MPP Project Review 2006 - HLL

Outline

DEPFET (ILC)
Sub electron noise measurements - RNDR
Back illuminated SiPM (MAGIC, EUSO)
Detectors for SLHC
and XFEL

Halbleiterlabor der Max-Planck-Institute für Physik und extraterrestrische Physik

HLL - Mitarbeiter

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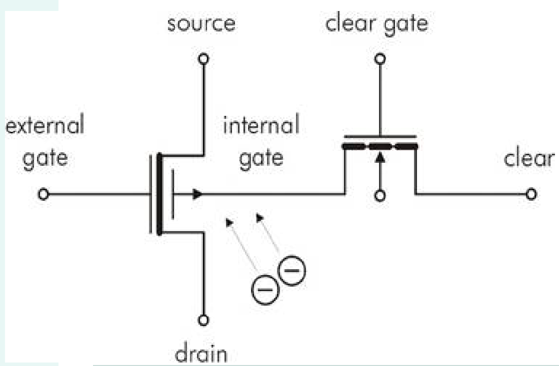
[a] MPI für Physik
[b] MPI für extraterrestrische Physik
[c] PN Sensor

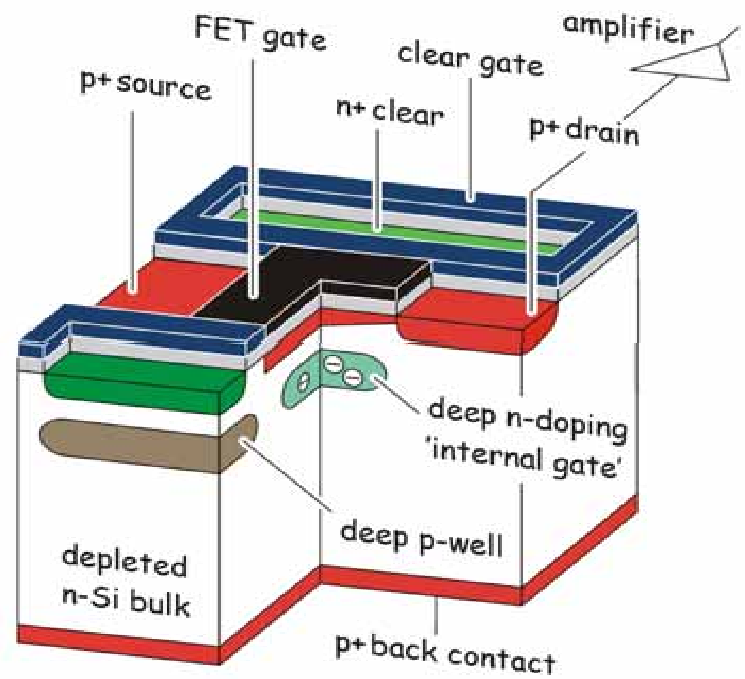
WHI:

- 6 physicists and engineers
- 4 technicians
- 2 secretaries
- 3 PhD students

DEPFET Principle of Operation

- A p-FET transistor is integrated in each pixel
- A potential minimum for electrons is created under the channel by sideward depletion
- Electrons are collected in the "internal gate" and modulate the transistor current
- Signal charge is removed via a clear contact





- Fast signal collection in fully depleted bulk
- Low noise due to small capacitance and internal amplification
- Transistor can be switched off by external gate – charge collection is then still active!

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DEPFET for ILC - ^{55}Fe Spectrum (single ILC pixel)

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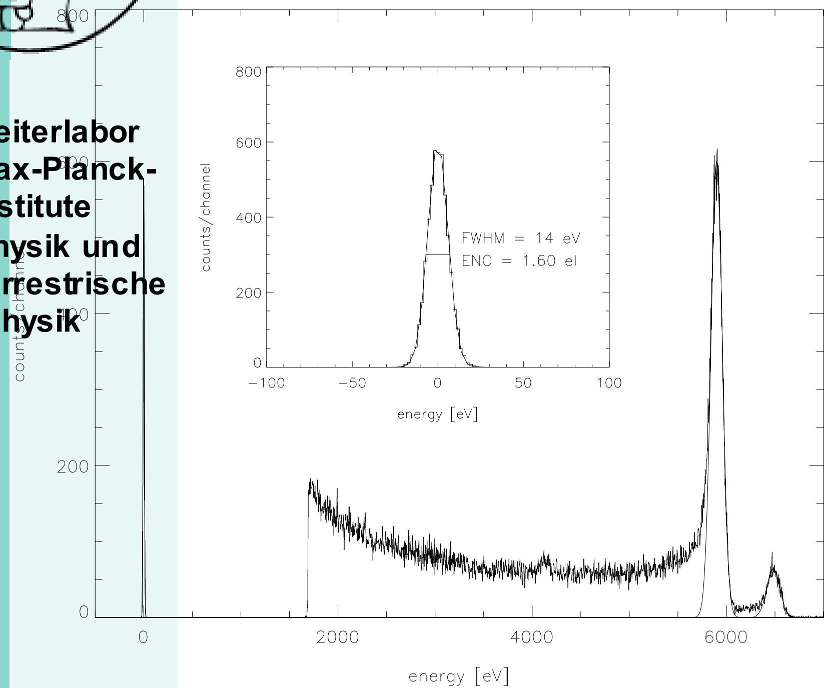

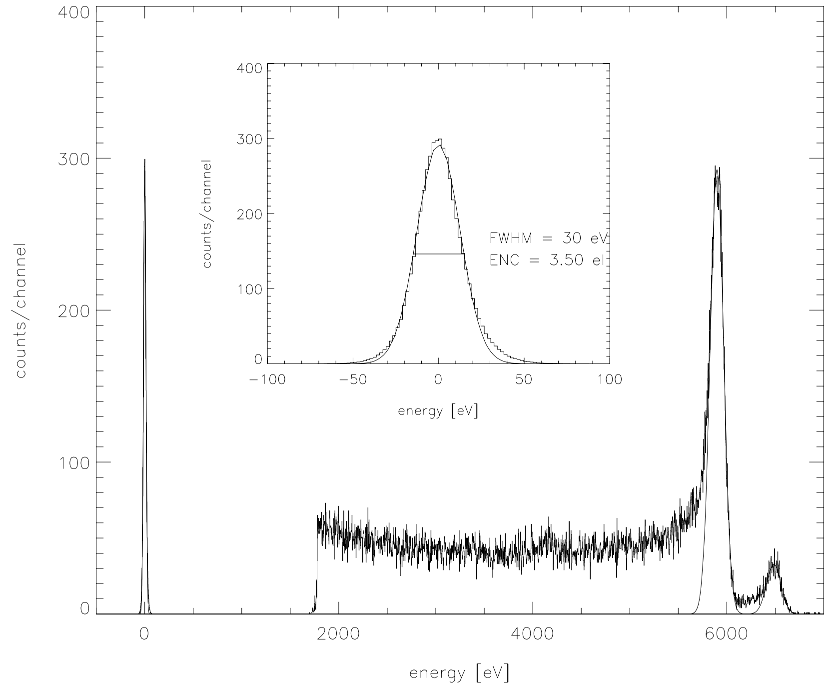

non-irradiated

$V_{thresh} \approx -0.2V$, $V_{gate}=-2V$

$I_{drain}=41\ \mu A$

time cont. shaping $\tau=10\ \mu s$

Noise ENC=1.6 e^- (rms)

at T>23 degC

912 krad ^{60}Co

$V_{thresh} \approx -4.0V$, $V_{gate}=-6.0V$

$I_{drain}=40\ \mu A$

time cont. shaping $\tau=10\ \mu s$

Noise ENC=3.5 e^- (rms)

at T>23 degC

DEPFETs at ILC speed

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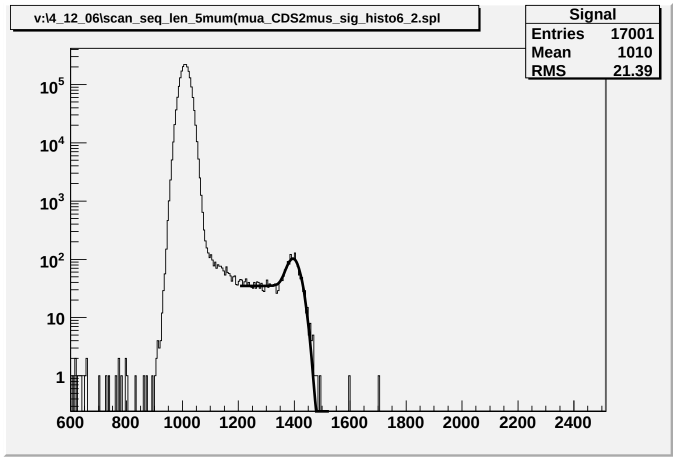
Single DePMOS devices

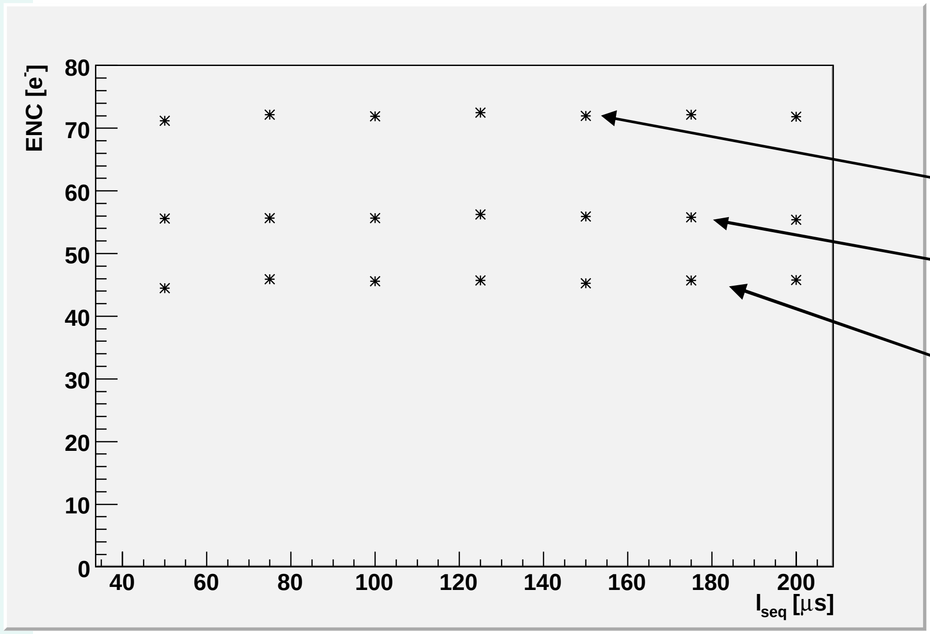
LG = 5µm

fast transimpedance amplifier

BW = 55MHz

Fe^{55} spectrum





DEPFET + Amplifier

Amplifier

DEPFET only

Goal for ILC about ENC ca.100e-

integration time (µs)

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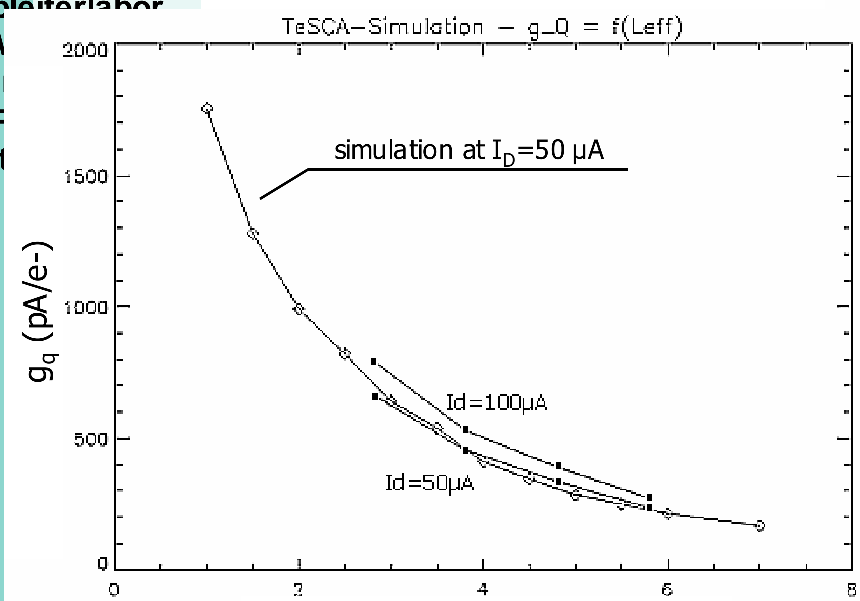
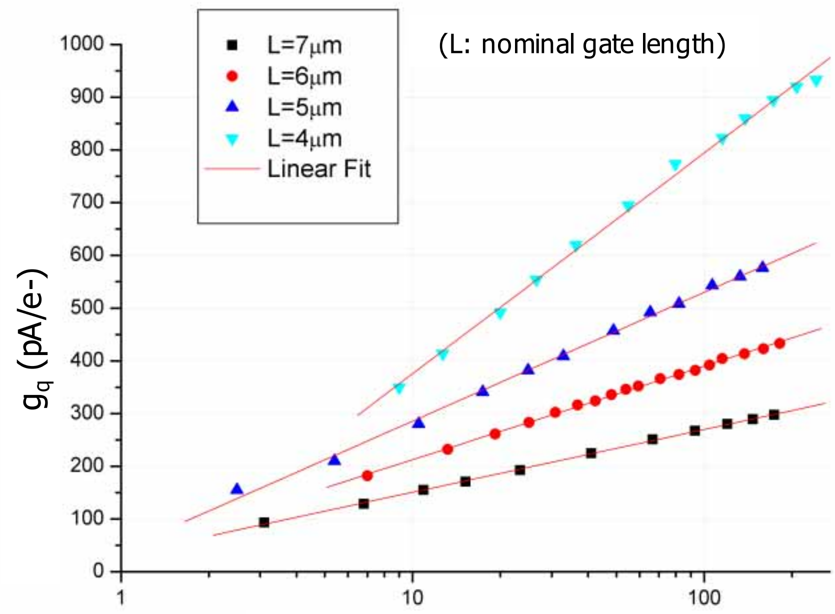
Internal amplification g_q

$$g_q = \frac{dI_D}{dQ} = -\frac{\mu_p}{L^2}(V_{GS} - V_{th})$$ (neglecting short channel effects)



effective gate length L_{eff} (µm)
L_{eff} = L - 2 x under etching of 1.2µm



- » As long as noise is dominated by r/o chip → S/N linear with g_q
- » PXD4 has L=6µm, some matrices in PXD5 have now L=4µm → expect factor 2 better S/N

Testbeam at CERN - Position resolution

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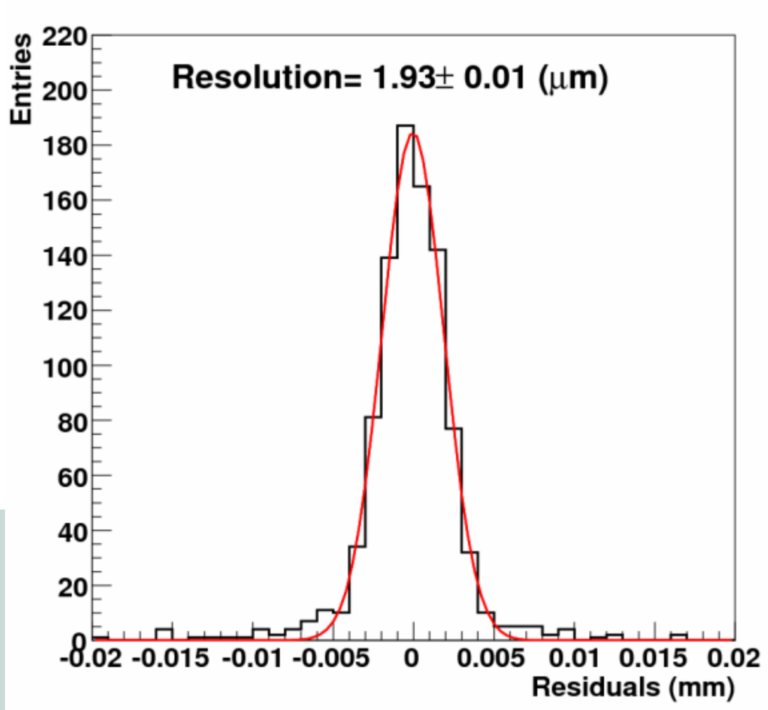

