Ultra-Fast Silicon Detector

- A parameterization of time resolution
- Low Gain Avalanche Detector
- A program to calculate Time resolution
- UFSD Timing capabilities

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With
LGAD group of RD50, FBK and Trento University, Micro-Electronics Turin group
The 4D challenge

Is it possible to incorporate the time-domain into the excellent position resolution of semiconductor sensors?

Can we provide in the same detector and readout chain:

- **Ultra-fast timing resolution** [~ 10 ps]
- **Precision location information** [10’s of μm]
A time-tagging detector

Sensor  Pre-Amplifier  Time measuring circuit

Time is set when the signal crosses the comparator threshold

The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning:

\[ \sigma_{\text{Total}}^2 = \sigma_{\text{Jitter}}^2 + \sigma_{\text{Time Walk}}^2 + \sigma_{\text{TDC}}^2 \]
**Time walk**:

The voltage value $V_o$ is reached at different time for signal of different amplitudes.

**Jitter**:

The noise is summed to the signal, causing amplitude variations.

\[ \sigma_{TW} = \left( \frac{t_{rise} V_{th}}{S^2} \right)_{RMS} \]

Due to the physics of signal formation

(see backup slides for full calculation and reduction techniques)

Mostly due to electronic noise

(see backup slides for capacitance and noise values used)
A parameterization of $\sigma_t$

$$\sigma_t^2 = \left( \frac{t_{\text{rise}}}{S/N} \right)^2 + \left( \left[ \frac{t_{\text{rise}} V_{\text{th}}}{S} \right]_{\text{RMS}} \right)^2 + \left( \frac{TDC_{\text{bin}}}{\sqrt{12}} \right)^2$$  \hspace{1cm} (1)

**Jitter**

**Time Walk**

**TDC**

- **d**: detector thickness [micron]
- **l**: pitch [micron]
- **C**: Detector capacitance [fF]
  - Depends on the pitch and thickness
- **N**: Noise at preamp.
  - Dominated by the voltage term
- **S**: Signal
- **t_{\text{rise}}**: Pre-Amp Shaping time
- **V_{\text{th}}**: Comparator threshold
  - Depends on the noise level
- **TDC**: Width of the TDC LSB [ps]

**Formulae**

$$C_{\text{Det}} = \varepsilon \varepsilon_0 \frac{l*l}{d} + 0.2*4l + 50$$

$$N \propto \frac{C_{\text{Det}}}{\sqrt{t_{\text{rise}}}}$$

$$V_{\text{th}} = 10*N$$

$$LSB = 20$$
State of the Art

Best resolution achievable: \(~ 100 \text{ ps}\)
(assuming Time Walk reduction of \(~ 3\))
As shown above, we can write

\[ \sigma_t^2 = \left( \frac{V_{th}}{S/t_r} \right)_{RMS}^2 + \left( \frac{N}{S/t_r} \right)^2 + \left( \frac{TDC_{bin}}{\sqrt{12}} \right)^2 \]

where as before:
- \( S/t_r = dV/dt = \text{slew rate} \)
- \( N = \text{system noise} \)
- \( V_{th} = 10 N \)

Assuming constant noise, to minimize time resolution we need to maximize the \( S/t_r \) term (i.e. the slew rate \( dV/dt \) of the signal)

➡ We need gain ➡
Gain in silicon detectors

Gain in silicon detectors is commonly achieved in several types of sensors. It’s based on the avalanche mechanism that starts in high electric fields:

**Charge multiplication**

\[ N(l) = N_0 \cdot e^{\alpha l} \]
\[ G = e^{\alpha l} \]

\[ \alpha = \text{strong E dependance} \]
\[ \alpha \sim 0.7 \text{ pair/} \mu \text{m for electrons,} \]
\[ \alpha \sim 0.1 \text{ for holes} \]

- **APD: gain 50-500**
  - Not radiation hard, not pixellated, sensitive to photons
- **SiPM: gain } ~ 10^4**
  - Not radiation hard, Geiger mode, sensitive to photons
Low Gain Avalanche Detectors (LGAD)

Goal:
- Pixelated silicon detector with internal gain
- Radiation hard
- Insensitive to photons

High field obtained by adding an extra doping layer

E \sim 300 \text{kV/cm}, closed to breakdown voltage
The goal: a diode with multiplication working in linear mode.

