Semiconductor Detectors for Experiments
In Basic and Applied Science

Detectors Systems for Astrophysics, High Energy Physics and Structure and Dynamics of Matter
Outline:

device basics of SDDs, pnCCDs and DePFETs
  - functional principle
  - technical realizations
  - formats and geometries
  - performance figures

SDDs present and future
  - Planetary Science
  - Material science
  - Basic science

pnCCD present and future
  - Astrophysics
  - Wave Front Sensing
  - X-ray FELs
  - Electron Imaging

DePFET- APS present and future
  - Functional principle
  - QE, energy resolution, position resolution, radiation hardness
  - Applications: BepiColombo, Athena, DSSC @ XFEL, Belle II,
Semiconductors as detector and electronics material

1. Semiconductors: $E_{\text{Gap}} \approx 1 - 2 \text{ eV}$
   → small leakage currents
   → low noise, operation @ r.t.

2. Pair creation energy: $w = 2 - 5 \text{ eV}$
   → large number of signal charges per energy deposit in detector

3. Density: $\rho = 2 - 5 \text{ g cm}^{-3}$
   → high energy loss per unit length
   → low range of $\delta$ - electrons

This leads to:

good energy resolution
high spatial resolution
high quantum and detection efficiency
good mechanical rigidity and thermal conductivity

Semiconductors equally offer:

fixed space charges
high mobility of charge carriers
Detector and electronics simulation and layout

1. The detector idea: simulation of electrical properties

2. Simulation of the production process

3. Design and layout of the entire detector system, including signal processing and DAQ
The location

Device tests and operation

or, Munich, germany
**Detector Structures**

- **diode**
  - material: silicon, germanium, compound semiconductors (CdTe, CZT, ...)
  - geometry:
    - size: $5 \text{ mm}^2$ ... several $\text{cm}^2$
    - thickness: 300, 500 $\mu\text{m}$, 1 mm
  - applications:
    - X-ray spectroscopy
    - particle detection
    - $\gamma$-ray spectroscopy

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Instrumentation @ BNL, 17.-18. Nov. 2011
Lothar Strüder, MPI Halbleiterlabor and University of Siegen
Detector Structures

- **structured diode:** single-sided strip detector
  - material: silicon, germanium, compound semiconductors (GaAs, CdTe, CZT, ...), diamond
  - geometry
    - size: wafer size
      - typ.: 6 x 6 cm², 10 x 10 cm²
    - thickness: 300, 500 µm
    - strip width/pitch: it depends ...
      - 10 µm ... 1 mm
    - position accuracy: down to few µm
  - applications: particle tracking
Detector Structures

- **structured diode:** double-sided strip detector
  - **material** silicon, germanium, compound semiconductors (GaAs, CdTe, CZT, ...), diamond
  - **geometry**
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      - typ. 6 x 6 cm²
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      - 10 µm ... 1 mm
    - **position accuracy** down to few µm
  - **applications**
    - **particle tracking**
Detector Structures

• double-sided strip detector
  
  - advantage
    \( n^2 \) resolution elements with
    2n readout channels
  
  - disadvantage
    ambiguity at high occupancy

\[\Rightarrow\] 2dim pixel sensor
Detector Structures

• pad detector ‘p on n’
  - material  silicon
    germanium
    compound semiconductors
    (GaAs, CdTe, CZT, …)
diamond
  - geometry
    • size  wafer size
      typ.  6 x 6 cm²
            10 x 10 cm²
    • thickness  300, 500 µm
    • pixel size  ≥ 50 µm
  - applications
    • particle tracking
      ⇝ detection of individual charged particles
    • imaging
      ⇝ count / integrate particles or photons
Detector Structures

- pad detector ‘n on n’
  - material  silicon
germanium
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- applications
  - particle tracking
    ↪ detection of individual charged particles
  - imaging
    ↪ count / integrate particles or photons
Detector Structures

- **diode**
  - electronic noise
    
    \[
    ENC = \sqrt{\frac{2kT}{g_m} C_{\text{tot}}^2 A_1 \frac{1}{\tau} + 2\pi a_\alpha C_{\text{tot}}^2 A_2 + q I_L A_3 \tau}
    \]

