(Semiconductor)
Pixel Detectors for charged particles
(and other applications)

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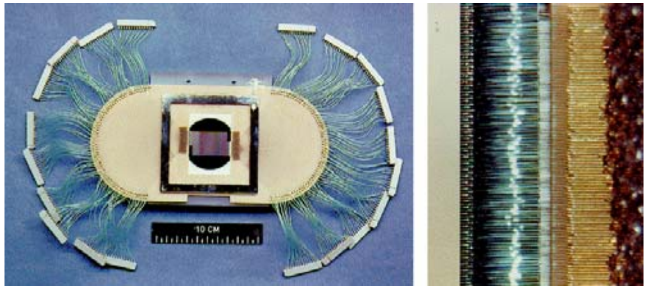
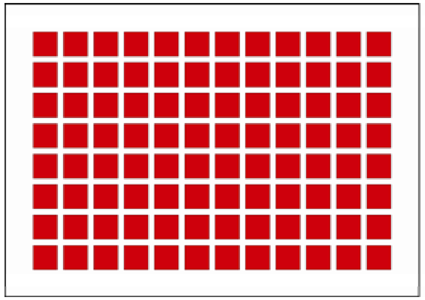
Introduction

First strip detector 1980



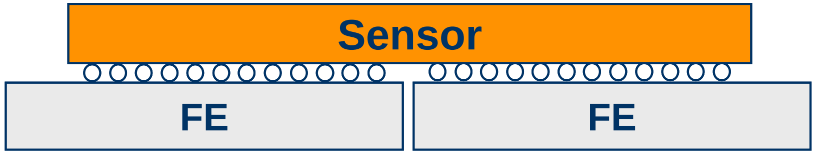
- Semiconductor detectors sensitive to ionizing radiation: charged particles and photons of a broad energy range
- Position sensitive Semiconductor detectors introduced ~1980 (strip detectors): one dimensional position measurement used for
- **charged particle tracking**
  Requirements: **position measurement** precision, **thin material** for low multiple scattering of traversing particles
  in contrast to eg. ***X-ray spectroscopic imaging***: ***energy measurement*** precision and ***large sensitive thickness*** for quantum efficiency at high energy
- Two dimensional position resolution from double sided strip detectors works for low track densities only
- True **pixel detectors** solve ambiguity problem

Semiconductor pixel detector principles

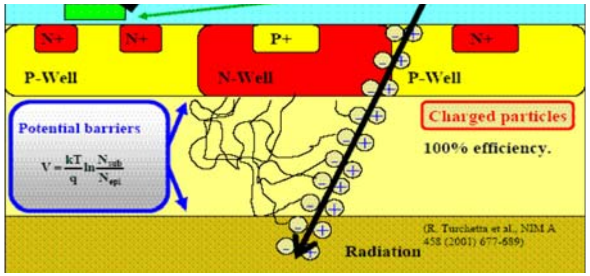


Pixel detector: Two dimensional array of sensors
monolithically itegrated on single silicon wafer
needs

- Storage capability for delayed serial readout
  can be provided by electronics attached to each pixel either by
  - Bump bonding to a separate wafer:
    Hybrid pixel detector



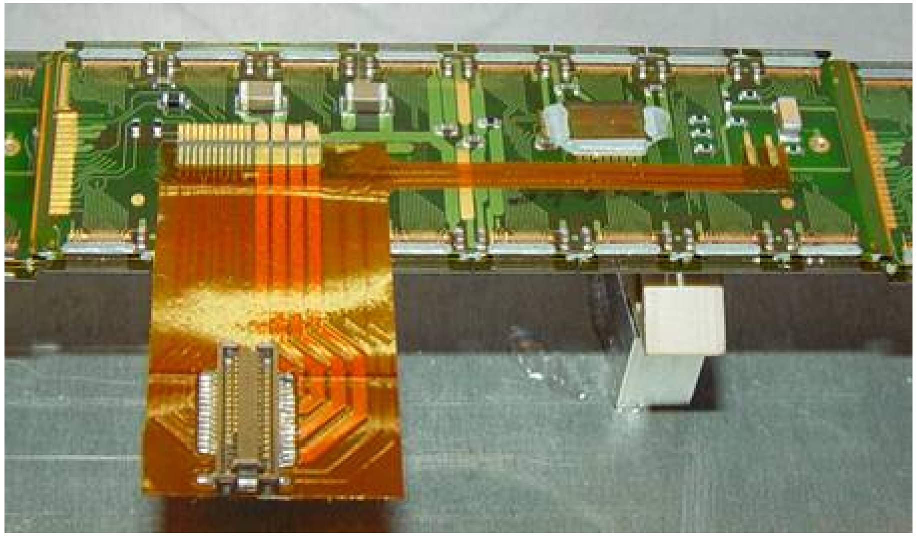
  - Integrating electronics into sensor wafer:
    „**M**onolithic **A**ctive **P**ixel **S**ensors“ (MAPS)
    „CMOS Sensors“, SOI sensors



  - Using a structure that combines sensor and electronics properties (**DEPFET**)
  - **CCD**s are also pixel detectors but use a different operation principle:
    - Transport of signal charge towards readout node

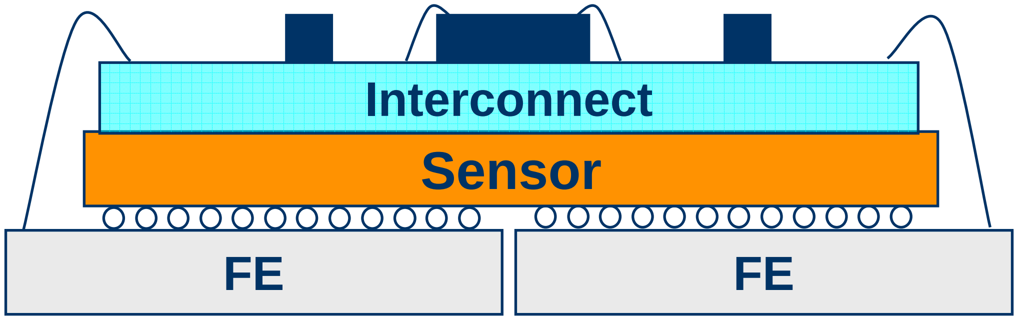
Hybrid pixel detector

Example: ATLAS pixel detector



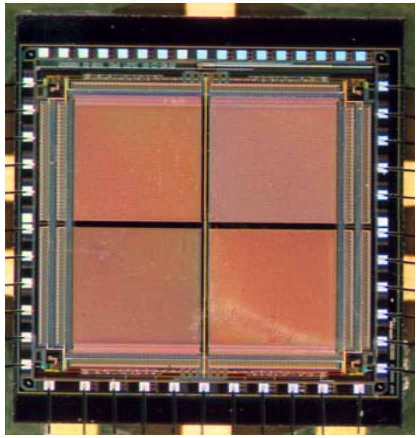
- Sensor and electronics can be optimized separately
- Pixel electronics may contain additional functions as:
  - Zero surpression
  - Time stamping

  These functions may require significant power, cooling if pixel electronics has to be permanently turned on

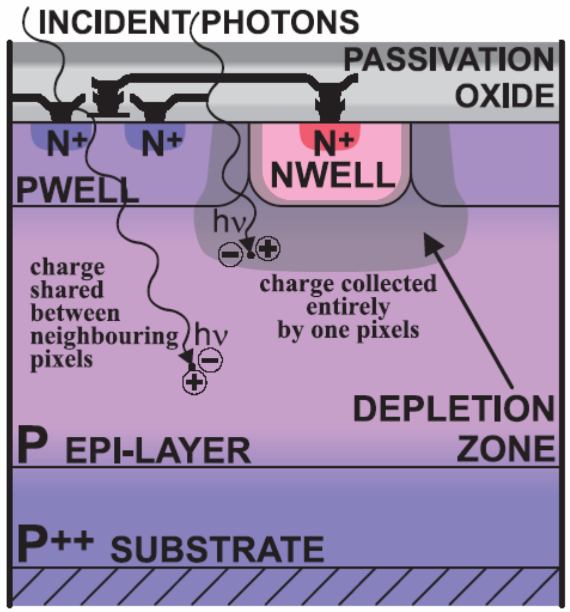


CMOS Sensors (MAPS)

Example: MIMOSA4



- Many groups working on CMOS sensors
  - Relying on **industrial available process technology**
    Requires compromises in design and performance
- Small feature size allows in **pixel integration of functions** as
  - data storage and reduction if power consumption allows
  - Full functional possibility of technology can not always be exployted due to influence of sensor function
- Charge collection by **diffusion** from undepleted bulk
  - Thin sensitive volume
  - Charge loss due to **recombination**
    - Sensitivity to **radiation bulk damage**
  - Signal spreads over several pixels
  - Uniformity of response over pixel area not insured



