Sensor Concepts for Pixel Detectors in HEP

Introduction

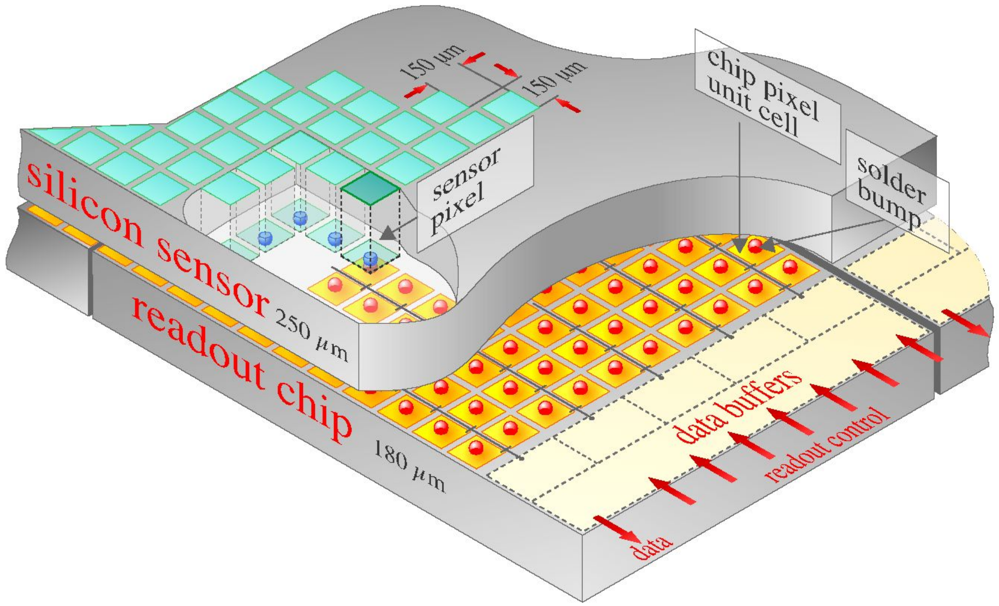
"p−in−n" Sensors
design, test, limits in radiation hardness

"n−in−n" Sensors for LHC−Experiments
radiation hardness requirements
n−side isolation and design

Other Experiments
"Super−LHC"
TESLA

transparencies available online http://people.web.psi.ch/rohe/

Introduction



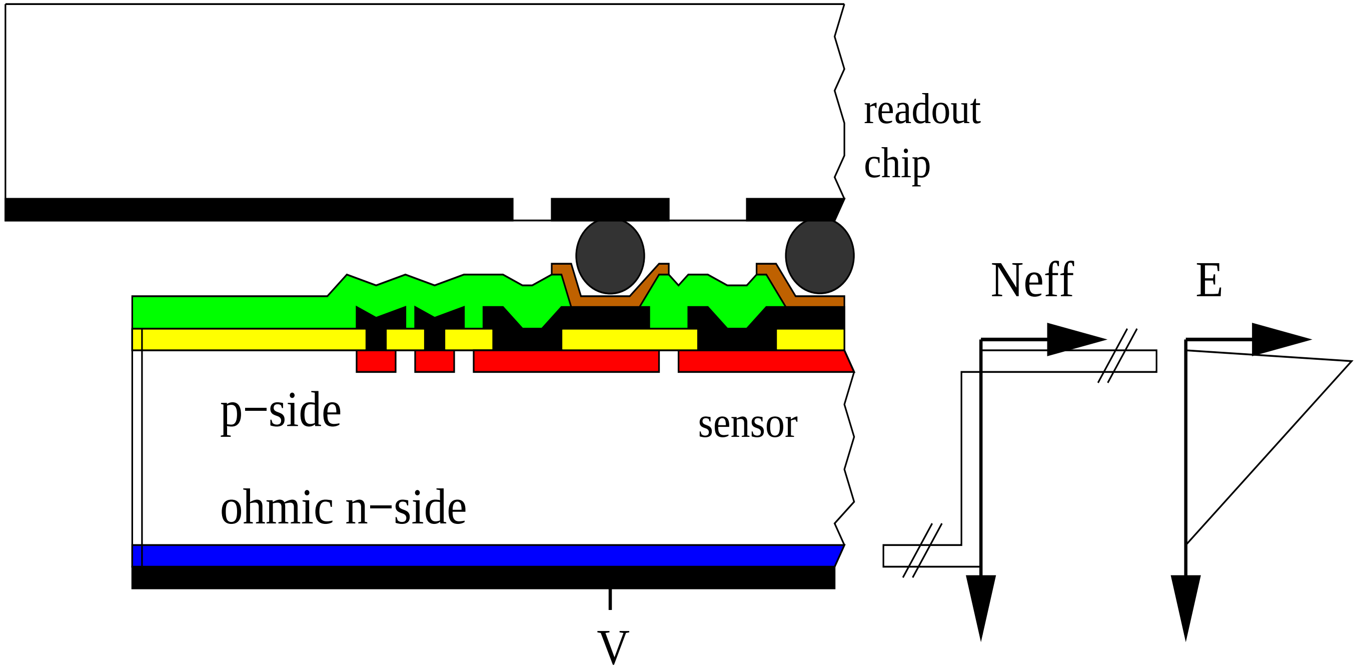
R&D of hybrid pixel detectors is usually concentrated on

•readout chip
•bump bonding

as the most crucial issues.

Further

•a typical readout chip contains ~ 500k transistors
•a sensor "just" ~ 50k diodes

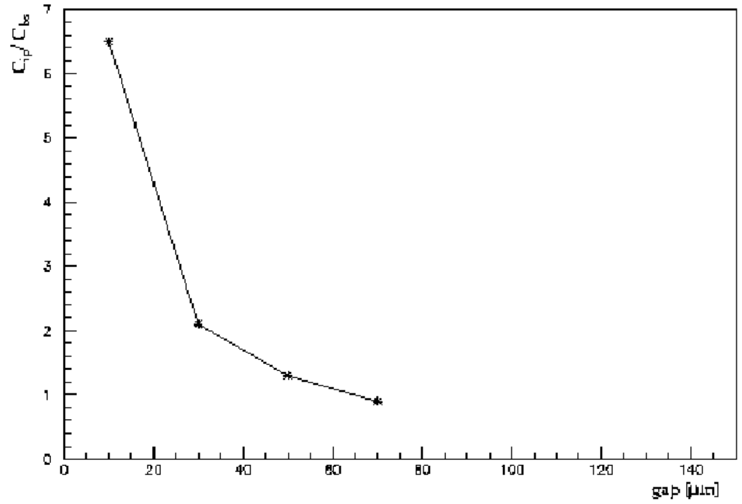


"1st Generation" Pixel Sensors

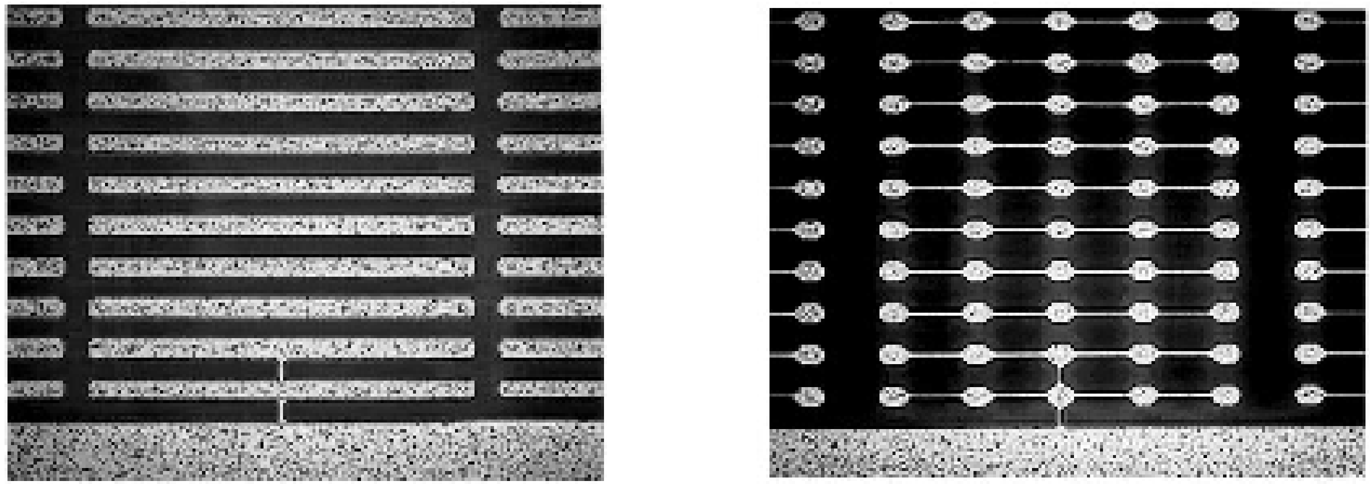
- simple process
  - only ~4 mask steps (plus bump bonding and 2nd metal layer)
  - single sided
  - Dephi sensor already contained bussing (2nd metal layer)
- requirements:
  - highest field on structured side → no over−depletion necessary no high voltage capability required (simple guard ring structure)
  - no radiation damage