For 5 σ seed cut

- Efficiency ≈ 99.96%
- Purity ≈ 99.6 %

First preliminary result from CERN test beam,

129 GeV π, 33x23.75 μm² pixels

position resolution ≈ 2 μm

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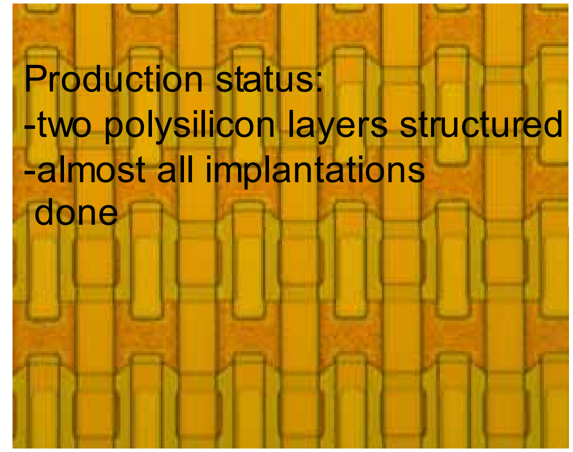
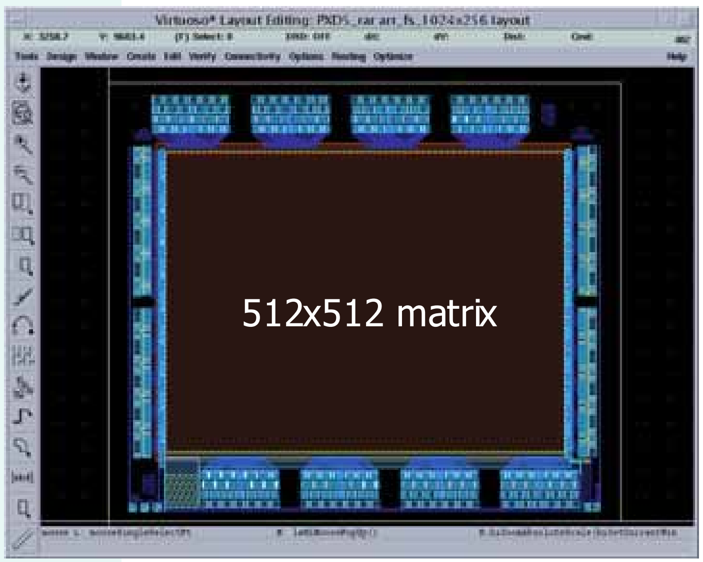
New DEPFET generation 'PXD5'

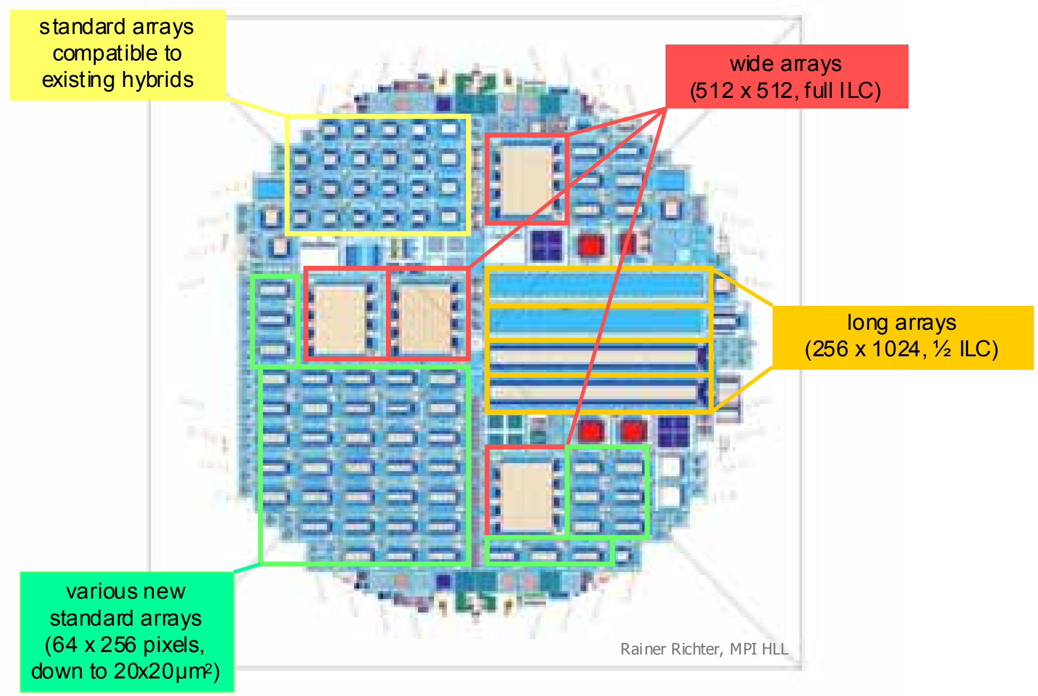
Mostly use 'baseline' linear DEPFET geometry
Build **larger matrices**
- long matrices (full ILC drain length)
- wide matrices (full Load for Switcher Gate / Clear chips)

Try new DEPFET variants:
- reduce **clear voltages** (required for radhard switcher technology)
  (modified implantations, modified geometry)
- very **small** pixels (20µmx20µm, baseline:24µmx24µm)

Add some bump bonding test matrices







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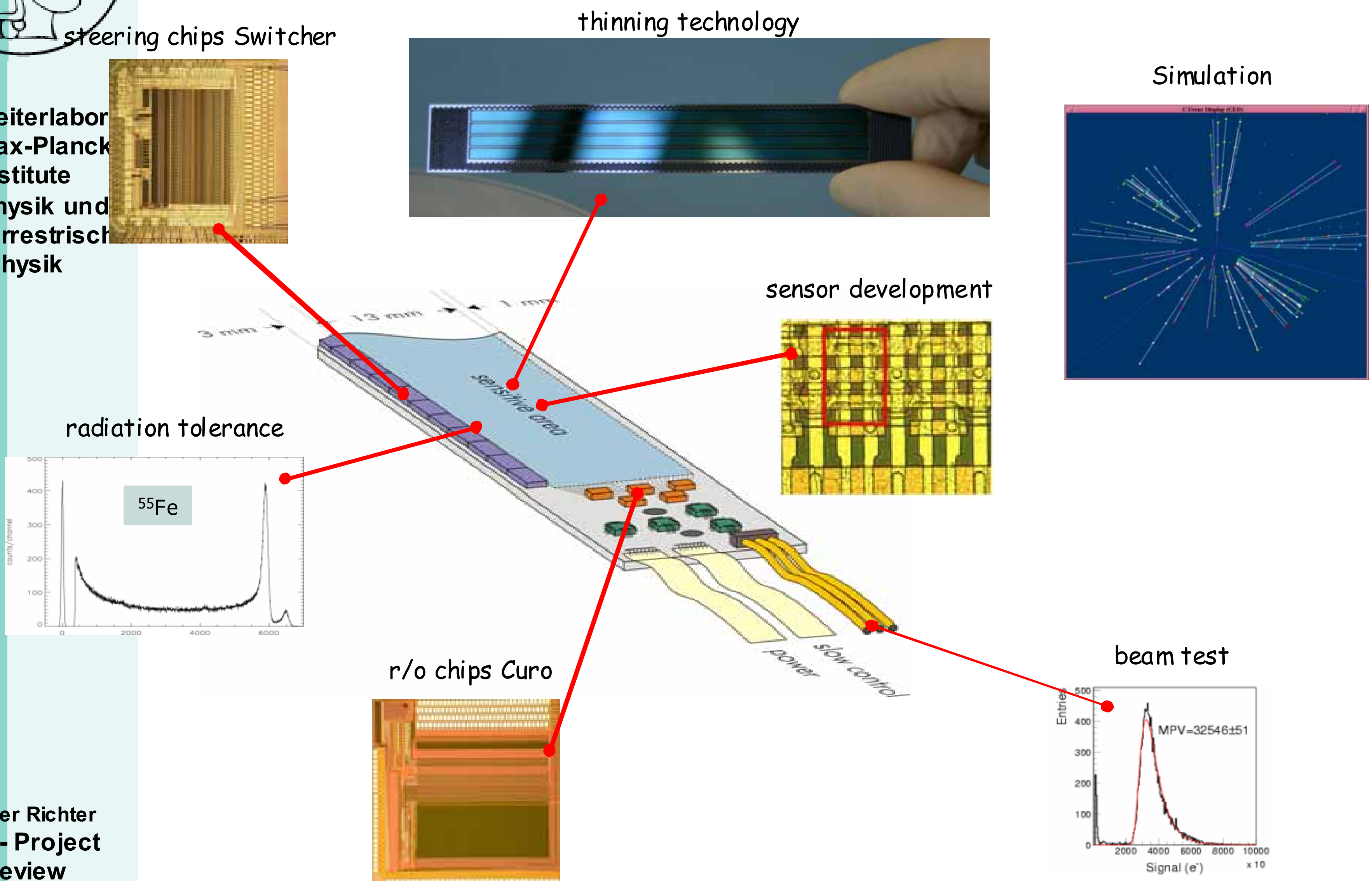
The DEPFET ILC VTX Project



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Growing collaboration

(www.depfet.org)

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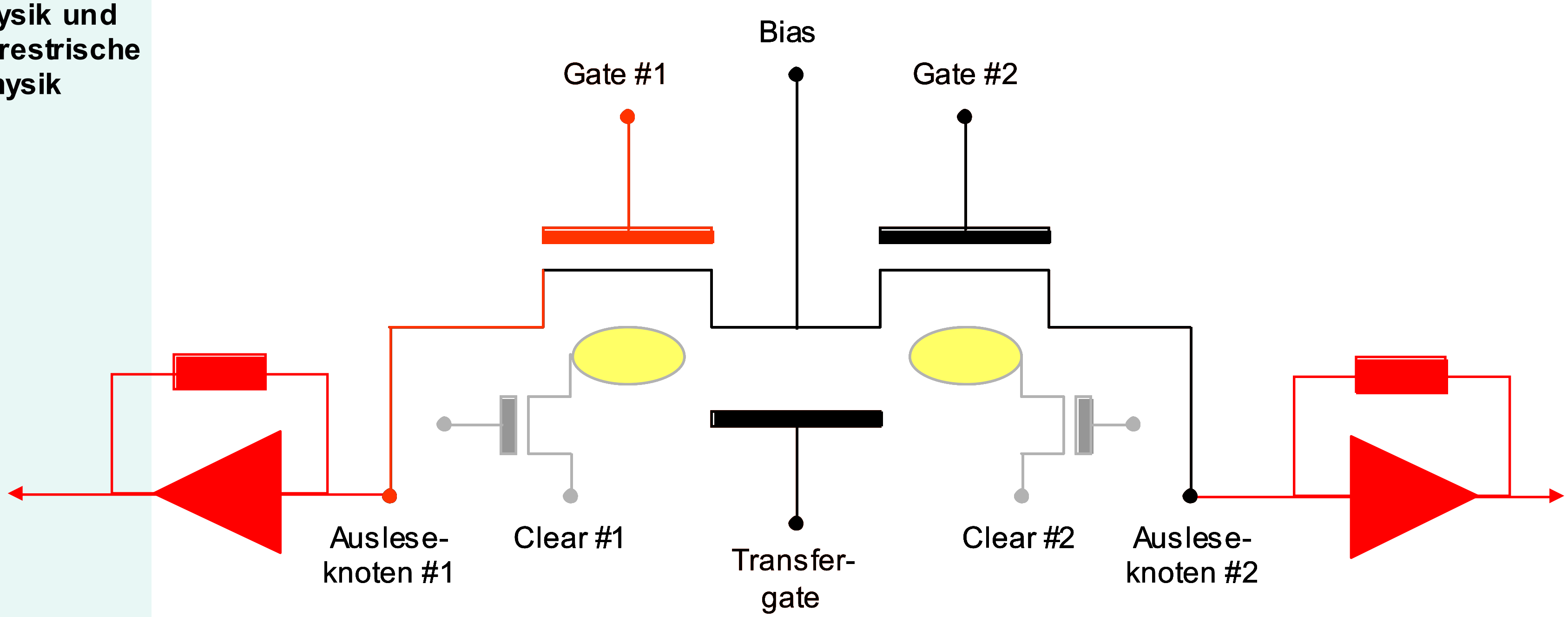
How to beat the 1e- noise threshold

RNDR (repetitive non destructive readout) with DEPFETs – Principle



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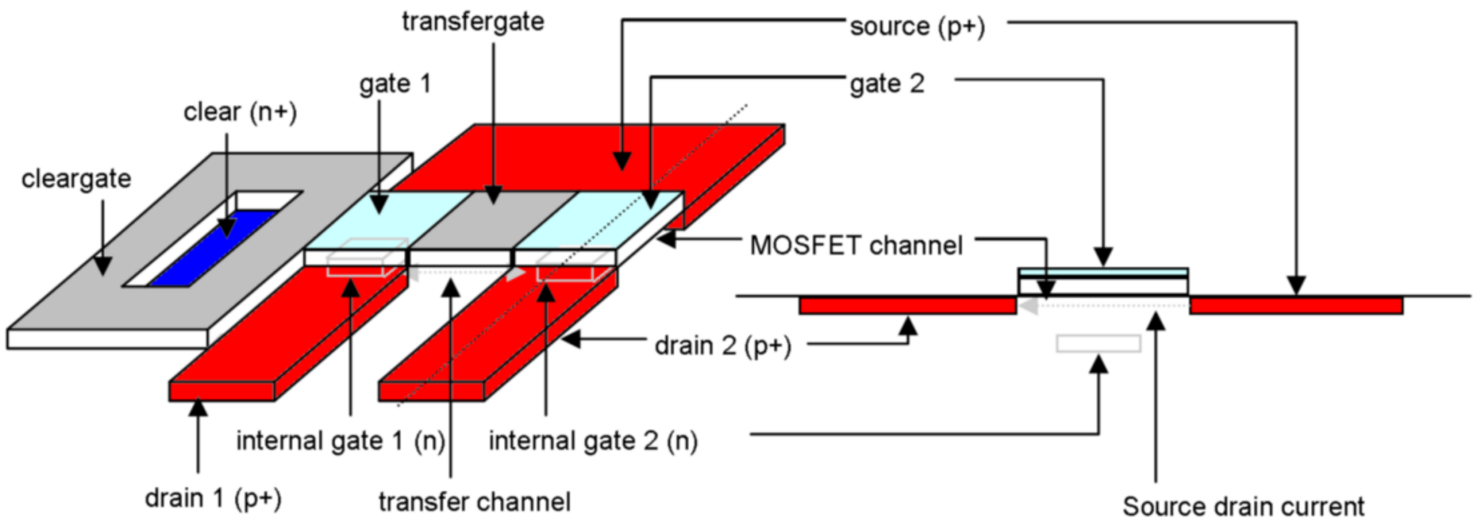
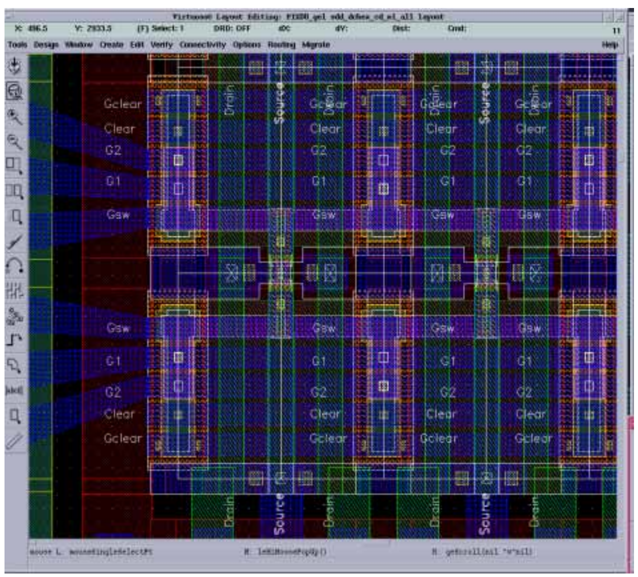
Realisation of a DEPFET- RNDR device





