Development of Silicon Drift Detectors and recent applications*

*a personal view

(dedicated to Pavel Rehak - 1945-2009)

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Outline

✓ The idea of sidewards depletion
✓ Optimized SDD Topologies
  - spectroscopy
  - 2D position sensing
✓ Evolution towards spectroscopic imaging: MLSDD and CDD
✓ Outlook to applications:
  - X-Ray Fluorescence and Proton Induced X-Ray Emission
  - Gamma-ray imaging
  - Advanced X-ray imaging modalities
  - Macro-pixel arrays with DEPFET readout for XFEL
✓ Conclusions
Planar pn diodes

p+ rectifying junction (V=-80V)

n-type substrate

n+ ohmic contact (V=0V)

- Detector capacitance increases with diode active area
- Detector capacitance decreases if diode thickness is increased
Planar pn diodes

\[ ENC_{opt}^2 = \sqrt{A_1 A_3} \sqrt{2kTq} \left( \frac{\alpha}{\omega_T} \sqrt{\frac{C_d I_L}{FET \text{ detector}}} \left( \sqrt{\frac{C_G}{C_d}} + \sqrt{\frac{C_d}{C_G}} \right) \right) + ENC_{1/f}^2 \left( C_T^2 \right) \]

Energy resolution

Count rate capability

require

capacitance minimization

[Graph showing optimum ENC and optimum shaping time for different pn-diode areas and microstrip conditions.]

\[ \tau_{opt} = \sqrt{\frac{A_1}{A_3}} \sqrt{2V_{th}} \left( \frac{\alpha}{\omega_T} \sqrt{\frac{C_d}{FET \text{ detector}}} \right) \]

\[ \left( \sqrt{\frac{C_G}{C_d}} + \sqrt{\frac{C_d}{C_G}} \right) = \sqrt{\frac{A_1}{A_3}} \tau_c \]

\( Cd, \) detector capacitance [F]

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"Advanced Radiation Detectors for Industrial Use"
The sideward depletion

Emilio Gatti & Pavel Rehak, Autumn 1982

basic idea of sideward depletion — the revolutionary concept at the heart of the Silicon Drift Detector — is to fully deplete the semiconductor substrate through a pointlike “virtual contact,” as it is called in Gatti and Rehak’s original paper.
The sideward depletion

- Detector volume fully depleted by “virtual contact” (point-like)
- Full depletion achieved with only a quarter of the bias necessary for standard p-n diodes
Below depletion

At full depletion

• At nearly full depletion the conductive channel at the middle of the detector retracts causing the capacitance to drop abruptly.

• At higher bias voltages the remaining capacitance is the lowest capacitance between the n+ contact and the p+ electrodes.
Silicon Drift Detector

- p+ junctions divided in strips with increasing potential on both sides \( \rightarrow \) nearly uniform drift field parallel to the surface
- signal electrons focused in the center of the wafer transported at constant velocity towards the readout anode
- 1-D position sensing with only 1 readout channel through drift time
- small anode capacitance \( \rightarrow \) low-noise measurement of time and amplitude

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1984: Patent filed...

United States Patent

<table>
<thead>
<tr>
<th>Rehak et al.</th>
<th>[19] Patent Number: 4,688,067</th>
</tr>
</thead>
</table>

| CARRIER TRANSPORT AND COLLECTION |
| IN FULLY DEPLETED SEMICONDUCTORS |
| BY A COMBINED ACTION OF THE SPACE |
| CHARGE FIELD AND THE FIELD DUE TO |
| ELECTRODE VOLTAGES |

<table>
<thead>
<tr>
<th>Inventors:</th>
<th>Pavel Rehak, Patchogue, N.Y.; Emilio Gatti, Lesmo, Italy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assignee:</td>
<td>The United States of America as represented by the Department of Energy, Washington, D.C.</td>
</tr>
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<tr>
<th>Appl. No.:</th>
<th>583,553</th>
</tr>
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<tbody>
<tr>
<td>Filed:</td>
<td>Feb. 24, 1984</td>
</tr>
</tbody>
</table>

FOREIGN PATENT DOCUMENTS

| 974659 9/1975 Canada | 357/24 M |

OTHER PUBLICATIONS


Primary Examiner: Gottlieb; Judson

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Multianode Silicon Drift Detectors