  - optimum shaping time
    
    \[
    \tau_{\text{opt}} = \frac{2A_3 kT C_{\text{tot}}^2}{A_1 q I_L} \frac{2}{3g_m}
    \]

  for
  - good resolution
  - high count rate capability

  the total capacitance must be minimised!!
Detector Structures

- sideward depletion structure

Emilio Gatti & Pavel Rehak, 1983

- symmetric bias
- volume is fully depleted by reverse biased diodes on both surfaces
- minimum capacitance of bulk contact, independent of overall area
- potential minimum for majority carriers (electrons @ n-Si) in the centre plane
Detector Structures

- sideward depletion structure
  - asymmetric bias
    - volume is fully depleted by reverse biased diodes on both surfaces
    - minimum capacitance of bulk contact, independent of overall area
    - vertical shift of the potential minimum
  - ?? signal extraction ??
  - advanced detector concepts
Detector Structures

- linear silicon drift detector (SDD)

- segmentation and bias of diodes
  - drift field $\parallel$ surface

- 1dim position resolution by drift time measurement
  start trigger required!
Detector Structures

- linear silicon drift detector (SDD)
  - segmentation and bias of diodes → drift field || surface
  - 2dim position resolution by + drift time measurement (trigger!) + segmentation of the anode
  - application: particle tracking
Detector Structures

- SDD with on-chip FET
  - one-sided field strip system
  - backside illuminated
  - integration of 1st amplifying FET
    dedicated n-JFET
    - minimization of total capacitance
    - good energy resolution
    - high count rate capability
    - robust against pickup, microphony
  - comparison
    - pin diode 10 mm² x 300 µm
      \[ C_{\text{tot}} = 3.5 \text{ pF} \]
    - SDD with FET 10 - 100 mm²
      \[ C_{\text{tot}} = 30 - 50 \text{ fF} \]
Principle of Sideward Depletion

Silicon Drift Detectors

- Linear SDDs
- Spiral SDDs
- Cylindrical SDDs
- Multi anode SDDs
- Multi Linear SDDs

Fully Depleted pnCCDs

- Frame Store pnCCDs
- Column parallel pnCCDs
- Avalanche Amplifying pnCCDs
- ARC CCDs
- ARC SDDs
- Split frame pnCCDs

Controlled Drift Detectors

- Full Frame pnCCDs
- Column parallel pnCCDs
- Charge injection pnCCDs
- Split frame pnCCDs

Multi linear controlled Drift Detectors

- linear DePFET
- Double cell DePFETs
- Thinned DePFETs
- ns reset DePFETs

Depleted n/p channel JFETs/MOSFETs (DePFETs)

- Depleted n/p channel JFETs/MOSFETs DePFETs
- Circular DePFETs
- Macro DePFETs
- Hexagonal DePFETs
- Gatable DePFETs
- Non-linear compression DePFETs
Spectroscopic performance of 5 and 10 mm² SD3 detectors

- operation temperature -20°C
- 1-stage Peltier cooler
- optimum shaping time 0.5 µs
- pulsed reset operation

`Optimized detector entrance window for light element detection - pnWindow`

A single SDD can process up to 1 M counts per sec below 170 eV

Instrumentation @ BNL, 17.-18. Nov. 2011

Lothar Strüder, MPI Halbleiterlabor and University of Siegen
Spectroscopic performance of 5 and 10 mm² SD3 detectors

- operation temperature -20°C
- 1-stage Peltier cooler
- optimum shaping time 0.5 μs
- pulsed reset operation

- Light element detection
  - FWHM @ B-K = 38 eV
  - P/B = 13,000 ÷ 20,000

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Spectroscopic performance of 5 and 10 mm SD3 detectors

Operation temperature -20°C
1-stage Peltier cooler
Optimized detector entrance window

Light element detection
FWHM @ B-K = 38 eV

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Instrumentation @ BNL, 17.-18. Nov. 2011
Lothar Strüder, MPI Halbleiterlabor and University of Siegen

A single SDD can process up to 1 M counts per sec below 170 eV
SDDs on Mars Explorers Spirit and Opportunity

The APXS system of the MPICH in Mainz:

Excitation with Curium-244:
- $\alpha$ - particles
- X - rays

$\Delta E$ @ Spirit&Opportunity @ 1.5 keV: 80 eV
$\Delta E$ @ Pathfinder @ 1.5 keV: 280 eV
Applications of SDDs

Scanning electron microscope with separated electron and X-ray detector

SDD – Modules from 5 mm² bis 100 mm², 1 – 77 Module/Chip

Measurements made by RÖNTEC, Berlin

SEM – image

``colour – image``

Instrumentation © BNL, 17.-18. Nov. 2011

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SDD with integrated FET

♦ SDDs as chips

SDD 10 mm²
6 x 6 x 0.45 mm³

SDD 20 mm²
8 x 8 x 0.45 mm³

SDD 30 mm²
9 x 9 x 0.45 mm³

SDD 100 mm²
14 x 14 x 0.45 mm³

♦ ... and as modules
Extra Large Detector Area
"Application adapted"

3 x 20 mm² SDD
(e.g. for fixed channel WDX instr.)

3 x 1 cm² SDD
(e.g. for sequential WDX instr.)
Multi-Element SDDs

19x5 mm$^2 = 95$ mm$^2$

12x5 mm$^2 = 60$ mm$^2$

6x5 mm$^2 = 30$ mm$^2$

77x7 mm$^2 = 539$ mm$^2$

61x5 mm$^2 = 305$ mm$^2$
Detection range and quantum efficiency - hard x-rays

- combining SDD with modern scintillators
CCD basics

- full depletion (50 µm to 500 µm)
- back side illumination
- radiation hardness
- high readout speed
- pixel sizes from 30 µm to 650 µm
- charge handling: more than $10^6$ e-/pixel
- high quantum efficiency
pnCCD operation
Limitations: quantum efficiency

- energy range
  - m.i. particles no problem
  - photons
    - Si is 'transparent'
      - at high energies $> 10$ keV
      - absorption $\sim Z^5/E^3$
      - in the IR
        - photon energy $< E_{\text{gap}}$
      $\Rightarrow$ transmission without interaction
    - Si is a good absorber
      - in the optical
      - in the UV
      - at X-rays from 100 eV to 15 keV
    $\Rightarrow$ loss of signal charges in the entrance window dead layer
What is limiting the quantum efficiency?

The thickness of Silicon !!
And the radiation entrance window !!

Q.E. = 38 % @ 24 keV
d = 1 mm

Q.E. = 20 % @ 24 keV
d = 0.5 mm
Limitations: Energy

- energy resolution
- limited by
  \[
  ENC_{el} = \sqrt{\frac{2kT^2}{g_m C_{tot} A_1 \tau} + 2\pi a_f C_{tot} A_2 + q I_{leak} A_3 \tau}
  \]
  - electronic noise can be influenced by
    - detector design, integrated electronics
    - cooling
    - fast operation
    - repetitive readout
  - Fano noise, ultimate statistical limit
    \[
    ENC_{fano} = \sqrt{\frac{F \cdot E_x}{w}}
    \]
  - total noise
    \[
    \text{ENC}_{tot}^2 = \text{ENC}_{el}^2 + \text{ENC}_{fano}^2
    \]
## pnCCD - Measured Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>pnCCD performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>1 eV ... 25 keV (optimized for 0.1 ... 15 keV)</td>
</tr>
<tr>
<td>Number of pixels per chip</td>
<td>up to 1024 x 1024</td>
</tr>
<tr>
<td>Sensor Pixel Shape</td>
<td>square or rectangular</td>
</tr>
<tr>
<td>Pixel size</td>
<td>30 x 30 µm² ... 600 x 600 µm²</td>
</tr>
<tr>
<td>Dynamic range / pixel / pulse</td>
<td>3.000 photons @1 keV</td>
</tr>
<tr>
<td>Resolution (S/N &gt;4:1)</td>
<td>Single photons @ 100 eV</td>
</tr>
<tr>
<td>Electronics noise</td>
<td>2 - 8 electrons r.m.s.</td>
</tr>
<tr>
<td>Frame rate</td>
<td>Up to 2.000 Hz</td>
</tr>
<tr>
<td>Sensitive detector thickness</td>
<td>50 µm ... 1.000 µm</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>0°C ... -100°C</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>10.000 : 1</td>
</tr>
</tbody>
</table>
Applications:

1. XMM-Newton
2. eROSITA
3. Adaptive optics
4. Surface analysis at BESSY
5. Clusters at FLASH
6. Fluorescence measurements
7. Diffraction measurements of biological samples
8. Structural analysis of nanocrystals
9. X-ray color camera (PNS, IFG)
10. SVOM MXT
11. Electron detection in TEMs
12. Channeling radiation
13. ....
XMM EPIC pnCCD

- **Device**
  - Monolithic array of 12 pnCCDs
  - 200 x 64 pixels each
  - Pixel size: 150 x 150 μm²
  - 6 x 6 cm² area
  - 4” wafer
  - 280 μm thick
  - Common entrance window

- **Performance**
  - 5 e- ENC
  - Readout time: 4.5 ms
  - Integration time: 100 ms
  - Energy resolution: 150 eV FWHM @ 5.9 keV

Instrumentation @ BNL, 17.-18. Nov. 2011

Lothar Strüder, MPI Halbleiterlabor and University of Siegen
P. O'Connor et al.,
Technology of the LSST Focal Plane
NIM A582, p 902 – 909, 2007

L. Strüder et al.,
The MPI / AIT X-Ray Imager (MAXI) –
High Speed pn-CCDs for X-ray Detection
NIM A 288 p 227 - 235, 1990
**Tycho SNR**

- Image and spectrum
- Supernova remnant
- Observed by Tycho Brahe in 1532

- Single photon counting in X-rays
- Timing with X-rays
- To date: 4,000 ref. XMM papers

XMM-Newton observations

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XMM measurement of the broadening of the iron line

Relativistic Fe-line was measured by XMM - Newton

courtesy of Chris Reynolds
The European Photon Imaging Camera on XMM-Newton: The pn-CCD camera

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Citations/Publication Year for 2001A&A...365L.18S

- Total citations: 1001
- Total refereed: 906

August 2011
eROSITA pnCCD CCD-Module, launch in 2013

Four 3cm x 3cm CCDs still on Si-Wafer. The CCDs have 384 x 384 pixels in both image and framestore area.

Pixelsize: 75 x 75 µm².

Measurements at C Ka (277eV) and Mn Ka (5,9 keV) on flight-CCDs show the expected energy resolution and low energy response.
Status of eROSITA

Mirror fabrication is contracted to the companies MediaLario and ZEISS

Mechanical and electrical models of the flight cameras have been built

Qualification models are tested

Launch is expected to be in 2014
48μm pnCCD with a double-sided readout, mounted onto a ceramic substrate

- detector size = 27×13.5 mm²
- 48 μm square pixel size
- 528×264 pixel in total
- readout transfer to both sides
- image transfer time = 30 μs
- OOT probability = 3% @ 1000 fps
- charge transfer loss CTI ≈ 10⁻⁵
- charge handling capability > 10⁵ e⁻
- 100% fill factor
- readout noise vs. frame rate:
  - 2.3 e⁻ @ 10 .. 400 fps
  - 2.8 e⁻ @ 400 .. 1000 fps
- With binning:
  - 2.8 e⁻ @ 2000 .. 4000 fps

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Lothar Strüder, MPI Halbleiterlabor and University of Siegen
90 eV X-rays in single photon counting mode !!!

\[ E = 90 \text{ eV} \]
\[ \Rightarrow 25 \pm 1.7 \text{ e-h pairs} \]
\[ \text{ENC} = 2.5 \text{ e}^- \text{ (rms)} \]

FWHM: 38.9 eV

T = -50° C

Spectrum from 4,000 frames with 0.01 photons/pixel/frame
pnCCDs for electron imaging spectroscopy
simultaneous measurement of electrons and X-rays
pnCCD: 2 x 1024 x 512, 60 cm²

for 6 keV X-rays the system delivers 4k x 4k resolution points in all the area with less than one photon per pixel (typ. 90 %)
CFEL-ASG MultiPurpose Chamber

The world's largest X-ray CCDs

FEL beam
Mimi virus experiment: Janos Haidu

*Nature* 470, 78–81 (03 February 2011)

**Back detector:**

- **Gain:** High gain/256
- **Max. charge:** $2.5 \times 10^5$
- **Noise:** 25 electrons
Mimi virus experiment:
PI: Janos Haidu

Nature 470, 78–81 (03 February 2011)
PSI experiment: Henry Chapman

Nature 470, 73–77 (03 February 2011)

PS1: Membrane protein photosystem I, typical size: 100 nm to 1 µm
Back detector:

Gain: High gain/256

Max. charge: $2.5 \times 10^5$

Noise: 25 electrons
Charge Handling Capacitance
Charge Handling Capacitance
Imaging Performance
1s² 2s² 2p⁶ 3s² 3p⁶ 3d¹⁰ 4s² 4p⁶ 4d¹⁰ 5s² 5p⁶
Expected system properties

- Pixel size: 50 x 50 µm² or 75 x 75 µm²
- Resolution: \( \sigma_{x,y} \leq 10 \text{ µm} \)
- Frame rate: 360 Hz
- Noise: 5 el. (rms)
- CHC: 1,000,000 el.
- PSF: typ. 3x3
- EDP: 3 MeV
- Thickness: 450 µm
Layout of a 1024 x 1024 pixel focal plane

- CAMEX ASICs
- Ceramic boards
- Split frame operation
- 1024 pixel
- X-rays
- Thermal spacer
4096 x 1024 pixel array

Gap in between active areas of the detectors:
D = 2 mm
2048 x 2048 pixel array

Array of 2048 x 2048
Pixel of 75 x 75 µm²

Gap in between detectors
D = 2 mm
**DEPFET readout**

- **Measurement of signal**
  - Measure signal levels
    - source potential / drain current
  - Measure both before and after clear
  - Calculate the difference
    - correlated double sampling (CDS)
DEPFETs for the Athena WFI

1. Flexible operating modes
2. Low power dissipation (less than 2 W in 100 cm², DePFETs only)
3. Fano limited energy resolution from 0.5 keV to 30 keV
4. Spatial resolution better than 20 µm @ 100 µm pixel size
5. Homogeneous radiation entrance window
6. Intrinsic radiation hardness, no charge transfer needed
7. ENC was lowered to 0.2 e⁻ rms with RNDR
8. Thin optical `Blocking Filter´ can be directly integrated
9. Operation at `warm temperatures´, e.g. – 40 °C
"Backside" illumination: Source on top of entrance window

- **timing**
  - 2 µsec/row <-> 32 µsec/32x512 sensor
- **room temperature**
  - 220 eV FWHM @ 5.9 keV (singles)
  - moderate cooling -40 °C
  - 126 eV FWHM @ 5.9 keV (singles)
  - 131 eV FWHM @ 5.9 keV (all events)
- **extrinsic speed & resolution limitations**
- **yield & homogeneity**
  - defect pixels
    - 2 in 45 devices (> 10⁶ pixels)
    - pixel yield > 0.99999
  - dispersions
    - offset < 2 % (of Mn-Kα)
    - gain < 5 %
    - noise < 10 %

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Instrumentation @ BNL, 17.-18. Nov. 2011
ATHENA: ESA's X-ray L-class mission

- Eff. area: 1.2 m²
- \( \Delta E \): 0.1 – 15 keV
- PSF: 5 arcsec

**Instrumentation:**
(1) XMS (TES)
(2) WFI (DePFET)

**Launch:** 2022
Frontend ASIC's

- **CAMEX 0.8\(\mu\)m**
  - readout ASIC for use with CCDs & DEPFET Pixel

- **ASTEROID & VELA & VERITAS 0.35\(\mu\)m**
  - readout ASICs for DEPFET Pixel & CCD

- **SWITCHER 0.35\(\mu\)m HV**
  - DEPFET matrix control → selection of a pixel row for readout or clear

- **DSSC ASIC 130nm**
  - preamplifier with high speed and high dynamic range for XFEL DEPFETs

- **DHP cluster engine 90nm**
  - data clustering engine for data reduction for tracklets of Belle II
Where to find - Examples
PCI DAQ System (PXD5+, SX, XL)

- 256 x 256 Pixels
- 4-8 Asteroids
- 8 SWITCHER S
- 80MHz SEQ
- 4Ch ADC

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What is the challenge for Detectors @ XFEL?

Time structure: difference with “others”

Electron bunch trains; up to 3000 bunches in 600 μsec, repeated 10 times per second.
Producing 100 fsec X-ray pulses (up to 30 000 bunches per second).

- 100 ms
- 600 μs
- 99.4 ms

30 000 bunches/s but 99.4 ms (%) no photons

200 ns

FEL process

X-ray photons 50 - 100 fs
The European XFEL project

DePMOS Active Pixel Sensor

Connecting Bumps
- 1 per pixel

CMOS Layer
- Signal processing
- Signal storage & output
Readout Concept

- Optimum analog shaping
- Immediate 8 bit digitization (9 bit for $f \leq 2.2$ MHz)
- In-Pixel SRAM
- Digitized data are sent off the focal plane during 99ms gap
- Sensor & Front-end electronics can be switched off during the gaps
Non-Linear DEPFET Working Principle

- The internal gate extends into the region below the source.
- Small signals assemble below the channel, being fully effective in steering the transistor current.
- Large signals spill over into the region below the source. They are less effective in steering the transistor current.
module, mechanics and power

- 1-2 mW/pixel peak power → 1-2 kW peak power
- Power cycling about 1/100
- 10-20 W mean power
- A careful thermal design is needed
- Voltage regulators have to be deliver a lot of power in a short time

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Lothar Strüder, MPI Halbleiterlabor and University of Siegen

K. Hansen - DESY
• 1024x 1024 pixels
• 16 ladders/hybrid boards
• 32 monolithic sensors
  128x256  6.3x3 cm²
• DEPFET Sensor bump bonded to 8 Readout ASICs (64x64 pixels)
• 2 DEPFET sensors wire bonded to a hybrid board connected to regulator modules
• Heat spreader
• Dead area: ~15%
## DSSC - Expected Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected DSSC performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>0.5 ... 25 keV (optimized for 0.5 ... 4 keV)</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>1024 x 1024</td>
</tr>
<tr>
<td>Sensor Pixel Shape</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Sensor Pixel pitch</td>
<td>~ 204 x 236 µm²</td>
</tr>
<tr>
<td>Dynamic range / pixel / pulse</td>
<td>&gt; 10,000 photons @1 keV</td>
</tr>
<tr>
<td>Resolution</td>
<td>Single photon @ 1 keV (5 MHz)</td>
</tr>
<tr>
<td>(S/N &gt;5:1)</td>
<td>Single photon @ 0.5 keV (≤ 2.5 MHz)</td>
</tr>
<tr>
<td>Electronics noise</td>
<td>&lt; 25 electrons r.m.s.</td>
</tr>
<tr>
<td>Frame rate</td>
<td>1-5 MHz</td>
</tr>
<tr>
<td>Stored frames per Macro bunch</td>
<td>≥ 512</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-10°C optimum, RT possible</td>
</tr>
</tbody>
</table>

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KEKB will be upgraded to reach a luminosity of $8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$.

The Belle detector, especially the vertex detector needs to be upgraded:

- Background occupancy $8x - 15x$ Belle
- Radiation damage (1-2 MRad/year)
- Better performance (resolution)

High occupancy excludes strip detectors

=> Pixel detector
=> Fast readout

Resolution dominated by multiple scattering:

=> Thin sensors needed

Due to its superior performance of the DEPFET can cope with this challenges

MPP (collaborators) will construct a pixel vertex detector based on DEPFET technology for Belle II.
Belle II Vertex Detector

- 20 modules
- with 400,000 pixel each
- thinned to 50 µm
- read out with 50 kHz
- DePFET noise level around 40 electrons
- System noise level around 100 electrons

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Monolithic all silicon module
No additional support structure

Thickness of active sensor: 50 µm
Pixel size: 50µm x 50µm
Number of Pixels: 400.000
Frame readout: 50 kHz

Low power: 0.1 W/cm² in active area
Prototype Module, thinned down to 50µm
Main projects at the MPI HLL

- XMM development
- eROSITA development
- ATHENA development
- SOHO
- Spirit + Opportunity
- XMM Launch
- BESSY
- FLASH
- CFEL, ICLS
- eROSITA
- BepiColombo
- e.g. NNXM
- ATHENA Launch

Timeline:
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030

Projects:
- ATLAS development
- Belle II & Belle II upgrade development
- ILC development
- NA11
- NA32
- ALEPH
- ALEPH development
- ALEPH
- ATLAS development
- SLHC
- Belle II
- ILC

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Summary and Outlook:

- SDDs are heavily used in science and industry
- pnCCDs are used in different fields of basic science
  Their performance figures are close to theoretical limits
- They can be monolithically built as large as $9 \times 9 \text{ cm}^2$
  they can be read out up to 1,000 times per second
- DePFET active pixel sensors are being developed for a
  5 MHz operation in a 3D technology for single photon counting
  from 300 eV up to 25 keV
- DePFET detectors are able to deliver a dynamic range
  up to $5 \times 10^4$ with non-linear signal compression
MPI Halbleiterlabor* on the SIEMENS Campus in Neuperlach
End