- ILC-Type RNDR
- Realised as a four by four Minimatrix

designed by G. Lutz

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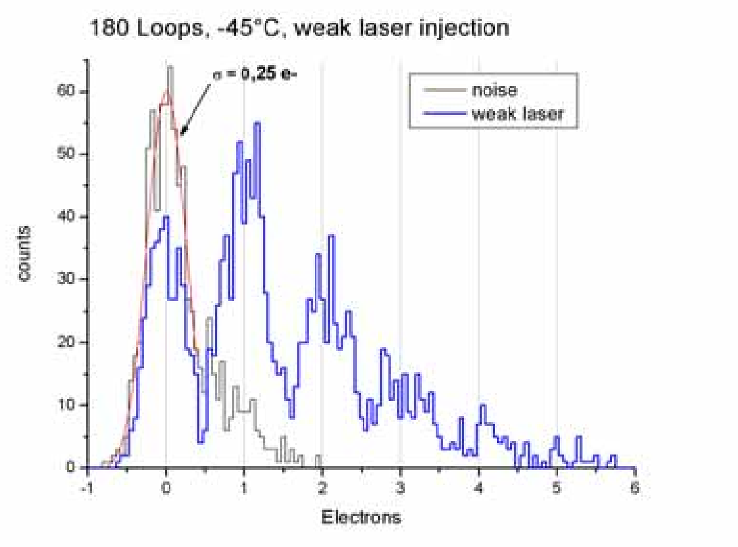
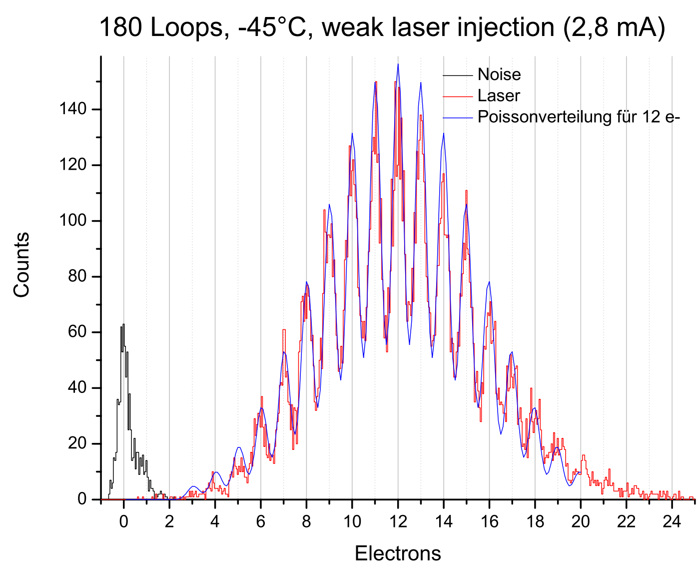
Laser spectra (S. Wölfel)





Measurement:

Charge injection with laser during integration time

180 Loops for the readout (duration: 9.18 ms)

-45 °C

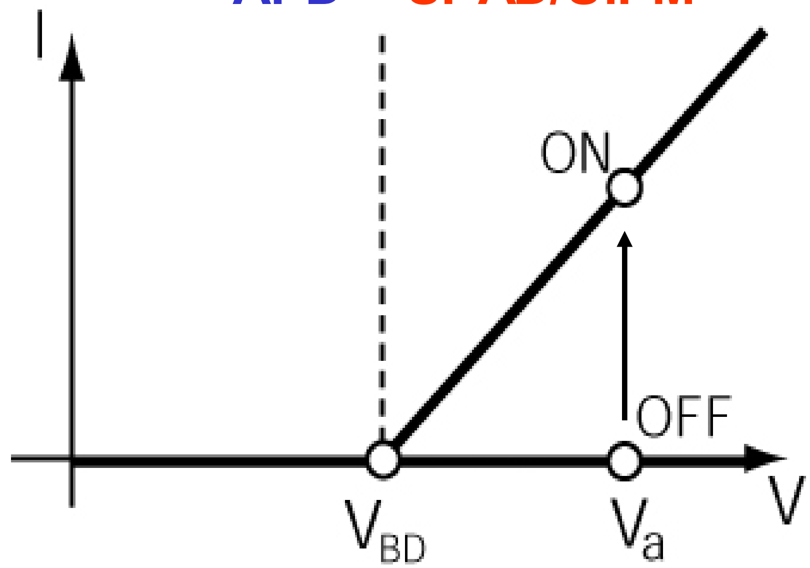
Measured leakage current:

ca. 0,4 e- in 180 loops

Avalanche PhotoDiode - Single-Photon Avalanche Diode

(after S. Cova)

APD **SPAD/SiPM**



- Bias: slightly ***BELOW*** breakdown
- Linear-mode: it's an ***AMPLIFIER***
- Gain: limited < 1000

- Bias: well ***ABOVE*** breakdown
- Geiger-mode: it's a ***TRIGGER*** device!!
- Gain: meaningless ... or "*infinite*" !!

Array of SPADs connected in parallel
to one readout node -> SiPM

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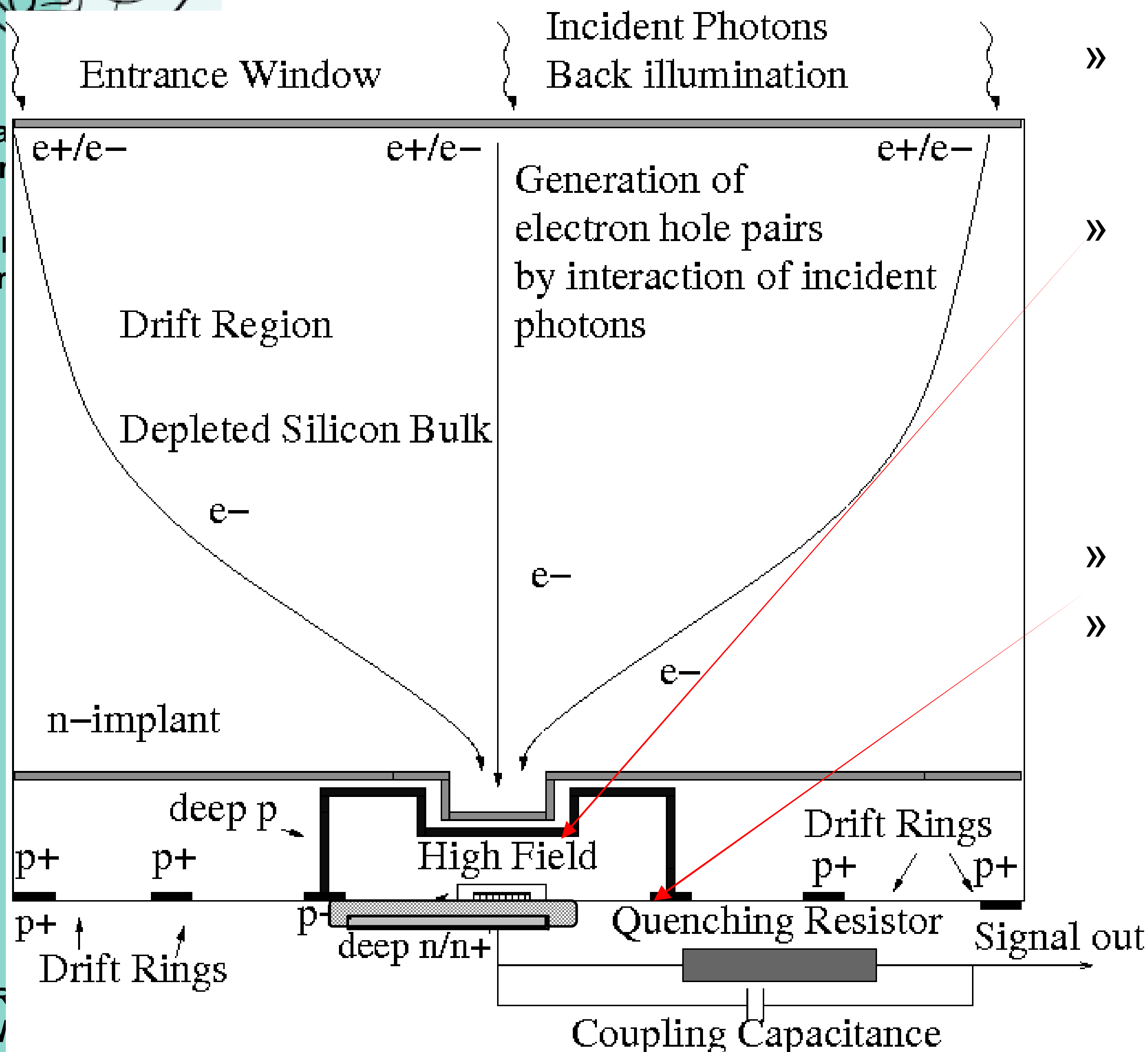
Concept of the BIDSiPM for high QE in the UV (MAGIC, EUSO, CTA)



» BID SiPM combines principle of Drift Diode and SiPM

» Modulated high field region necessary to avoid edge breakdown, modulated region has to be fully depleted for electron collection

» Passive quenching

» Combination of avalanche region with a drift region requires sideways connection of bias voltage for the avalanche region as amplifying unit

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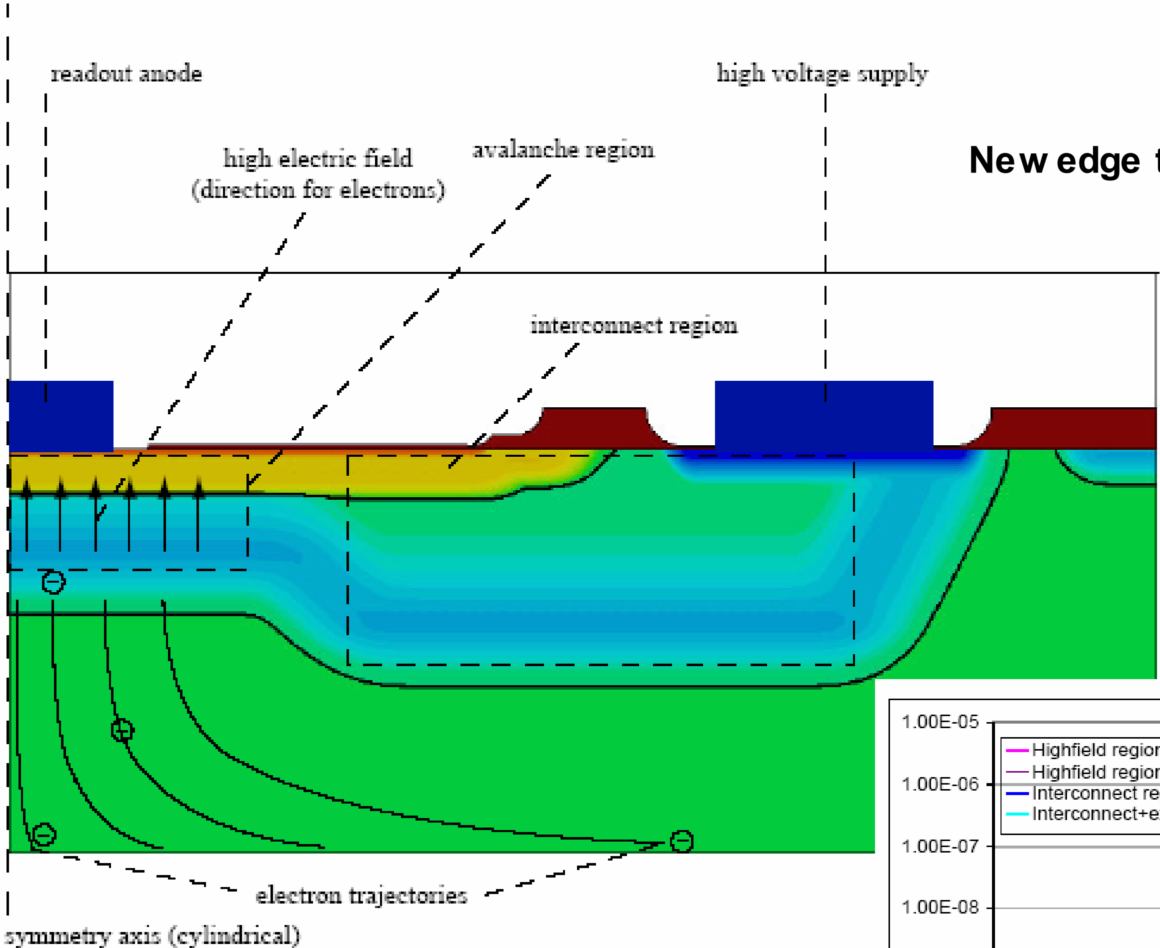
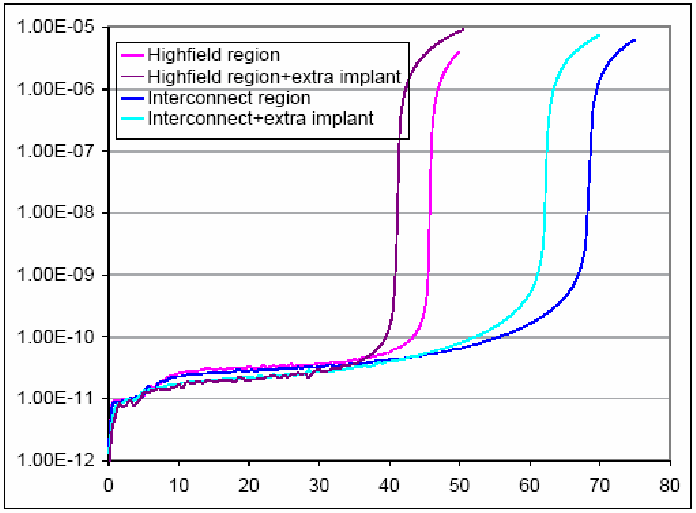
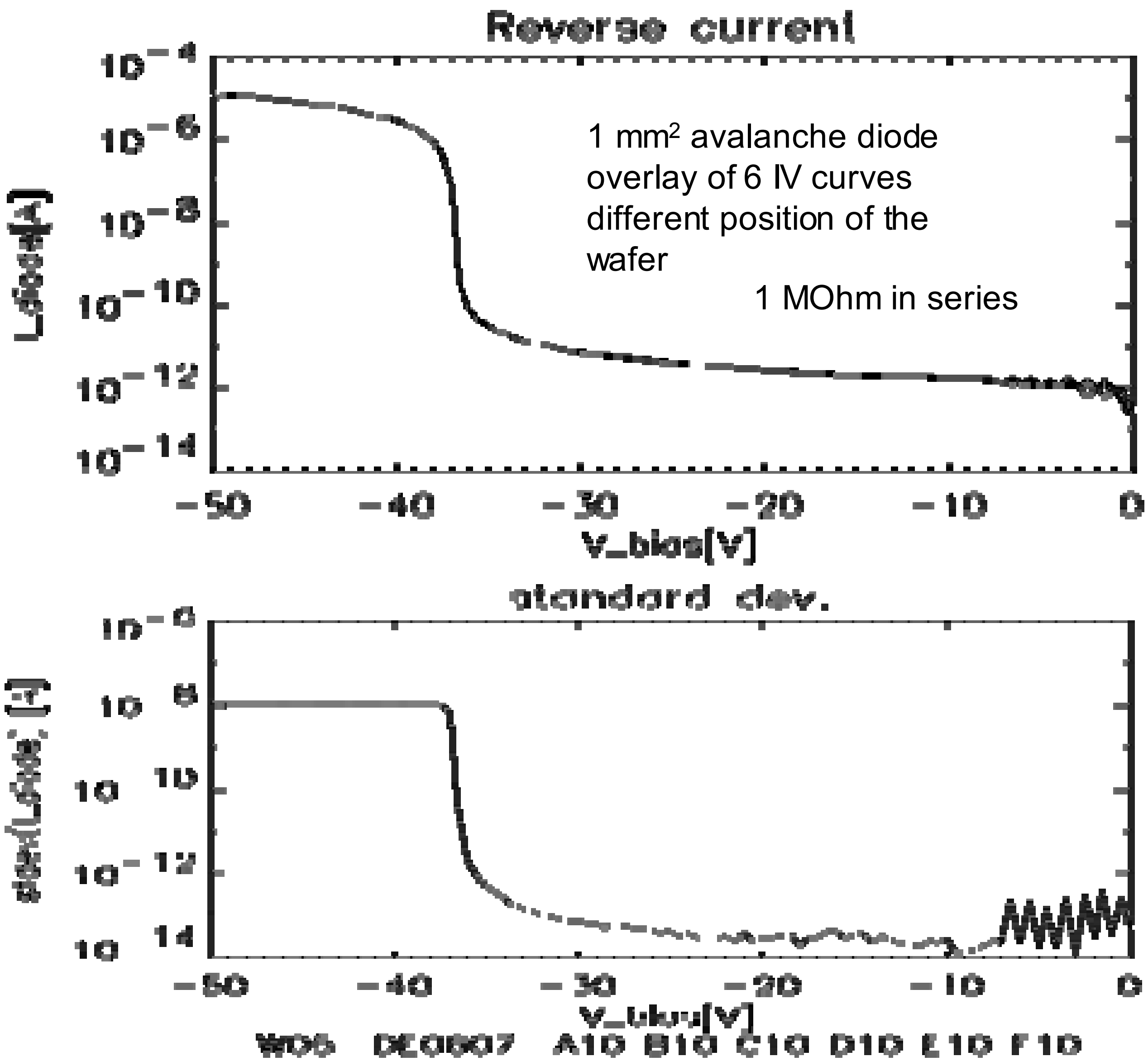
First Prototyping – single sided technology only



