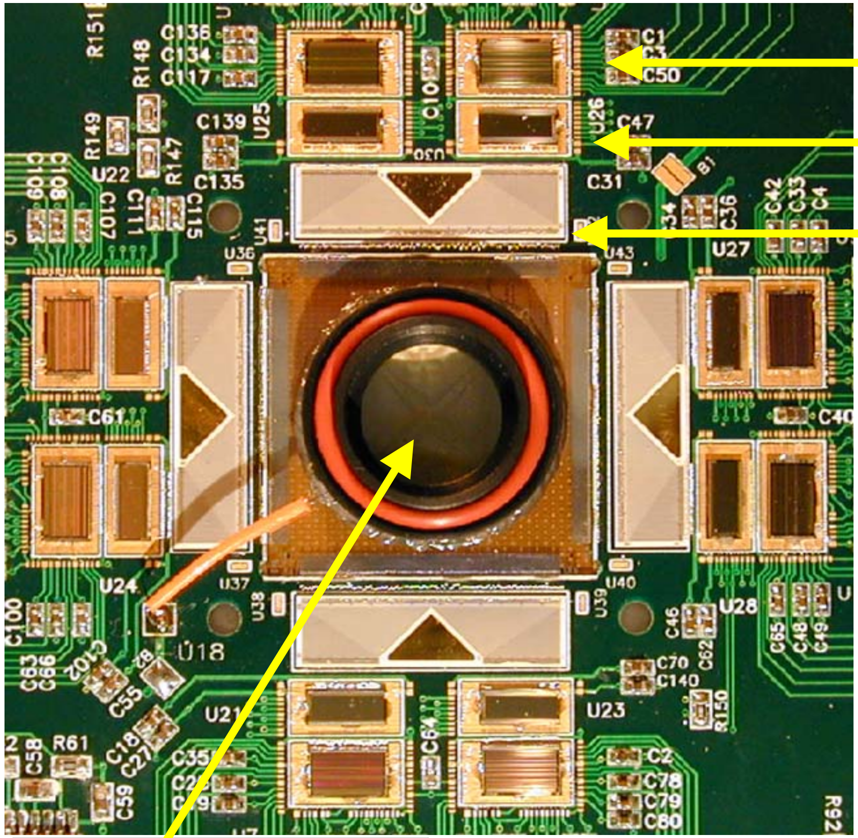


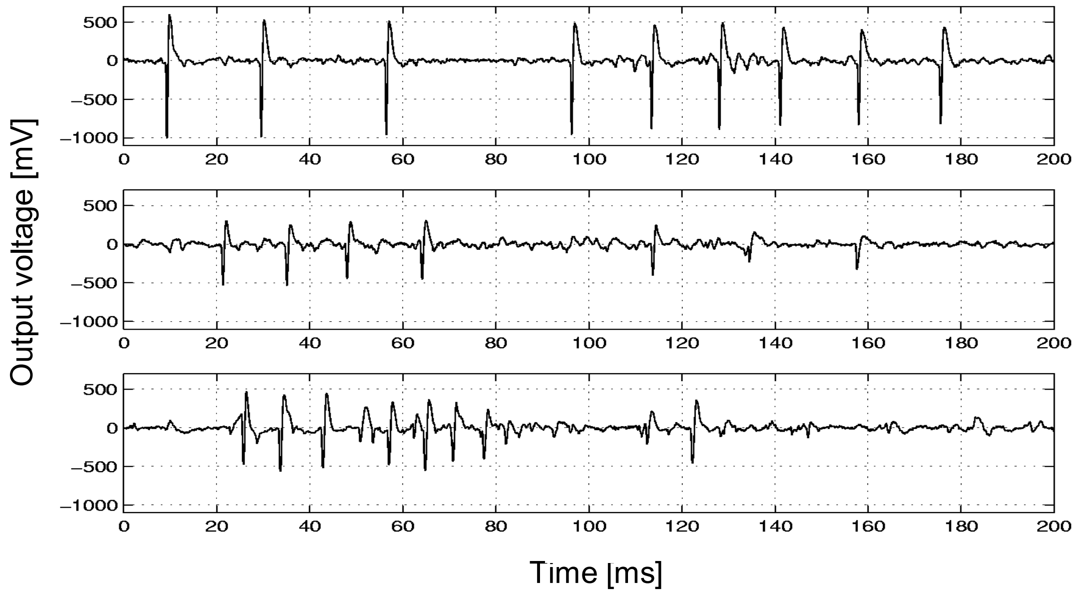
Retinal tissue placed on top of mulielectrode array