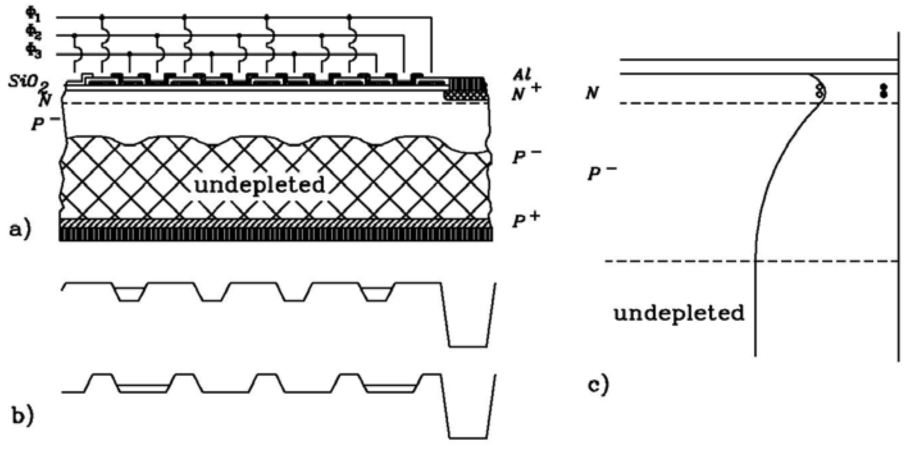
Charge coupled devices (CCDs)

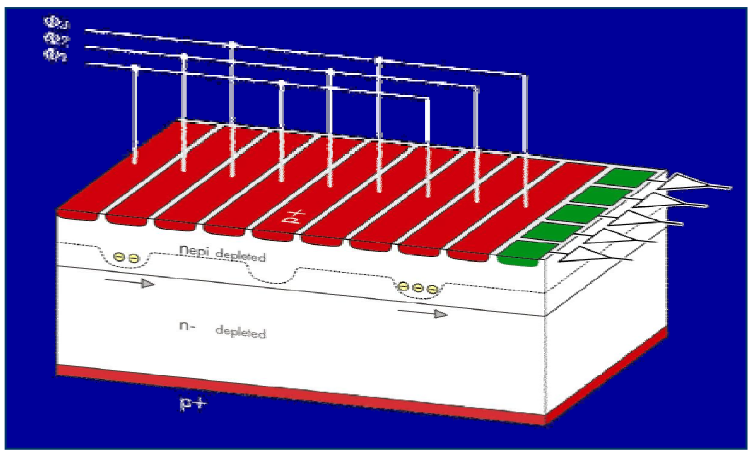
- Collect charge in potential wells near surface transfer pixel charge towards readout node

- **MOS-CCD**s:
  - MOS transfer gates
  - Partially depleted
  - Charge collection partially by diffusion from undepleted bulk region
  - Driving of large (overlapping) transfer gate capacitance requires power, limits transfer speed

- **PN-CCD**s
  - Pn-diode gates
  - Fully depleted – fully sensitive bulk
  - Charge transfer in depth of ~10µm
  - Fast column parallel readout
  - Radiation hard (compared to MOS CCDs)
    - Insensitive to Oxide charge
    - Transfer efficiency deteriorates little

Buried channel CCD

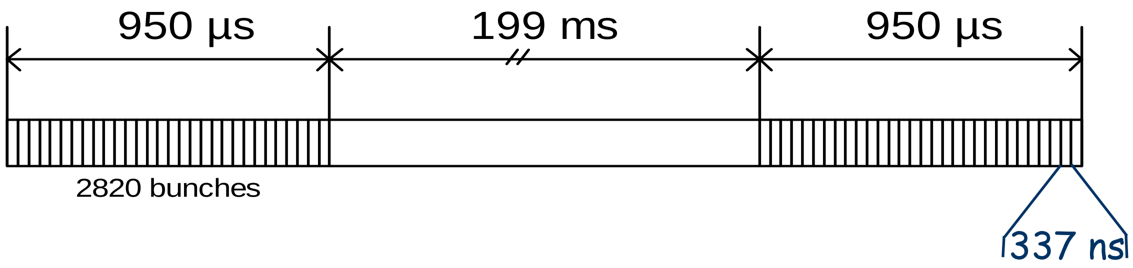




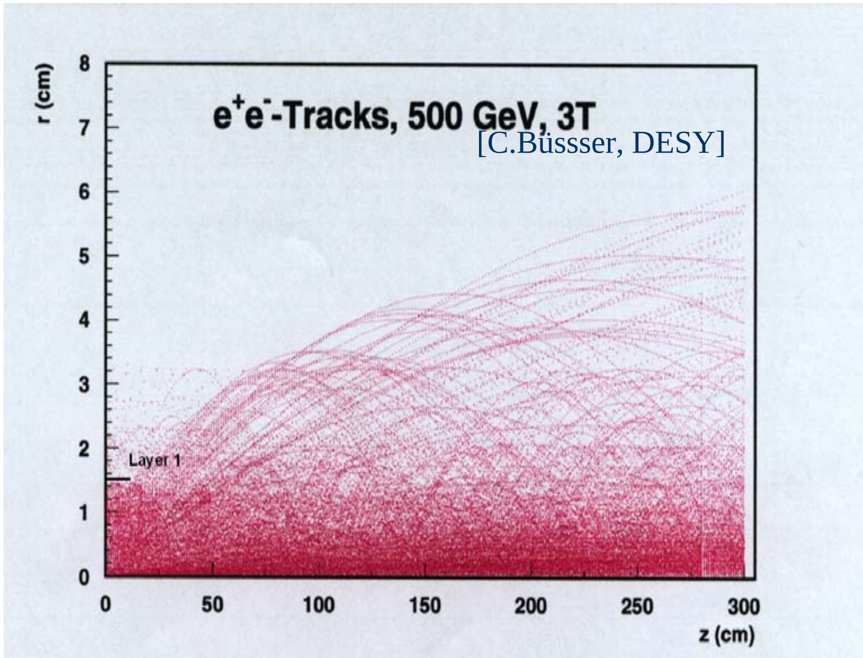
Requirements for tracking

- Requirements on detector properties vary wildly with intended appplication
- Take an actual example from particle physics: The proposed
- **International Linear Collider (ILC)**

Beam structure:
1ms bunch train
spaced by 200ms gap



Large e+/e- pair background
Leading to high occupancy
Requiring repeated readout during puse train
or in pixel storage for readout during gap



[C.Büssser, DESY]

Development of DEPFET pixel detectors

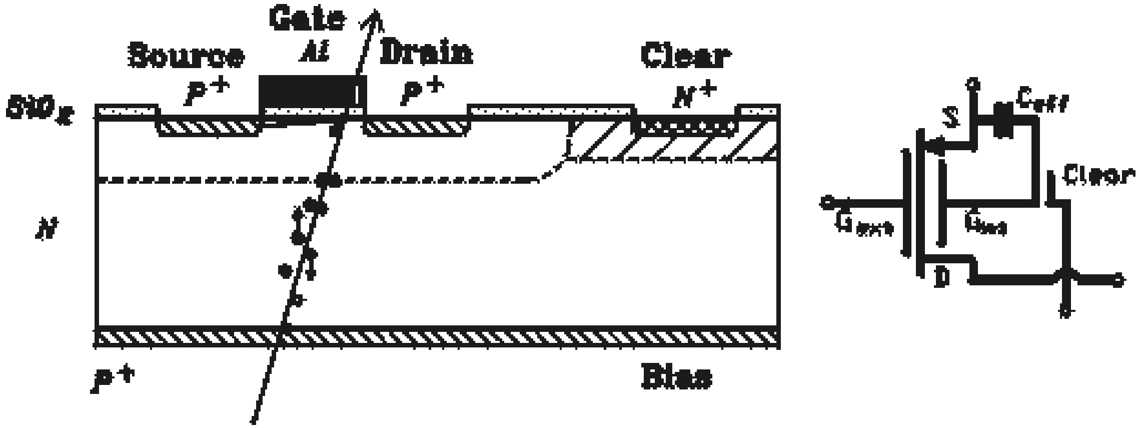
- At the MPI semiconductor laboratory (only place for DEPFET sensors)
- In collaboration with
  - Universities Bonn and Mannheim
- For particle tracking (at the ILC)
- For X-ray Astronomy (XEUS X-ray observatory) [Treis, session S5, Tuesday]

- Sensors are designed fabricated and tested in own laboratory posessing
  - Complete silicon technology including
  - technology and device simulation tools as well as
  - extensive testing facilities

