Development of Novel Silicon Detectors at the MPI Semiconductor Laboratory

Gerhard Lutz
MPI-Semiconductor Laboratory, München
RAL, Sept.12, 2003

Content

Introduction

- Activity in semiconductor detector since beginning (1979/80)
- Initiated by particle physics (strip detectors)
- Introduction of new detector concepts
- Extended to X-ray astronomy
- Culminating in the foundation of own Laboratory with complete semiconductor technology
- Supported by two Max-Planck institutes
- Development of novel detectors for institue experiments in astrophysics and particle physics

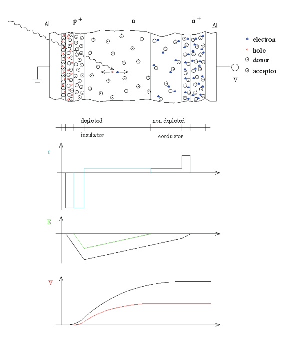
Semiconductors as Nuclear Radiation Detectors

Outstanding Material Properties}
- small band gap (Si 1.12eV) Þ low e-h pair generation energy (Si 3.6 eV) (ionisation energy for gases » 30 eV)
- High density (Si 2.33 g/cm²) Þ large energy loss/length for ionising particles Þ thin detectors; small range d-electrons; precise position measurement
- Almost free movement of electrons and holes
- Mechanical rigidity; self supporting structure, windowless operation
- Doping creates fixed space charges; building of sophisticated field structures
- integration of detector and electronics in single device

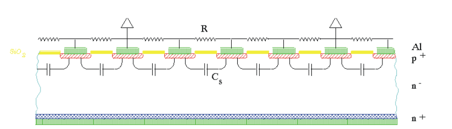
Basic Detector Structures

The Diode

Operation
- unbiased: radiation level measurement only
- partially biased: single particle energy measurement
- biased above full depletion: fast and complete charge collection



(Diode) Strip Detectors



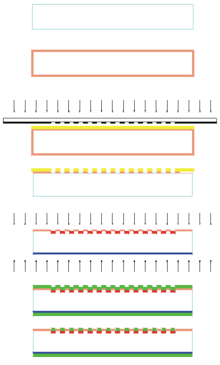
Divide diode into strips and measure charge arriving at individual strips Þ position measurement

Further developments:
- charge division readout
- double sided readout
- capacitive coupled readout
- biasing methods
- breakdown protection
- radiation hardening

Planar Technology

A "simple" production sequence:

Strip Detector



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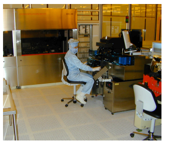
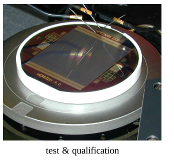
MPI semiconductor laboratory

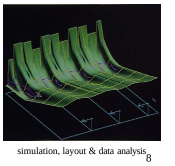

800 m² cleanroom up to class 1 ...


... with modern, custom made facilities ...


... for a full 6" silicon process line


mounting & bonding


test & qualification


simulation, layout & data analysis

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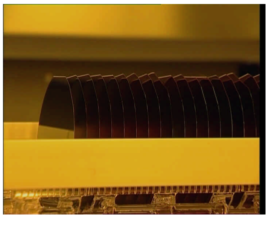
Why own technology:

- **Use of ultra-pure silicon:**
- **properties not to deteriorate during processing**
- **wafer size defect free processing**
- **double sided processing**
- **sophisticated detectors require complete and detailed control over process**



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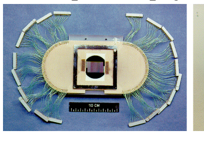
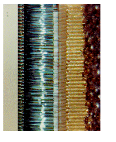
(Historical) **Detectors for particle physics**

Particle tracking: position measurement

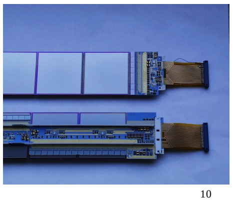
- **First strip detectors (NA11/NA32)**





Na11 strip detector

- **First double sided**
- **Capacitive coupled, simple biasing**
- **Radiation hard**
- **Pixel sensors**
- **(First drift detectors)**
- **Readout electronics**



Aleph strip detectors

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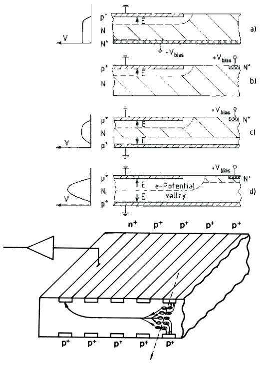
Semiconductor Drift Chamber

Sideward depletion

Drift chamber(Gatti and Rehak 1984)

- **Sideward depletion + graded potential on outer surface**
- **signal charge collected in centre valley, moves parallel to surface towards collecting anode**
- **drift time gives position**
- **small capacitive load gives good energy resolution**