A movie is focused on the retina tissue
⇓
The patterns of electrical activity generated by hundreds of retinal output neurons are recorded

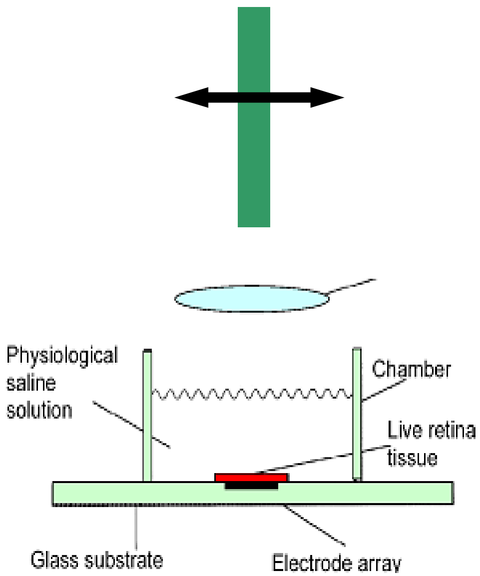
Working system with 512 readout channels

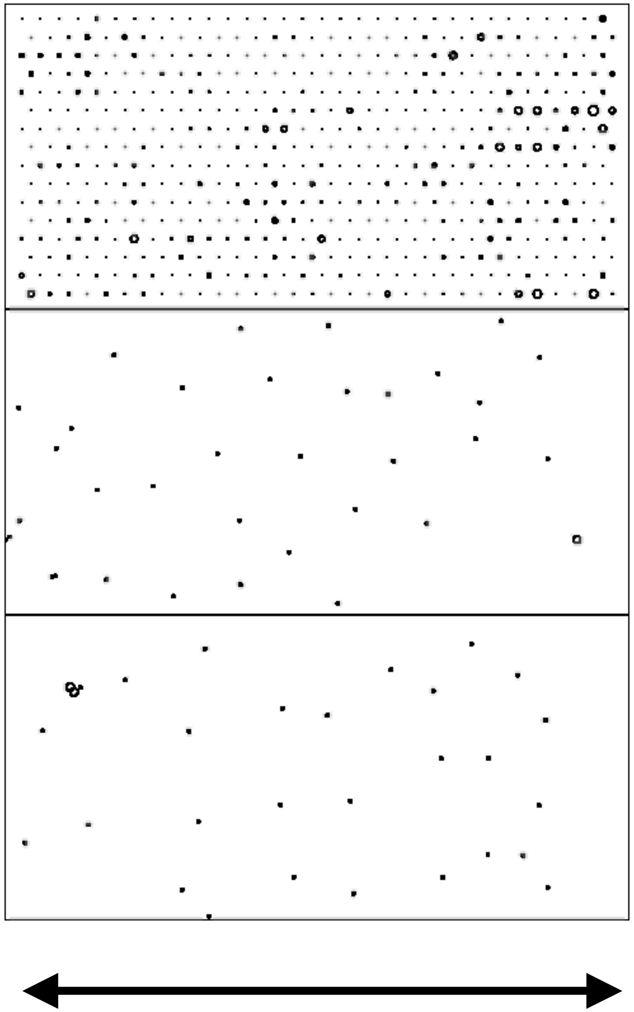
To understand how the retina processes and encodes dynamic visual image





Tests with the monkey retina – moving bar
(Litke, et. al.)





Electrode spike-rate

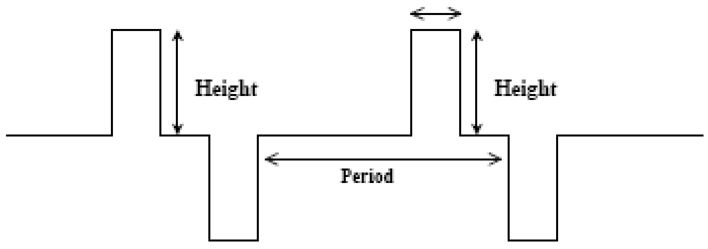
Spike-rate for On-off DS neurons →

Spike-rate for On-off DS neurons ←

2 mm

Additional functionally required:

RECORDING + STIMULATION+TELEMETRY

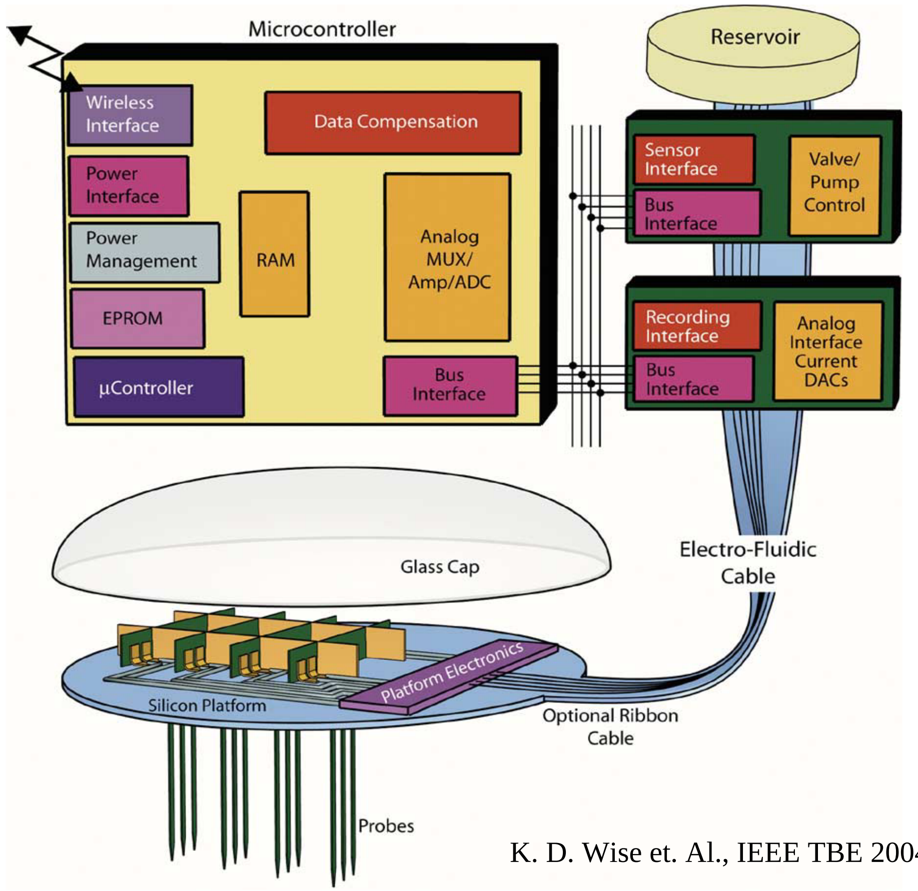


Width - [0.1ms-2ms]

Period - [10Hz-125Hz]

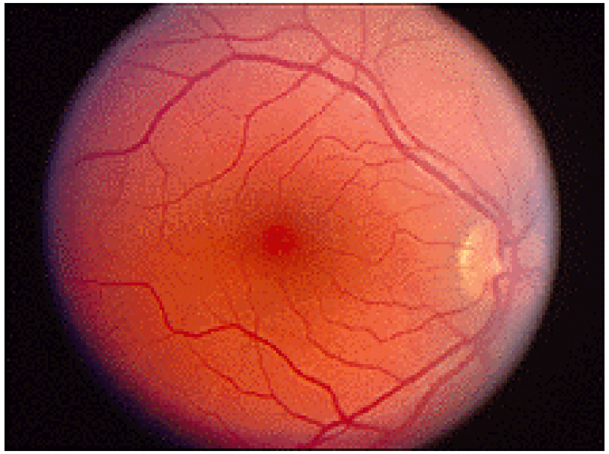
Height - [100µA-600µA]

IDEAL SYSTEM

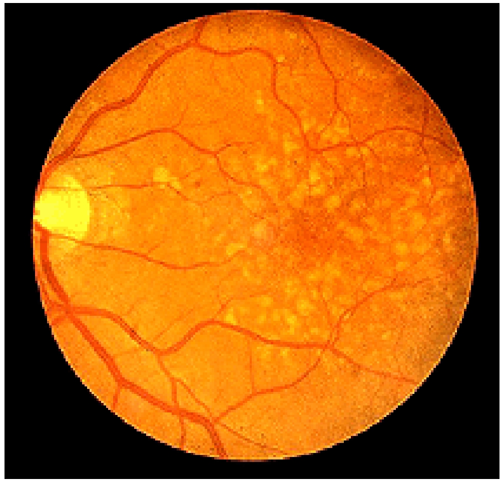


K. D. Wise et. Al., IEEE TBE 2004

Effect of Retina Diseases.