- Most devices are based on own new concepts

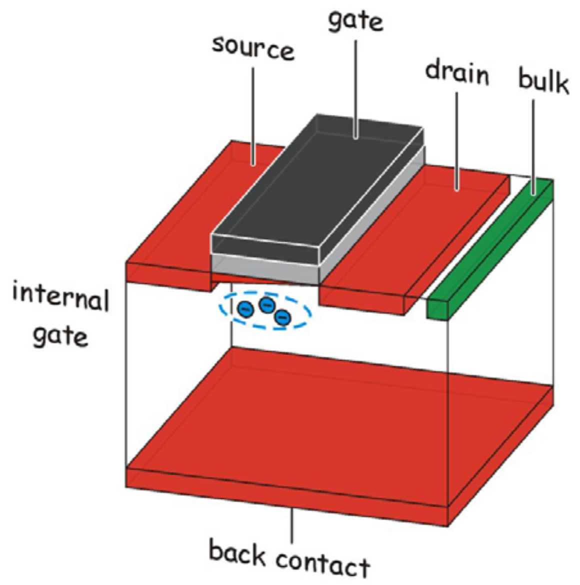
- DEPFET concept dates back to 1985, verified soon afterwards but devices for specific applications exist only now

DEPFET structure and device symbol



- **Function principle**
- Field effect transistor on top of fully depleted bulk
- All charge generated in fully depleted bulk
  drifts into potential minimum underneath the transistor channel
  steers the transistor current
- Clearing by positive pulse on clear electrode
- Combined function of sensor and amplifier

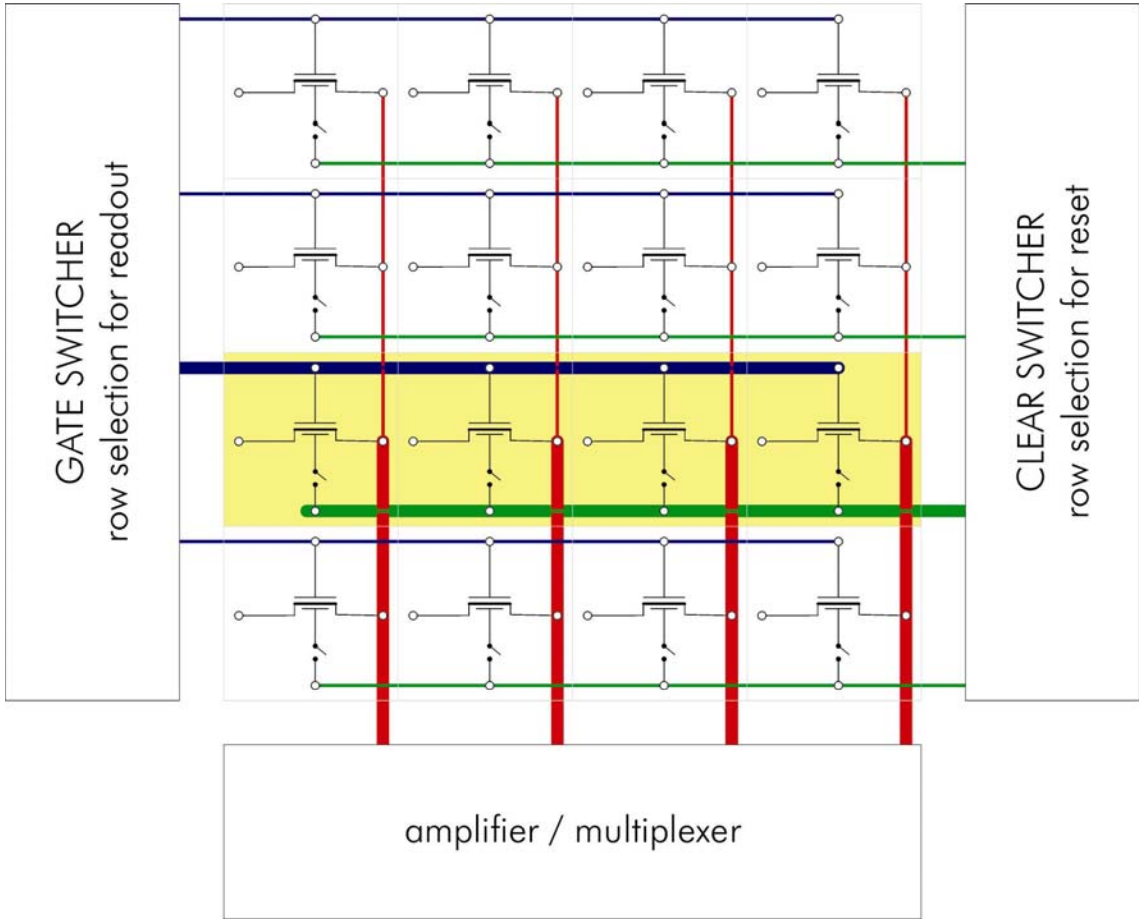
DEPFET concept



Properties

- Charge collection by drift mechanism over full wafer thickness
- low capacitance ▸ low noise
- Signal charge remains undisturbed by readout ▸ repeated readout
- Complete clearing of signal charge ▸ no reset noise
- Full sensitivity over whole bulk ▸ large signal for m.i.p.; X-ray sensitivity at large energies
- Thin radiation entrance window on backside ▸ X-ray sensitivity at low energy
- Charge collection also in turned off mode ▸ low power consumption
- Measurement at place of generation ▸ no charge transfer (loss) ▸ Operation over very large temperature range ▸ no cooling needed

DEPFET Pixel Detector Operation Mode

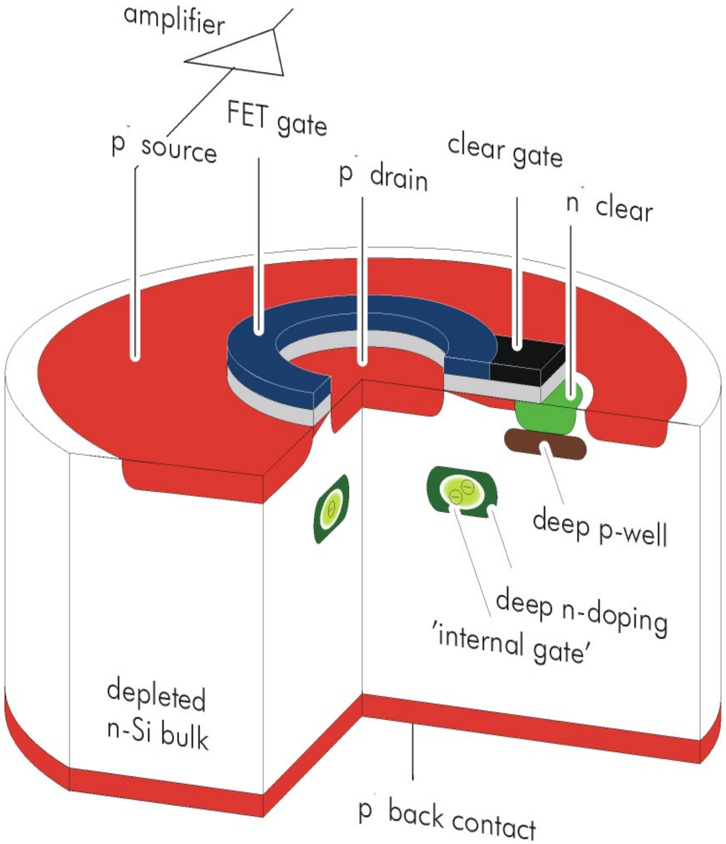


Large area covered with DEPFETS
Individual transistors or rows of transistors
Can be selected for readout
All other transistors are turned off
Those are still able to collect signal charge
Very low power consumption

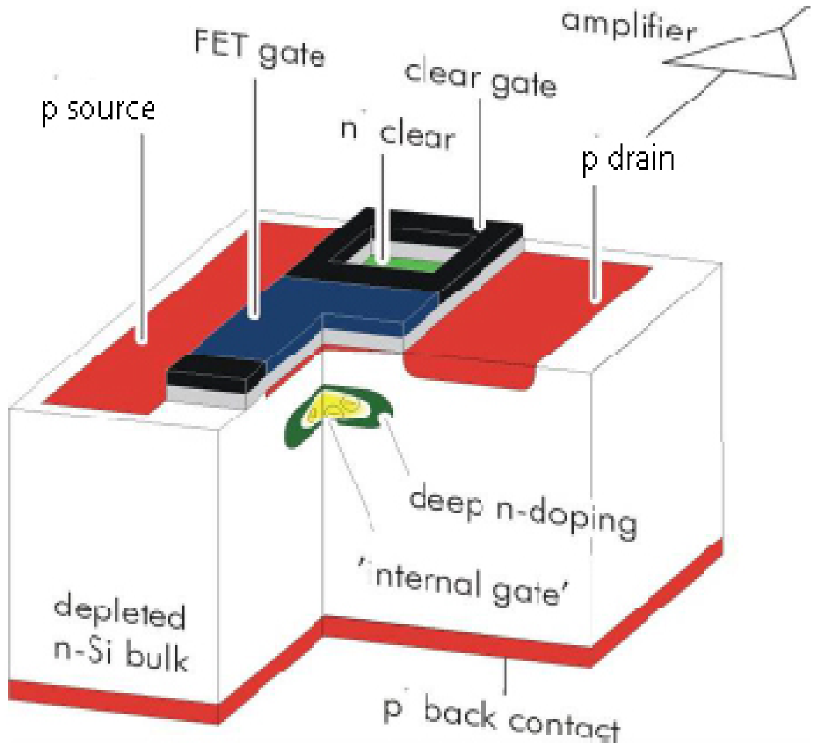
DEPFET pixel detector prototypes

Two projects on same wafer, two different geometries:

XEUS (future X-ray observatory):
Circular (enclosed) geometry
Source readout



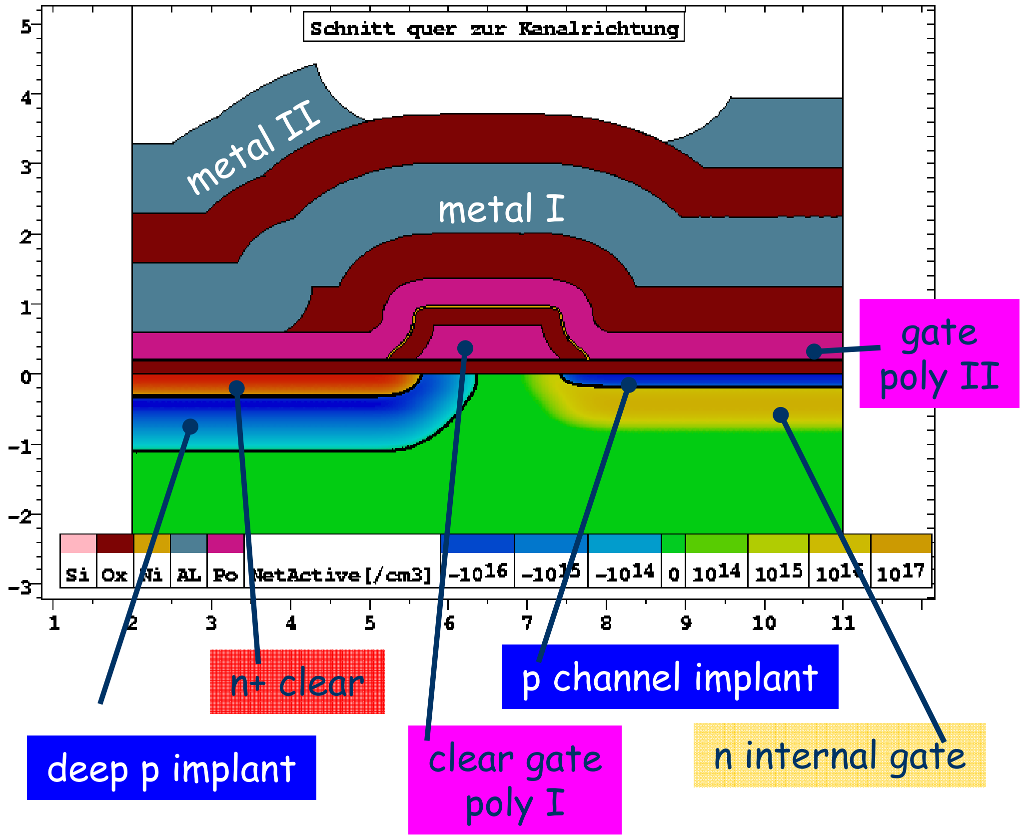
Linear collider:
Rectangular geometry
Drain readout



DEPFET Technology at MPI

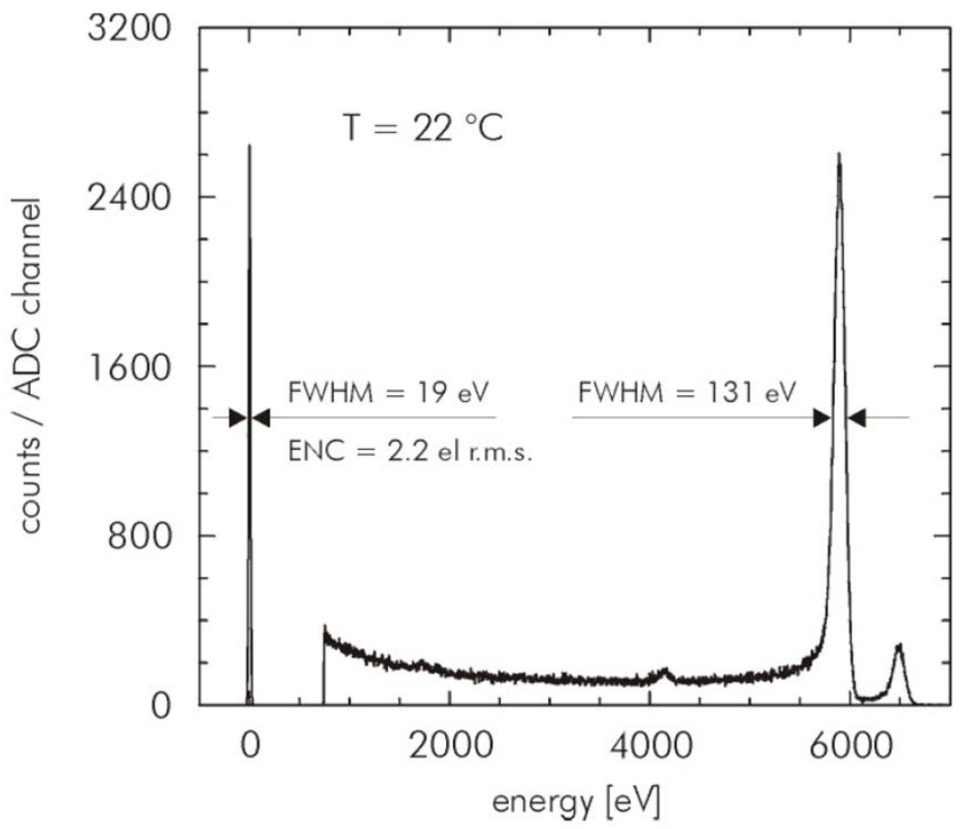
- Extendet technology:
  - Double metal
  - Double poly

cut perpendicular to channel (with clear)



DEPFET noise

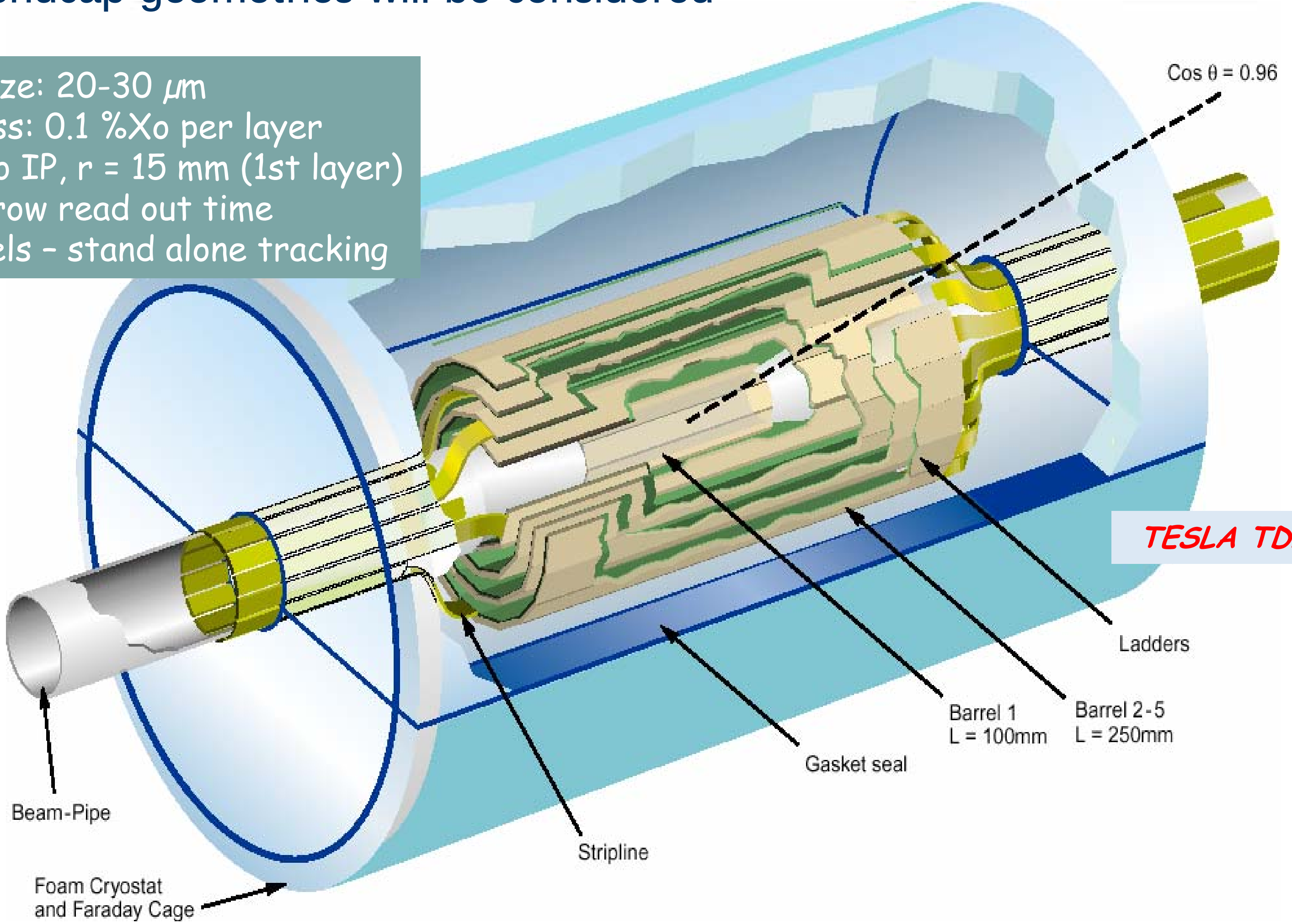
- Fe55 spectrum measured with single circular (XEUS-type) DEPFET:
- 2.2 electrons rms
  at room temperature
  with slow shaping