- n-type substrate
- HV
- LVp
- HVp
- LV

- Granularity of the anodes provides lateral interaction coordinate
- Drift time measurement gives position along drift coordinate with high resolution:
  - ~2 µm in lab,
  - ~10 µm in test beam
  - ~20 µm in experiments
- External trigger required for 2D position sensing
Anode capacitance (of a 300-μm-thick silicon detector), achievable optimal ENC, and optimal shaping time, in the case of no 1/f noise and of triangular shaping for matched conditions between the detector capacitance and the front-end electronics input capacitance, as a function of detector side length for different detector families. The stars report the corresponding values for silicon drift detectors (SDDs) for X-ray spectroscopy. Due to their circular shape, as side length we considered the radius of the active area. This shows how detectors based on the sideward depletion principle broke the tie between active area and output capacitance. The bubble chart represents the number of detector channels needed for a given active area.
## SDDs in High Energy Physics

### NA45 - CERES

- **Wafer:** 1st ver.: 3” Silicon, 280 μm thick  
  2nd ver.: 4” Silicon  
- **Active area:** 32 cm²/55 cm²  
  360 collecting anodes  
- **Foundry:** BNL/Sintef

### STAR

- **@ BNL RHIC (install Feb.01)**
- **Wafer:** 4” (NTD) Silicon, 3 kΩcm resistivity, 280 μm thick  
- **Active area:** 6.3 × 6.3 cm²  
  2 × 240 collecting anodes  
- **Foundry:** Sintef

### ALICE

- **@ CERN’s LHC**
- **Wafer:** 5” (NTD) Silicon, 3 kΩcm resistivity, 300 μm thick  
- **Active area:** 7.02 × 7.53 cm²  
  512 collecting anodes  
- **Foundry:** Canberra

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SDD for high resolution X-ray spectroscopy

- continuous p+ back contact acting as entrance window
- cylindrical geometry with anode in the center
- transistor located in the center of the detector.

- drift field azimuthally symmetric
- electrons produced anywhere within detector active area are collected at the central anode
- detector capacitance \( \approx 100 \text{ fF} \)
SDDs for high res. spectroscopy

- Anode capacitance: ~200 fF
- Energy resolution: $\Delta E_{\text{FWHM}} = 125$ eV (equivalent to ENC=4 el. r.m.s.) @ 200kcps
- Count rate capability: up to $10^6$ cps
- Peak/Background $\approx 10,000 : 1$
- Quantum efficiency: $> 90\%$ @ 0.3-10 keV (Boron line detection)
- Rad. hardness: $> 10^{14}$ Mo$_K$ photons
- Operating temperature: $T \approx -10^\circ C$

with pulset reset PA thanks to on-chip reset diode
Silicon quantum efficiency

- 137 µm @ 10 keV
- 18 µm @ 5 keV
- 443 µm @ 15 keV
Silicon quantum efficiency

![Graph showing the quantum efficiency of silicon detectors as a function of energy and detector thickness.](graph.png)
SDDs for high res. spectroscopy

Commercially available classic cylindrical SDDs with sensitive area of 5, 10 and 20 and 30 mm² up to 1 cm²

SDD 5 mm²
chip 5 x 5 x 0.45 mm³

SDD 10 mm²
chip 6 x 6 x 0.45 mm³

SDD 20 mm²
chip 8 x 8 x 0.45 mm³

SDD 30 mm²
chip 9 x 9 x 0.45 mm³

SDD 100 mm²
chip 14 x 14 x 0.45 mm³
Droplet SDDs: novel evolution

- Anode + on-chip JFET outside detector active area $\rightarrow$ improvement of the peak-to-background ratio.
- Very small collecting anode $\rightarrow$ output capacitance about 120 fF much lower than conventional SDDs (larger than 200 fF)

![Anode diagram](image)

![Graphs](image)

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Multichannel SDDs

- 19x5 mm² = 95 mm²
- 12x5 mm² = 60 mm²
- 61x5 mm² = 305 mm²
- 6x5 mm² = 30 mm²
- 77x7 mm² = 539 mm²
- 4x10 mm² = 40 mm²
- 16 mm² each

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Sideward Depletion Family Tree

Sideward Depletion

Silicon Drift Detectors
- Linear geometry
  - Multi-anode SDDs
  - Multi-Linear SDDs
- Round-shape
  - Circular
  - Droplet SD³
  - Multichannel

Fully Depleted pnCCDs
- "normal"
- Frame-store

DePMOS Arrays
- Circular
- Macro-Pixels
- Linear
- Multiple Readout

Controlled-Drift Detectors

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Limitations of SDD for 2D position sensing

- **START TRIGGER NEEDED!**
  - no imaging of random sources (x/γ/...)!

- **FREE LATERAL BROADENING**

- 🎉 position resolution along anodes improved by interpolation

- 😞 centroid algorithm not optimal for all incident positions

- 😞 charge sharing limits spectroscopic performance and reduces event rate

- **DOPING INHOMOGENEITIES**

- 😞 systematic deviations (up to +/- 200µm) along anode direction

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F. Prino, ALICE Club (2008)
Suppression of lateral broadening

- cloud size independent of interaction point
- compensation of doping inhomogeneities
- high count rate applications
- event timing via signal induction

Multi-Linear SDD architecture

- fully depleted n-type bulk
- p+ entrance window implanted on the back side
- array of p+ strips implanted on the front side
- channel-stops (deep p-implants) for lateral confinement
- channel-guides (deep n-implants) for lateral confinement and drift enhancement
- HE n implant locates the drift channel close to the finely structured surface
- on-chip electronics (JFET in source follower configuration)
MLSDD operating modalities - I

- **free-running mode** (external trigger)
- **free-running mode** (self-trigger from back side)

\[ T_{\text{drift}} = 1-3 \, \mu s/cm \]

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**start-time and event-trigger** (back side induction or ext. trigger)

**stop-time and charge** from anode signal
MLSDD operating modalities - II

Integration phase

INTEGRATION
Clock
Anode

READOUT

hv

T_d

Q

Readout phase

1-3 µs/cm

Integrate-readout mode
Controlled-Drift Detector (1997)


Pixel 180µm x 180µm

270 eV FWHM @ 300K @ 0.25 µs 
(28.6 el. r.m.s.)

198 eV FWHM @ 223K @ 0.5 µs 
(18.7 el. r.m.s.)

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2-D spectroscopic X-ray imaging with CDDs

2D imaging & spectroscopy

pixel 120 µm, 10^5 frame/s
15 keV x-rays, T=300K

* no animal was killed or suffered for this measurement

Sincrotrone Trieste – SYRMEP beam line


219 Hz sine wave
Mask displacement: 2.3 mm p-p

Time-sliced X-ray images

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Outlook to applications...

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Outlook to applications...

- X-Ray Fluorescence and Proton Induced X-Ray Emission
- Gamma-ray imaging
- Advanced X-ray imaging modalities
- Macro-pixel arrays with DEPFET readout for XFEL
X-ray fluorescence imaging

- Energy of XRF X-ray is characteristic of element present in sample.
- Intensity of XRF signal is related to concentration of element in sample.
- XRF is non-destructive.

1. Incident X-ray
2. Ejected electron
3. Electron falls into vacant space
4. Characteristic fluorescence X-ray

Usually technique performed by a 2D positional scan of a sample against a collimated beam with an energy dispersive detector.
XRF elemental mapping with multi-cell SDDs

Experiment FELIX INFN Gr.5 2002-05

- polycapillary X-ray lens → high photon flux in small excitation spot
- ring-shaped SDD → larger collection angle of XRF
Geological analyses: fossil fish

Map of Fe Kα line @ 6.4keV
10x10mm with 500μm step
2 sec per point
Total meas. time 900sec


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Works of art

Lombard buckle - inlaid work (agemina) - beginning of VII century A.C. - Trezzo d’Adda, Italy

Milano

Trezzo d’Adda

Ravenna

Au ~97%
Ag+Cu ~90%+7%
~3 mm
Fe

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XRF biomedical applications with SDDs

- study of the distribution of drugs and diagnostic agents in biological samples
  - in collaboration with Centro Studi Fegato, University of Trieste, Bracco Centro Ricerche Milano, Center of Molecular Biomedicine (Ts)
  - measurements @ SYRMEP beamline - ELETTRA SINCROTRONE Trieste, Italy

- theranostic imaging of tumours labelled with gold nanoparticles
  - in collaboration with Dept. of Medical Physics and Bioengineering, UCL, Division of Surgery and Interventional Science, UCL Medical School, IfG GmbH)
  - measurements @ DIAMOND Beamline B16, Didcot, UK and in our lab - Polimi&INFN, Milano, Italy
Drugs and diagnostic agents distribution in biological samples

**Michaelis-Menten kinetics**

\[ y = N_s \times x + \left( \frac{V_{\text{max}} \times x}{K_m + x} \right) \]

- \( N_s \) = nonspecific binding
- \( V_{\text{max}} \) = max velocity
- \( K_m \) = enzyme/substrate affinity

**Gadolinium calibration curve**

**Scanned area**:
- 9mm x 9mm
**Step**:
- 500\( \mu \)m x 500\( \mu \)m
**Measurement time**:
- 60 s/point

**Hepatic uptake of Gadocoletic acid trisodium salt (B22956) agent**

- no Gadolinium is detected in spleen, kidney and lung

\[ k_m = 0.0960 \pm 0.0339 \text{ mg/ml} \]

of the same order of magnitude of the value assessed with radioactive markers


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“Advanced Radiation Detectors for Industrial Use”
Theranostic imaging of tumours labelled with gold nanoparticles

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1.9 nm GNP's uptake

GNP calibration curve

minimum detection limit: 3 ppm

IBA techniques and PIXE

Ion Beam Analysis (IBA) techniques

- Nuclear reaction products (NRA)
- \( \gamma \) - rays (PIGE)
- Ion beam
- X-rays (PIXE)
- Scattered particles (RBS)
- Secondary electrons (SEI)
- Light (IL)

TARGET / SAMPLE

- Charge pulse (IBIC)
- Recoil nuclei (ERDA)
- Transmitted particles (STIM)
- Scattered particles

PIXE (Particle Induced X-ray Emission)

- Multi-elemental
- Quantitative
- Non-destructive

- Ionization cross-section for PIXE and XRF

- sample as target of beam of accelerated particles with energy of the order of few MeV.
- secondary radiation energy is characteristic of the emitting atom or nucleus.

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advantages of SDDs in count rate and energy resolution

problem: at low X energies (medium-light elements) back-scattered particles degrade energy spectra even at low particle rates

SDD+ customized front-end electronics with optimized pulsed reset able to manage the large signal of particle events without degradation
SDD-based PIXE setup - 2

Lapis-lazuli pigment

3 MeV ext. proton beam
SDD 10 mm² @ -27°C
Polycapillary lens
(0.5mm focal spot on sample)

Cinnabar pigment


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SDD-based PIXE setup - 2

with optimized pulsed reset readout

4 MeV proton beam
SRM 610 500ppm trace elements glass standard

proton rate on the detector

- blue: 105 Hz
- black: 350 Hz

channels

counts

Outlook to applications...

- X-Ray Fluorescence and Proton Induced X-Ray Emission
- Gamma-ray imaging
- Advanced X-ray imaging modalities
- Macro-pixel arrays with DEPFET readout for XFEL

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interaction time given from fast induction signal on back strips

→ fast coincidence imaging in Compton telescope arrangement

electron tracking with high spatial and energy resolution

→ vertex of the interaction
→ initial direction of recoil electron
(reduction multiple Coulomb scattering issue)
→ estimate of $dE/dx$

Silicon MLSDD scatter detector with readout of backside strips
Timing resolution

Time jitter vs. signal charge $Q$

$\Delta t_{\text{RMS}} \propto 1/Q_{\text{p-side}}$

$T=300 \text{ K}$

Pulsed IR 904 nm laser (pulse duration <100ps)

Measured time jitter @ $Q=31300 \text{ el}$

Time jitter with gamma-rays (Na-22)

- 6.08 ns FWHM with 243 V applied at the back side
- 9.09 ns FWHM with 154 V applied at the back side

$\sim 6 \text{ ns FWHM}$

Opens to coincidence imaging with $\sim 10 \text{ ns rms time resolution}$

Electron tracks

Na-22 source, \( T = 300 \text{K} \)

**internal absorption**

1-st experimental evidence of electron tracks resolved in space and energy in a single silicon layer

\[ T_{\text{electron}} = 405.1 \text{ keV} \]
\[ \sigma = 0.118 \text{ keV/\mu m rms} \]

\[ E_{\text{out}} = 758 \text{ keV} \]

\[ T_{\text{electron}} = 959.8 \text{ keV} \]
\[ \sigma = 0.028 \text{ keV/\mu m rms} \]

\[ E_{\text{out}} = 758 \text{ keV} \]

Silicon Drift Detectors for Readout of Scintillators in Gamma-Ray Spectroscopy

Carlo Fiorini, Luca Bombelli, Paolo Busca, Alessandro Marone, Roberta Peloso, Riccardo Quaglia, Pierluigi Bellutti, Maurizio Boscardin, Francesco Ficorella, Gabriele Giacomini, Antonino Picciotto, Claudio Piemonte, Nicola Zorzi, Nick Nelms, and Brian Shortt

- Started in 2011 within a project supported by ESA for LaBr3 scintillator readout with SDD arrays.
- Back entrance window optimized to achieve QE > 80 % at 380 nm (→ suitable also for soft X-rays).
- Considered suitable for the upgrade of the Siddharta-2 apparatus, with preliminary evaluation on prototypes in 2012/2013.

FBK production:
- 4” wafer
- 6” wafer upgrade now operative
- 8 mm x 8 mm
- 12 mm x 12 mm
- 9 SDDs array (8 mm x 8 mm each)

thin entrance window suitable for both soft X-ray detection (>200eV) and scintillator readout

area = 64mm²
Outlook to applications...

- X-Ray Fluorescence and Proton Induced X-Ray Emission
- Gamma-ray imaging
- Advanced X-ray imaging modalities
- Macro-pixel arrays with DEPFET readout for XFEL
X-ray Scatter Imaging (XSI)

- Polycapillary technology for beam collimation and angular selection
- Materials scatter X-rays at distinctive angles and energies.

Polycapillary technology allows full exploitation of detector pixel resolution

- 2D spectroscopic imager (Controlled Drift Detector) allows imaging at multi-momentum transfer values

\[ \chi = \frac{E}{hc} \sin\left(\frac{\theta}{2}\right) \]

Controlled Drift Detector as 2D imager with high spectroscopic resolution
Scatter images vs TX images with standard collimation @ Synchrotron ELETTRA

**pork sample with 2mm detail**

Transmission image (pixel 180µm)
- contrast = 33%

Scatter image (pixel 500µm)
- contrast = 46%

Transmission image (pixel 180µm)
- contrast = 11%

Scatter image (pixel 500µm)
- contrast = 29%

- contrast optimization with energy selection
- conventional mechanical collimation limits spatial resolution


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X-ray Scatter imaging with X-ray tube and high-resolution polycapillary collimation

Perspex / Nylon6,6 Phantom

Perspex

M3 Nylon Grub Screw

3mm

Perspex

Threads

9.15mm 3mm

Perspex

Threads

C = 0.03

16.5-18.5keV

Nylon

linear scattering coefficient for Nylon 6.6 and Perspex

C = 0.15

12-14keV

16.5-18.5keV

C = 0.43

Multi-momentum imaging (energy selection)

A. Bjeoumikhov, et al.

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- Macro-pixel arrays with DEPFET readout for XFEL
2D area detectors for XFEL beams

- high dynamic range (<10^4 X-rays/pixel)
- high speed (~5 Mframes/s)
- low noise (E=2-15 keV)

scheduled for operation end 2015

Max bunch rate: 4.5 MHz
DePMOS Sensor w/ Signal Compression

- Drift structure to allow fast and complete collection at buried gate
- DEPFET readout
  ✓ collecting anode=internal gate
  ✓ high energy resolution (2 keV photon counting)
  ✓ analog compression


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A constant charge is injected at fixed time intervals and the internal gate regions are progressively filled.

- 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.

In the experiment, the charge is deposited once, but the DEPFET response is the same.
Developed by DSSC consortium (Italy-Germany) under contract with DESY/XFEL GmbH


- 1024x1024 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%
Conclusions

- Silicon Drift Detectors were invented by E. Gatti and P. Rehak almost 30 years ago as particle-tracking detectors in physics experiment.
- Nowadays widely spread in X-ray spectroscopy, and commercially available in different shapes and sizes.
- Conventional and non-conventional applications have been shown (e.g., nondestructive analysis of cultural heritage, environmental monitoring, industrial control based on XRF and XRD, novel diagnostic tools for biomedical imaging with X and gamma-rays, etc.).
- As Gatti and Rehak stated in their first patent, “additional objects and advantages of the invention will become apparent to those skilled in the art.”

Let us hope to be skilled enough in the art to reach new milestones in this fascinating field and keep “drifting” on towards new horizons...
Thank you for your attention...

...and a special thank to everyone who actively contributed in this exciting development.