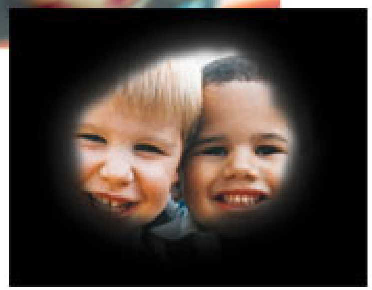


Normal

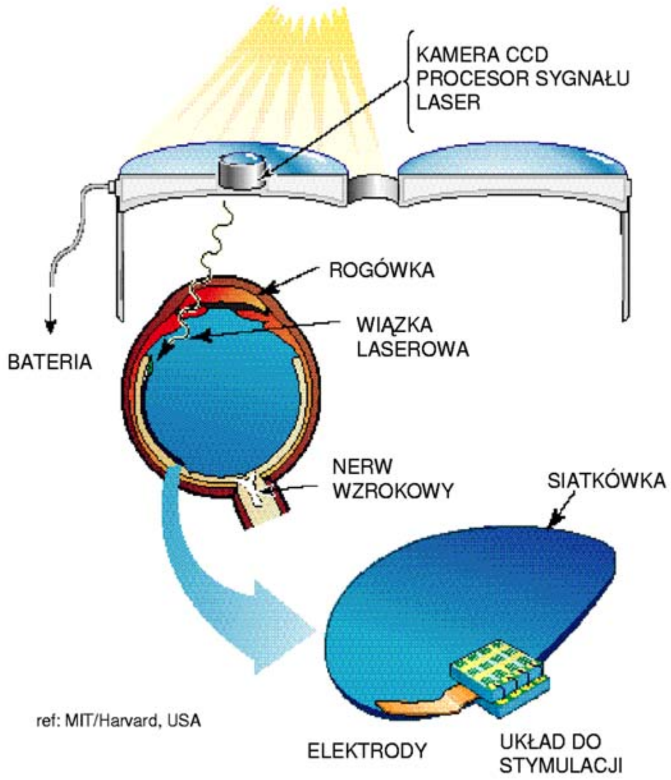


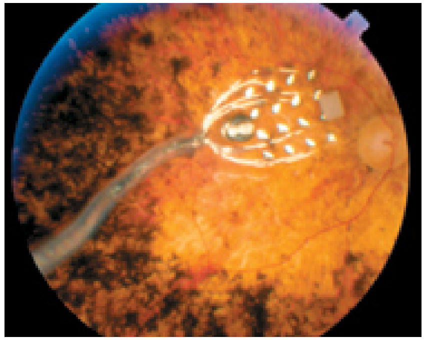
Macular Degeneration (AMD)

RP - Retinis Pigmentosa
(12 mln people)

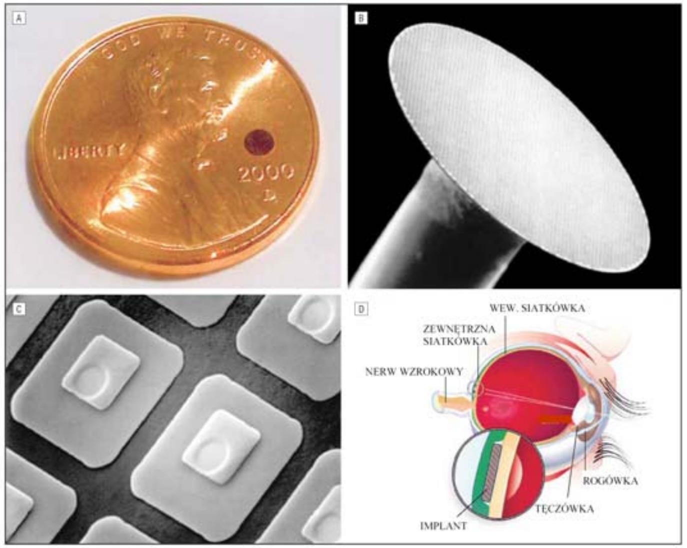


System MIT/Harvard (epiretinal implant)