Design of "p−in−n" sensors

Most important design parameter is gap/pitch ratio. C_{pixel} decreases with larger gaps but extreme geometries turned out to be problematic (slow charge collection)



[Wüstenfeld 2001]

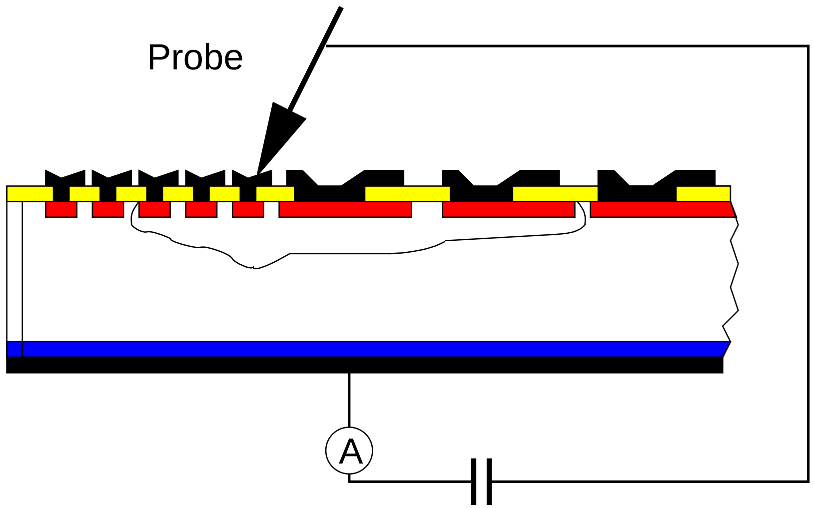


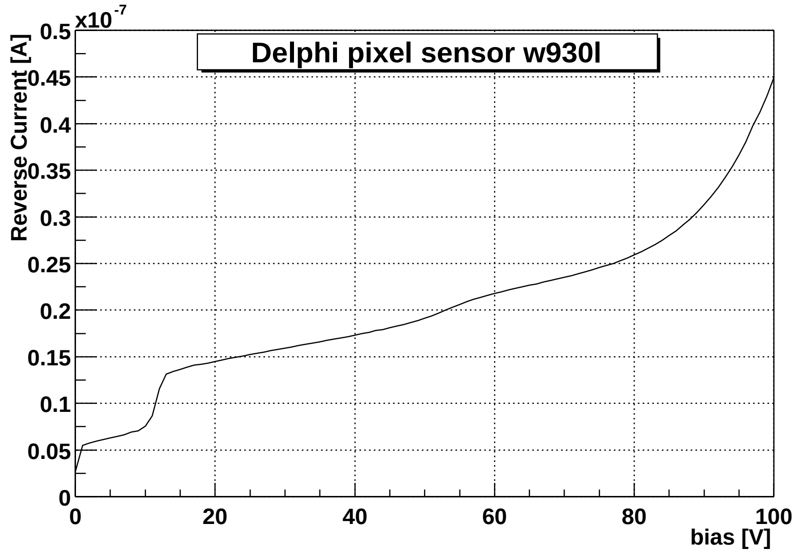
(a) (b)

I. Ropotar: NIM A 439 (2000) 536−546

Test of Sensors

- Most kind of failures lead to visible current increase in the IV−curve if the damaged region is reached by the
- It is not easily possible to connect all pixels or a significant fraction of directly. IV−test are usually performed with 2 probe needles
- In Delphi guard current was measured
  - it was possible to select "obviously problematic" sensors with high current at the beginning of the IV−curve
  - ~8% of the modules were lost due high sensor current (damage during processing?)
  - ~5% due to high number of noisy pixels (probably due to defects in the chip?)





[S. Heising, private communication]

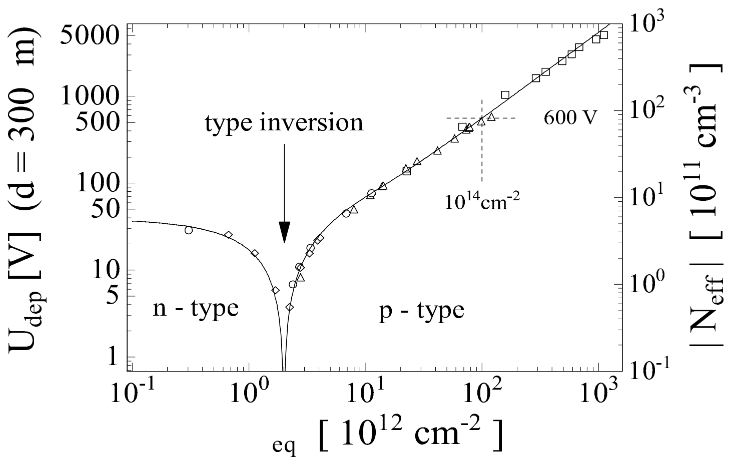
Irradiation Induced Changes in Silicon

Surface damage

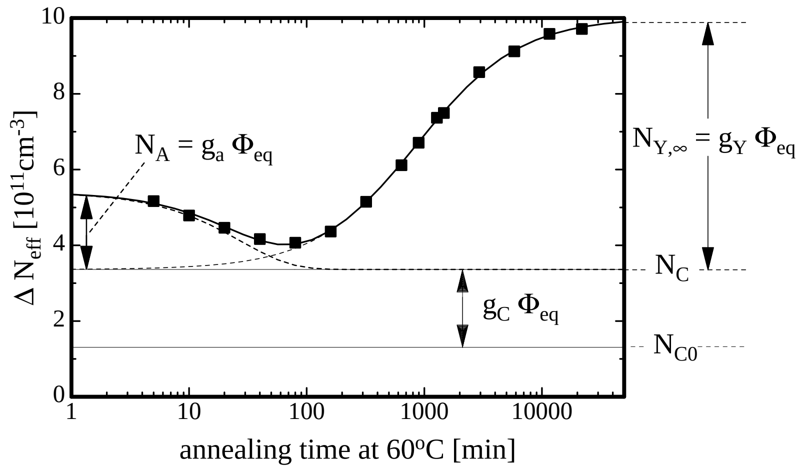
- Built up of oxide charge (~3E12 cm^{-2})
- Built up of interface states

Bulk damage

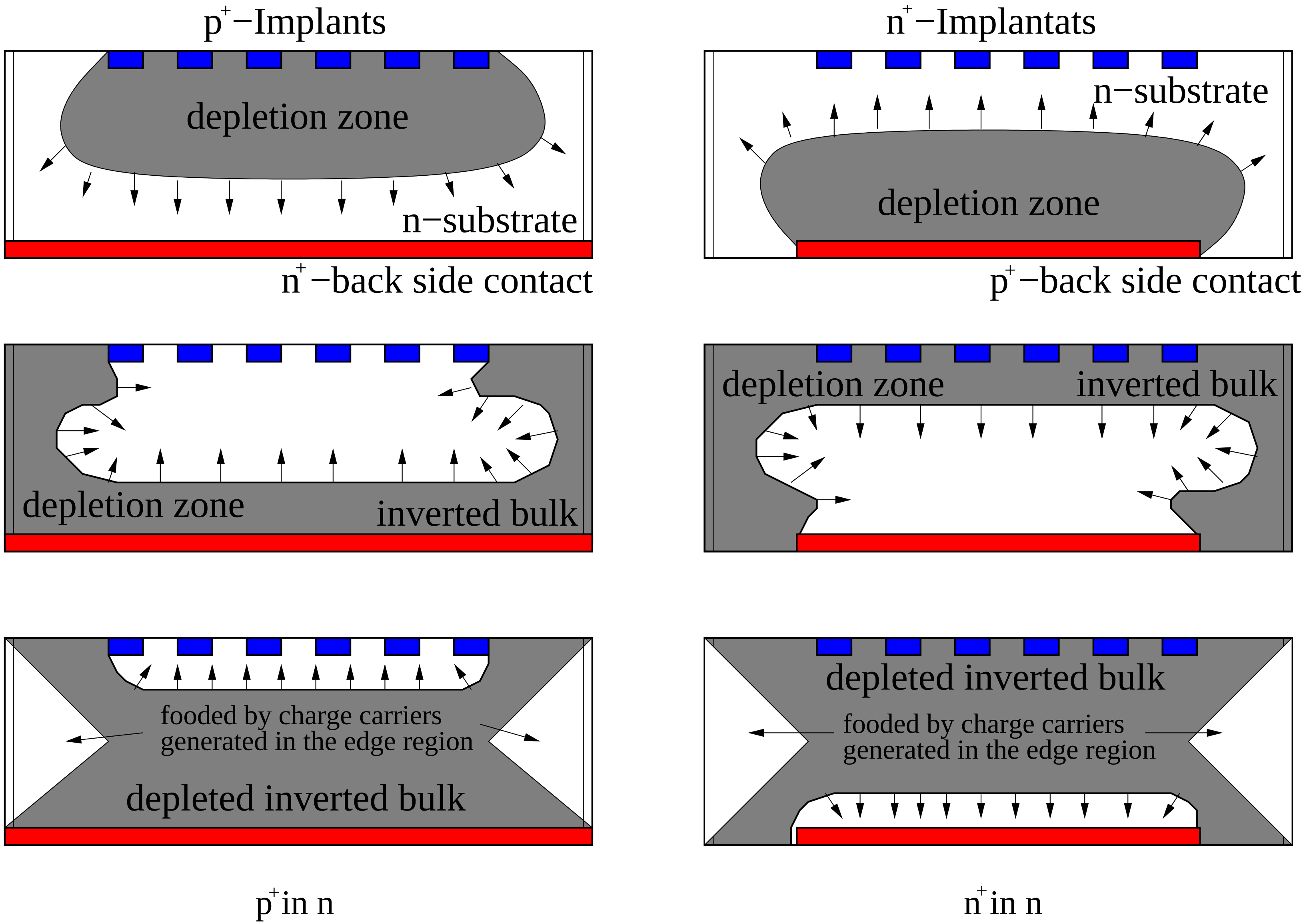
- Type inversion of the bulk material n→p
- Increase of effective doping and full depletion voltage
- Complex "annealing" behaviour
- Increase of N_{eff} and reverse annealing can be reduced by oxygenation
- Undepleted bulk becomes high resistive (important for edge)
- trapping of signal charge (important for segmented sensors)