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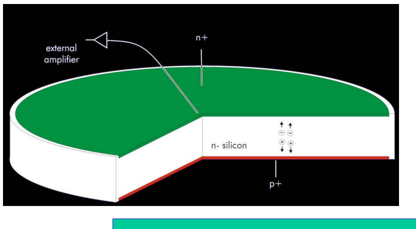
Semiconductor Detector



electronic noise

$$ENC^2 = A_1 \cdot 2qI_{leak} \cdot t + A_2 \cdot C_{tot}^2 H_{1/f} + A_3 \cdot C_{tot}^2\, 2kT \frac{a}{g_m} \cdot \frac{1}{t}$$

- leakage current
- low frequency noise
- thermal noise

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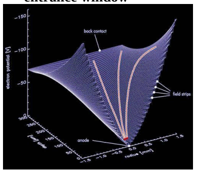
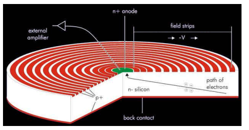
Semiconductor Detectors for Spectroscopy

Drift Diode *(Kemmer+Lutz 1987)*

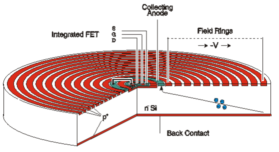
- **Single sided structured**
- **Point anode Þ small capacitance, small electronic noise**
- **Thin, homogeneous radiation entrance window**





Integration of first amplification

- **Further improvement of noise performance**



SDD performance

typical performance (10 mm², -10 °C)

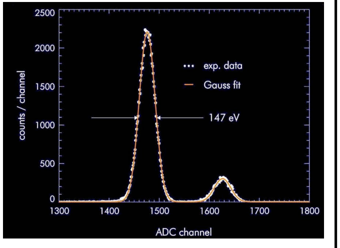
- **energy resolution**

  147 eV FWHM @ 5.9 keV
- peak-to-background

  > 3.000
- thin entrance window

  q.e. > 80 % (250 eV … 12 keV)
- count rate capability

  1.000.000 cps



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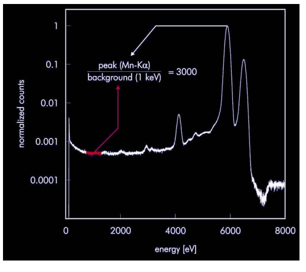

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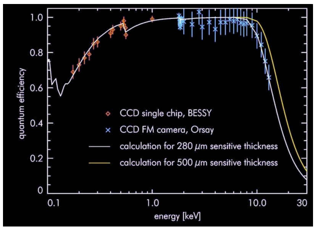

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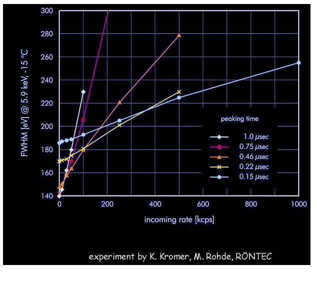


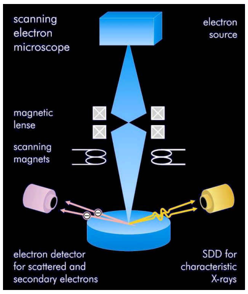
SDD vs. other spectroscopy systems

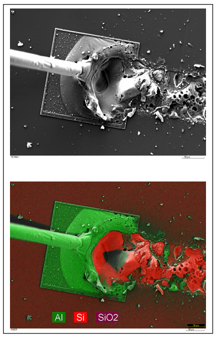
detector type	cooling method	thickness [mm]	active area [mm²]	max. throughput [kcps]
Si(Li)	liquid nitrogen	3 ... 5	10 ... 200	30 ... 50
HPGe	liquid nitrogen	3	10 ... 20	30 ... 50
SDD	thermoelectric	0.3 ... 0.5	5 ... 10	400

detector type	dead time vs. count rate			FWHM [eV] Mn-Ka vs. count rate			
	100 kcps	150 kcps	800 kcps	1 kcps	50 kcps	100 kcps	1 Mcps
Si(Li)	50 %	95 %	-	~ 129	~ 190	-	-
HPGe	50 %	95 %	-	~ 109	~ 175	-	-
SDD	5 %	10 %	50 %	~ 145	~ 160	~ 215	~ 260

SDD - applications

electron microprobe analysis





figures by RÖNTEC

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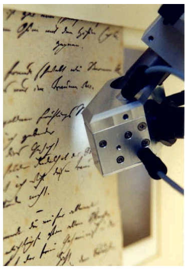
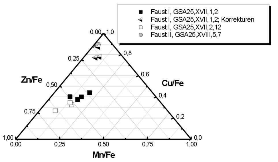
SDD - applications

X-ray fluorescence analysis, studies of art & archeological objects



J. W. v. Goethe, Faust I original manuscript



"fingerprint" of Goethe's ink

⇒ editing of Faust I during Faust II work

experiment & figures by O. Hahn (BAM, Berlin) with portable system "artTAX" (RÖNTEC)

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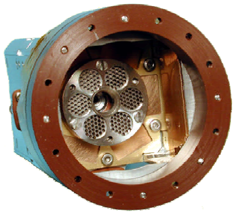
SDD - applications

particle induced X-ray emission



APXS

alpha-proton-X-ray spectrometer

- ESA mission ROSETTA
  comet orbiter & lander
  67P/Churyumov-Gerasimenko
- NASA missions
  2003 Mars Exploration Rover I + II

APXS systems by J. Brückner, R. Rieder (MPI für Chemie, Kosmochemie, Mainz)

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SDD - applications

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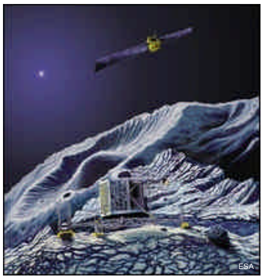

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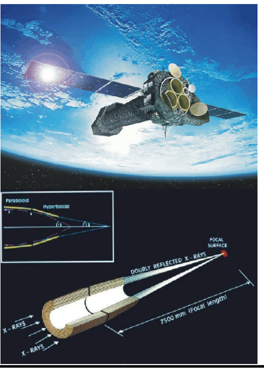
Detectors for X-ray astronomy

pn-CCD for ESA's XMM-Newton satellite

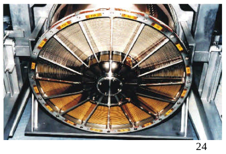


XMM: three X-ray telescopes

- **one dedicated to imaging (with pn-CCD)**
- **two with additional reflecting gratings (andMOS CCDs)**
- **one optical telescope**
- **all pointing on same object**

Wolter I type mirror telescopes

- **58 nested mirror shells**
- **Wall thickness 0.5 to 1mm Ni**



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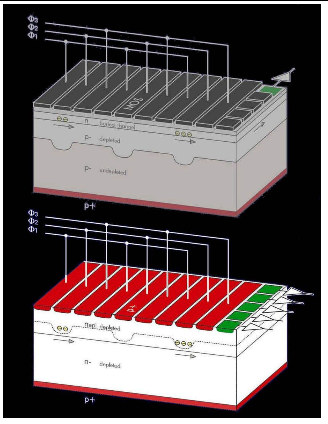
pn-CCD principle

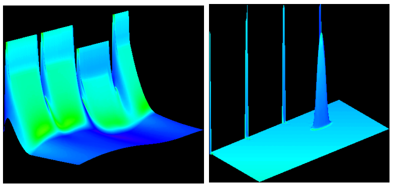
MOS-CCD (´video CCD´)

- MOS transfer gates
  - ➢ implanted pn-junctions
- buried channel
  - ➢ deep transfer
- partial depletion
  - ➢ full depletion
- frontside illumination
  - ➢ back entrance window
- serial readout
  - ➢ 1 preamp / channel

pn-CCD



CCD device simulation



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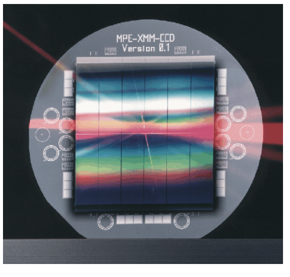
pn-CCD performance

- largest monolithic CCD
  - 6 x 6 cm²
  - 384 x 400 pixel
  - 150 µm pixel
- fast, parallel readout
  - 5 msec full frame
- low noise
  - 4 el. rms
- high quantum efficiency
  - 90 %
- radiation hard
  - 400 Mp/cm²



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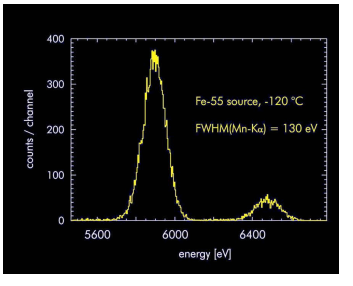

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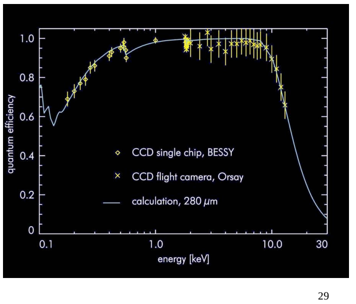

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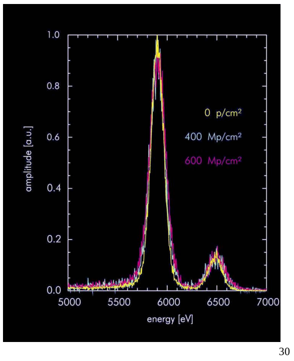

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pn-CCD vs. MOS-CCD

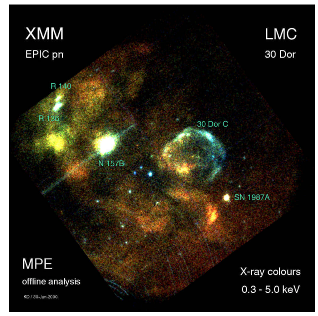
	type	energy resolution @ 272 eV & 5.9 keV FWHM [eV]		quantum efficiency @ 272 eV & 10 keV [%]		readout time [msec]	pixel cell size [µm²]	detector size [cm²]
CHANDRA (original)	MIT/LL-FI	60	130	3	20	500	24 x 24	2.5 x 2.5
	MIT/LL-BI	125	200	50	10	500	24 x 24	2.5 x 2.5
XMM	Leicester	80	130	25	30	500	40 x 40	2.4 x 2.4
	SRON	100	145	65	15	500	27 x 27	2.8 x 2.8
	pn-CCD	70	130	**90**	**90**	**4,6**	150 x 150	6 x 6

backside illumination (quantum efficiency 90 @ 272 eV)

full depletion (quantum efficiency 90 @ 10 keV)

large pixels, parallel readout (readout time 4,6)

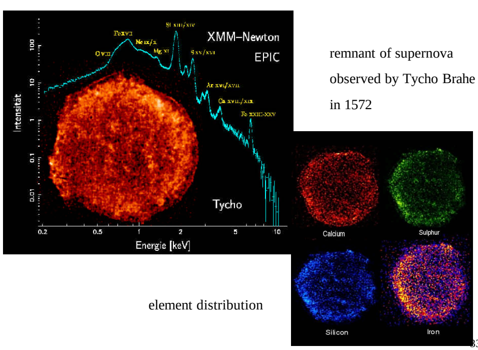
XMM-Newton – first light (January 2000)



large Magellanic cloud

supernova remnant 1987A

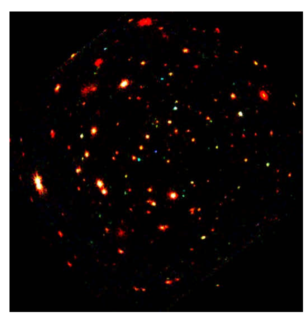
XMM-Newton – observations



remnant of supernova
observed by Tycho Brahe
in 1572

element distribution

XMM-Newton – observations



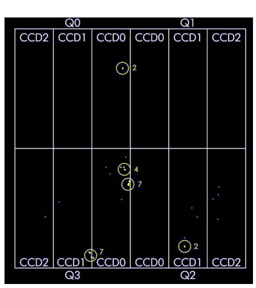
Lockman hole:
a look into deep space

first observation of
´green´ and ´blue´
hard x-ray sources

no diffuse background?

pn-CCD performance in space

- perfect imaging since launch
- detector performance equal to ground qualification
- no significant change of energy resolution and charge transfer efficiency
- few pixels lost in rev. 156 impact of micro-meteorite?
- effect reproduced on ground using a dust accelerator



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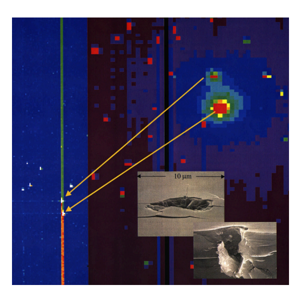
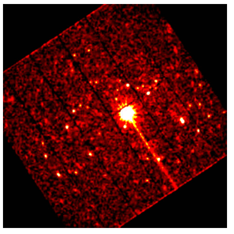


pn-CCD - limitation

charge transfer speed limited
by the time needed for readout

⇒ ´out of time´ events
pn-CCD: ~ 6 %



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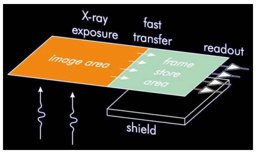
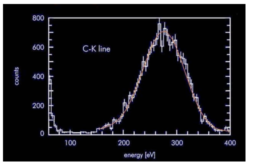
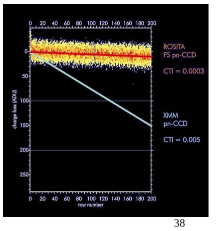
Frame Store pn-CCD

- frame store area
  - separation transfer / readout
  - reduction of out-of-time events
    6 % (XMM) → 0.4 %
- prototypes under test
  - smaller pixels (50 … 75 µm)
  - larger format 128 x 128
  - improved performance







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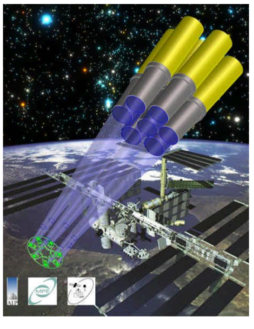
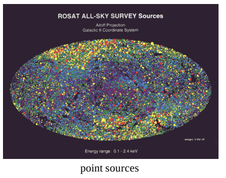
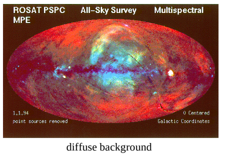
ROSITA - ROentgen Survey with an Imaging Telescope Array





point sources



diffuse background

Pn-CCD works with low Clock voltage amplitude Dj

1486 eV (Al-K):

Dj = 8.0 V	CTI = 116 E-6	FWHM = 87 eV	← a-particle meas.
Dj = 2.0 V	CTI = 155 E-6	FWHM = 96 eV	
Dj = 1.5 V	CTI = 181 E-6	FWHM = 98 eV	
Dj = 1.3 V	CTI = 237 E-6	FWHM =103 eV	(XMM: CTI = 660 E-6)

13.9 keV (Am^{241} X-ray line) low gain mode:

Dj = 8.0 V	CTI = 83 E-6
Dj = 3.0 V	CTI = 96 E-6
Dj = 2.0 V	CTI = 179 E-6
Dj = 1.5 V	CTI = 200 E-6
Dj = 1.3 V	CTI = 265 E-6

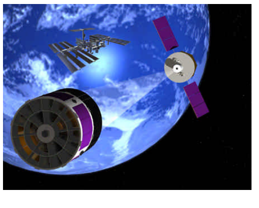
(j = [-10 V; -25 V])

advantages of small Dj : - safety (lower electric field)
- faster clocking pulses
- less power dissipation

Future X-ray Mission: XEUS (X-ray Evolving Universe Spectroscopy)

Scientific aim:
investigation of the universe at an early evolution stage:
- early black holes
- evolution and clustering of galaxies
- evolution of element synthesis

Experiment
- Increase in collecting area (factor 100)
- Increase of collection area (0.5 to 6-30m^2)
- Increase in focal length (7.5 to 50m)
- Optics and focal imaging on separate satellites

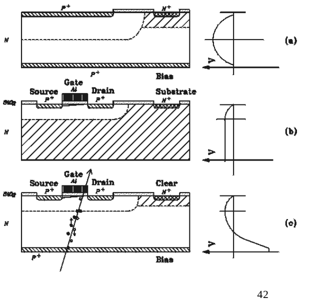


Focal detector requirements:
- faster readout (factor 10 to 100)
- avoidance of "out of time" events
- larger size focal detector (7x7cm^2)
- smaller pixel size (50•50µm^2)

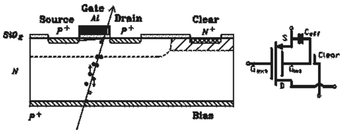
Detector requirements can be met with DEPFET pixel detectors

The Depleted Field Effect Transistor (DEPFET)

Device concept:
- Combination of FET transistor with
- Sideward depletion (Drift chamber)



Operation principle of DEPFET



DEPFET structure and device symbol.

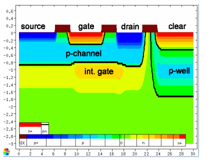
- **Field effect transistor on top of fully depleted bulk**
- **All charge generated in fully depleted bulk**
- **assembles underneath the transistor channel**
- **steers the transistor current**

Combined function of sensor and amplifier

- **low capacitance and low noise**
- **Signal charge remains undisturbed by readout**
- **repeated readout for noise reduction**
- **Complete clearing of signal charge**
- **no reset noise**
- **Full sensitivity over whole bulk**
- **Thin radiation entrance window on backside**

DEPFET types:

- MOS-enhancement
- MOS-depletion
- JFET
- Open (rectangular) geometry
- Closed (circular) geometry



DEFET applications

- Readout element of
  - Drift detector
  - CCD
- Element of pixel detector

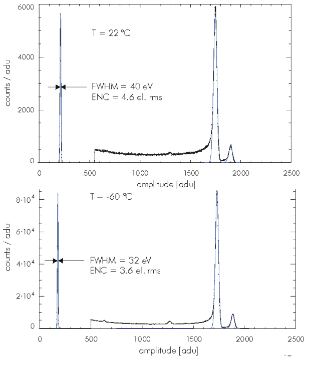
DEPFET ^{55}Fe Spectrum

Single DEPFET

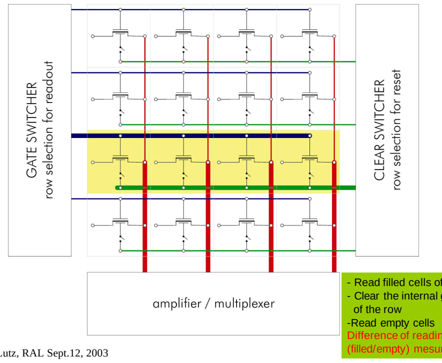
(JFET, closed geometry)

At room temperature

Cooled



DEPFET **pixel matrix**

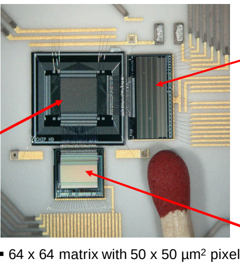


- Read filled cells of a row
- Clear the internal gates of the row
- Read empty cells

Difference of readings (filled/empty) mesures charge

Prototype DEPFET-System

developed with Bonn university



Control-Chip: Switcher

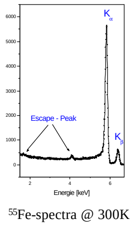
64x64 pixel DEPFET-Matrix JFET type Closed geometry (50x50µm² pixel)

low noise Readout-Chip: CARLOS

- 64 x 64 matrix with 50 x 50 µm² pixel
- designed for Biomedical Applications
- clock rate : 50 kHz
- achieved noise in matrix: ~50e

results with prototype system

Single-pixel spectra:



^{55}Fe-spectra @ 300K

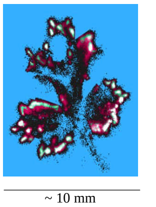
ENC = 4.8 +/- 0.1 e⁻

Matrix-picture with ^{55}Fe:

~ 3.2 mm

spatial resolution: ~ 9µm (with 50x50 µm² pixel)

Autoradiography with ^{3}H:



~ 10 mm

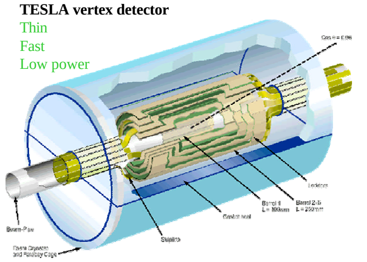
detection of Tritium ^{3}H (5,6keV mean energy)

[J.Ulrici, Bonn]

Present DEPFET pixel detector development for XEUS and TESLA

In collaboration with Bonn (N.Wermes) and Mannheim (P.Fischer)

TESLA vertex detector
Thin
Fast
Low power



Options:
CCD
MAPS
HAPS
DEPFET

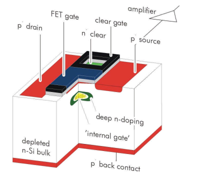
Layer	Module size	No. Of modules
I	13 x 100 mm	1 x 8
II	22 x 125 mm	2 x 8
III	22 x 125 mm	2 x 12
IV	22 x 125 mm	2 x 16
V	22 x 125 mm	2 x 20

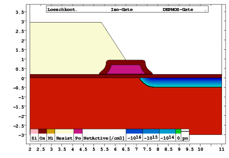
Total > 500 MPixel (with 25x25 µm Pixelsize)
(read out speed 50 MHz)

Design of DEPFET pixel detectors

Type of DEPFETS:
MOS-depletion type
XEUS: zylindrical geometry
TESLA: rectangular geometry

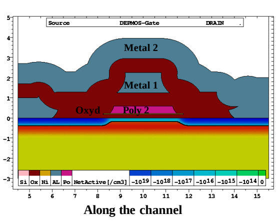
Technology:
6 Inch
Double-poly,
double metal,
Self-aligned



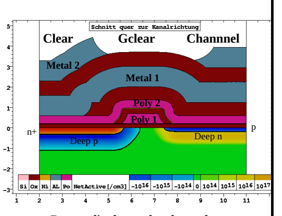


DEPMOS Technology Simulation

DEPMOS pixel array cuts through one cell



Along the channel

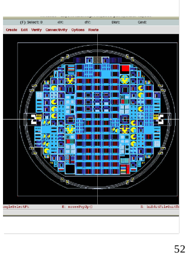


Perpendicular to the channel

Pixel prototype production (6" wafer) for XEUS and LC (TESLA)

Aim: Select design options for an optimized array operation
(no charge loss, high gain, low noise, good clear operation)
On base of these results => production of full size sensors

Many test arrays
- Circular and linear DEPFETS
  up to 128 x 128 pixels
  minimum pixel size about 30 x 30 µm²
- variety of special test structures

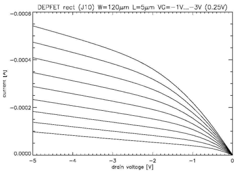


Structures requiring only one metalization layer
Production up to first metal layer finished
Devices are under test
Test results agree very well with device simulations

First DEPFET measurements on rectangular test transistors (W = 120µm L = 5µm)

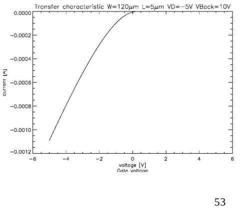
Output characteristics:

Correct transistor behavior



Transfer characteristics:

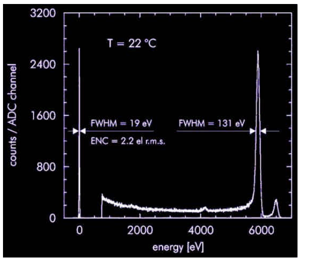
Device can be completely switched off



Transistor parameters agree with simulation

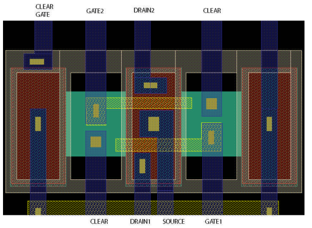
DEPFET test results: Noise and Spectroscopy

Single circular DEPFET
L = 5 µm, W = 40 µm
time-continuous filter, t = 6 µsec



Rectangular double cell test structure

as used in TESLA pixel prototype



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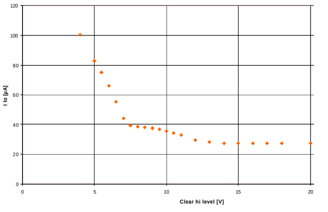
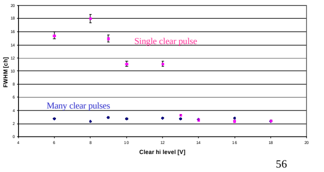
DEPFET test results
Clearing of internal gate:
complete clearing possible?
At which voltage?

Single rectangular DEPFET:
measure current with
cleared internal gate
As function of clear voltage



Measure pedestal noise
Compare situation of
charge generation followed by
single clear pulse
with
many clear pulses
before reading



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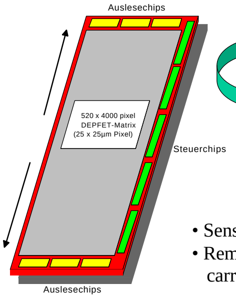
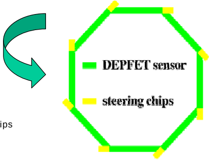
TESLA Module concept with DEPFETs





- Sensor area thinned down to 50 µm
- Remaining frame for mechanical stability carrying readout and steering chips

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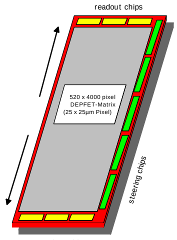
Module Concept



5-layer (CCD-like) layout for the vertex detector
1st layer module: sensitive area 100x13 mm²

Estimated Material Budget (1st layer):

Pixel area: 100x13 mm², 50 µm : 0.05% X_0
steer. chips: 100x2 mm2, 50 µm : 0.008% X_0
(massive) Frame :100x4 mm², 300 µm : 0.09% X_0

reduce frame material!!!
by
etching of "holes" in the frame

perforated frame: 0.05 % X_0

total: 0.11 % X_0

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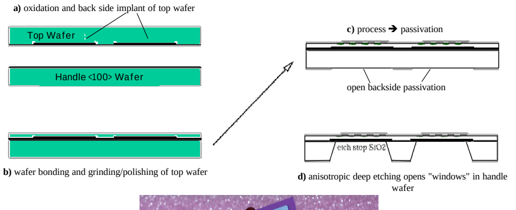
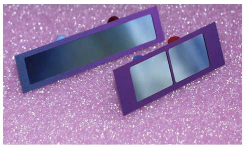
Processing thin detectors
- the Idea -





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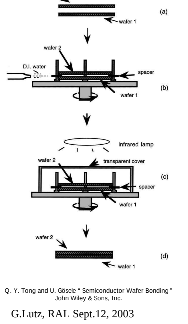
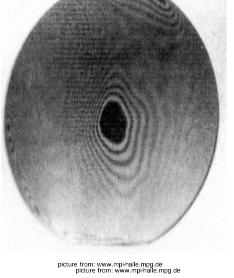
Processing thin detectors
- Direct Wafer Bonding -



Q.-Y. Tong and U. Gösele " Semiconductor Wafer Bonding " John Wiley & Sons, Inc.

"SOI" Wafer prepared by
MPI für Microstrukturphysik, Halle



picture from: www.mpi-halle.mpg.de

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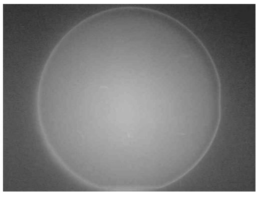
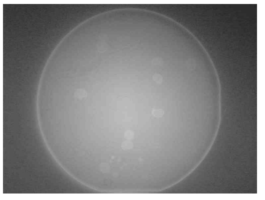
Direct Wafer bonding after Implantation

Bonded wafers (structured implant through BOX):

Direct Wafer Bonding possible, but some voids after annealing!

➔ improve surface condition before bonding

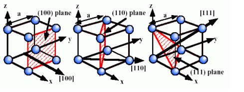



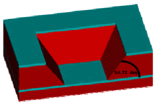
infrared transmission pictures from MPI Halle (M. Reiche)

Anisotropic Wet Etching
- TMAH -

Tetra-Methyl-Ammonium-Hydroxide

good selectivity to oxide
almost perfect selectivity to Al
no alkali ions



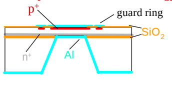



Diodes & Teststructures on thin Silicon

* test bondability of implanted oxide & electrical performance of diodes on thin silicon *

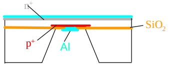
2 types of thinned diodes

Type I: Simplified standard technology



structured p+ on top
unstructured n+ in bond region
3 Wafers

Type II: Implants like DEPFET config.

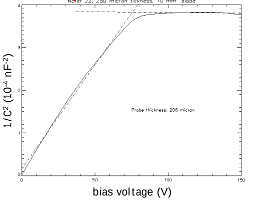


unstructured n+ on top
structured p+ in bond region
3 Wafers

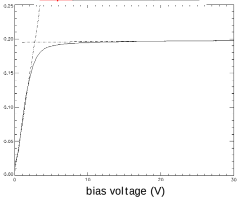
* *+ 4 Wafers with standard Diodes as a reference* *

Diodes & Teststructures on thin Silicon
- Type I: CV curves, full depletion voltage -

250 µm, standard diode, 10 mm²



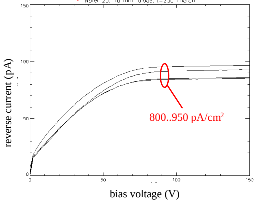
50 µm, standard diode, 10 mm²



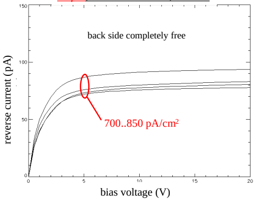
$C(V_{fd})$ ➔ t = 46 µm

Diodes & Teststructures on thin Silicon
- Type I: IV curves -

250 µm, 4 standard diodes, 10 mm²



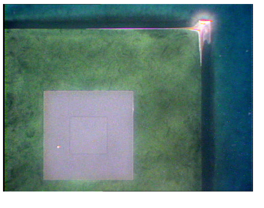
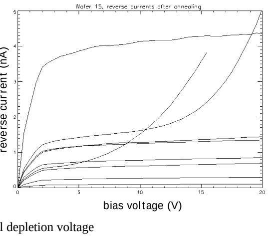
50 µm, 4 standard diodes, 10 mm²



Diodes & Teststructures on thin Silicon
- Type II: IV curves -

Diodes of various sizes: 0.09 cm² – 6.5 cm²
- no guard ring -
- surface generated edge current included –
reverse currents after annealing

contact opening and metallization
after etching of the handle wafer

➔about 2V full depletion voltage
➔ about 1 nA/cm2 including edge generated current

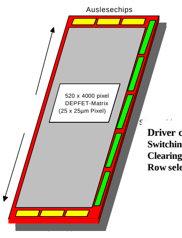
Readout electronics for DEPFET pixels

Developed in collaboration with other groups:

•XEUS: MPE,Jülich,Buttler

•TESLA: Bonn, Mannheim,MPI

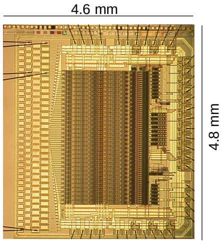
TESLA readout chip
Current based readout



New steering chip

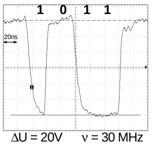
I.Peric (Bonn), P.Fischer (Mannheim)

Switcher II:

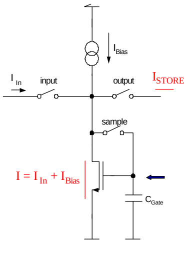


• AMS 0.8µm HV
• versatile sequencing chip
(internal sequencer → flexible pattern)
• high speed + high voltage range (20V)
• drives 64 DEPFET-rows
(can be daisy chained)
• produced 12/2002

Results:
• power consumption:
~1W /channel
• tested ok to 30MHz



Current based Readout



How to store a current ??

Storage phase: input and sample-switch closed :
→ gate-capacitance of nmos charged

Sampling phase: input and sample-switch opened :
→ voltage at capacitance „unchanged“
→ current unchanged

Transfer phase: output switch closed :
(done immediately after sampling)
→ I_{STORE} is flowing out

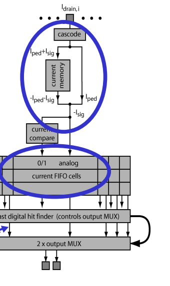
CURO - Architecture

CURO : CUrrent Read Out

▪ front end:
automatic pedestal subtraction
(double correlated sampling)
- easy with currents -

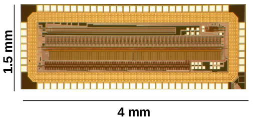
▪ analog currents buffered in FIFO

▪ Hit-Logic performs 0 suppression
and multiplexes hits to ADC
(ADC only digitizes hits !)



Results - CURO I (Marcel Trimpl, Bonn)

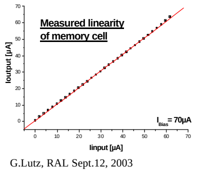
CURO I:



▪ TSMC 0.25µm, 5metal
▪ contains all blocks for a fast DEPFET R/O
▪ radiation tolerant layout rules with annular nmos
▪ produced 05/2002

digital part:
works with desired speed (50MHz)

analog part (current memory cell):
• tested up to: 25MHz
• differential non-linearity: 0.1 %
• noise contribution to readout: < 39nA



Crucial parts of readout work
Design of CURO II submitted
Delivery Dec.03

TESLA Goal:
Thin fullsize pixel matrix 2005

Summary/Conclusions

Introduction of semiconductor detectors into particle physics (~1980)
- **Position (and energy) sensitive**
- **applications in various fields**

Foundation of our laboratory
- **with high-tech production technology**
- **design and test facilities**
- **dedicated to experiments of two MPIs**
  - **particle physics**
  - **X-ray astronomy**
- **detectors based on new concepts**
- **developers are also participating in experiments**

Present main activities
- **DEPFET pixel detectors**
- **other spectroscopic (drift) detectors**

Large development potential
Exciting work lies ahead