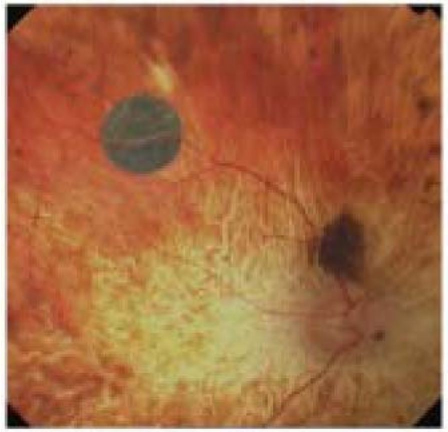


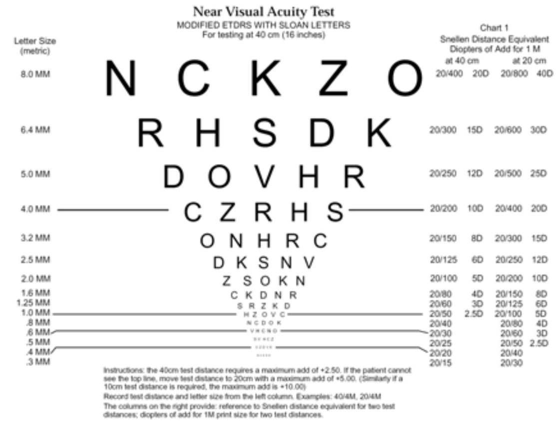


Optiobionics Corporation (subretinal implant)

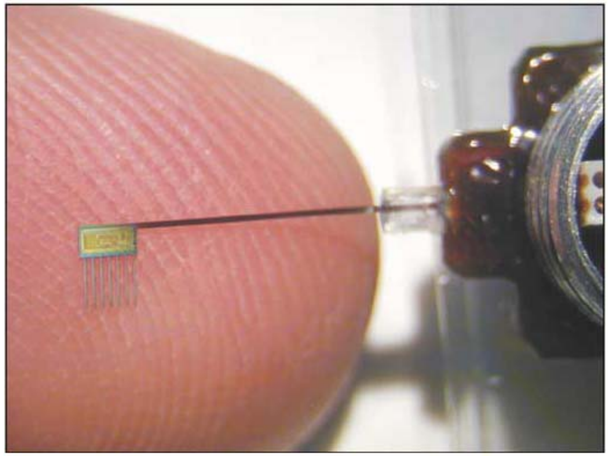


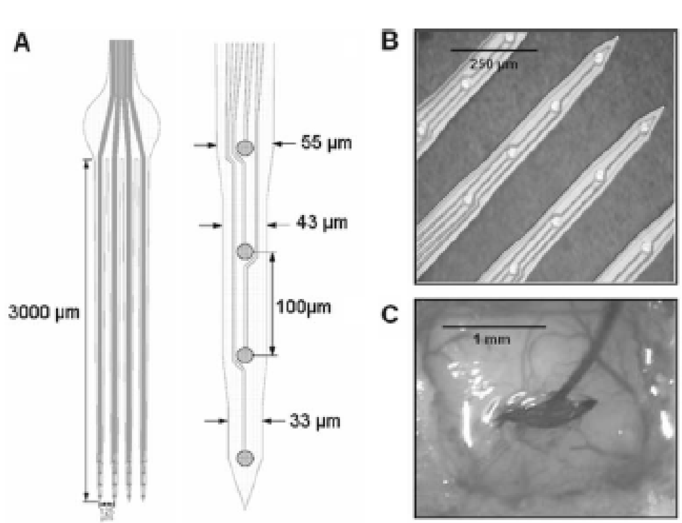
ASR: 2 mm x 25 um
5000 pixels,: 20 um x 20 um

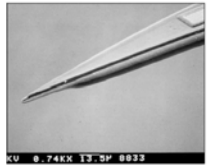


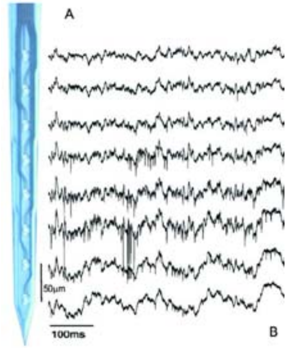


Deep brain stimulation – microprobes









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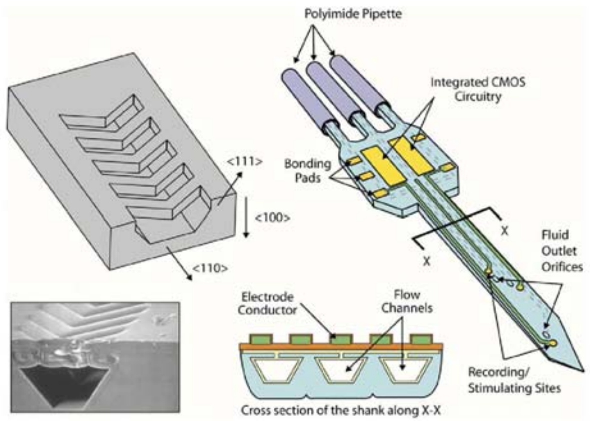
Next step - MEMS



J Neurophysiol 90: 1314–1323, 2003; 10.1152/jn.00116.2003.

Summary