Review of Semiconductor Drift Detectors

Talk given by Pavel Rehak following a presentation on 5th Hiroshima Symposium of Semiconductor Tracking Detectors
Outline of the Review

• Principles of Semiconductor Drift Detectors
• Drift Detectors for Position and Charge sensing
• Lessons learned from utilization of Drift Detectors in Heavy Ion Experiments
• X-ray spectroscopy with Drift Detectors
• Controlled Drift Detectors
• Conclusions and predictions
Concept of Semiconductor Drift Detector

Transport of charged carriers in thin fully depleted semiconductor detectors in direction parallel to the large surface of the detector.

1.) Charge carriers induce a signal on the anode only on the arrival. The drift time measure the distance between the position of the ionizing particle and the anode.

2.) The capacitance of the anode is small -> low series noise of the read-out.
Analyses of buried channel Charge Coupled Devices. (CCDs) in 1983

Negative potential in the region of the channel.
Reversed biased one sided step p-n junction in 1 dimension

Space charge region

Neutral region

Space charge density $\rho = qN$

$N$ is donor or acceptor volume density
Equations of electrostatics

\[ \text{Negative electric field } -E \]

\[ \text{Negative potential } -U \]

\[ \text{div } E = \rho / \varepsilon \]

In one dimensional case the above reduces into: \( dE/dx = \rho / \varepsilon \)

Electric field is a piecewise linear.

Electric potential \( U \) is defined by:

\[ E = -\nabla U \]

In one dimensional case the above reduces into: \( E = -dU/dx \)

\( U \) is parabolic and depleted depth \( d \)

\[ d = \sqrt{2\varepsilon U / qN} \]
Depletion from two sides

- P+ rectifying contacts
- N+ ohmic contacts
- n- bulk

Section shown below

Undepleted region(s)

Graph showing potential variation with depth coordinate (μm).
Summary of principles

Unambiguous 2 dimensional measur.

Precision:
- 2um in lab
- 10 um in the test beam
- 20 um in experiments
Optimal signal processing

\[
\varepsilon^2 = \frac{C^2 e_n^2 / 2 \int_{-\infty}^{+\infty} w^2(t) dt + q^2 v \int_{-\infty}^{+\infty} w^2(t) dt + q^2 N \int_{-\infty}^{+\infty} f(t) w^2(t) dt}{q^2 N^2 \left[ \int_{-\infty}^{+\infty} f'(t) w(t) dt \right]^2}
\]

Where: \( w(t) \) is unknown weighting function, \( f(t) \) is pulse shape induced on the anode normalized to the area of 1, \( N \) is the number of electrons in the signal pulse, \( C \) total input capacitance, \( e_n^2 \) physical spectral density of the series noise, \( \nu q \) is the leakage current and \( q \) is the positive value of charge of an electron.

To minimize the above time variance can be reduced to the solution of the following equation:

\[
- \frac{C^2 e_n^2}{q^2 N^2} w''(t) + \frac{2 f(t)}{N} w(t) + \frac{2 \nu}{N^2} w(t) = 2 \varepsilon_{\text{min}}^2 f'(t) \cdot \text{const}
\]
Position sensing in high energy heavy ion experiments

- NA45 (CERES) Experiment at SPS at CERN
  - a) 3” cylindrical drift detector
  - b) 4” cylindrical detector (past)
- STAR Experiment at RHIC at BNL (present)
- ALICE Experiment at LHC at CERN (future)
Innovations in CERES cyl. Det.

- Collection of leakage current generated at the Si-SiO interface at a sink anode
- Interlaced anodes (Nyquist filtering in linear dimension)
STAR Drift Detector
SDD collaboration

• INFN - Turin – Italy
• INFN - Trieste - Italy
• INFN - Bologna – Italy
• INFN - Rome – Italy
• INFN - Alessandria- Italy
• Ohio State University - Columbus - Ohio - USA
• University of Jyvaskyla - Jyvaskyla - Finland
• Nat. Acad. of Sciences, Bogolyubov Inst. for Th. Phys. - Kiev - Ukraine
• Scientific Res. Techn. Inst. of Instrument Making - Kharkov - Ukraine
• Acad. of Sciences of Czech Republic - Rez U Prahy - Czech Republic
• St. Petersburg State University - St. Petersburg - Russia
**SDD barrels**

Silicon Drift Detectors

- Tot. No. channels: $133 \cdot 10^3$
- Tot. No. detectors: 260
- Total area: 1.37 m²

<table>
<thead>
<tr>
<th></th>
<th>Layer 3</th>
<th>Layer 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (mm)</td>
<td>14.9</td>
<td>23.8</td>
</tr>
<tr>
<td>Ladders</td>
<td>14</td>
<td>22</td>
</tr>
<tr>
<td>SDDs per ladder</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>
**ALICE Silicon Drift Detector**

**Wafer:** 5”, Neutron Transmutation Doped (NTD) silicon, 3 kΩ·cm resistivity, 300 µm thickness  
**Active area:** 7.02 × 7.53 cm² (83% to total)
Detector design features

**Charge collection zone**
- guard cathodes (32 µm pitch)
- 292 drift cathodes (120 µm pitch)
- implanted HV voltage dividers
- 256 collection anodes (294 µm pitch)