New edge termination structure !



Uniformity of leakage current and breakdown voltage



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Separation of Center and Edge Currents

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Constant area:1 mm^2

Different circumferences:

4mm (6x)

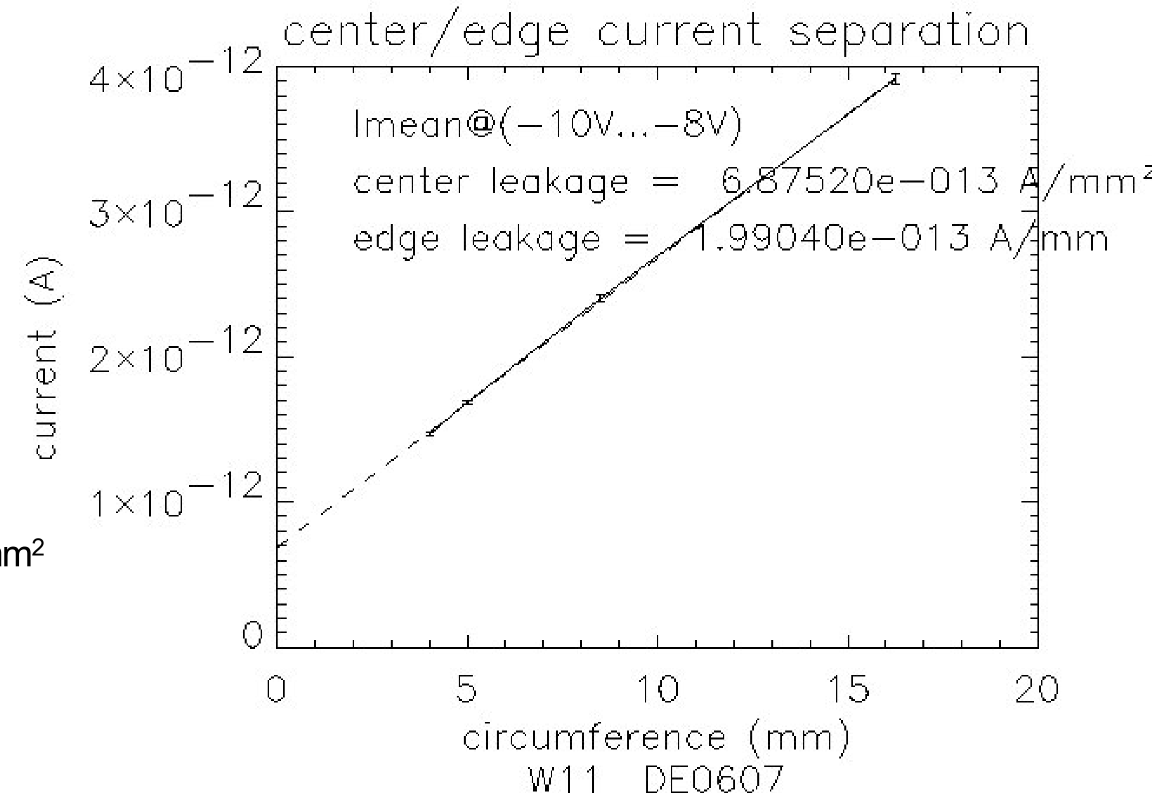
5mm(3x)

8.5mm(3x)

16.25mm(2x)

Leakage current

from the center ca. 0.5 pA/mm^2



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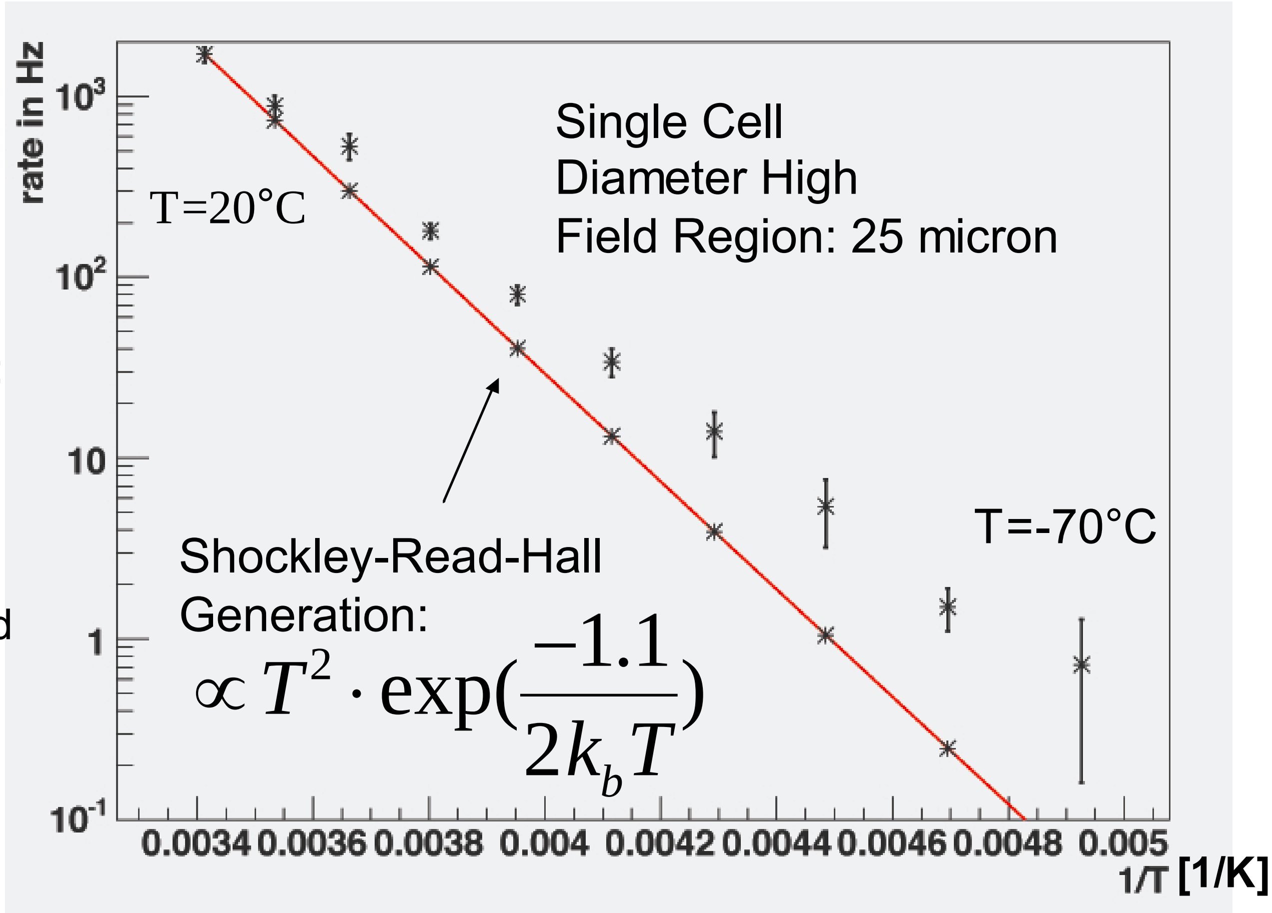
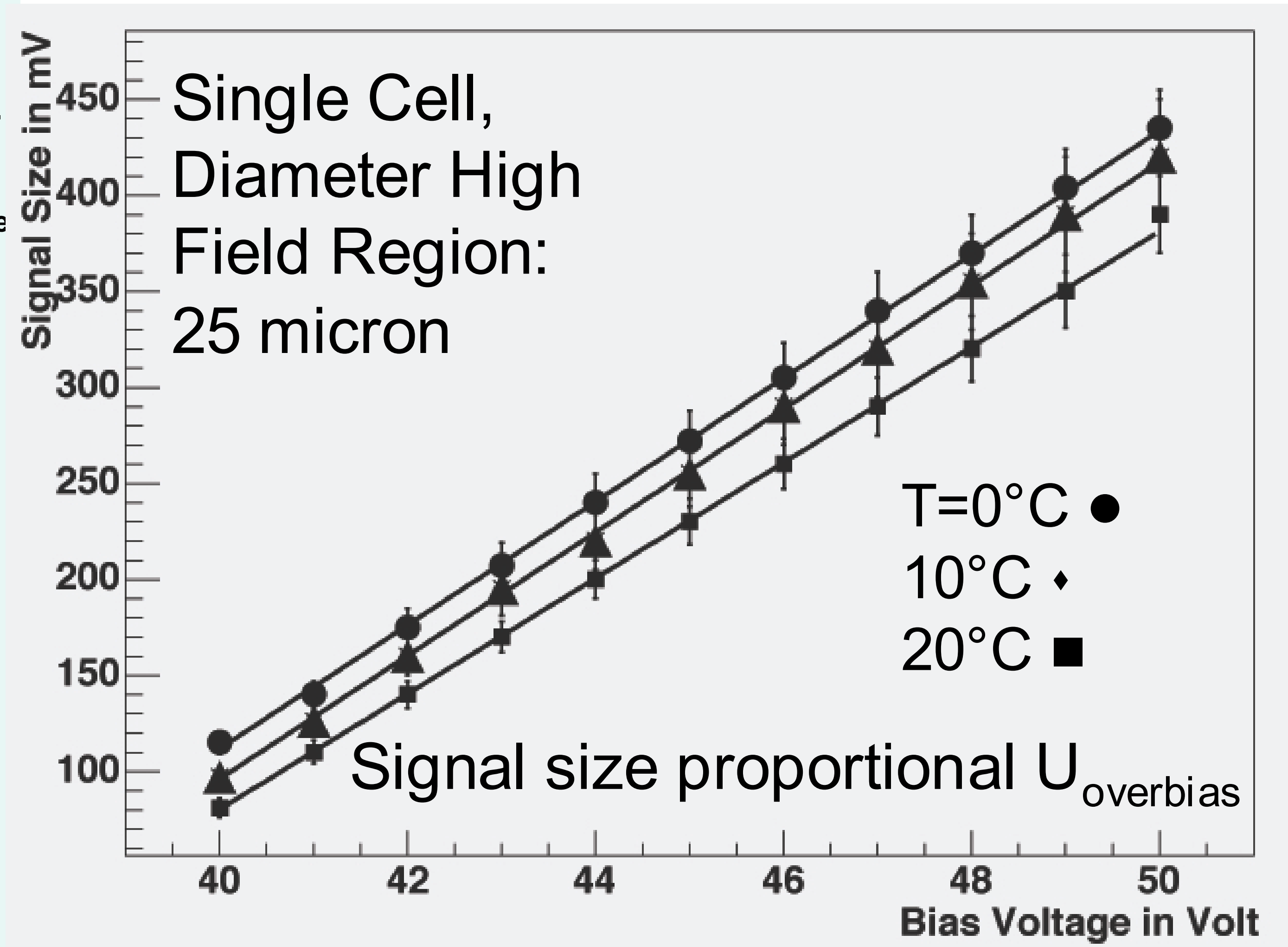
Dark Rate vs. Temperature

Rate for low temperatures higher than theoretically predicted from Shockley-Read-Hall Generation

Possible reasons:
- Traps ->afterpulsing
- diffusion of electrons into the high field region
- tunneling



Signal Size vs. Bias Voltage



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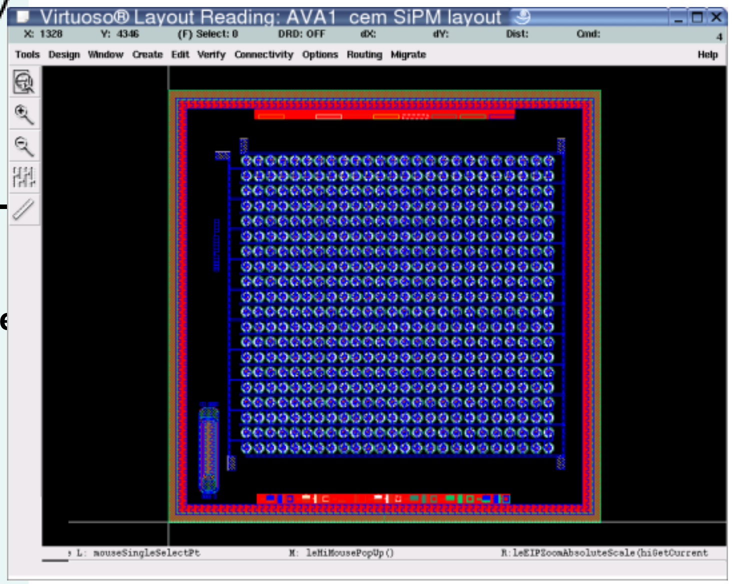
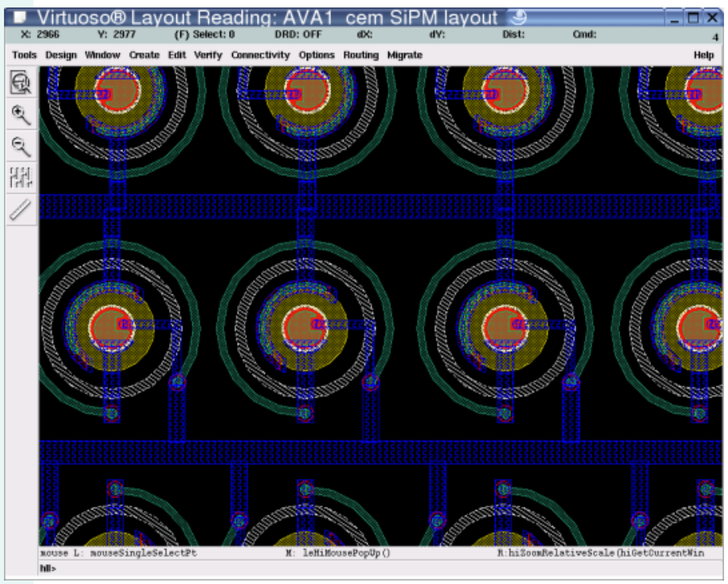
Photon spectrum