Starting point: PiN-PAD diode with an area of 5mm x 5mm.

**Structure**: highly resistive p-type substrate
- n+ well for the cathode
- p diffusion under the cathode
  => enhance electric field => multiplication layer

The doping profile of this layer is a very critical technical parameter.
Various fabrication runs to improve the characteristics of the LGAD devices.

**Latest run:**
- High resistivity p-type substrate; 300μm thick;
- 3 couples of wafers with increasing p-layer doping
- A PiN wafer for reference

<table>
<thead>
<tr>
<th>Wafer Number</th>
<th>P-layer Implant (E = 100 keV)</th>
<th>Substrate features</th>
<th>Expected Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>$1.6 \times 10^{13}$ cm$^{-2}$</td>
<td>HRP 300 (FZ; $\rho &gt; 10$ KΩ·cm; $&lt;100$; T = 300±10 μm)</td>
<td>2 – 3</td>
</tr>
<tr>
<td>3-4</td>
<td>$2.0 \times 10^{13}$ cm$^{-2}$</td>
<td>HRP 300 (FZ; $\rho &gt; 10$ KΩ·cm; $&lt;100$; T = 300±10 μm)</td>
<td>8 – 10</td>
</tr>
<tr>
<td>5-6</td>
<td>$2.2 \times 10^{13}$ cm$^{-2}$</td>
<td>HRP 300 (FZ; $\rho &gt; 10$ KΩ·cm; $&lt;100$; T = 300±10 μm)</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>(---) PiN Wafer</td>
<td>HRP 300 (FZ; $\rho &gt; 10$ KΩ·cm; $&lt;100$; T = 300±10 μm)</td>
<td>No Gain</td>
</tr>
</tbody>
</table>
- Devices with active area of 5mmx5mm
- Window in the cathode metallization for light source characterization
CNM: pixellated sensors, Run II

Trial run to manufacture full pixels and strips detectors based on LGAD principle.

Studies of gain layer geometry
CNM: Fabrication Layout, Run II
### Sensors in Torino

**Thickness:** 300 µm

<table>
<thead>
<tr>
<th>Run</th>
<th>Sensor</th>
<th>P-Layer Implant (E=100 KeV)</th>
<th>Gain</th>
<th>V\textsubscript{break}</th>
<th>Metal Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>6474</td>
<td>W8_B4</td>
<td>?</td>
<td>~ 10</td>
<td>&gt; 500 V</td>
<td>DR</td>
</tr>
<tr>
<td>6474</td>
<td>W8_C6</td>
<td>?</td>
<td>~ 10</td>
<td>&gt; 500 V</td>
<td>DC</td>
</tr>
<tr>
<td>6474</td>
<td>W9_B6</td>
<td>No implant</td>
<td>No Gain</td>
<td>&gt; 500 V</td>
<td>DR</td>
</tr>
<tr>
<td>7062</td>
<td>W1_F3</td>
<td>1.6 x 10^{13} cm\textsuperscript{-2}</td>
<td>~ 1-2</td>
<td>&gt; 500 V</td>
<td>DR</td>
</tr>
<tr>
<td>7062</td>
<td>W3_H5</td>
<td>2.0 x 10^{13} cm\textsuperscript{-2}</td>
<td>~ 10</td>
<td>&gt; 500 V</td>
<td>DR</td>
</tr>
<tr>
<td>7062</td>
<td>W7_D7</td>
<td>No implant</td>
<td>No Gain</td>
<td>&gt; 500 V</td>
<td>DR</td>
</tr>
</tbody>
</table>
CV system

Keithley 2410
Agilent E4980A

QV System

DUT

Laser
\[ \lambda = 1064 \text{ nm (MIP)} \]
\[ \lambda = 400 \text{ nm (Alpha)} \]

Picosecond diode Laser

LeCroy 625Zi

Keithley 2410

DUT
Acquisition system

Labview controlled acquisition system.
It allows selecting the type of measurement and fully automatized operation.