**injector lines**
- MOS injector (every 8th anode)
- injector line bonding pad
Beam Tests in 2003 – Position resolution

Exhaustive test of the front-end parameters performed in beam test: gain, sampling & ADC frequencies...
Linear absorption coefficient

Photon energy (keV)

Abs. coeff. (1/cm)

Absorption coefficient for silicon

\[
l = l_0 e^{-\sigma_L x}
\]

\[
\sigma_L = \sigma_r + \sigma_{ph} + \sigma_c + \sigma_{gr}
\]

Rayleigh or coherent \(\sigma_r\)

Compton or incoherent \(\sigma_c\)

Pair production \(\sigma_{gr}\)

K shell absorption edge

 Photon energy (keV)

Absorption coefficient (cm⁻¹)

Photon energy (keV)
\[
\sigma_{Si}^2 = F \cdot E_{\text{photon}} W
\]

\[
\text{ENC}_{\text{par}}^2 = qI_{\text{leak}} \int_{-\infty}^{\infty} h(t)^2 dt \approx qI_{\text{leak}} t_{\text{peak}}
\]

\[
\text{ENC}_{\text{series}}^2 = \frac{1}{2} e_n^2 C_t^2 \int_{-\infty}^{\infty} [h'(t)]^2 dt \approx e_n^2 C_t^2 / t_{\text{peak}}
\]

\[
t_{\text{peak}}^{(\text{optimal})} = e_n C_t / \sqrt{q \cdot I_{\text{leak}}}
\]

\[
w = 3.62 eV
\]
Leakage Current: \[ i_{\text{leak}} = \frac{q \cdot n_i}{(2 \cdot \tau)} \]

Where \( n_i \) is the density of carrier in intrinsic silicon, \( \tau \) is the life time and \( N_t \) the density of traps in silicon bulk.

\[ n_i \propto \exp\left(\frac{-E_{\text{gap}}}{(2kT)}\right) \]

\[ \tau \cong \frac{1}{(\sigma \cdot v_{th} \cdot N_t)} \]
X-ray drift detector

Silicon Drift Chamber
Potential within Drift Detectors
Single sided junction FET

N-Channel JFET on Depleted N-type Silicon

size & characteristics (typical):

- gate length: 5 μm
- gate width: 50 μm
- saturation current: 400 μA
- transconductance: 400 μA/V
The best room temp. spectrum
Low energy tails

Spectral Response

- Shaping time 1,0 μs
- Temperature -18°C
- Energy resolution 128 eV (Mn-Kα)
X-ray fluorescence system
Applications in Art studies

XRF-Analyse (X-Ray Fluorescence)

Untersuchung eines Leichentuchs
(Antinopolis, III. Jahrhundert n.Chr., Vatikanische Museen)

Die Farbe besteht aus einer Mischung von Orpiment (As₂S₃) und Goldstaub.
The **Controlled-Drift Detector (CDD)**

(*) Patents: US 6,249,033 EP0862226

- **2D position sensing** (100-200µm)
- low capacitance (~100fF) and integrated JFET ⇒ high energy resolution
- low no. of channels ($n$ instead of $n \times n$)
- integrate-readout mode

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**Readout phase**

- The X-ray position along the drift is obtained from the electrons' drift time
- The X-ray energy is obtained from the electron charge collected at the anodes
Transport mechanism and Readout speed

**Charge-Coupled Device (CCD)**

L. Strüder et al., NIM A257 (1987) 594

**Controlled Drift Detector**

A. Castoldi et al., IEEE TNS, 44(5) oct. 1997 p.1724

- **long readout time** as charge transfer and processing are done sequentially

\[ T_{\text{readout}} = N_{\text{pixel}} (T_{\text{proc}} + \Delta t_{\text{tr}}) \] \[ \sim 1 \text{ ms/cm} \]

- **shorter readout time** as charge transfer and processing are simultaneous

\[ T_{\text{readout}} = T_{\text{drift}} \] \[ \sim 3 \mu s/cm \]
1-D imaging and spectroscopy of a Fe-55 source @ 100 kHz


- $\Delta t = 55 \text{ ns}$
- $\text{FWHM} = 11 \text{ ns}$

Pixel 180µm x 180µm

- $\sim 250 \text{ eV FWHM @ 300K}$
- $(\text{ENC}=26 \text{ electrons r.m.s.})$

$T_{sh}=0.25 \mu\text{s}$

Frame frequency=100 kHz

6x6 mm$^2$ prototype
X-ray spectroscopic imaging with CDDs

Radiographic image of a lizard*...

…and spectroscopic analysis of each pixel

* no animal was killed or has suffered for this measurement
A fast readout speed allows to reduce both readout and integration times:

- higher frame rate (i.e. better time resolution between X-ray images)
- better energy resolution at room temperature due to lower integrated leakage charge.

Time-resolved imaging at frame frequency greater than 10 kHz
State-of-the-art energy resolution near room T
Summary and Conclusions

- Extended use of SDD for tracking in high energy heavy ions experiments
- Industrial use of Silicon Drift Detectors for X-ray fluoroscopy
- Development of Controlled Drift Detector
- Use of Drift concept for Detectors on High Z materials. (insensitive to hole trapping)
- Future-high resistivity silicon for X-rays
- Future – tracking with electronics grade Si