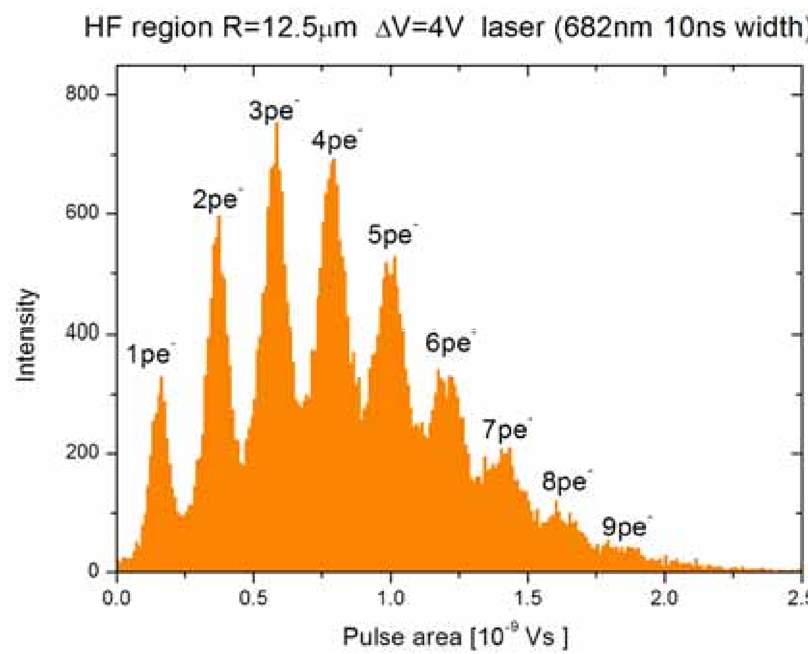




first prototype studies

still with provisional means (implanted resistors instead of polysilicon ones)

20x25 SiPM arrays



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BIDSIPM - further steps

Merge of Avalanche diode and Drift detector technology

-> backside illumination possible

Integration of readout network (quenching resistor and coupling capacitor) into each cell

Next production starts in February 07.

Open issue: optical crosstalk

Optical photons generated by the avalanche process itself trigger neighboring cells

Reduction of parasitic capacitances-> reduction of generated charge

-> reduction of generated photons

If this is not enough: Optical insulation by V-groove etching becomes necessary.

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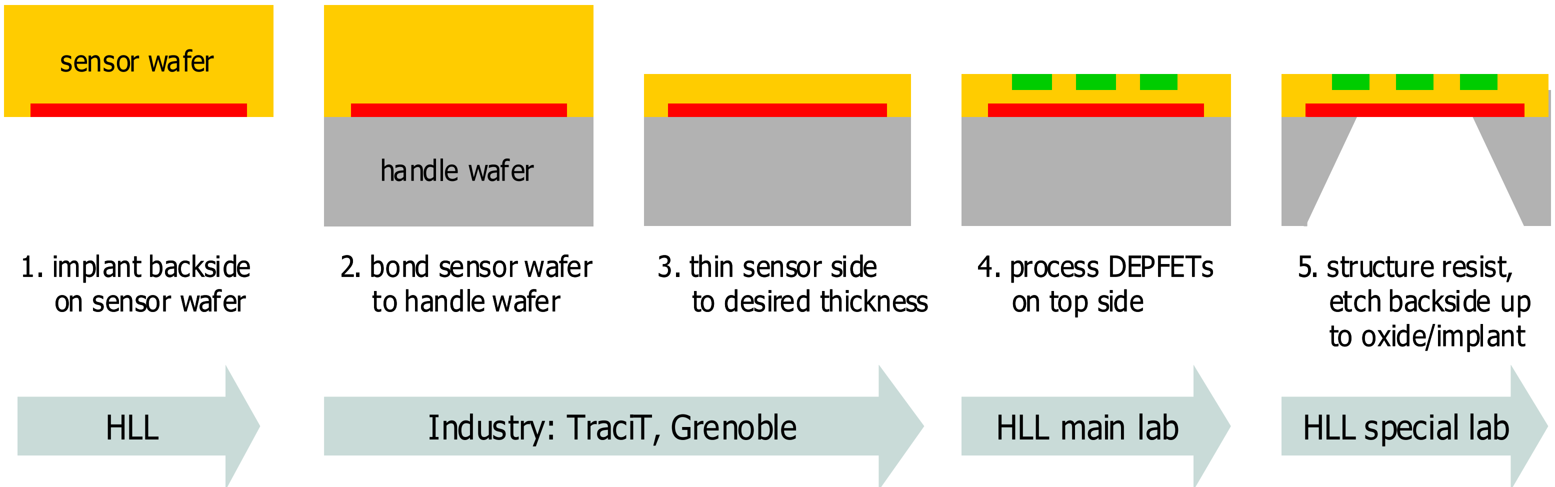
Backside thinning – based on wafer bonding



» New: **150mm Ø** wafers!

» New: Wafer bonding and thinning in **industry**

» New: Processing in **HLL main lab**

⇒ Still in R&D phase:

⇒ 1: process test structures on SOI wafers

⇒ 2: mechanical samples

rev2

PiN Diodes on thin Silicon

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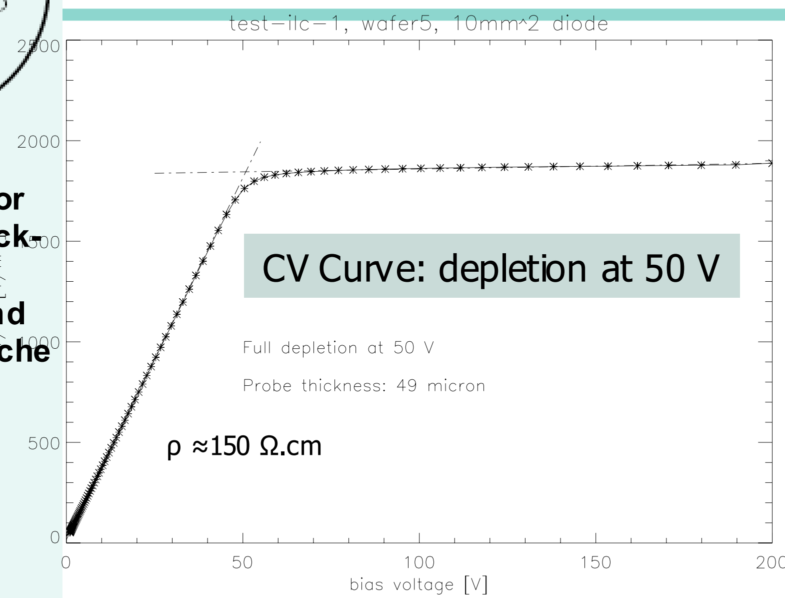
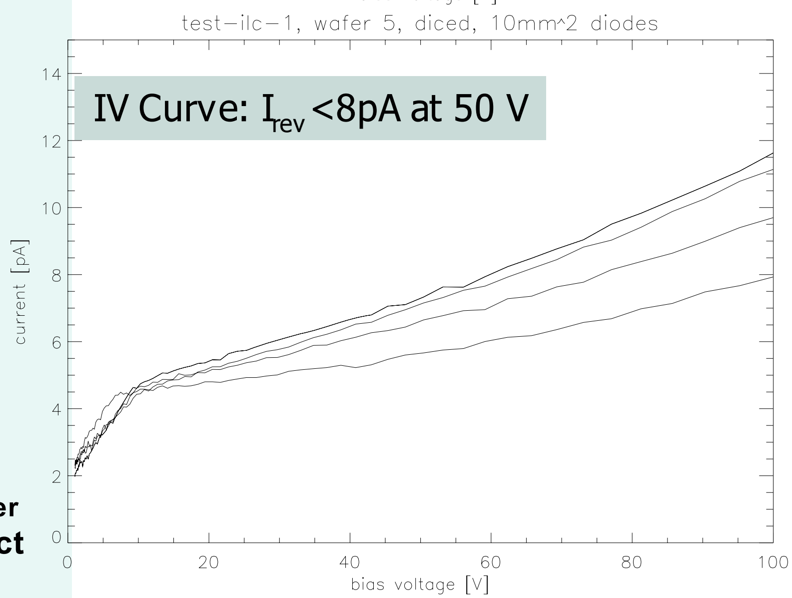
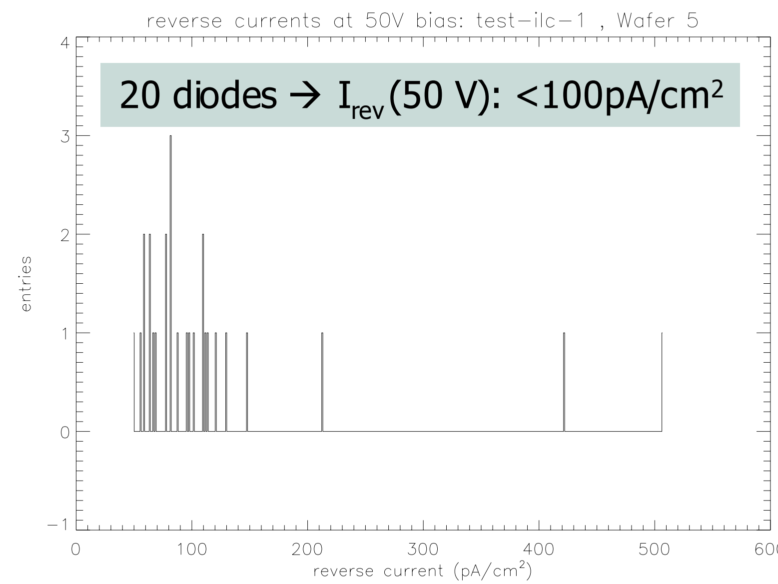


Thin diodes have **excellent** leakage currents.

Processing of the SOI wafers and removal of handle wafer **does not degrade devices**!





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Slide 24

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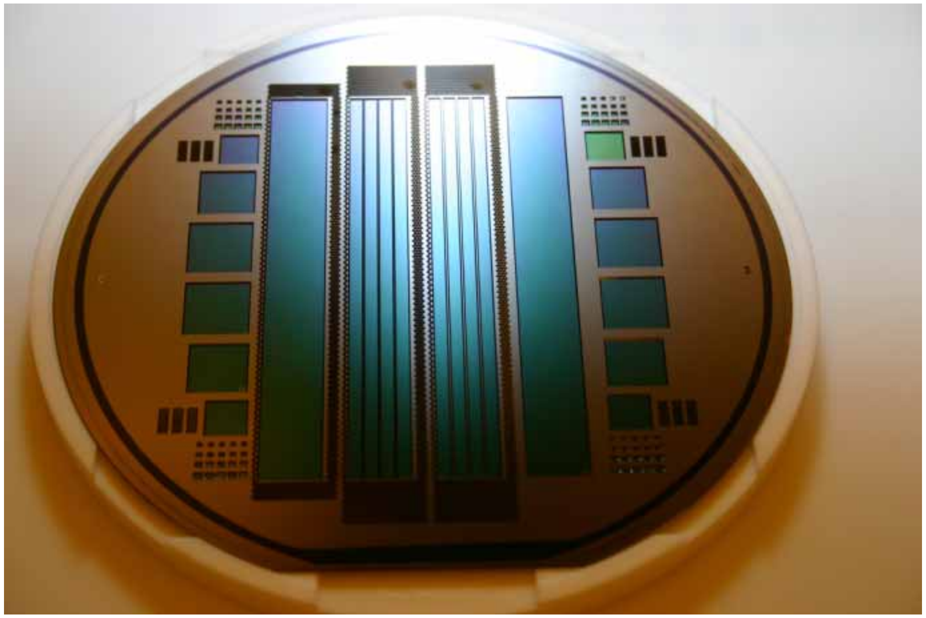
rev2 These are encouring results not only for DEPFETs but also for our back illuminated avalanche diodes as we will see later

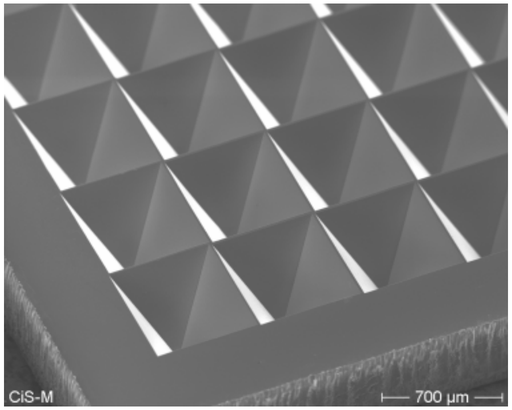
rar, 12/16/2006

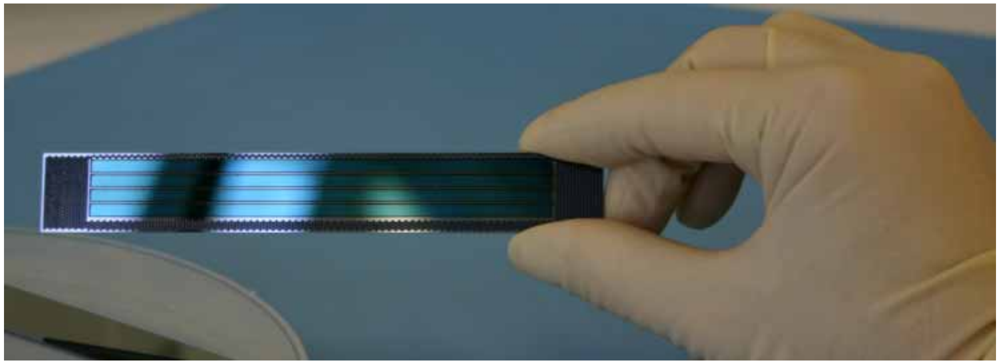
Prototypes

Thin (50 μm) silicon successfully produced at MPI.

- **MOS diodes.**
- **Small strip detectors.**
- **Mechanical dummies.**
  1.3 x 10 cm^2 plus stiffening frame & reinforcement bars.
- **No deterioration of detector properties, keep I_{leak} < 100pA/cm^2**







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R&D for a novel pixel detector for SLHC

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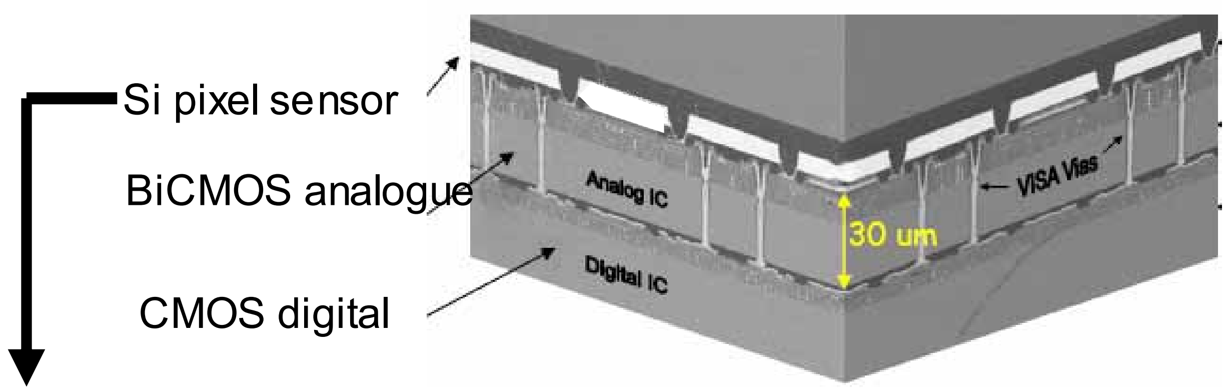
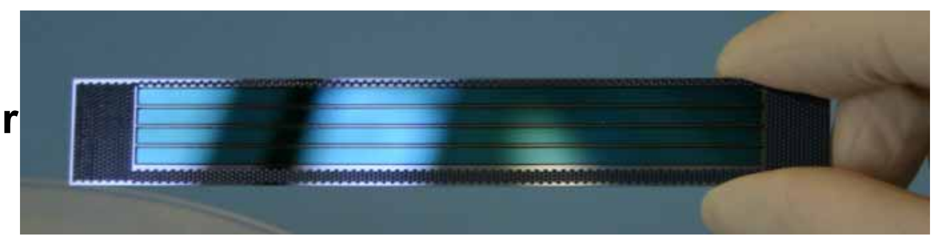
3D integration (sensor – electronics; electronics – electronics):

Alternative to bump bonding (fine pitch, potentially low cost?).
New possibilities for ASIC architecture (multilayer, size reduction).
Optimization of rad. hardness, speed, power.
Impact on module design (ultra thin ASICs, top contact, 4-side buttable).



R&D on thin (O(50μm) FZ silicon detectors:
Based on well known pixel sensor technology.
Can be operated at 10^{16} n/cm^2 (V_{dep}, I_{leak}, CCE).



Can lead to an advanced module design: rad hard with low material budget
MPI will work with Fraunhofer IZM, Munich.

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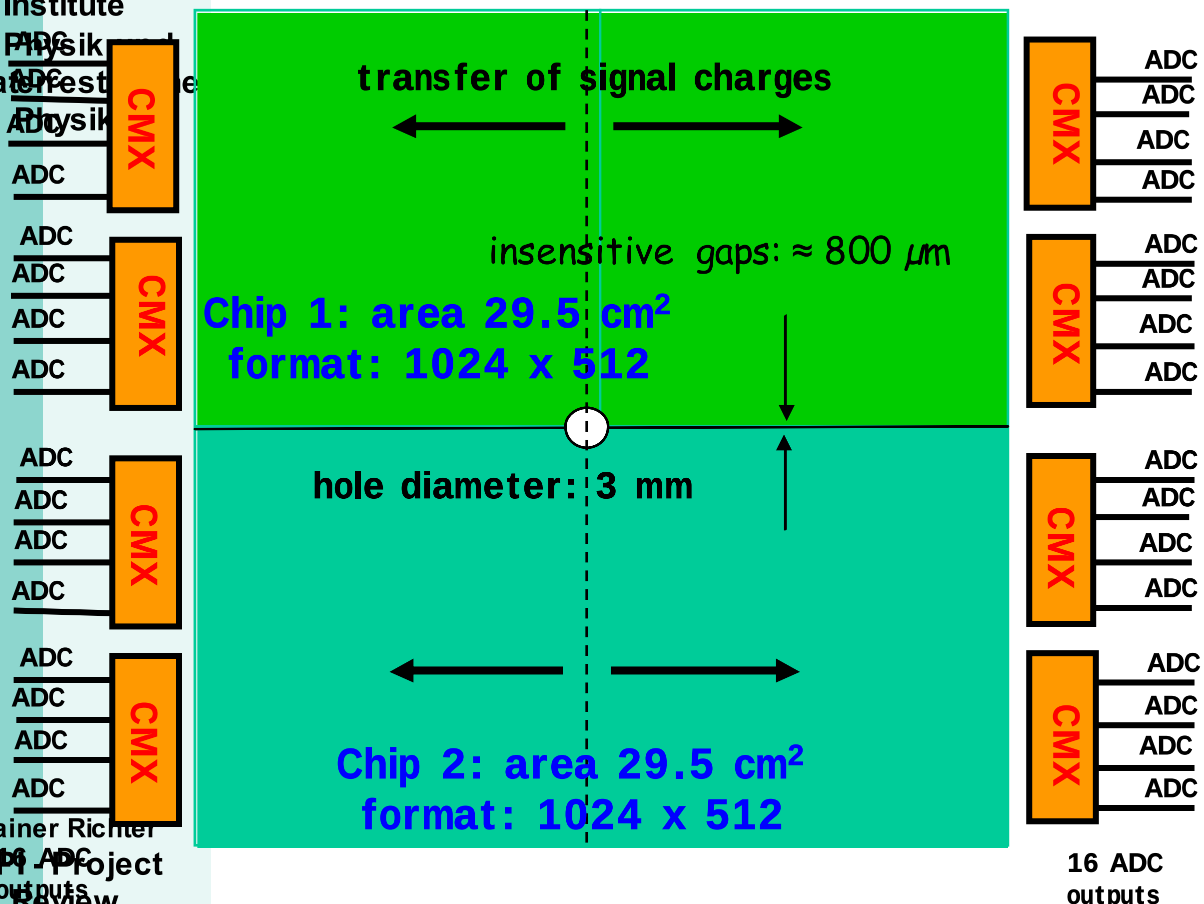
Proposal for the LCLS+XFEL detector

devices are in preparation, fabrication ready: mid. 2007

The full sensitive area of the system is 59 cm² with 75 µm pixels, 1024 x 1024



Full Frame imaging area per chip 512 x 1024

pixel size 75x75 µm²

total area per chip: 29.5 cm²

readout time per frame: 4 ms i.e. 250 fps

Total sensitive system area: 59 cm

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Device proposal for the XFEL: CDD+int. frontend (phase I, prototyping)

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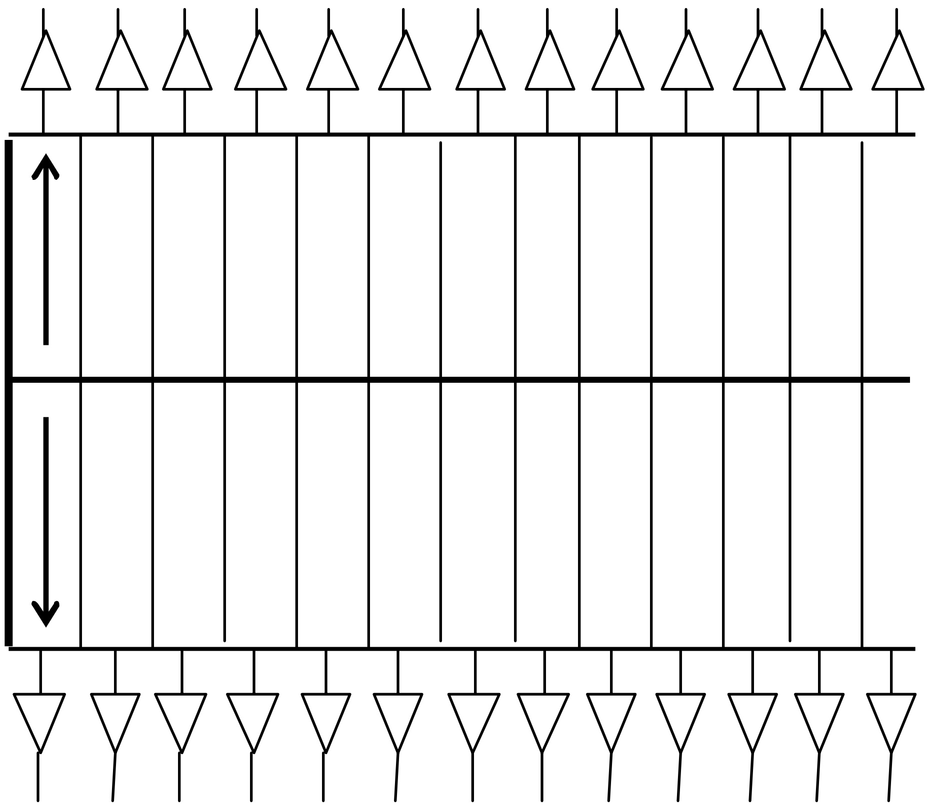
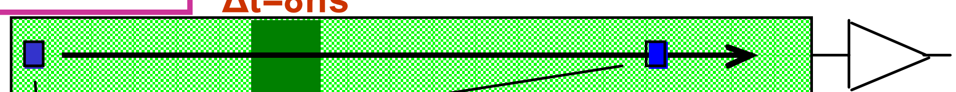
- 256x256
- 2x256 channels
- 1 MHz
- 100µm pixel
- room temp.
- 10^3 - 10^4 X-rays
- QE>80%@10keV
- ENC<30 el.
- Expandable to:
- 512x512
- 1024x1024
- (no dead area)



Δx=100µm
Δt=8ns



The final pixel size will be 100µm < x < 200 µm

drift velocity calibration with electron injectors

V_{drift} ≈ 13 µm/ns (i.e. ~3.5V/30µm bias)
$T_{drift, max}$ = 1000 ns

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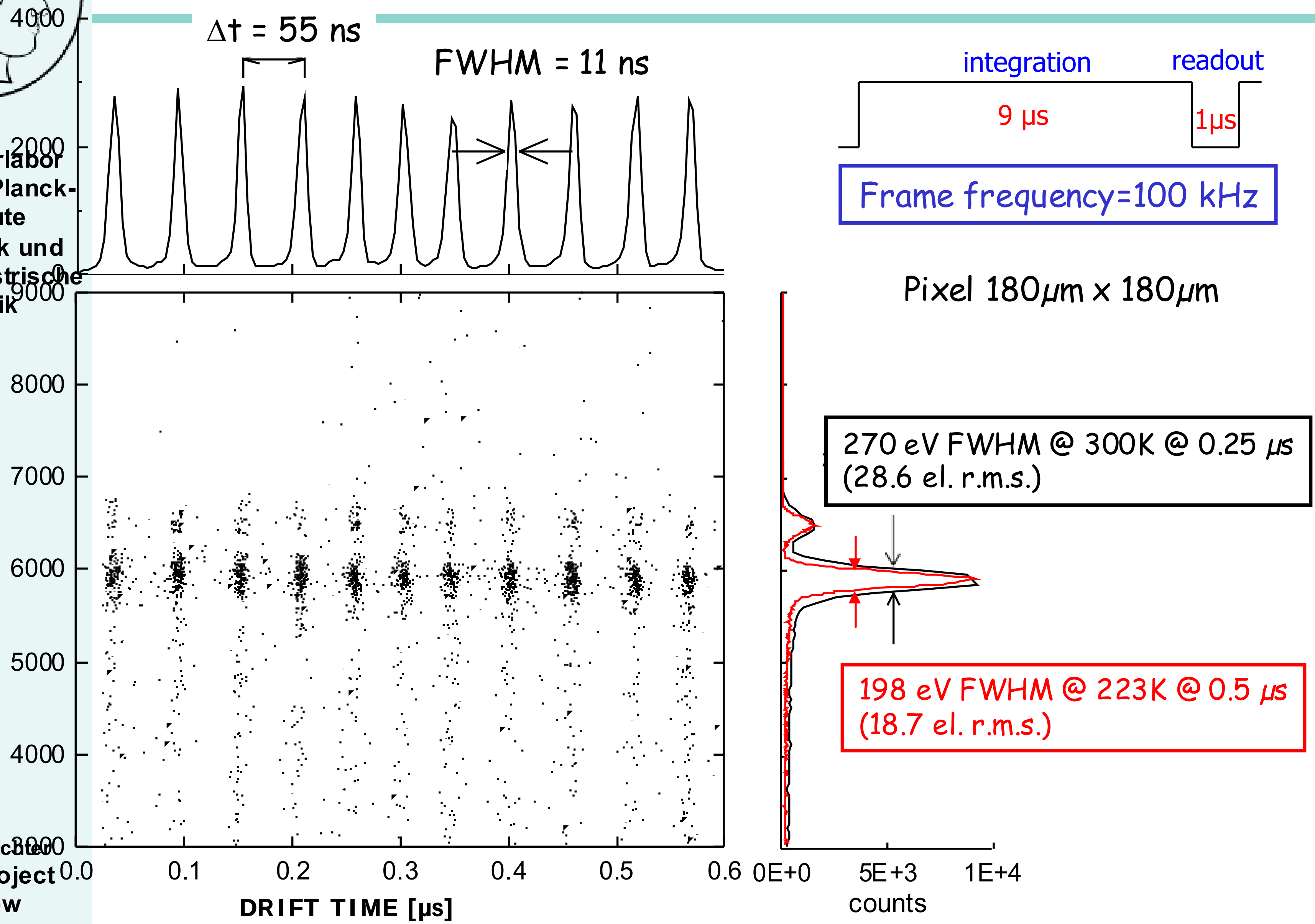
Imaging and spectroscopy of a Fe-55 source @ 100 kHz

A.Castoldi, C.Guazzoni, P.Rehak, L.Strüder, et al, Trans. Nucl. Sci. 49 (3) June 2002



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Detector technologies and Projects

- DEPFET – ILC, Bepi Colombo, Symbol-X, XEUS, XFEL
  - RNDR with DEPFETs
- pn-CCD – eRosita, XFEL

  Si Drift Diodes, XFEL
- Avalanche photodiodes

  Si Photomultiplier (BIDSIPM) - MAGIC, EUSO, CTA

  AA-pnCCD - HTRA
- Thinning Technology – ILC, MAGIC, SLHC

- Back thinning based on wafer bonding becomes a key technology for many projects!

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Projects at the MPI Semiconductor Laboratory

(Stand: November 2006, LTS,)

MPE main project
MPE project
HLL project
MPP main project
MPP project
MPE & MPP project
CFEL project ASG of MPG

Present projects	Institute	Physics goal	Basic method	Semiconductor device	Status	Funding	Perspectives
XEUS (X-Ray Evolving Universe Spectrometer) The wide field imager	MPE ESA (LU ?)	First massive black holes. First galaxy groups and their evolution into the massive clusters Evolution of heavy element abundances. Intergalactic medium using absorption line spectroscopy.	Large area X-ray mirror telescope with a large area silicon detector	Thick DEPFET-pixel detector sensitive thickness: 500μm Format: 1024 x 1024 pixel	First small size prototypes produced and under test *System test starting in beginning of 2004*	TRP contracts with ESA: 2001: 300 k€ 2002: 550 k€ 2003: 550 k€ *2004: 550 k€* 2006: 150 k€	XEUS will get additional funding in 2005 and 2006 *XEUS is still on* the ESA agenda with high priority

eROSITA	MPE ROSK DLR ESA	All sky X-ray survey	X-ray mirror telescope of same construction as in DUO	Same as in DUO pixel size: 75·75 μm^2	Same as in DUO	248 k € in 2006	launch: 2011, mission approved
SIMBOL-X	MPE Saclay Brera IAAT Tsinghua	X-ray astronomy	Macropixel detector in focal plane of X-ray mirror telescope	Macro-pixel-detector (combination of drift detector and DEPFET)	In production on the MEGA wafers	No funding	Project no yet approved by nat. funding agencies
BepiColombo	MPE MPI LUniv	planetary science, Processes and chemical composition of Mercury	Imaging optics – scanning – with spectroscopic X-ray detectors	Macropixel detectors	MM; EM, QM, FM, FS actually in production	220 k€ by ESA approved, 700 k€ promised by ESA, 750 k€ requ. by MPI L.	
XMM ``consulting''	MPE ESA	Early universe, diffuse X-ray background, etc.	Wolter type X-ray telescope, X-ray CCD	Full frame pn-CCD	launched in 1999 - operational	no funding	operation guaranteed up to 2010
HTRA, old High Time Resolution Astrophysics	MPE MPIA MPA Opticon	Observation of rapidly varying objects	Optical ground based telescopes 4 – 8 output nodes	pn-CCD pixel size: 51·51 μm^2	Produced together with DUO	no funding	More systems will be needed at a later stage
HTRA new High Time Resolution Astrophysics	MPE MPIA MPA Opticon	Observation of rapidly varying objects	Optical ground based telescopes 4 – 8 output nodes	AApn-CCD pixel size: 48·48 μm^2	Produced together with AApnCCDs and BIDSiPM	from 2004-2006 500 k€ through OPTICON in EU – FP6, ESO	More systems will be needed at a later stage
XEUS: The fast timing detector	MPE CESR ESA	Fast timing observation of bright X-ray sources	SDD in focal plane of XEUS wide field imager	Silicon drift detector array, 19 cells	Prototypes produced together with SIDDHARTA	Up to now: No funding	Decisions: Upon approval of XEUS through ESA
Hard X-ray detector	MPE	High energy X-ray detection up to 200 keV	Scintillator readout with SDDs	Silicon drift detector arrays	In production	Up to now: No funding	Project MAGIC discontinued at MPE
Mars Mission EXOMars	MPE MPI Che. Uni Mainz ESA	Marsian geology	Mößbauer strectrometry, XRF	circular SDDs	proposal phase PI: Univ. Mainz (Klingelhöfer)	funding through University of Mainz	similar to the previous NASA Mars mission

Wide Field camera from IR to X-rays	MPE MPQ LMU EXcluster	Attosecond lasers for table top light source	Qualification of test set up	pnCCD 256 x 256 50 or 75 µm pixel size	Project **approved** devices are operational	250 k€ from DFG thru LMU thru EXcluster	More systems needed for the same type of experiments
BIB Detektoren	MPE, IR	IR astronomy	Silicon BIB detector up to 300 µm	pn diodes on epi silicon	preliminary study	none	not yet discussed with RG
Front-end electronics DLR - First chance	MPE, DLR	Development of commercially useful frontend ASICs	Arrays of parallel amplifiers with MCDS and gaussian shaping	CAMEX and ROTOR type devices	contract end in march 2004, extension possible up to 2006	2002: 125 k€ 2003: 125 k€ 2004: 40 k€	abgeschlossen
ESA Scint	MPE, Politecnico di Milano	basic technological tests	Gamma spectroscopy	SDDs coupled to scintillators	design, fabrication	ESA funding: 30 k€	subcontractor of Politecnico di Milano
Sensors for adaptive optics, wave front sensors	MPE ESO Opticon	Rapid corrections for change of athmosphere	4 – 8 output nodes, Reduction of readout capacitance, low noise required	pn-CCD pixel size: 51·51 μm^2 No Reset implemented	Produced together with DUO	Total return through PNSensor: 140 k€	If successful in 2007, 15 systems needed
SIDDHARTA	MPE Frascati Wien	Investigation of kaonic atoms	X-ray spectrum and lifetime	Drift detectors ~200 of 1cm2	fabrication start July 2004	Funded through EU FP6; PNSensor + HLL: 498 k€	Start of the experiment in 2005
DRAGO	MPE Politecnico Milano	Medical imaging	Combination of CsI crystal with multicell SDD	Multicell Silicon drift detector	In production on MEGA wafers. Process finished: March 2004	65 k€ through INFN to PNSensor for layout and simulation	
FELIX	MPE Milano	X-ray fluorescence (art)	Direct detection of radiation	Silicon drift detectors	In production on MEGA wafers	25 k€, through INFN to PNSensor for layout and simulation	Project finished in 2006

Projects under the umbrella of ASG and CFEL (MPE+MPP)							
XFEL Detector LSDD	MPE, Uni Mannheim CFEL, DESY, Uni Siegen, etc.	Structure of solids, molecule imaging, chemical reactions	Diffraction and scattering experiments at synchrotrons	CDDs terminated with DEPFET amplifiers, CMOS electronics development	conceptual design study, prototype development	Funding through XFEL GmbH, 10 participating institutions recommended for funding from 2007-11 total: 7 M€	Nutzer XFEL Hamburg, CFEL
FLASH detector systems	MPE, Uni Siegen DESY	Structure of solids, molecule imaging, chemical reactions	pump-probe x-ray ph.correlation coherent diffraction and single particle imaging	pnCCD detector system	``small`` pnCCD system, 384x384 tests and experi-ments @ DESY	funding through DESY (300 k€) not yet approved !	
pnCCD Camera for PETRA III	MPE, CFEL DESY Uni Siegen	Structure of solids, molecule imaging, chemical reactions	pump-probe x-ray ph.correlation coherent diffraction and single particle imaging	pnCCD detector system	1024 x 1024 format	funding through DESY (1.800 k€) not yet approved !	
LCLS Detector	MPE, CFEL DESY Uni Siegen	Structure of solids, molecule imaging, chemical reactions	pump-probe x-ray ph.correlation coherent diffraction and single particle imaging	pnCCD detector system	1024 x 1024 format	funding through CFEL, 3.100 k€ APPROVED !	

Present projects	Institute	Physics goal	Basic method	Semiconductor device	Status	Funding	Perspectives
ILC Vertex detectors	WHI Bonn Präg Berkeley	e+e- collider physics	Thin fast vertex detector	Thin DEPFET pixel detector	Thick detector prototypes produced. Thinning technology developed	2002: 45 k€ 2003: 45 k€	Funding(BMBF) discontinued TESLA (or any LC) is still under study
SLHC LHC Upgrade	MPP, ATLAS Team	Higg´s spectroscopy	Particle detection and reconstruction identification HEP detector	silicon strip detector, thinned, luminosity increase	Start of concept development Exp. start: 2013	none	major future high energy physics experiment
EUSO and successors	WHI and others	Very high energy cosmic ray observation	Observation of showers in atmosphere from space (ISS)	Back side illuminated avalanche detectors	Concept being developed	No funding	Project no yet approved by nat. funding agencies
MAGIC, CTA SiPMs and successors	WHI	Very high ener-gy air shower detection	Imaging of fluorescent and Cerenkov light with SiPMs	Avalanche embedded Silicon Drift Detectors operated in Geiger mode	Design, Fabrication of first test structures	Funding thru MPG Grossgeräteantr ag: approx. 250 k€ to PNS	Potential candidates for HESS and other low light level applications
GERDA	MPP MPI-KP	neutrinoless double beta decay		Ge detectors	pending	none	
Muon collider	WHI	Accellorator development	Muon capture cross section measurement	Silicon drift detectors	Test samples of SDDs delivered	Up to now: No funding	Funding through BMBF envisaged at later stage
Radiation dammage	MPP, RD50	Understanding, modelling of RD	solid state analysis before and after RD	Diodes , SSDs	in progress	none	ongoing activity

ATLAS ``consulting''	WHI and others	Higgs spectroscopy, test QCD, etc..	Vertex detection	radiation hard silicon strip detectors	development completed, module test ongoing, test	no funding	first data from LHC in 2007
CAST (Cern Axion Search Telescope	WHI MPE CERN and others	Search for solar axions with an X-ray telescope	Wolter-type X-ray optics, pn-CCD in the focus	pn-CCD (XMM type, or later DUO type)	Operational since 2002	2002: 99 k€ 2003: 99 k€ 2004: 99 k€	Upgrade foreseen in 2004/2005 (Helium inside the magnet volume)

Conceptual Module Design of a SLHC pixel module

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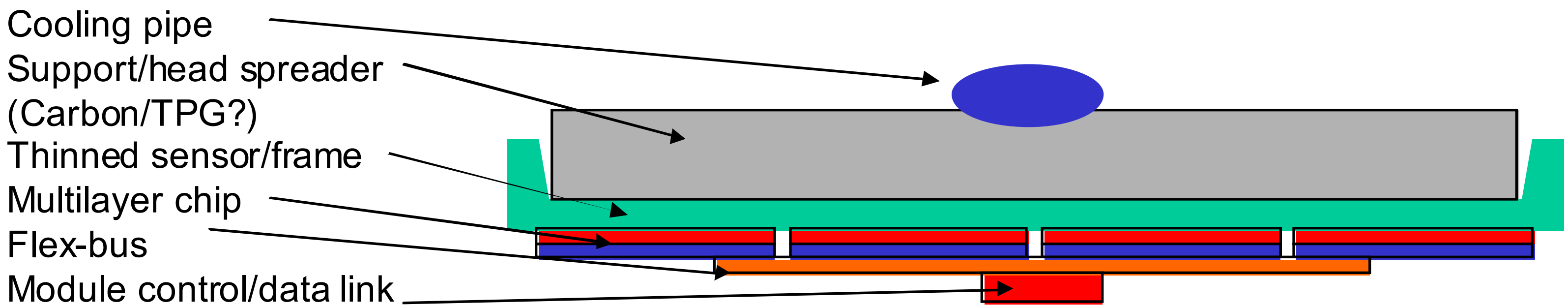
Work on conceptual module design:

use potential of 3D technology.
reduce material: reduced thickness,
higher integration -> less services.



Cooling of ASIC & Sensor:
~ 100 μm Si ΔT < 10mK for p=50μW/pixel (50x200 μm^2).

Material (X_0):

Sensor & ASICs:	**0.12 – 0.26 %**
Carbon/TPG (.5 mm):	**0.2 %**
Flex, MCC,..	**~0.1 %**

	0.42-0.56 % & less support & services

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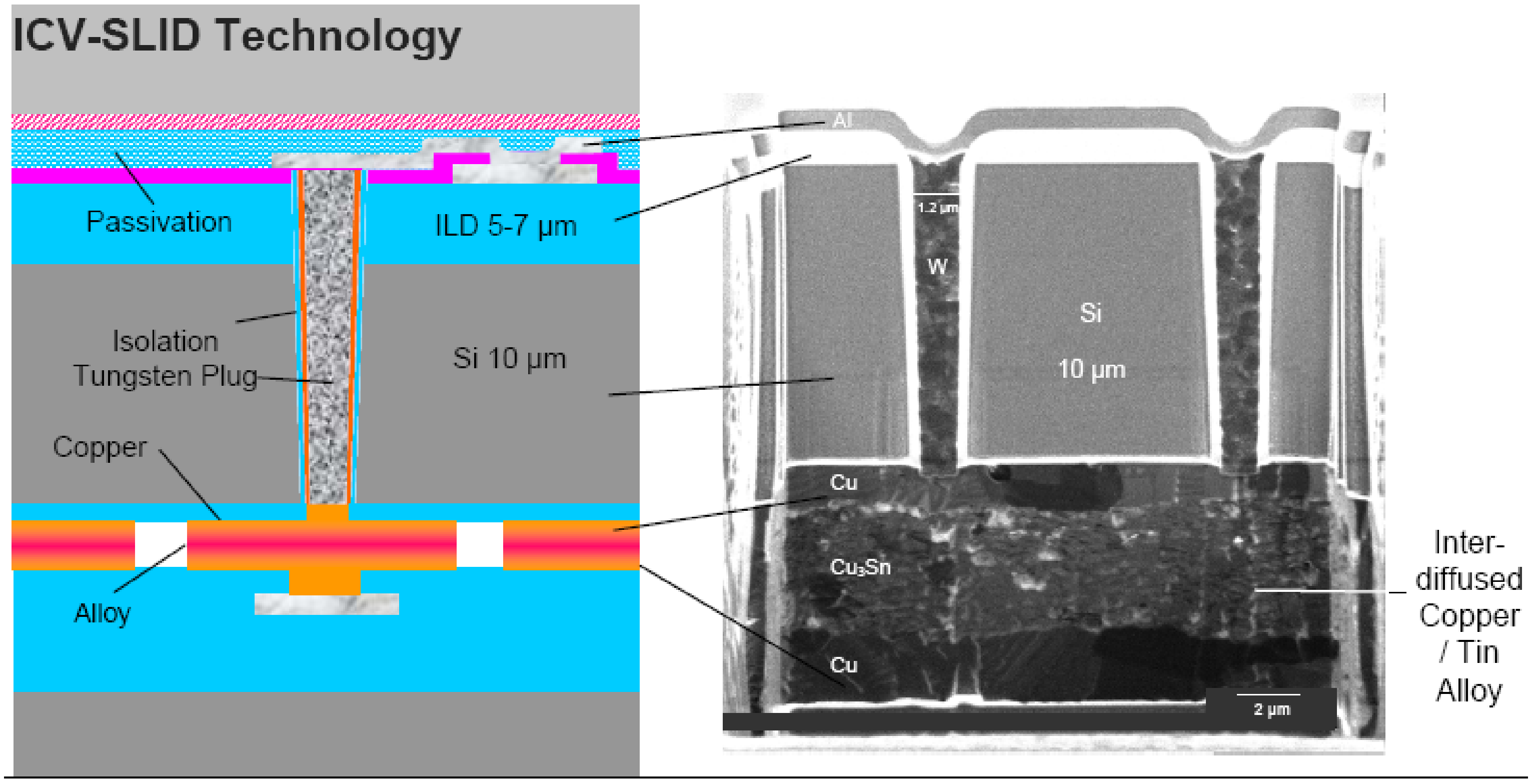
Through Silicon Vias



ICV = Inter Chip Vias

Fraunhofer IZM
Institut Zuverlässigkeit und Mikrointegration

- **Hole etching and chip thinning**
- **Via formation with W-plugs.**
- **Face to face or die up connections.**
- **2.5 Ohm/per via (including SLID).**
- **No significant impact on chip performance (MOS transistors).**

Linear – Silicon -Drift Detector - simulation

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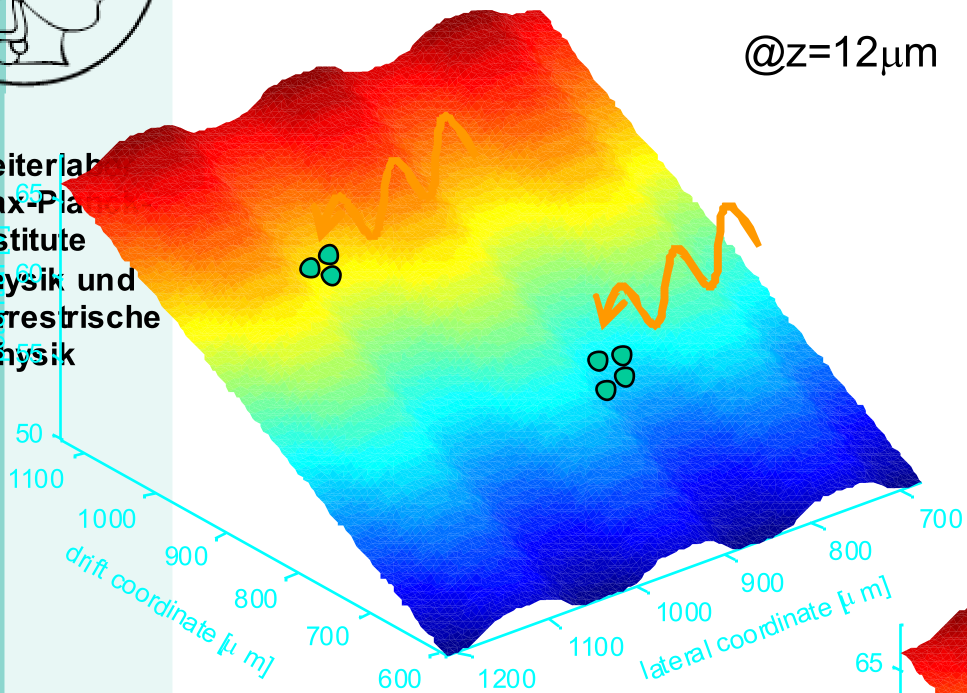
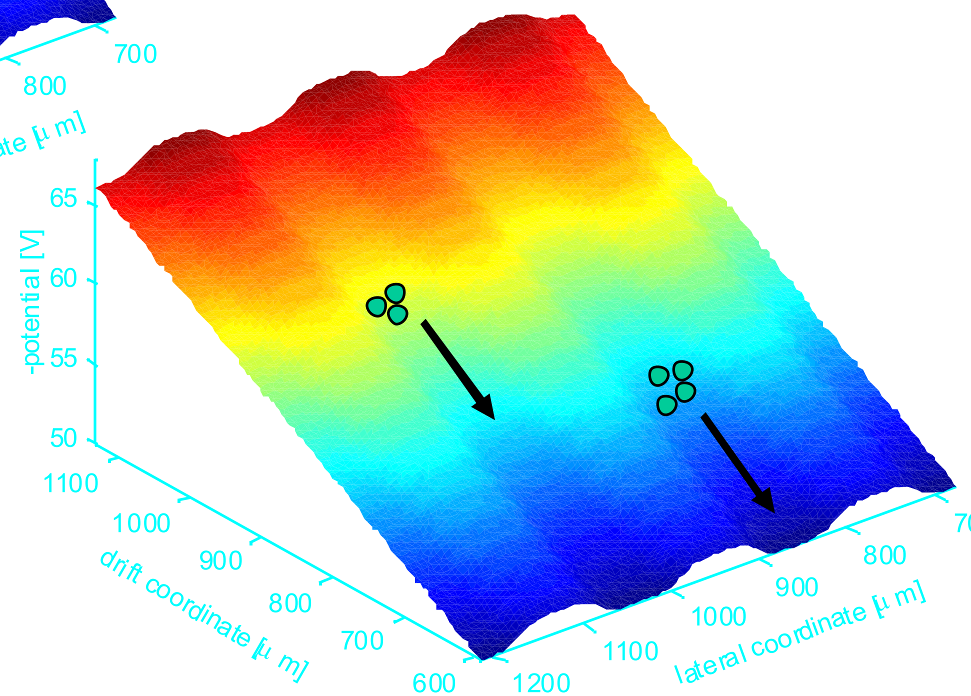
@z=12μm





The X-ray position along the drift is obtained from the electrons' drift time

T_{drift}~1000 ns / 12.8 mm

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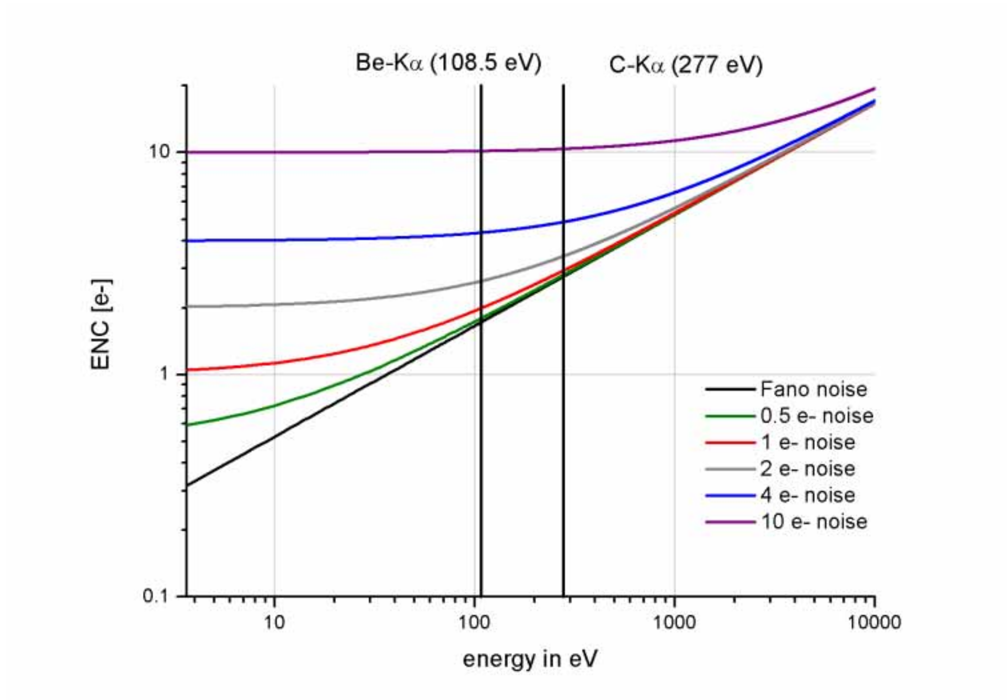
What are possible applications?

» Ultra low noise detector for x-rays

- low energy x-rays
- strong red-shifted x-ray sources



$$ENC_{tot} = sqrt(ENC^2_{fano} + ENC^2_{el.noise})$$

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Efficiency & Position resolution

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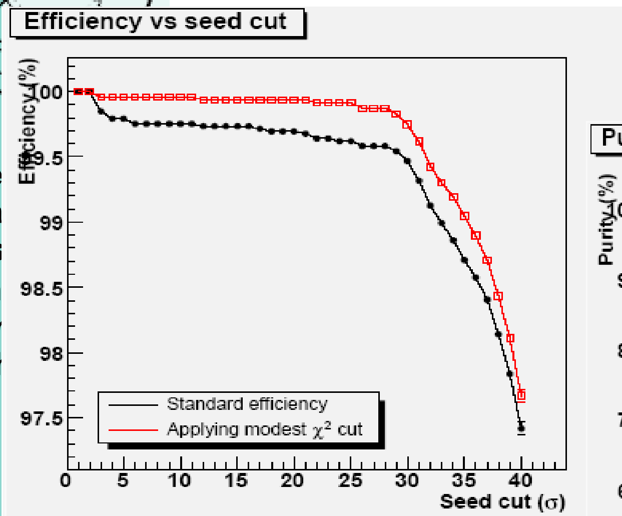
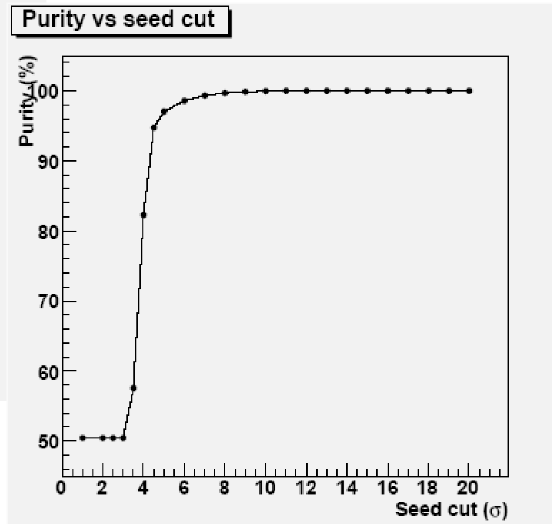
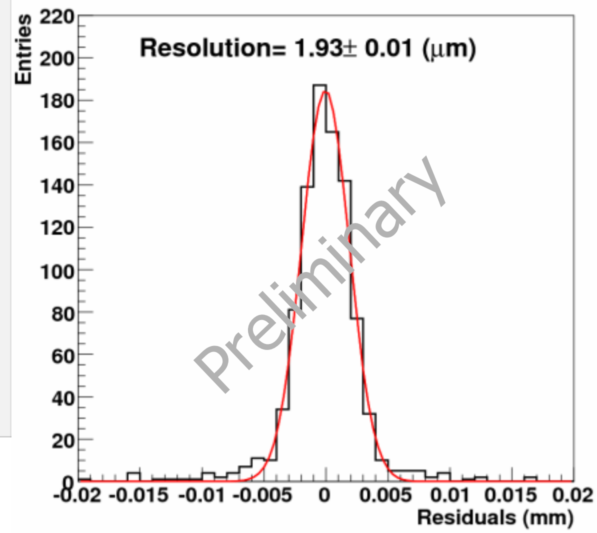


$$\text{Efficiency} = \frac{\text{Number of tracks with cluster}}{\text{Total number of tracks}}$$

$$\text{Purity} = \frac{\text{Number of clusters with tracks}}{\text{Total number of clusters}}$$





(Jaap Velthuis)

For 5 σ seed cut

- Efficiency ≈ 99.96%
- Purity ≈ 99.6 %

First preliminary result from CERN test beam,

129 GeV π, 33x23.75 μm² pixels

position resolution ≈ 2 μm

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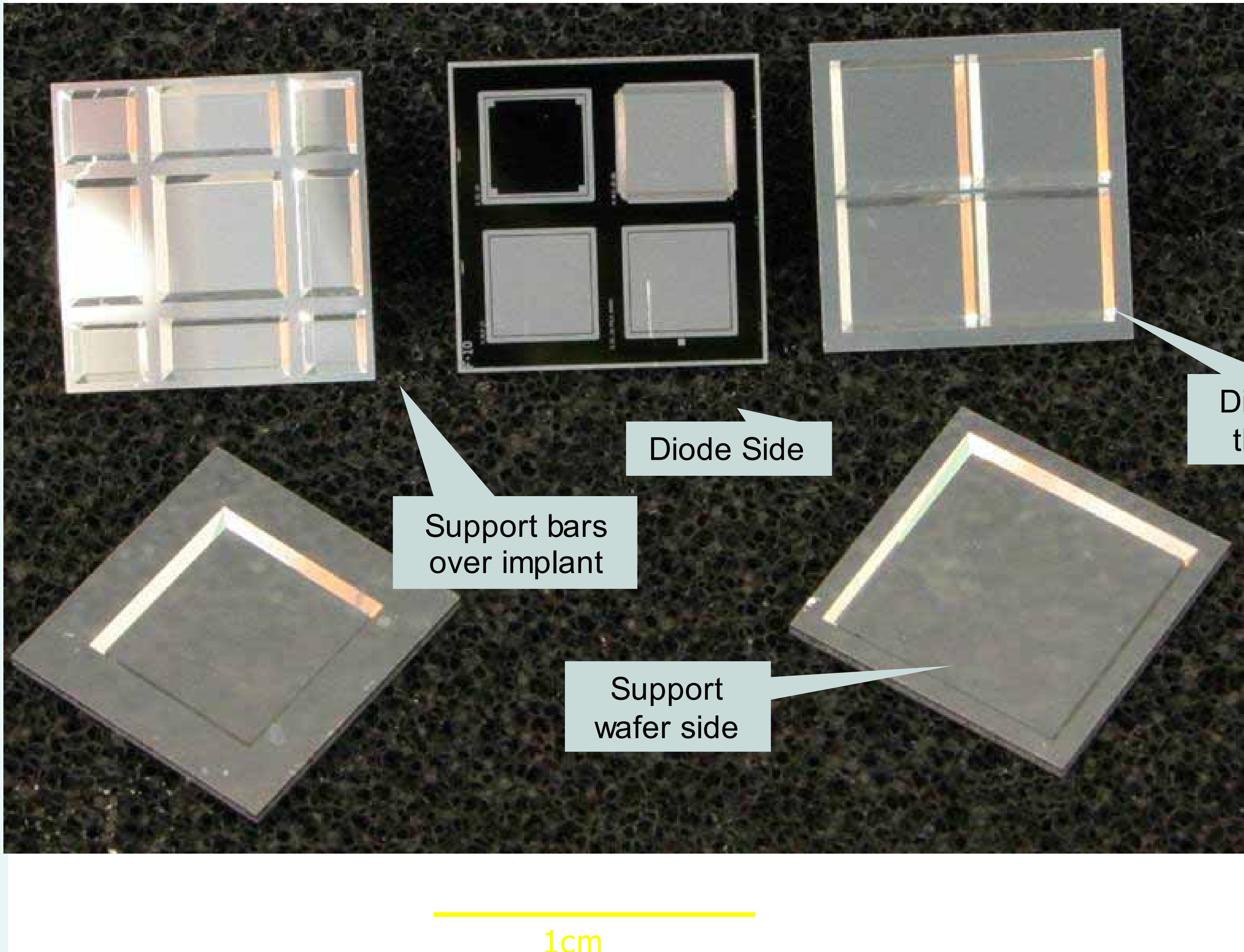
PiN Diodes with Different Support Sides



The 3rd round - SOI Wafers in preparation…

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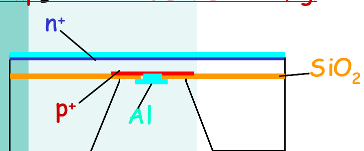
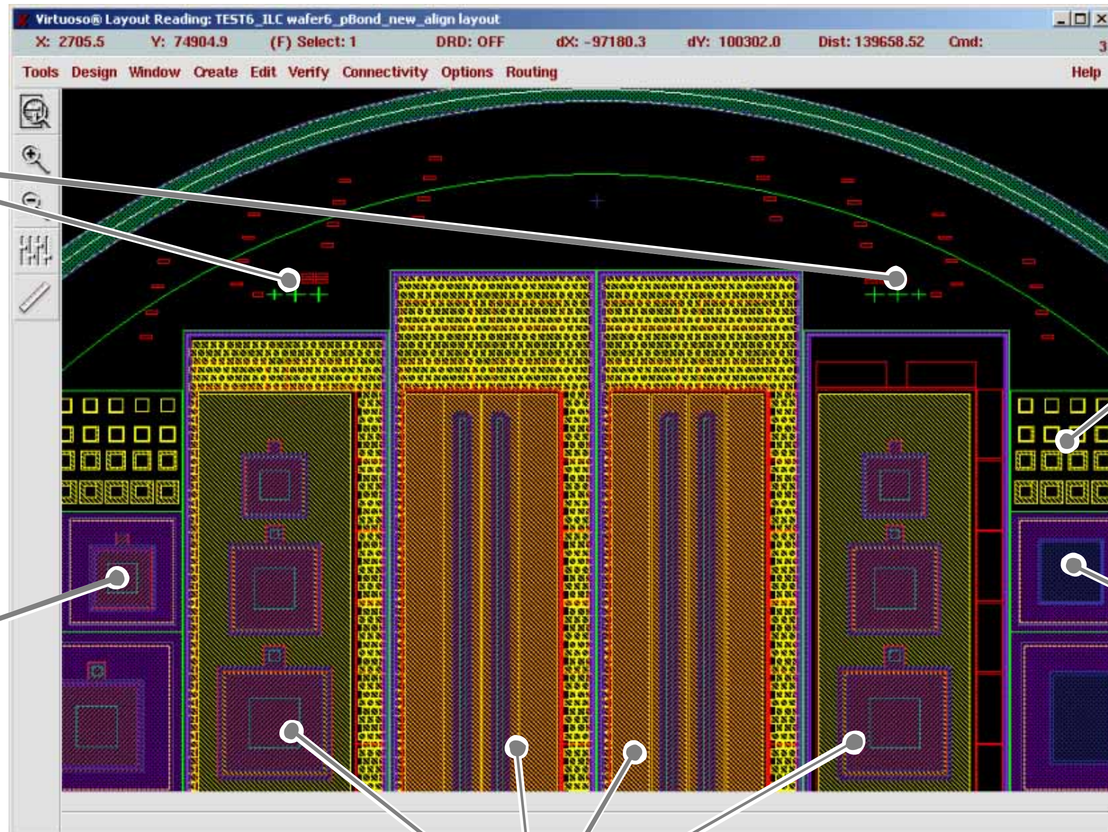
Alignment marks in BOX to find the partial p-implant after bonding

Implants like DEPFET config.



unstructured n+ on top
structured p+ in bond region



Some test structures

Diodes with various areas

MOS-C with various areas

4 "full size" 1st layer ladders
100x13 mm², 1 and 3 mm frame
along the long side

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