N_{eff} vs Φ for standard float zone silicon [Wunstorf 1996]

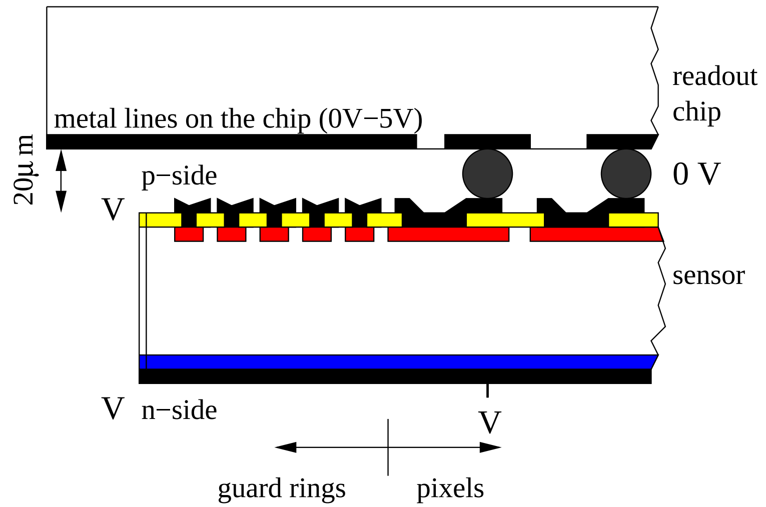


N_{eff} vs t for standard float zone silicon [Moll 2000]



after G.Lutz NIM A 406 (1998) 184−193

Radiation Hardness of "p in n" Sensors



Have to be (almost) fully depleted meaning that

radiation hardness = high voltage stability.

Current limit of strip detectors (ATLAS/CMS): Φ = 2−3E14cm^{-2}. High voltage stability has to be provided by

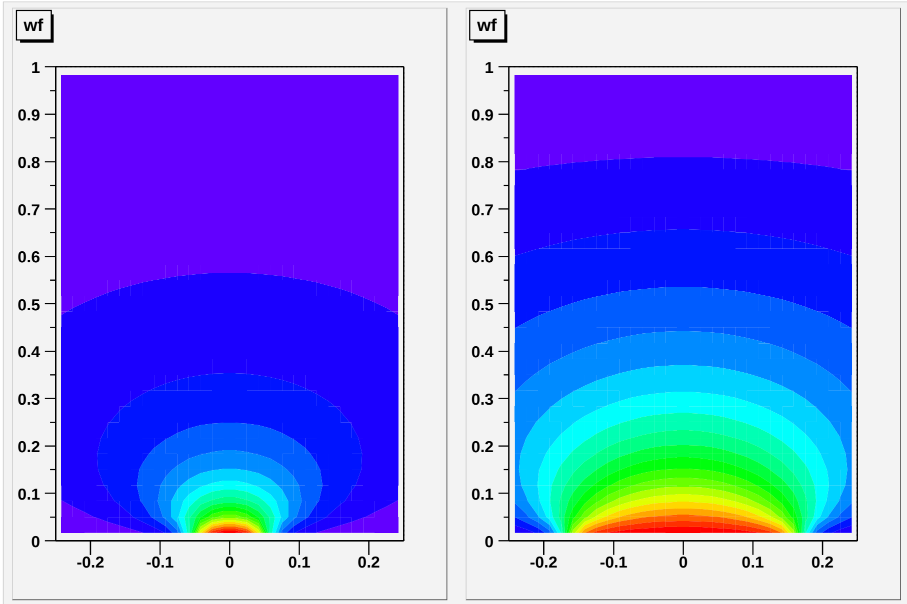
- guard rings
- module construction

Further considerations:

- backside scratches more problematic(?), testing(?)
- protection of unconnected pixels necessary(?)

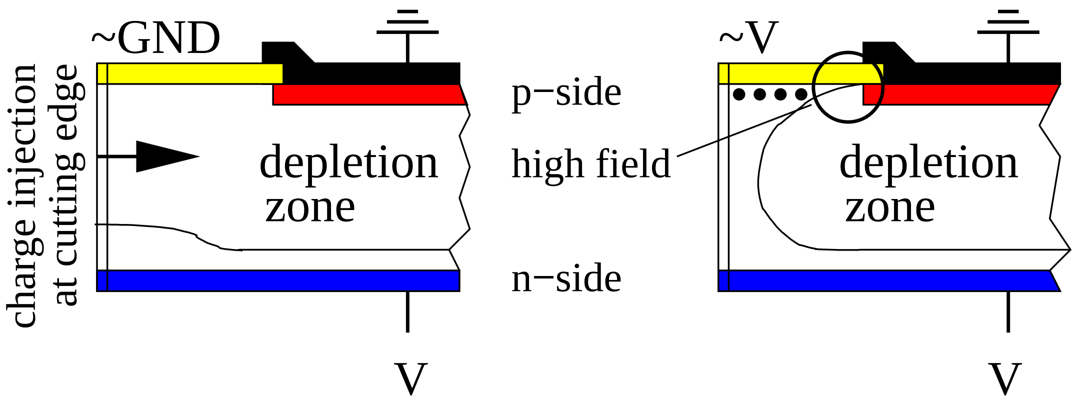
Reduce impact of trapping

- small gap between implants



collecting electrode: 0.1 and 0.33*waferthickness

Guard Rings

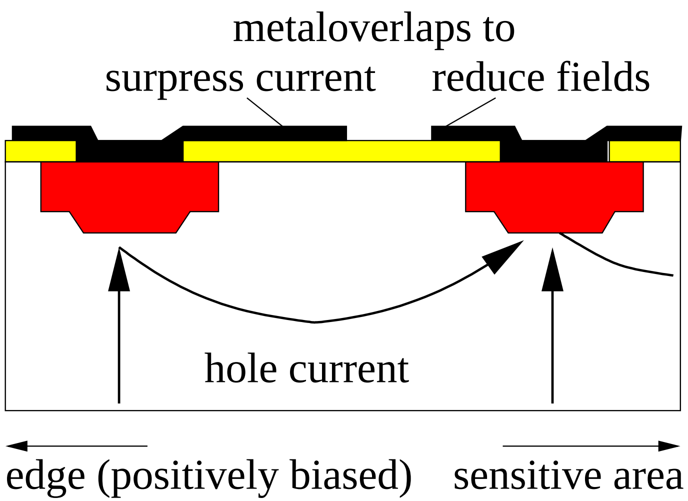


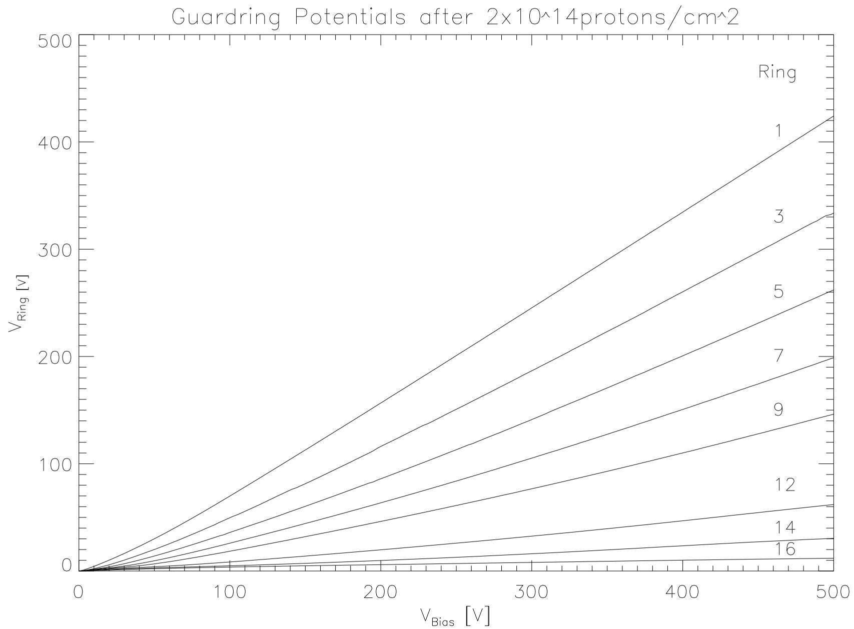
Two purposes:

- limit lateral extension of depletion region
- prevent breakdown at the device edge

Both reached if gentle potential drop towards edge is provided. Commonly used design strategy:

- outwards metal field plate for field reduction
- inwards metal field plate to increase voltage drop between rings
- increasing gaps from inner to outer region

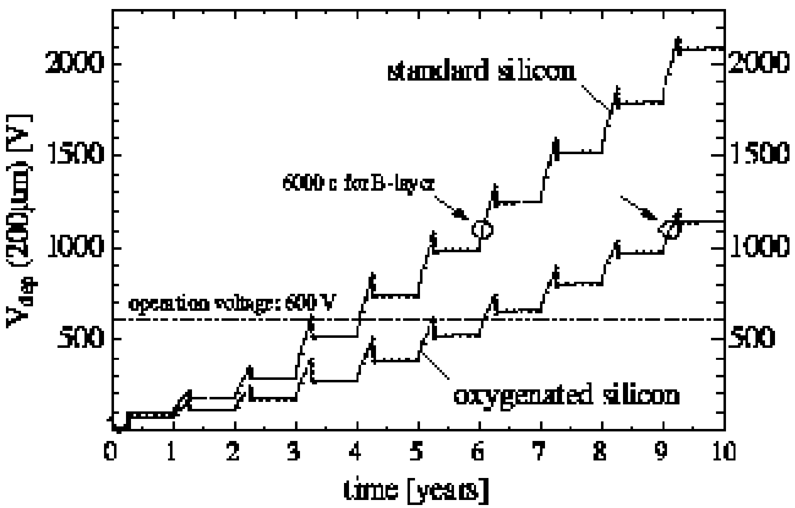


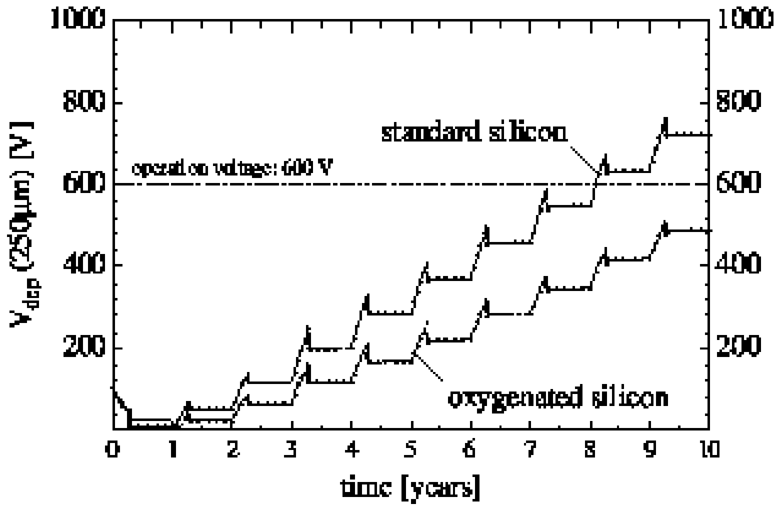


[Andricek 97]

Radiation Hardness Requirements of LHC Experiments

- maximum Fluence in the order of 6−10E14cm^{-2}
- pions are dominant (oxygenation recommended)
- cooling has to be interrupted for certain periods → reverse annealing
- V_{depl} after 10years of LHC:

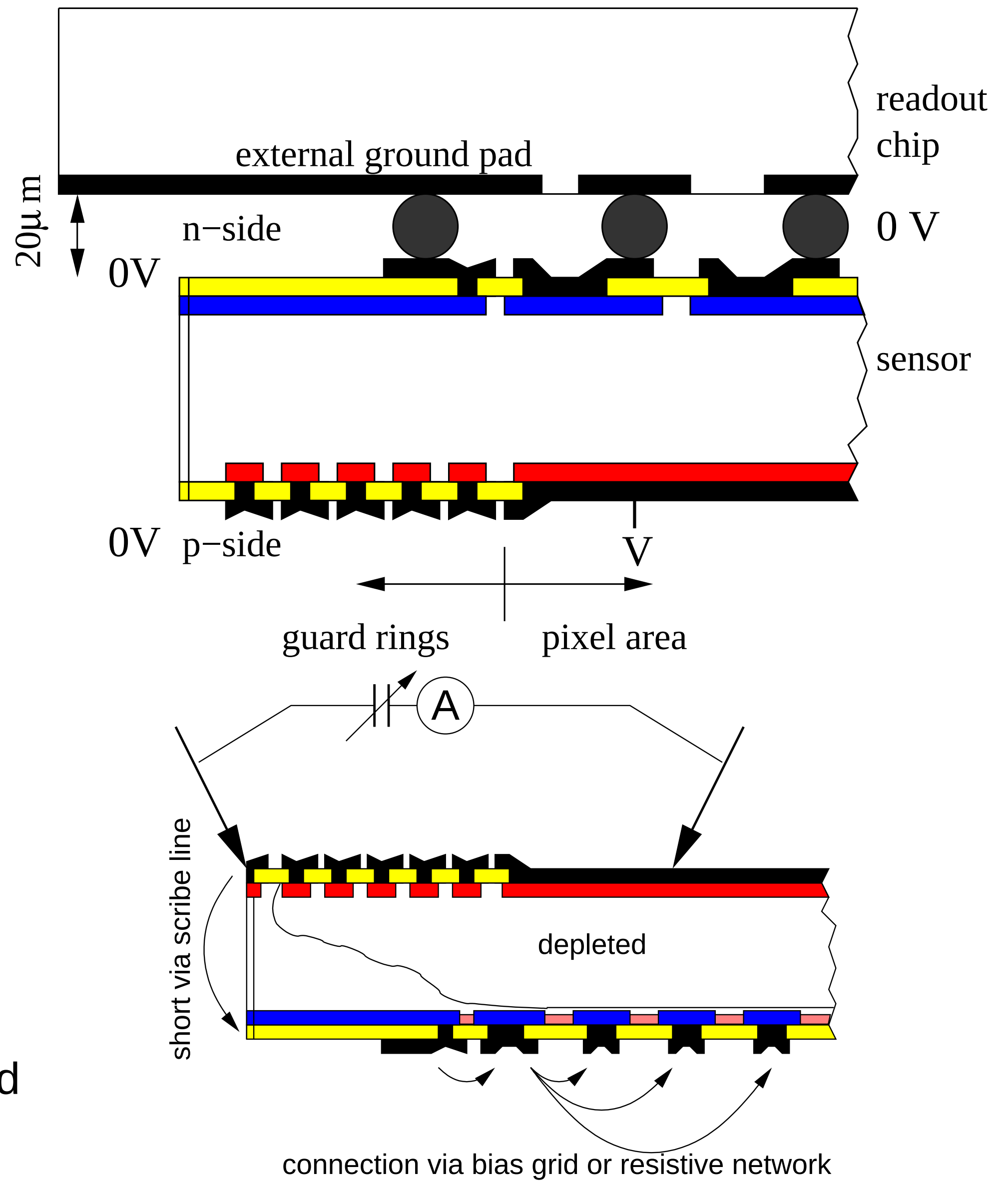




[3rd ROSE−Status Report 1999]

"n−in−n" concept

- strongly underdepleted operation possible after type inversion
- double sided processing
  - all sensor edges on ground
  - costs:
    - twice as much mask steps
    - n−side isolation
    - yield extensive testing necessary (bias grid/resistive network)
- Design has to optimized for high voltages after irradiation
  - guard rings
  - pixel design (small gaps, protection of unconnected pixels, inter pixel isolation)
  - radiation hardness in the end limited by trapping



n−Side Isolation

p−stops

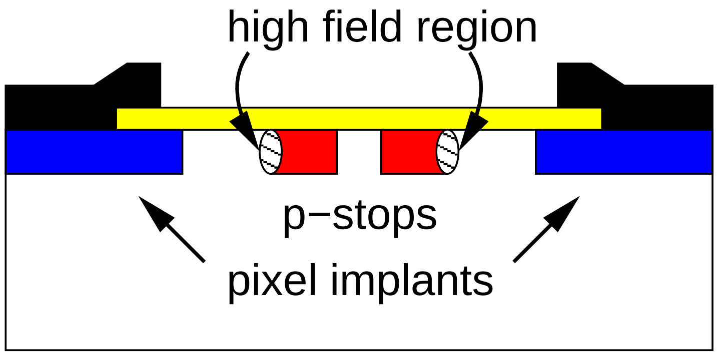
- most vendor's standard (from double sided strips)
- boron dose uncritical
- (at least) one additional mask step
- alignment critical (lead to large gaps)

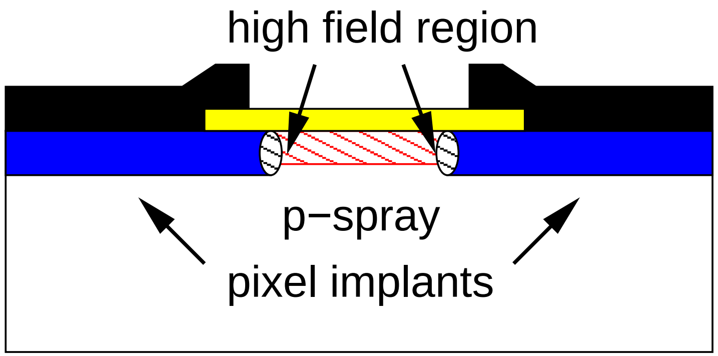
p−spray

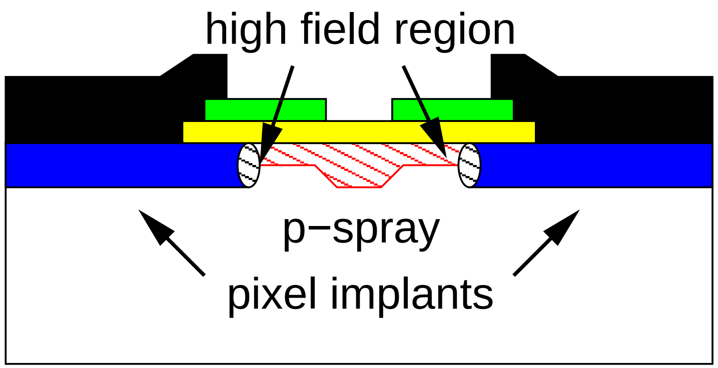
- no mask step
  - costs
  - no alignment (small gaps)
- high voltage capability after irradiation
- boron dose has to be adjusted (turned out to be uncritical)

moderated p−spray

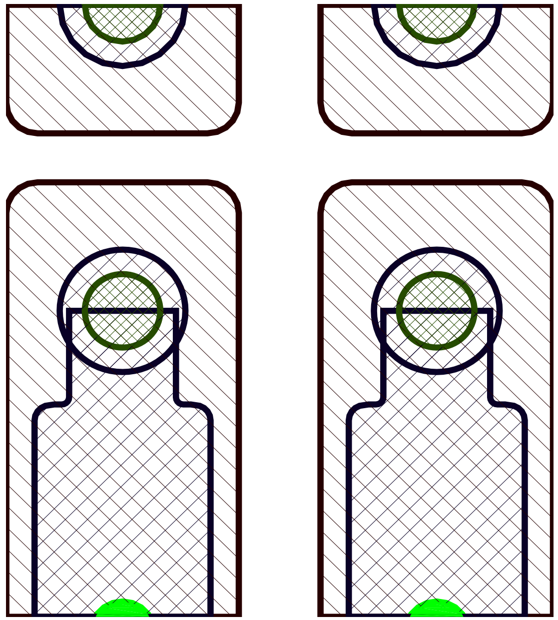
- no additional mask step (in most cases)
- good HV capability before and after irradiation
- increased gaps (punch through bias grid still possible)



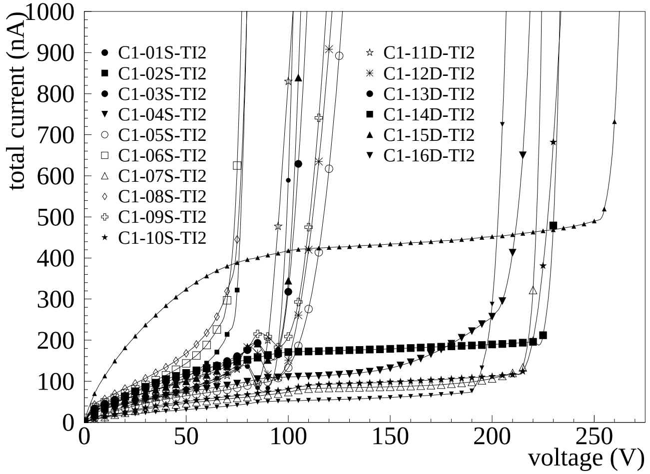


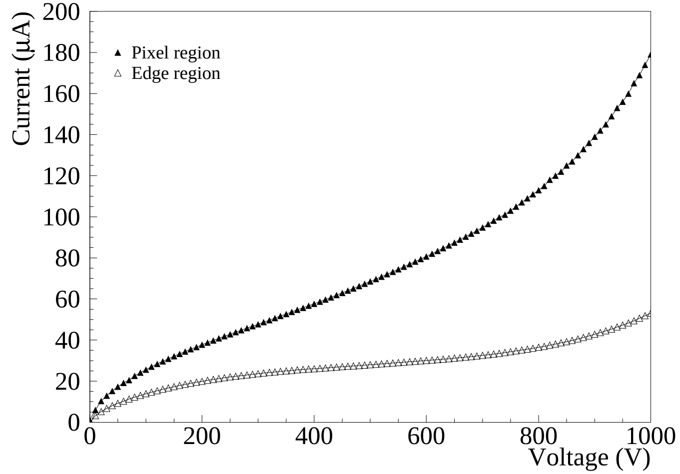


Typical p−spray design



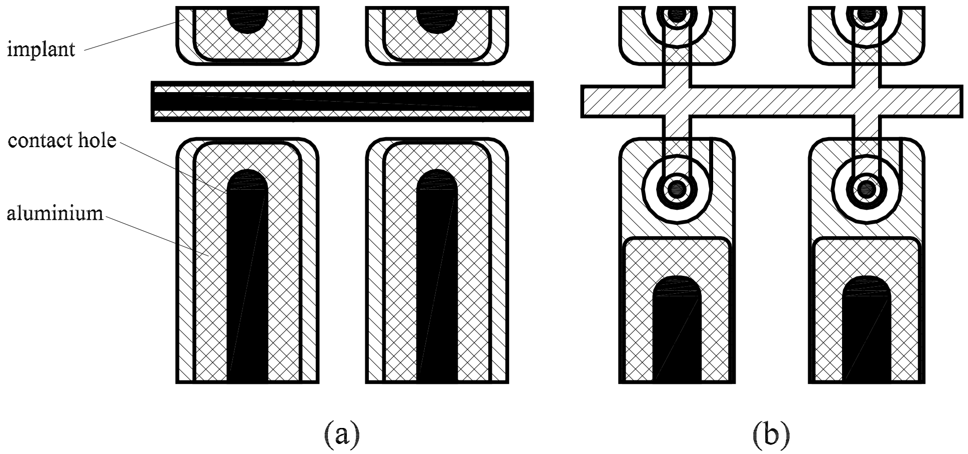
- small gaps (in non squared pixels un−symmetric to reduce diagonal distance)
- breakdown voltage limited to ~200V before irradiation
- breakdown voltage exceeding 1kV reachable after irradiation
- devices operated in test beam after Φ=1E15cm^{-2} with detection efficiency above 95%

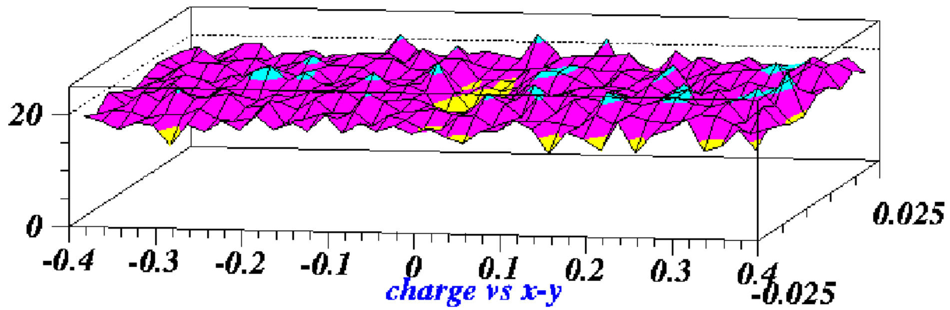




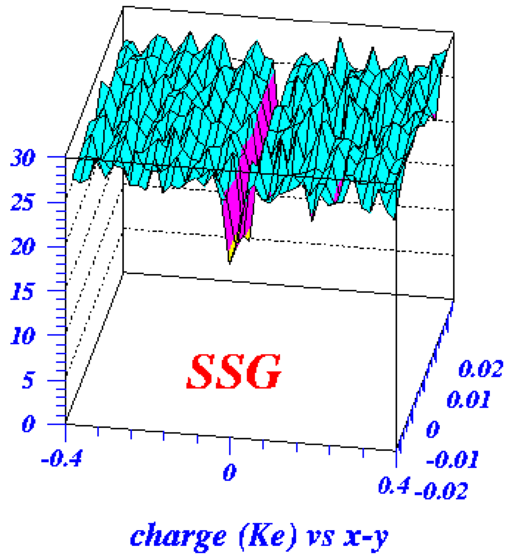
Bias Grid

- Punch−through biasing
  - voltage drop limited
  - hardly dependent on back side bias and radiation
  - efficiently protects (=fixes potential of) unconnected pixels
  - no access noise
- Two possible implementations
  - minimum demands on production process but charge loss
  - more difficult to produce but less influence on charge collection





[Troncon]

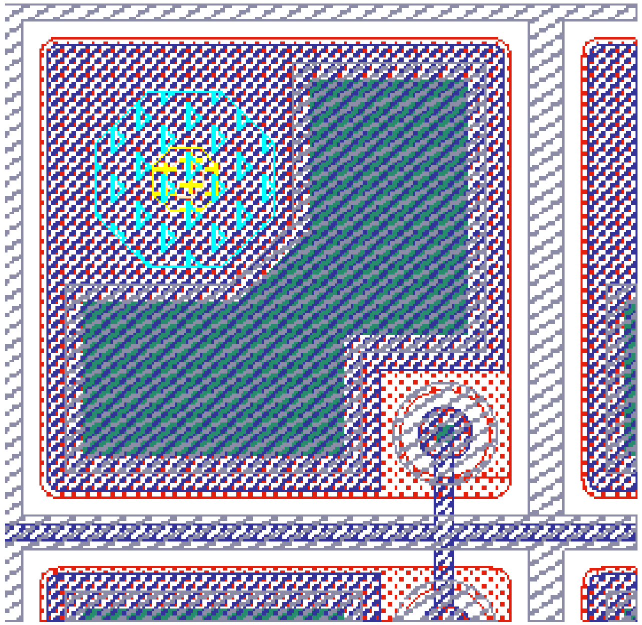


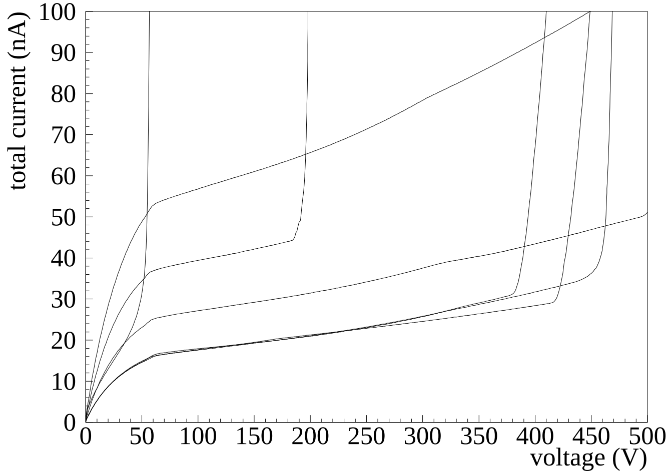
[Troncon]

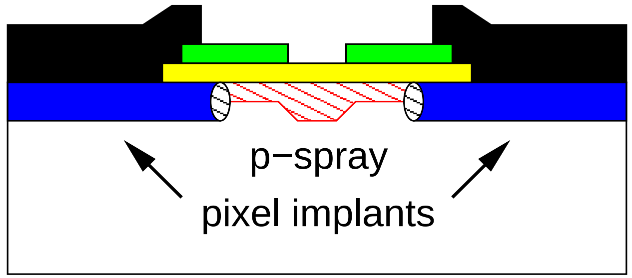
Moderated p−Spray

- pre−radiation breakdown voltage increased
- post−radiation behaviour preserved
- gaps larger than in "normal" p−spray
- implementation of bias grid a bit "tricky"

- solution chosen by the ATLAS pixel collaboration



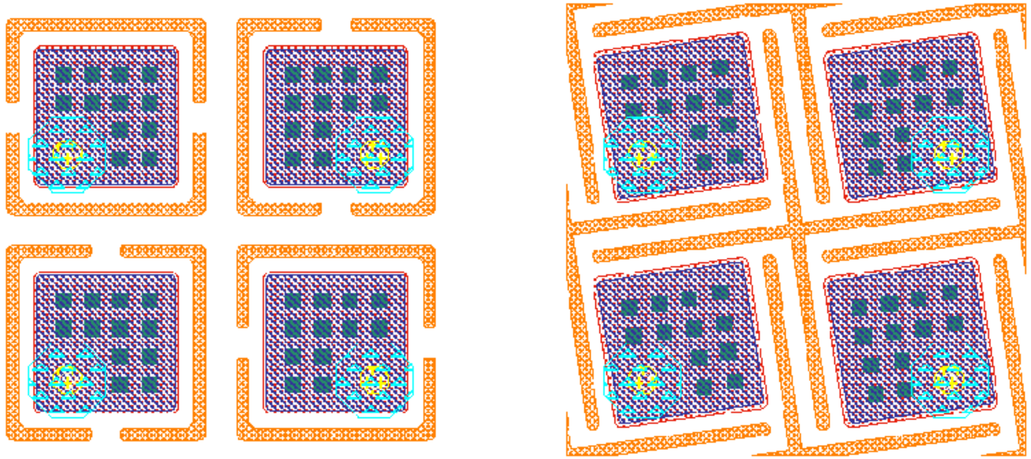


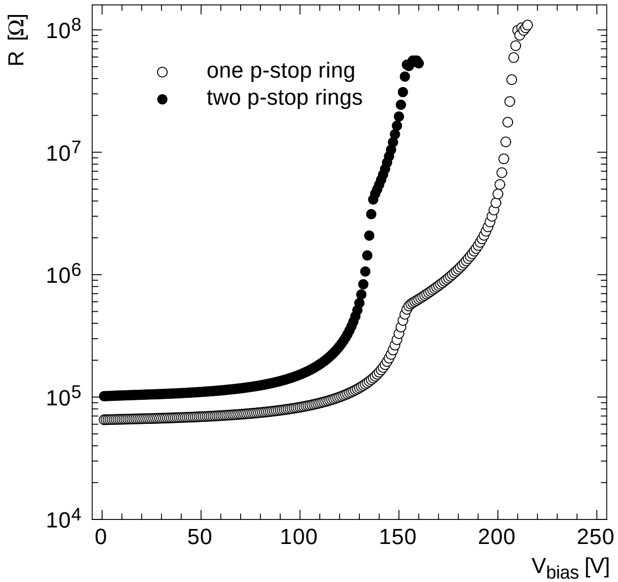


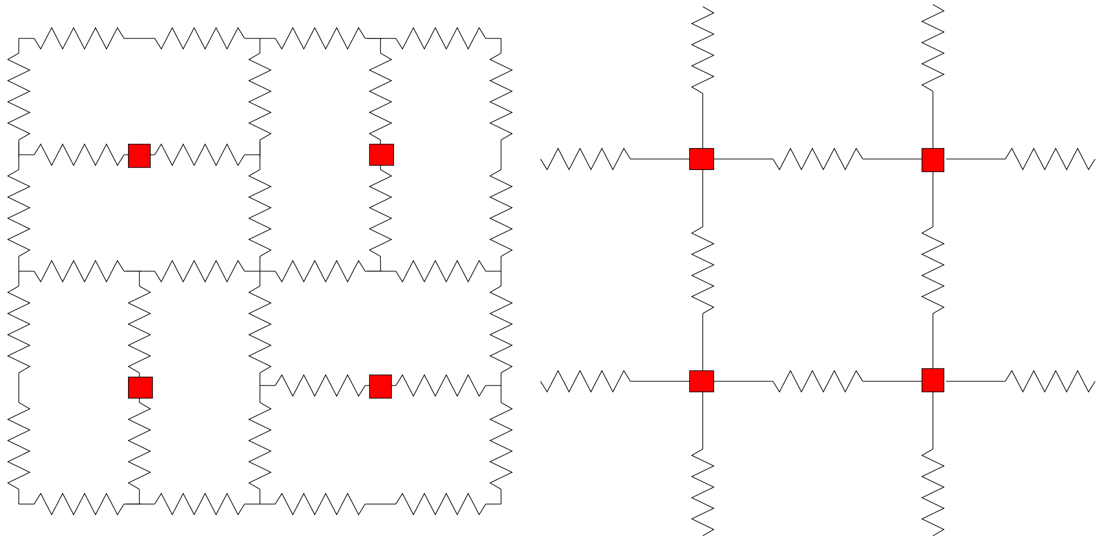
p−Stop Designs

Opening in p−stops provides resistive connection between pixels:

- testability given
- over−depletion limited by "pinch off"
- interpixel resistance exceeds some GΩ and becomes independent of the design after irradiation

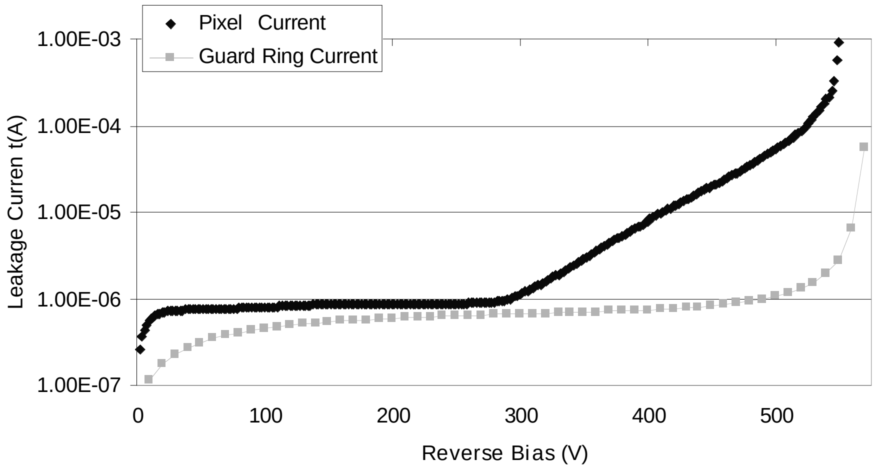


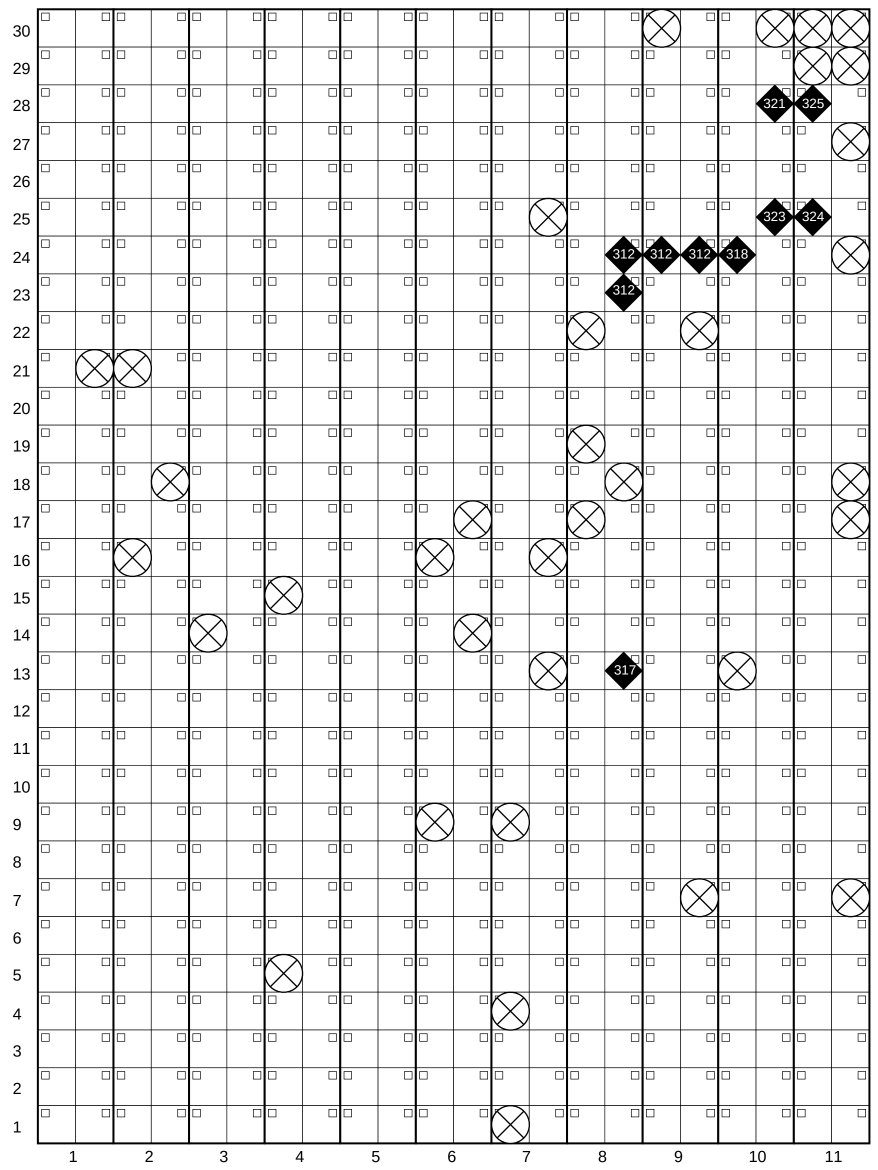




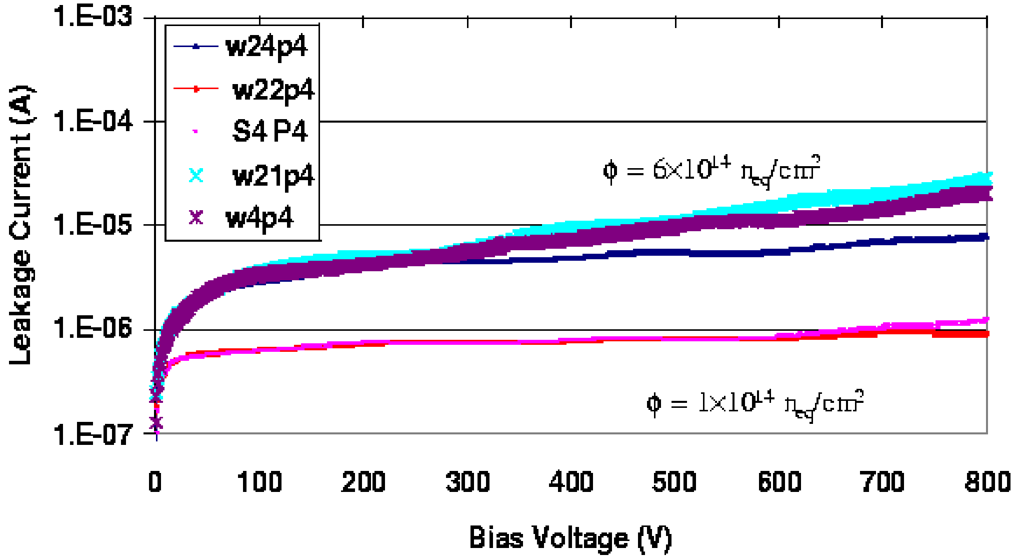
Radiation hardness of p−stop devices

- Devices tend to show exponential current increase below the maximum foreseen operation voltage
- current is drawn by little number of pixels that become noisy
- noisy pixels are not correlated with missing bump bond connections





Improvements



Desing

- small gaps (one p−stop ring instead of two)
  - IV curves improoved:
    - "slope" of exponential region is reduced
    - not "hard" breakdown
- flied plates
  - higher capacitance (?)

[A.Roy Vertex 2001]

Technology

- Reduction of p−stop dose eventually leading to "structured p−spray"

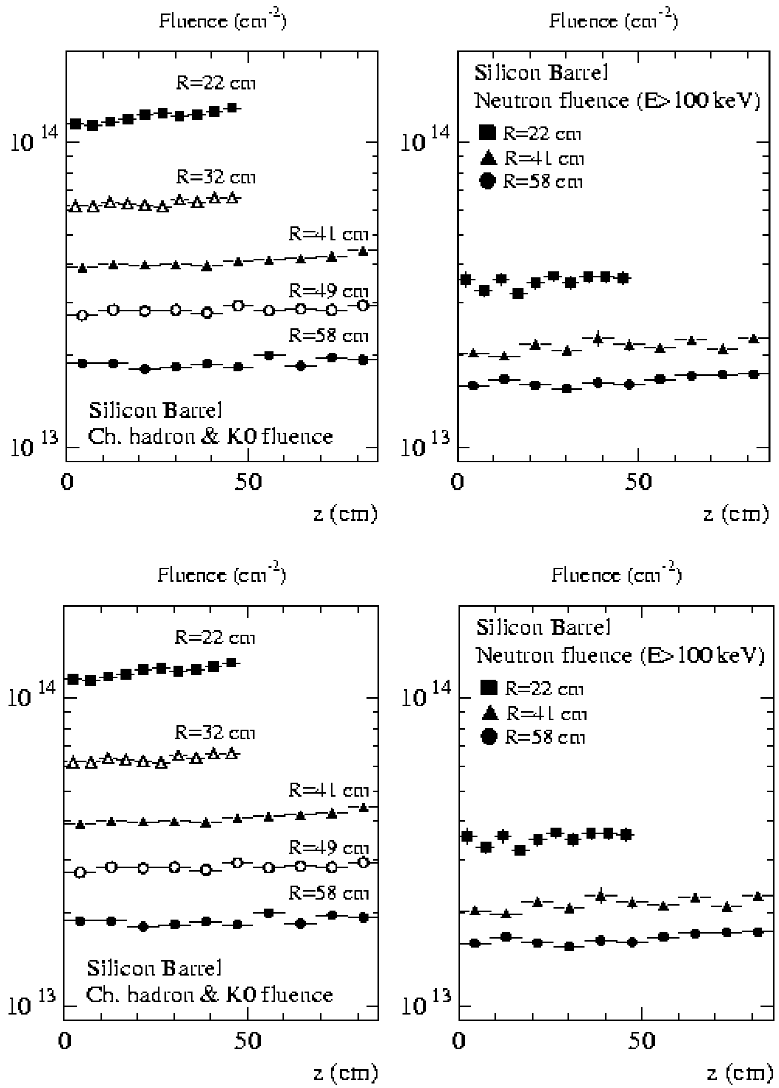
Devices are currently under investigation (IV, noise, test beam)

Pixel−Detectors for "Super−LHC"

Proposal exists to increase LHC's luminosity in 2010 and to increase the total integrated luminosity of each experiment from now 500 fb^{-1} to 2500 fb^{-1}.

- Radiation hardness requirements of up to 1E16cm^{-2} for the innermost pixel layer at r=4cm → new R&D collaboration CERN RD50 formed (talk by Z. Li)
- The area with r > ~20cm ("now" covered by strips) could in principle be equipped with the present LHC's pixel technology, however these approach much too expensive.
  Most cost driving:
  - total coverage of sensitive area by readout electronics
  - double sided sensor technology
  - (large HDI)

Fluences for 500 fb^{-1}



[CMS−Tracker−TDR]

"Macro−Pixels" with single sided sensors

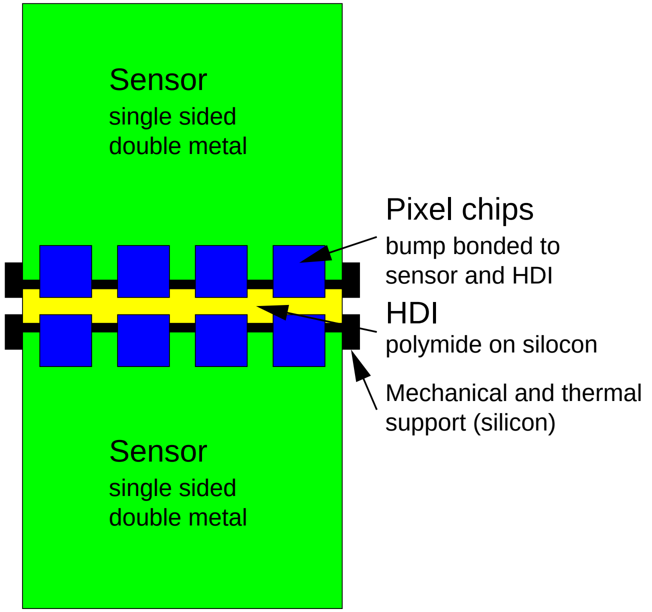
Cells on chip smaller than on sensor. Signals are routed via 2nd metal layer or MCM−D

Single sided sensors:

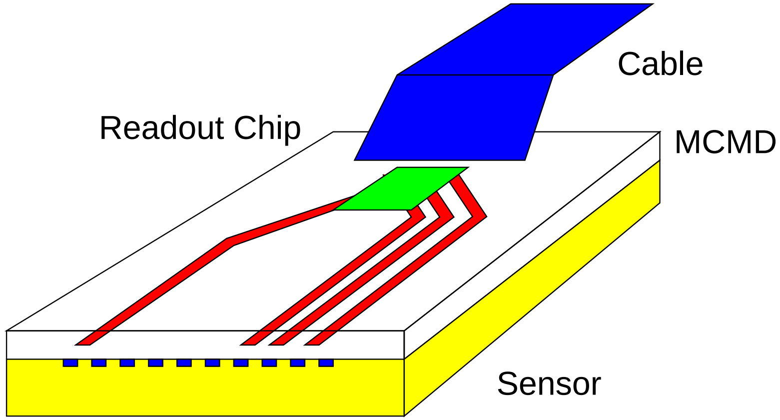
- Thin "p−in−n" sensors with "low" resistive oxygenated silicon
  - will not invert (in the given fluence)
  - initial signal is small
- "n−in−p" sensors
  - will not invert
  - can be operated under−depleted
  - N_{eff} will be higher than in "n−in−n" sensors

Sensor R&D required:

- Thinning sensors and their handling and processing (also done in the R&D for TESLA)
- Edge termination on module level



[Horisberger 2000]



TESLA

Requirements:

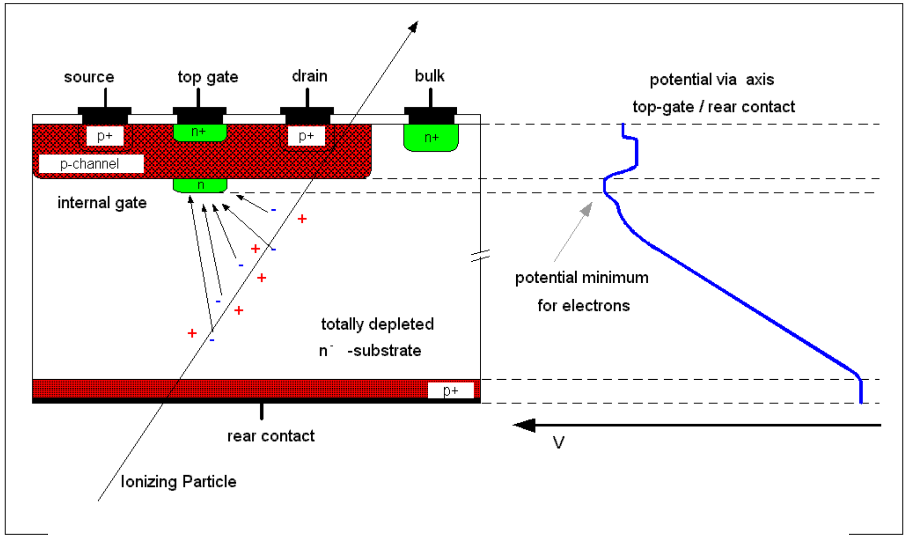
- very thin
  - only ~50µm silicon
  - self supporting
  - air cooled → low power dissipation
- little radiation expected (~1E9cm^{-2}, more than in typical space applications)
- Fast readout (clock rate of ~20−40MHz)

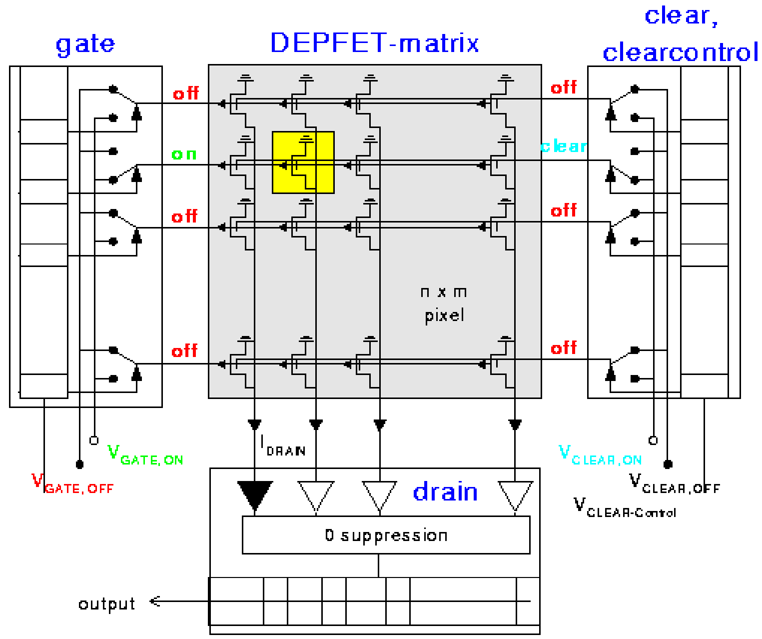
"Candidate" technologies

- CCDs (not topic of this talk)
  - Good experience from SLD
- Active CMOS (see talks of Fossum, Deputch, Passeri)
- DEPFET/DEPMOS
  - low noise
  - low power dissipation
  - not commercially available
  - experiences from imaging applications (UniBN)
- Hybrid pixels (backup solution, because of material)

DEPFET/DEPMOS

- 1st amplifying stage is integrated on the sensor
- very low noise (capacitive load of the internal gate is very little ~10fF)
  - K_α of ^{55}Fe has been measured with FWHM of 148eV (ENC of 4.8)
  - can deal with low signals (50µm silicon)
  - can work with small readout currents.
- power consumption only during readout ($V_{ds}\approx5V$, $I_d\approx100\mu A$)
- Reached cell size (DEPMOS) $50\times50\mu m^2$. In next prototyping (DEPMOS): $25\times25\mu m^2$.
- Prototypes of Readout electronics working
- Sensors currently under production





[Uni–Bonn and MPI]

Conclusions

- p−in−n sensors are successfully used in all pixel applications which do not require radiation hardness
- their radiation resistance can be exceeded up to ~2−3E14 cm^{-2} if the high voltage stability is provided (edges, guard ring)
- n−in−n sensors are the "state of the art" solution for LHC (up to ~1E15 cm^{-2} in the end limited by trapping).
- Future application (Super LHC r > 20cm) need cheaper solutions
- For r < 20cm "ultra radiation hard" concepts are required
- In future linear colliders "massless" detectors are favoured leading to integration of certain signal processing (CMOS/DEPFET)