Tabs to select the measurement:
- I - V
- C - f
- C - V
- Q - V

Graphs showing measurements as a function of voltage.
Doping profile from CV measurement - I

\[ \frac{1}{C^2} = \frac{2}{A^2 q \varepsilon_0 \varepsilon_r N} \ast V \]

No-gain sensor

\[ N = \frac{2}{q \varepsilon_0 \varepsilon_r A^2} \frac{d}{dV} \left( \frac{1}{C^2} \right) \]

Doping profile
Doping profile from CV measurement - II

This “bump” creates the high field needed for the gain.
Signal amplitude

Using laser signals we are able to measure the different responses of LGAD and traditional sensors.
The gain is estimated as the ratio of the output signals of LGAD detectors to that of traditional one.
We developed a full sensor simulation to optimize the sensor design

WeightField2, F. Cenna, 9th Trento workshop, Genova 2014
Available at http://personalpages.to.infn.it/~cartigli/weightfield2

It includes:

- Custom Geometry
- Calculation of drift field and weighting field
- Currents signal via Ramo’s Theorem
- Gain
- Diffusion
- Temperature effect
- Non-uniform deposition
- Electronics
WeightField2: a program to simulate silicon detectors
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Drift Potential
Weighting Potential
Currents and Oscilloscope
Electronics

File Name

Batch
Set Batch mode ON
Number of events:

Detector Properties
Dimensions
Detector Width (um):
Detector Height (um):
Strip Pitch (um):
Strip Width (um):
Gain Scale (1 = no Gain):

Voltage
Bias Voltage (V):
Depletion Voltage (V):

Doping
Strip: n-type p-type
Bulk: n-type p-type

Electronics
Oscilloscope BW (GHz):
Shaper Int. Time (ns):
Shaper Decay Time (ns):
Vth (in noise unit):

Select Particles
- MIP: uniform Q, Q(0) = 75\text{\textmu}m
- MIP: non uniform Q, Q(0) = 75\text{\textmu}m
- MIP: non uniform, Q(0) = Landau
- MIP: uniform Q, Q/\text{\textmu}m = 75
- alpha from top
- alpha from bottom

Set range (um):

Plot Settings
- Draw Electric Field
- Update Plot while Calculating

Currents
Switch B-Field on and set to (T):

Temperature (K):

Switch:
Calculate Potentials
Calculate Currents
Est

On Strips
Between Strips

Drift Potential V [V]
Drift Field E [kV/cm]
WeightField2: a program to simulate silicon detectors
WeightField2: a program to simulate silicon detectors
The effect of gain - MIP

Now we set the gain...

Case: MIP with uniform Q

Drift potential with Gain

\[ V_{\text{bias}} = 200 \text{ V} \]
\[ V_{\text{dep}} = 50 \text{ V} \]

Currents with Gain

...and with oscilloscope on
The effect of gain - Alpha

Now we set the gain...

Case: Alpha particle from bottom

Drift potential with Gain

$V_{bias} = 200\,\text{V}$
$V_{dep} = 50\,\text{V}$

Currents with Gain

...and with oscilloscope on
Comparison Data Simulation

MIP

Alpha from Top

Alpha from bottom

blocks are still reachable in loss record.
Wrapping things up so far

- Time resolution depends on the signal slew rate
- LGAD are silicon detectors with enhanced signals
- LGAD prototypes works very well, with gain ~ 10, and no added noise
- We developed a simulation program able to correctly reproduce LGAD features

Now we need to optimize the design to obtain the best possible silicon sensor for timing applications
How to make a \textbf{good} signal

Signal shape is determined by Ramo’s Theorem:

\[ i \propto q v E_w \]

A key to good timing is the uniformity of signals:

\textbf{Drift velocity} and \textbf{Weighting field} need to be \textbf{as uniform as possible}.
\[ i \propto qvE \]

- Highest possible E field to saturate velocity
- Highest possible resistivity for velocity uniformity

**Figure**: Electron and hole velocities vs. the electric field strength in silicon.
The weighting field needs to be as uniform as possible, so that the coupling is always the same, regardless of the position of the charge.

\[ i \propto qvE_w \]

**Strip:** 100 µm pitch, 40 µm width  
**Pixel:** 300 µm pitch, 290 µm width
Non-Uniform Energy deposition

**Landau Fluctuations** cause small difference in signal shape

We implemented in Weightfield a full simulation of this effect using libraries obtained with GEANT 4.