Vertex Detector

Layout so far follows the TESLA TDR concept
Barrel-endcap geometries will be considered

- pixel size: 20-30 μm
- low mass: 0.1 %Xo per layer
- close to IP, r = 15 mm (1st layer)
- 20 ns/row read out time
- 5 barrels – stand alone tracking

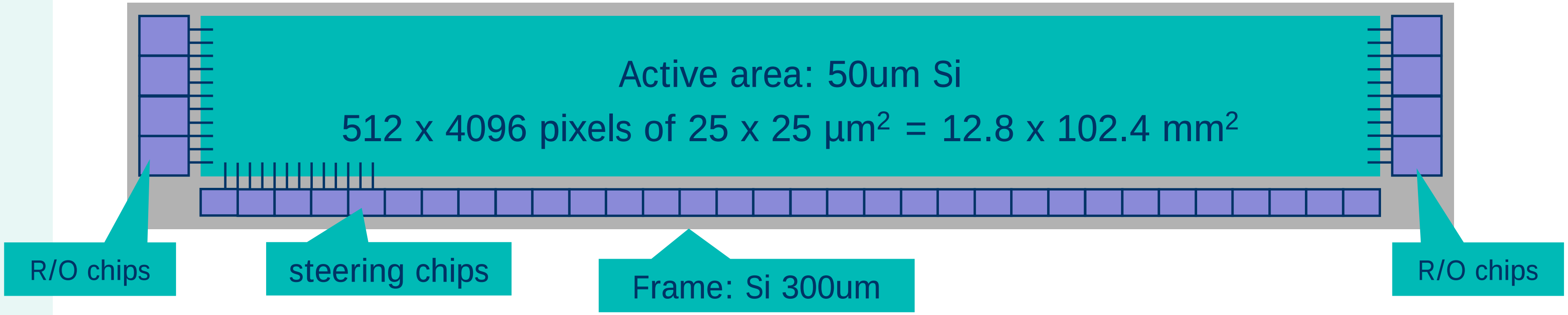


TESLA TDR Design

1st layer module: 100x13 mm², 2nd-5th layer : 125x22 mm² ➔ Σ120 modules

ILC DEPFET Module (Layer 1)

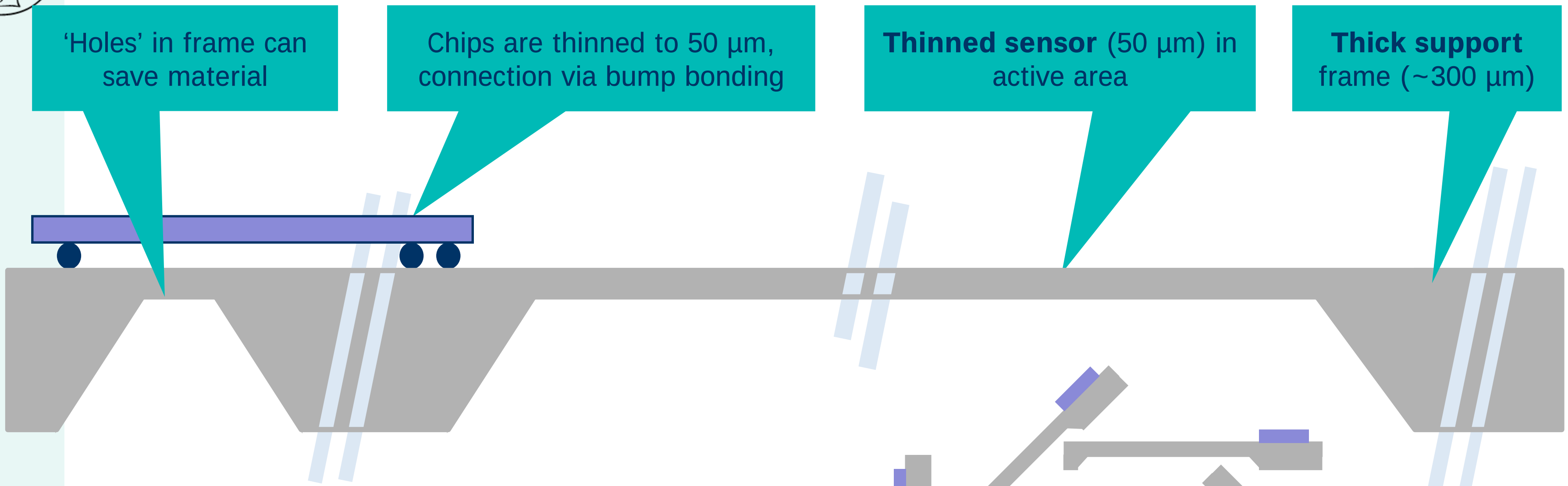
- Modules have active area ~**13 x 100 mm²**
- They are read out on **both sides**.



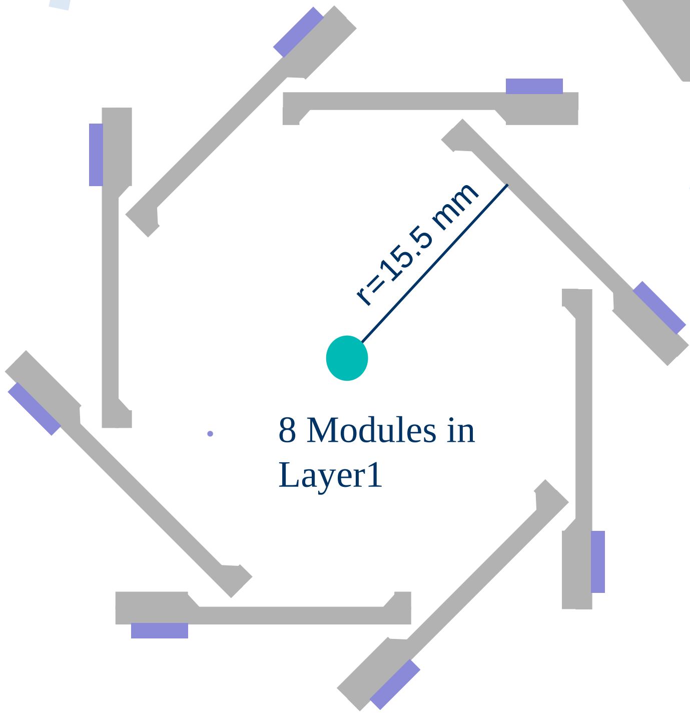
Rigid self supporting structure of single material (all silicon)
Avoids thermal stress and distortions

Electronic chips thinned and bump bonded to frame

Possible Geometry of Layer 1



- Cross section of a module



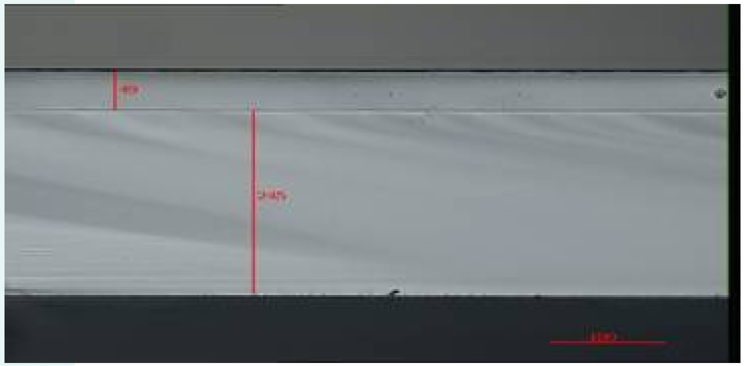
- 8 Modules in Layer1

- Estimation of material budget:
- pixel area: 13x100 mm^2, 50µm: 0.05% X_0
- steering chips: 2x100 mm^2, 50µm: 0.01% X_0
- frame w. holes: 4x100 mm^2, 50% of 300µm: 0.05% X_0
- total: **0.11% X_0**

Making thin Sensors

Technology developed in MPI Semiconductor Laboratory

1. implant backside on sensor wafer
2. bond wafers with SiO_2 in between
3. thin sensor side to desired thick.
4. process DEPFETs on top side
5. etch backside up to oxide/implant

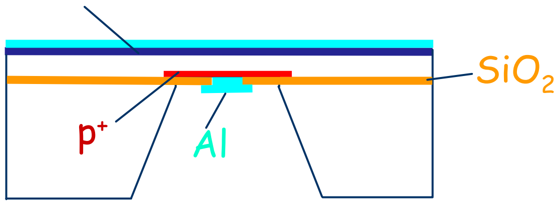


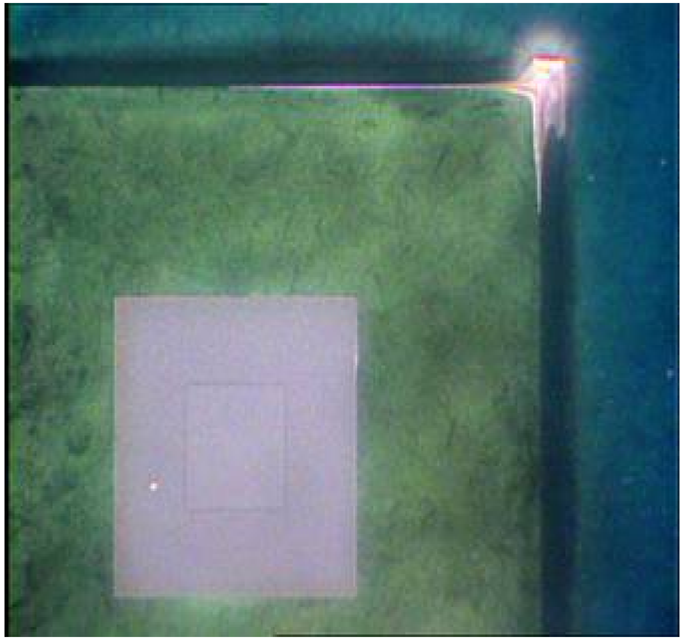
Electron micrograph of cut through bonded and thinned wafer

first ‘dummy’ samples:
50µm silicon with 350µm frame

PiN Diodes on thin Silicon

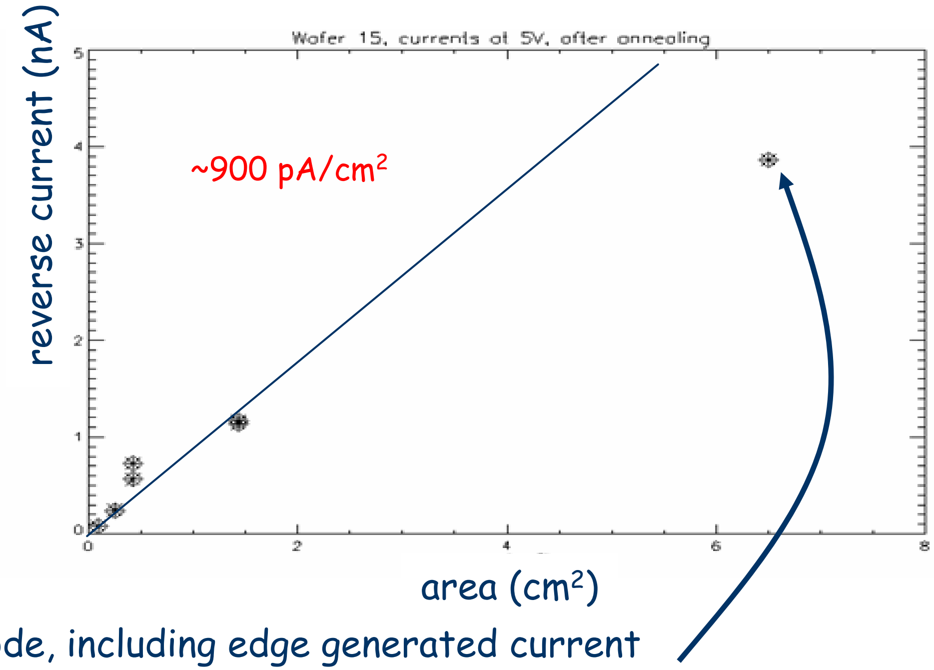
Implants like DEPFET config.





contact opening and metallization
after etching of the handle wafer

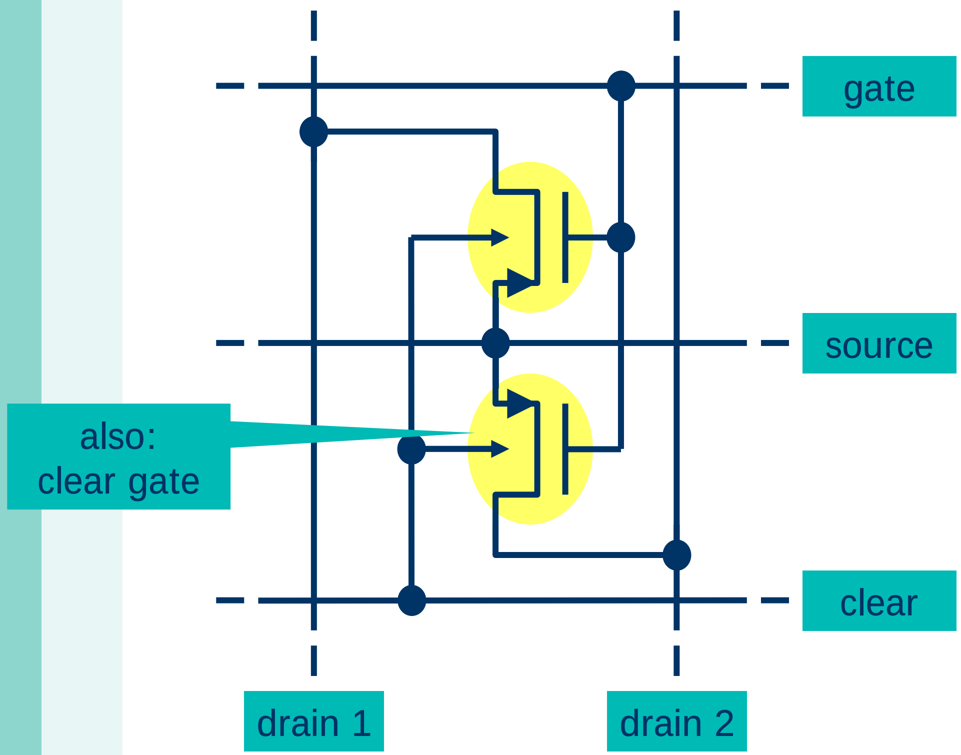
Diodes of various sizes: 0.09 cm² - 6.5 cm²
surface generated edge current included
reverse currents at 5 V bias

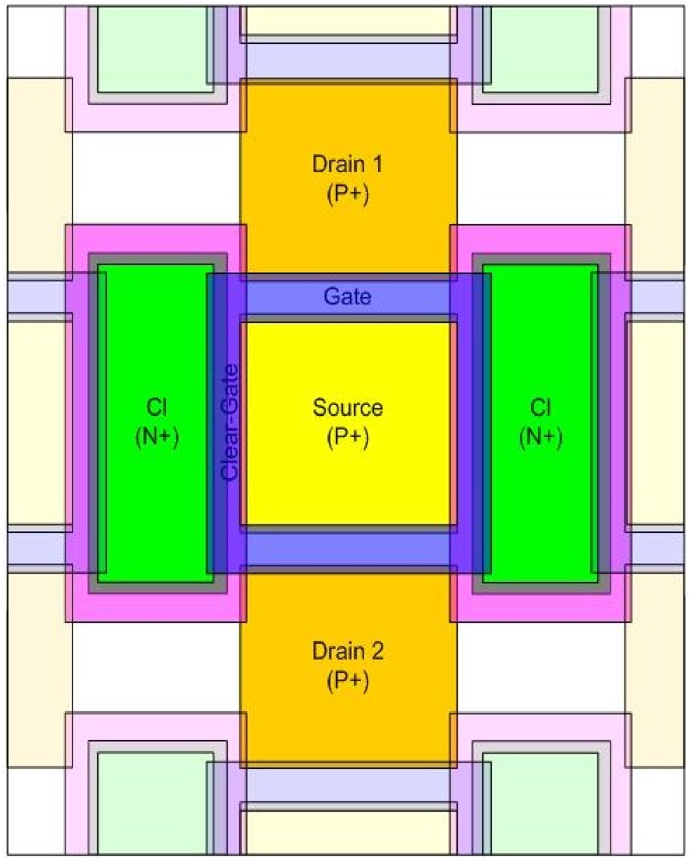


➔ about 4 nA @ 5V for the 6.5 cm² diode, including edge generated current

Sensor Design: MOS Devices

- PMOS type DEPFETs
- Double pixel cells
  with common source and clear
  for readout of two rows at a time



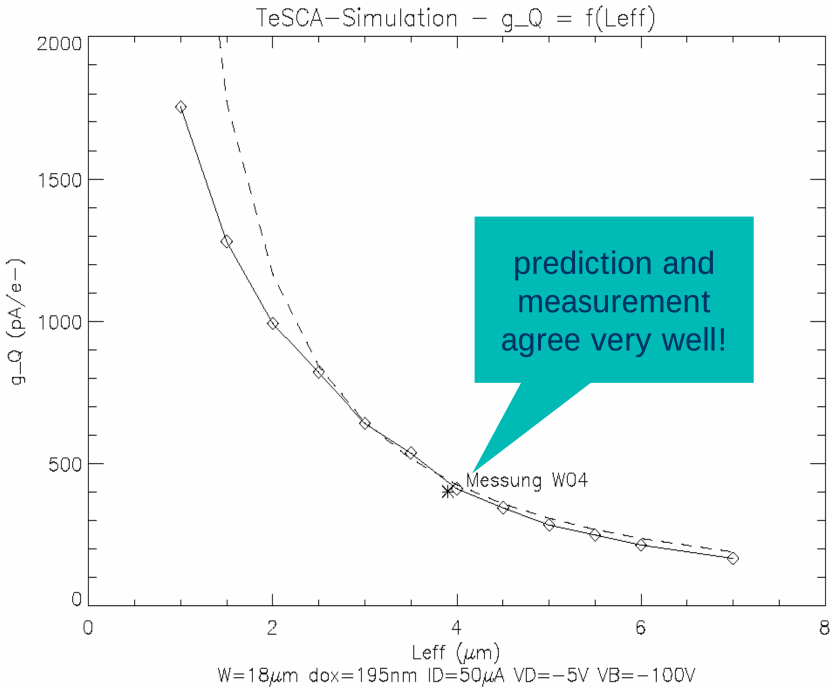


Sensor Simulations

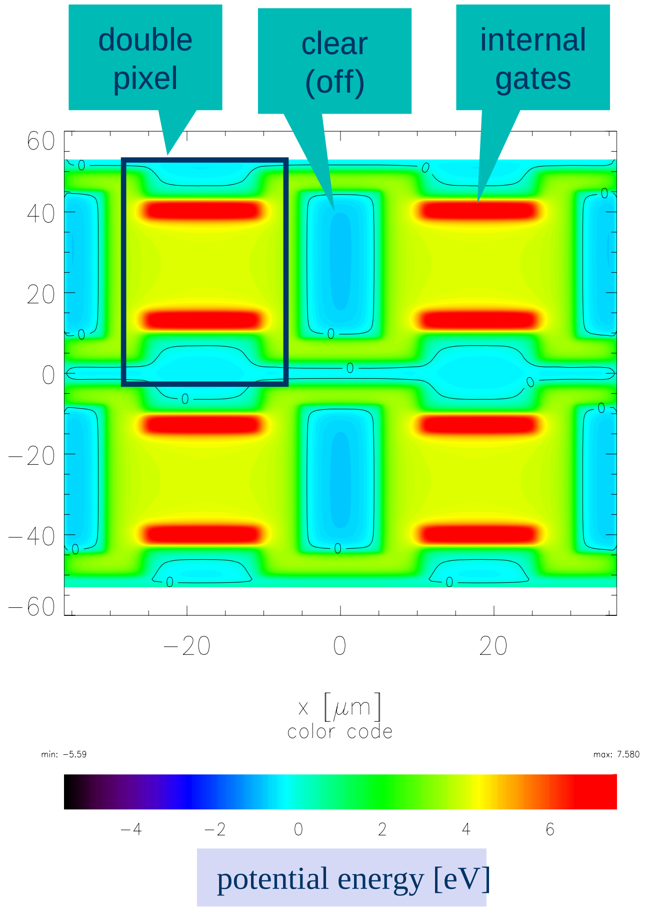
Design relies heavily on device simulations: 2D TeSCA and 3D Poseidon

- 2D simulation of current response to signal charge as function of channel length
- Device behavior can be predicted accurately.

Important for successful new designs!



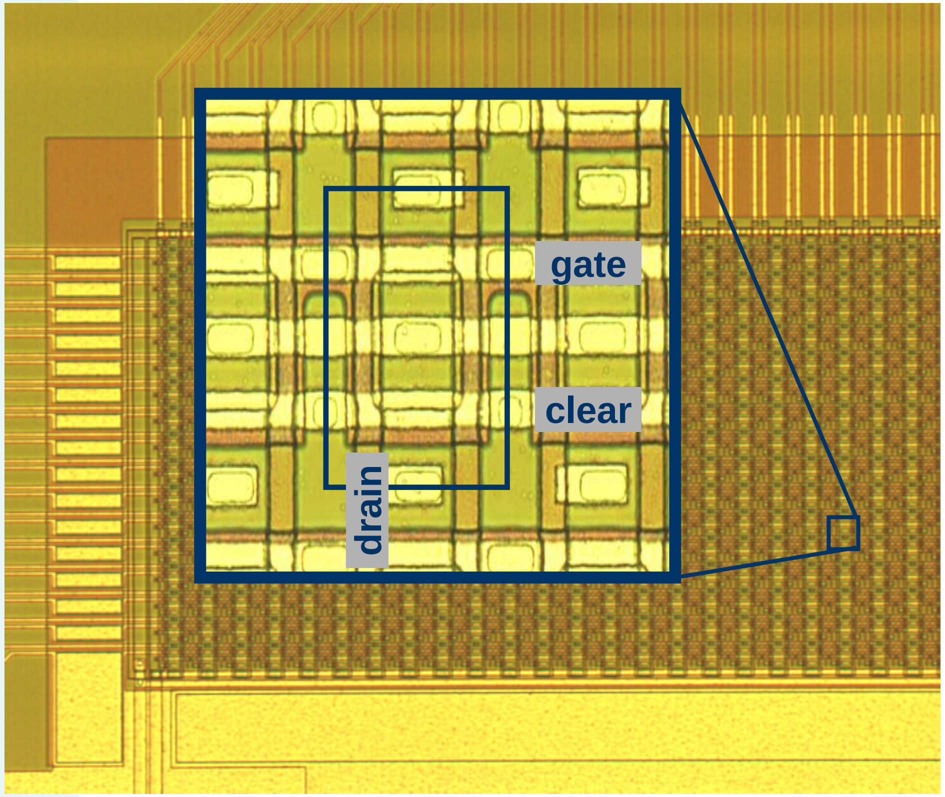
charge gain g_q for varying gate length



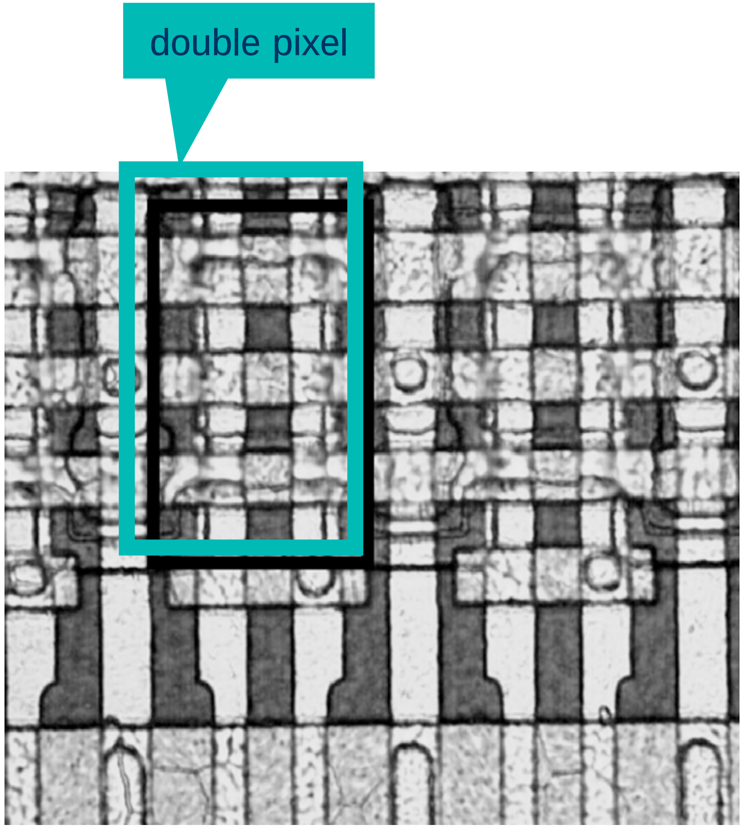
Potential distribution in 1μm depth in charge collection mode

Prototype matrix production

- A sensor-compatible technology with **2 poly and 2 metal layers** has been developed at the MPI Semiconductor Detector Laboratory
- These are required for large matrix designs



16x128 test matrix, double pixel cell 33 x 47 μm^2



double metal matrix

Radiation hardness

- Threshold shifts due to oxide damage could have been a serious problem
- Irradiation tests with Co60 up to 1 Mrad and with X-rays demonstated that this is not the case

  Poster presentation by Laci Andricek et al.

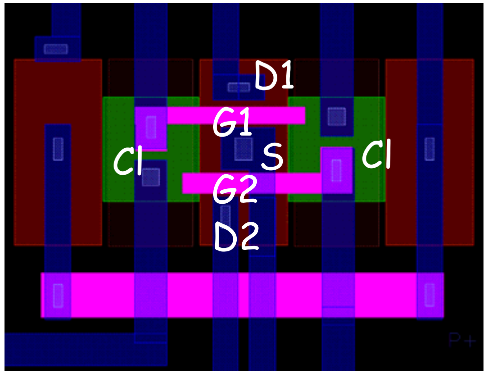
- The moderate threshold shift observed can be compensated by a change in external gate voltage
- Excellent spectroscopic properties after irradiation

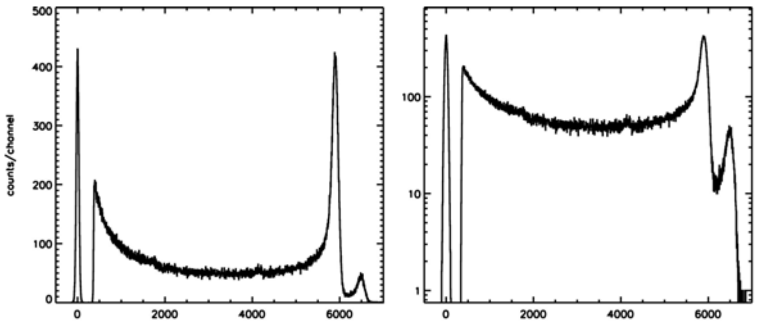
Noise after 1 Mrad Co60 irradiation

Single pixel test structure irradiated with 913krad ^{60}Co

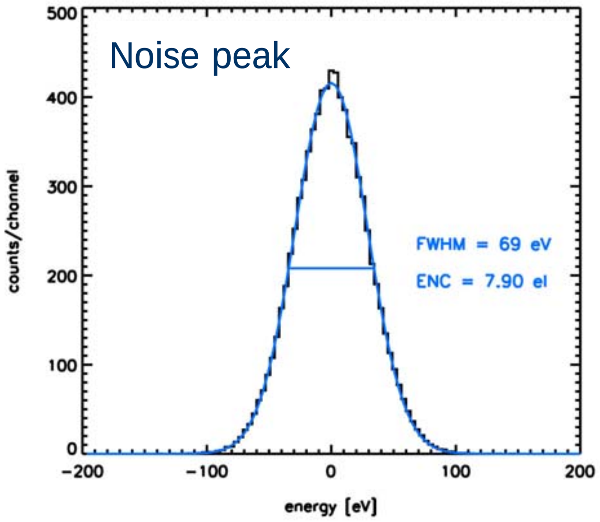
30 uA drain current
-5 V drain voltage
-5 V gate voltage
6 µs Gaussian shaping

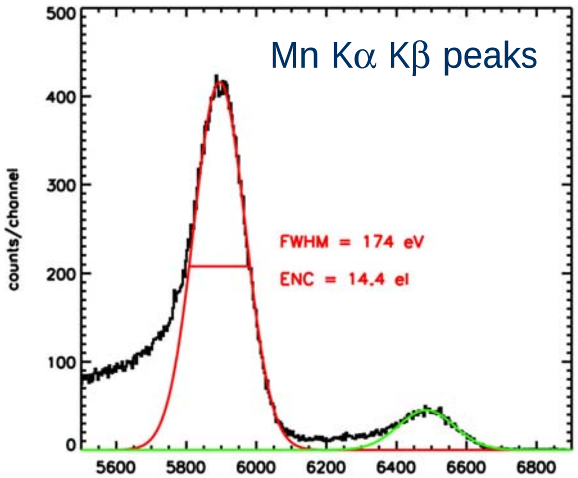
ENC=7.9 electrons after irrad.





Fe55 spectrum after 1Mrad irradiation



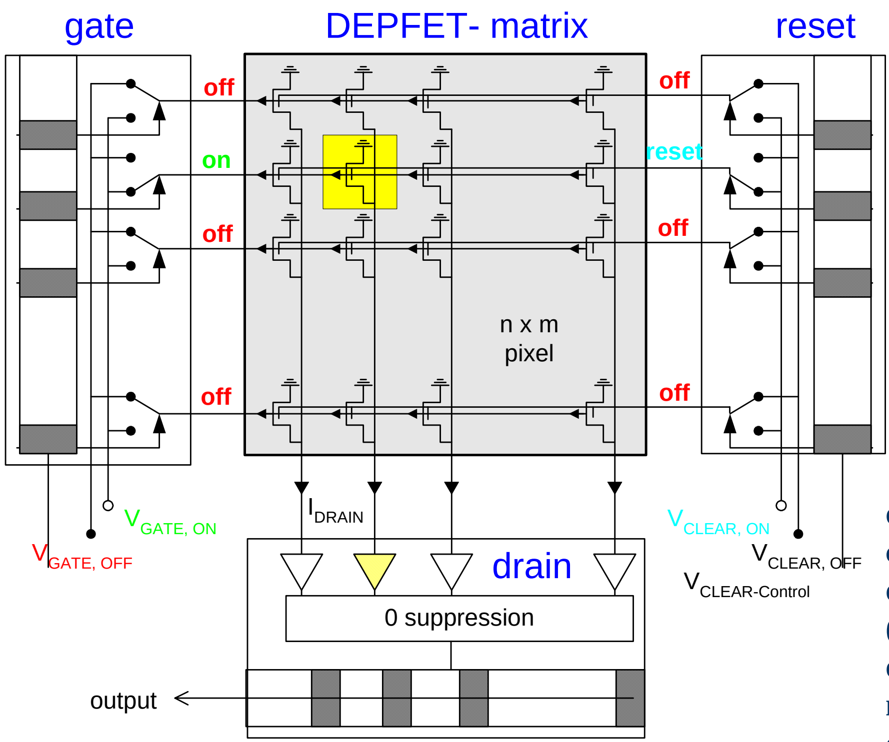


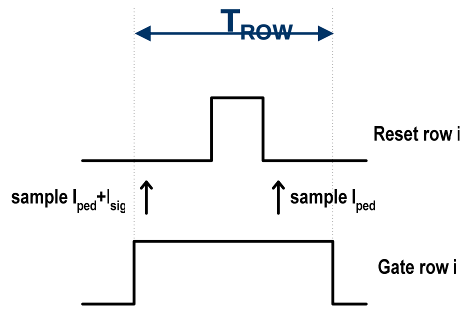
On module electronics

- Switcher ASIC:
  - provides steering signals (double) row by (double) row:
    - external gate voltage pulse
    - clear voltage pulse

- CURO:
  - subtracts drain currents before/after clear for all columns in parallel
  - shifts differences into analog FIFO
  - identifies pixels with signals
  - sends analog signals of hit pixels to outside ADC

Matrix operation of DEPFET pixel matrix





Readout sequence

- **Reset that row and measure pedestal currents**
- **Collected charge in internal gate ~ (Difference of both currents)**
- **Select one row via external Gates and measure Pedestal + Signal current**
- **continue with next row ...**

Requires additional on and off module electronics to be described in last talk of this session

Power consumption: Only selected rows dissipate power
but
Sensor still sensitive even with the DEPFET in OFF state

Summary/Conclusion

- Tried to
  - Explain working principles of pixel detectors for particle tracking
  - Derive some general properties from these principles
  - Very few illustrating examples were selected, therefore not doing justice to the many approaches being taken
  - Left out in particular were questions on detectors suitable for very high luminiscence hadron colliders (Super LHC)
- Large part of the presentation concentrated on DEPFET pixel detectors (satisfying my personal prejudice considering them as best suited for ILC applications)
- Important DEPFET properties
  - Complete charge collection by drift in fully depleted bulk
  - Very low noise / high S/N
  - high spatial resolution
  - Low power dissipation
  - Developed thinning technology - Low radiation length
  - Radiation tolerance
  - Operation at room temperature
- Other approaches will be presented in detail at this conference