With appropriate geometries, it can be controlled and kept around **10-20 ps**.
How to maximize $dV/dt$

Contributions to the total current as simulated by Weightfield2

Pads with no gain
Current only decreasing.
Rise time limited by electronics

Pads with gain
Electrons entering the gain layer produce $e-h$ pairs.
Current due to holes creates a longer and higher signal
Rise time limited by physics
1) The amplitude of the current generated by a single electron (e) depends on the thickness \( d \) of the detector (via the weighting field):

\[
i \propto qv \frac{1}{d}
\]

⇒ One electron generates higher current in thin detectors (while the integral is a constant = \( q \)).

2) The initial current for a silicon detector does not depend on how thick (d) the sensor is:

\[
i = Nq \frac{k}{d} v = (75dq) \frac{k}{d} v = 75kqv \sim 1 - 2 \times 10^{-6} A
\]

⇒ Initial current = constant

Number of e/h = 75/micron

Weighting field

Velocity
3) The rate of particles produced by the gain does not depend on \( d \) (assuming saturated velocity \( v_{\text{sat}} \))

\[
\frac{dN_{\text{Gain}}}{dt} \propto 75Gv_{\text{sat}}
\]

\( \Rightarrow \) Constant rate of production

4) The gain current depends on \( d \) (via the weighting field)

\[
i_{\text{gain}} \propto \frac{dN_{\text{Gain}}}{dt} \frac{kq}{d} v_{\text{sat}}
\]

\( \Rightarrow \) Gain current \( \sim 1/d \)
5) A given value of gain has much more effect on thin detectors:

\[
\frac{i_{\text{gain}}}{i} \propto \frac{dN_{\text{Gain}}}{dt} \frac{kq}{d} v_{\text{sat}} = \left( \frac{G}{d} \right) \]

\[\Rightarrow \text{Go thin!!} \]

(Real life is a bit more complicated, but the conclusions are the same)

Significant improvements in time resolution require thin detectors

Nicolo Cartiglia, INFN, Torino - UFSID - RD50, Bucharest, 13 June 2014

300 micron:
~ 2-3 improvement with gain = 20

50 micron:
~ 7-8 improvement with gain = 20

Full simulation

Gain = 20
Gain = 15
Gain = 10
Gain = 5
Ultra Fast Silicon Detectors

UFSD are LGAD detectors optimized to achieve the best possible time resolution

Specifically:

1. Thin to maximize the slew rate ($dV/dt$)

2. Parallel plate – like geometries (pixels..) for most uniform weighting field

3. High electric field to maximize the drift velocity

4. Highest possible resistivity to have uniform $E$ field
First Timing Measurement on CNM LGAD

First test organized at CERN: a very fruitful collaboration among TOTEM, ATLAS and CMS, aimed at evaluating the timing performance of UFSD, diamond detector and a custom read-out chip (SAMPIC).

- Two LGAD sensors have been illuminated with a split laser signal (\(\lambda = 1064\) nm), and the time difference has been measured

  \[\text{estimate of time jitter}\]

The setup comprised of:
- 2 UFSD sensors (LGAD pad 5x5 mm\(^2\) – 300 micron thick)
- 2 CIVIDEC broadband amplifiers, 2 GHz (180 ps rise time), 2 mV of noise
- waveform digitizer: SAMPIC – a SAMPler for PICosecond time measurement
Experimental Setup

Digitizer

2 sensors

Laser split into 2
Timing Measurements: signal stability

Is the gain mechanism stable?

Mean 22.784 fC
RMS 1.678 fC

Very stable multiplication mechanism ~ 7%
The jitter is evaluated by SAMPIC using a software Constant Fraction Discriminator.

This result is consistent with the simulation predictions: 300-micron thick UFSDs with gain of ~ 15 improve by ~ 2 the timing resolution

Gain ~ 15

Gain ~ 15

Laboratory Results

Time Resolution vs Vbias

Jitter [ps]

UFSD

No gain

Voltage [V]

0 200 400 600 800 1000 1200

0 20 40 60 80 100 120

Nicolo Cartiglia, INFN, Torino - UFSD - RD50, Bucharest, 13 June 2014
The gain decreases with irradiations: at $10^{14}$ n/cm$^2$ is 20% lower

➔ Due to boron disappearance

Expected fluence in the PPS: $3 \times 10^{15}$ n/cm$^2$ for $L = 100$ fb$^{-1}$ (to be checked)

Current UFSD design good up to $L = 1-2$ fb$^{-1}$ @ LHC-CMS

What-to-do next:

Planned new irradiation runs (neutrons, protons)

Use gallium instead of boron for gain layer (winter run)
**Rule**: when the depletion volume reaches the edge, you have electrical breakdown.

It’s customary to assume that the field extends on the side by ~ 1/3 of the thickness.

\[
\text{edge} = k \times \text{thickness}
\]

- \( k = 1 \) very safe
- \( k = 0.5 \) quite safe
- \( k = 0.3 \) limit

By construction, thin detectors (~ 100 micron) might have therefore slim edge
Proposal for a different gain configuration

Is there a better design than n-in-p for LGAD finely segmented sensors?

Gain layer position/doping

Moving the junction on the deep side allows having a very uniform multiplication, regardless of the electrode segmentation.
Rome2 (AFP) is proposing to develop a **Si-Ge based** timing system (starting in summer-fall). Testbeam in fall to assess current precision and how to develop the system.

- Saclay (AFP): read-out based on **multi-sampling (SAMPIC)** techniques.
- Bologna (ALICE): **NINO based** read-out (as in the Alice RPC)

In the next 8-12 months we will evaluate possible read-out schemes, the achievable time resolution, and see which groups are actually interested in building it.
Next Steps

Test beams:
- PSI: performed by the TOTEM community, results under study
- PS, SPS with the TOTEM community
- Frascati with Rome2

Wafer Production:

200 micron thick sensors by fall-2014
- new geometry that includes isolation structures (p-stop, collector ring, channel stop). Mask already defined.
  => Generic multi-pad geometry included

100 and 50 micron thick sensors by early 2015.
- Masks to be defined.
  => It might include custom multi-pad geometry
UFSD – Summary

We are just starting to understand the timing capability of UFSD

The internal gain of UFSD makes them ideal for accurate timing studies

We developed a program, **Weightfield2**, that is able to reproduce accurately the output response of UFSD (available at [http://personalpages.to.infn.it/~cartigli/Weightfield2.0/](http://personalpages.to.infn.it/~cartigli/Weightfield2.0/))

With laser, **we measured a jitter of 40 ps** for a 300-micron thick pad LGAD detectors

Extrapolations indicate that a resolution of ~ 20 ps can be achieved:

→ thin detectors require much smaller gains.

Use Gallium to obtain a more radiation hard doping layer

**Timescale: 1 year for a full scale prototype**
This research was carried out with the contribution of the Ministero degli Affari Esteri, “Direzione Generale per la Promozione del Sistema Paese” of Italy.

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The work at SCIPP was partially supported by the United States Department of Energy, grant DE-FG02-04ER41286.
References

Several talks at the 22\textsuperscript{nd}, 23\textsuperscript{rd} and 24th RD50 Workshops:

23\textsuperscript{rd} RD50: https://indico.cern.ch/event/265941/other-view?view=standard
22\textsuperscript{nd} RD50: http://panda.unm.edu/RD50_Workshop/

9\textsuperscript{th} Trento Workshop, Genova, Feb 2014.

F. Cenna "Simulation of Ultra-Fast Silicon Detectors"

N. Cartiglia "Timing capabilities of Ultra-Fast Silicon Detector"

Papers:
