The Impact of Avalanche-based Detectors in Particle Tracking: from 3D to 4D tracking

Hiroshima @ Vancouver
Silicon life in 2010

Very mature silicon systems, very large silicon trackers

Millions of channels, very reliable, very radiation hard

Two simple facts in 2010:
1. Silicon sensors are not suitable timing detectors
2. Silicon sensors were not considered good detectors for 1-5 keV x-rays

One nagging problem: radiation damage causes charge trapping, reducing the signal in heavily irradiated sensors.
“Spontaneous” charge multiplication

By 2010, there was clear evidence of charge multiplication in highly irradiated planar strip sensors.

This effect was considered a possible key to design sensors able to overcome charge trapping at high radiation levels:

• Trapping reduces the signal
• The internal gain will re-establish the original signal amplitude

Note: this type of charge multiplication was not a planned feature of the sensor, it was unexpectedly measured in irradiated sensors.
“Designed” charge multiplication

Add moderate gain, just enough to compensate for charge trapping
“to control and optimize the charge multiplication effect, in order to fully recover the
collection efficiency of heavily irradiated silicon detectors” [1]

[1] G.Pellegrini et al., Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD)

RD50 funding request
- November 2012-

Title of project: Fabrication of new p-type pixel detectors with enhanced multiplication
effect in the n-type electrodes.

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The LGAD approach can be used in any silicon structure,

This is an example of LGAD strips
Another R&D needed internal gain: fast timing

RD50 June 2012, Bari

Ultra-Fast Silicon Detectors

Hartmut Sadrozinski, Abe Seiden (UCSC)
Nicolo Cartiglia (INFN Torino)

Ultra-Fast Silicon Detectors (UFSD)
provide in the same detector and readout chain
• ultra-fast timing resolution [10’s of ps]
• precision location information [10’s of μm]

(N.B. a time resolution = 50 ps would already be competitive with SiPM)

Benefits of Gain in Detectors

+ Charge multiplication (CM) in silicon sensors (discovered by RD50 institutions) might have applications beyond offsetting charge lost due to trapping during the drift of electrons or holes.
+ Charge multiplication makes silicon sensors similar to drift chambers (DC) or Gas Micro-strip Detectors (GMSD), where a modest number of created charges drift to the sense wire, are amplified there (by factors of > 10⁴) and are then used for fast timing.
+ We propose considering silicon detectors for simultaneous precision position and fast timing measurements.

2 questions:
• can they work: signal, capacitance, collection time vs. thickness
• will they work: required gain and E-field, fast readout

Disclaimer: data are still coming in, so conclusions and extrapolation are tenuous!
Design innovation: low gain avalanche diode (LGAD)

- In LGAD, a moderately p-doped implant creates a volume of high field, where charge multiplication happens.
- It turned out that the LGAD design does not solve the charge-trapping problem as the LGAD mechanism does not work well in high radiation environments (above $1E15 \text{n}_{\text{eq}}/\text{cm}^2$)

However, the LGAD design did help solving a few other problems.
Was it actually an innovation?

An Optimized Avalanche Photodiode

HEINZ W. RUEGG, MEMBER, IEEE

Abstract—The feasibility of a fast, high-gain photodetector based
on the phenomenon of avalanche multiplication in semiconductors has
been investigated. Based on the process of carrier multiplication in
a high electric field, criteria for the design of an optimized ava-
lanche photodiode and for the choice of the best semiconductor
material are developed.

The device theory of an optimized, realizable avalanche photo-
diode is presented. A practical silicon device optimized for the de-
tection of light with a wavelength of 9000Å is suggested and design
parameters are presented. Details of the fabrication process are
given and the performance of experimental devices is compared to
the device theory presented.

The results of the study indicate that it is possible to achieve a
silicon photomultiplier with a quantum efficiency-bandwidth product
of the order of 100 GHz for the detection of light up to a wavelength
of over 9000Å.

gion. Indeed, the analog of a photomultiplier can be
envisaged with the notable advantage that the photo-
generated carriers need not be emitted into the vacuum,
a process which is characterized by a low quantum
efficiency for present-day photocathodes.

Signal enhancement through avalanche multipli-
cation in a photodiode has been reported for the first time
by Johnson [4]. By operating a p-i-n silicon photodiode
at a voltage where some carrier multiplication occurred,
he was able to improve the output signal-to-noise ratio.
The results obtained by Johnson have been confirmed
by Anderson et al., who reported on a similar experi-
ment using a microplasma-free silicon diode, and by
Lucevsky and Emmons, who used an InAs diode in an

Probably not...
Why the idea of LGAD has been so successful?

- **There is a real need for 4D tracking** in future experiments.
  - 4D tracking is not simply “better”, it is an enabling technology

- **It is technologically easy.**
  - Large knowledge base in silicon sensors, SiPM.
  - Fully compatible with standard testing tools
  - Availability of high resistivity thin p-bulk to use electron-initiated avalanche (much easier to control than hole-initiated avalanche)

- **Complementary to non-HEP needs.**
  - LGADs are used in medicine, space application, x-rays.

- **Modularity: no need for a full 4D tracker**
  - one layer is enough to have an impact
In the past 10 years, **a lot of different gain layer designs** have been developed, either because they are technically easy, or because they have interesting properties.

Two main parameters to play with:

**The width and position of the gain implant**
- The wider the gain implant, the lower the doping level.
- The deeper the gain implant, the lower the doping level.

Different designs lead to different properties, such as more or less radiation resistance, easier fabrication, more uniformity, etc…
Why do LGADs allow developing 4D tracking?

• Sensors produce a current pulse
• The read-out measures the time of arrival

The “secret” is the signal-to-noise ratio
Caveat: noise is a boring subject, but you have to endure this slide to reach a brighter future.

First concept: gain (G) increases the signal (I):

\[
\text{Signal} = G \times I_{\text{signal}}
\]

Second concept: gain increases noise more than increases the signal

\[
\sigma_{\text{Signal}} = G \times I_{\text{signal}} \sqrt{F}
\]

Excess noise factor: noise of the multiplication process

Use ‘electron-initiated avalanche’

==> lower noise than holes-initiated avalanche

Conclusion: internal gain decreases the signal-to-noise ratio of the signal (not good so far..)
Signal, noise in LGAD + Electronics

Why do LGADs work then?

1) The electronics has a noise floor
2) The signal increases with gain
3) The noise increases with gain, with steeper characteristics
4) The total noise is flat at low gain, and then it increases fast

“Low gain” needs to be understood in connection with the noise of the electronics: it is the range of gain with an improved signal-to-noise ratio.

The success of LGADs rests on the fact that the sensor noise is hidden by the electronic noise.
Timing layers and 4D tracking

By “4D tracking” we mean the process of assigning a spatial and a temporal coordinate to a hit.

Timing can be available at different levels of the event reconstruction:

1) Timing in a single point (timing layer ATLAS, CMS): 3+1 tracking
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3) Timing at each point along the track: 4D tracking
Timing layers and 4D tracking

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1) Timing in a single point (timing layer ATLAS, CMS)
2) Timing at some points along the track
3) Timing at each point along the track

Many timing coordinates per track yield better-performing detectors but require more complex read-out systems.

Some projects will be perfectly fine with having a limited set of timing points.
LGAD popularity @ RD50

N. Cartiglia, INFN - Torino, Hiroshima13, 5/12/23

G. Pellegrini

∑ = 260 Talks !!!!
Clean Rooms developing LGAD technology

Market size in 2024-25:
ATLAS, CMS purchase: 25 – 30 m²
(5-6 million CHF)

G. Pellegrini
Large variety of LGAD designs

- LGAD
- DJ-LGAD
- inverse LGAD \((p\text{-}in\text{-}p)\)
- inverse LGAD \((n\text{-}in\text{-}n)\)
- RSD
- Monolith

or the new DC-RSD
4D tracking with LGADs: kept, broken, and future promises

**The grand plan:**
- Temporal resolution: $\sim 10$ ps
- Spatial resolution: $\sim 10$ micron
- Radiation hard

**Mostly yes:** LGADs deliver large signals so that the electronic jitter is 10 – 20 ps. However, LGADs have an “intrinsic time resolution due to the ionization process.”
Why LGAD have an “intrinsic” time resolution?

It is a combinatorial problem: how many different ways are there to produce a given amplitude summing up individual ionization clusters (imagine there is 1 cluster every 1 micron)?

50 microns thick ==> 50! Permutations…
10 microns thick ==> 10! Permutation

The thinner the sensor, the smaller the intrinsic time resolution

(This effect is a consequence of non-uniform ionization due to local Landau fluctuations)
UFSD temporal resolution improves in thinner sensors:

$$\Rightarrow$$ reasonable to expect 10-20 ps for 10-20 $\mu$m thick sensors.

Be aware: very difficult to do timing with small signals… power consumption increases
4D tracking with LGADs: kept, broken, and future promises

The grand plan:

- Temporal resolution: ~10 ps
- Spatial resolution: ~10 micron
- Radiation hard

Mostly no: there is not an LGAD-based demonstrator achieving such combined spatial and temporal resolutions
Spatial resolutions

In standard applications with hybrid design, the position resolution determines:

- The pixel size
- The space available for the electronics.

Good position resolutions implies the use of small pixels

Power will determine:

- The architecture of 4D tracking detectors
  - how many layers will be 4D and how many will be 3D
- The pixel size and the temporal precisions.
4D tracking with LGADs: kept, broken, and future promises

The grand plan:

- Temporal resolution: ~10 ps
- Spatial resolution: ~10 micron
- Radiation hard

Yes and no: thanks to a very strong R&D program, LGADs survive to about $2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
Acceptor removal in LGADs

**Unfortunate fact:** irradiation de-activate p-doping removing boron from the reticle

\[ N(\emptyset) = N(0) \times e^{-c\emptyset} \]

Defect engineering (Carbon addition) and process tuning (low-temperature dopants activation) improved the initial LGAD resistance by a factor of 2-3.

This path seems to have exhausted its potential, new approaches are needed.

Several new venues are presently explored (V. Sola in the afternoon proposing “compensation”)

Boron
Radiation creates Si interstitial that inactivate the Boron:
\[ Si_i + B_s \rightarrow Si_s + B_i \]
The large variety of LGAD designs addresses the needs of spatial and temporal resolutions at various degrees of resolutions.

**Several possible paths:**

- **Traditional approach:** design LGADs with a small pitch.
- 55 x 55 micron$^2$ (TimePix compatible) Trench Isolated LGADs have been manufactured and work well.
- **Resistive read-out** (RSD – AC-LGAD): design LGADs with large pixels and excellent position resolution.
- **Monolithic LGADs** are being studied, and first prototypes exist.

**The fulfillment of the 4D promise is mostly a “front-end design” problem.**

LGADs are a mature technology, the difficult part is the design of the ASIC.
LGAD legacy: a few examples

The development of LGAD has stirred the R&D in several other fields

- Better understanding of how to control low gain in silicon.
  - Charge screening
  - Gain dependence upon the gain implant shape and position
  - Effects of manufacturing parameters such as heat, initial wafer type, and doping
  - Simulation in 2D and 3D
- Radiation damage in devices with gain
  - Improved understanding of acceptor (donor) removal
  - Defect engineering to control acceptor removal (Carbon is fashionable again)
  - Dependance upon the initial doping density
- Low power electronics for timing
  - There has been a strong interest in designing the appropriate circuits. A wide range of technologies have been used (CMOS, BiCMOS, 110, 64, 28 nm)
Conclusions and outlook

In the past 10 years, the LGAD concept has been the center of a strong R&D phase that has established basic design parameters.

Many variations are being explored to progress from the present 3+1 tracking to the full 4D tracking.

The main issue is the development of low-power front-end electronics for 4D tracking. In this moment, sensors are the easy part.

The future trackers will be a combination of 3+1 and 4D designs.

I hope that in the next 10 years, we will have as much fun as we had in the past 10 years.
Materials and ideas

**Vertex 2023 conference,**
Ivan Vila, Challenges and new trends in LGAD technologies

**RD50**
Giulio Pellegrini: LGAD: a Little bit of the early history
Frank Hartman: RD50 from Experiment perspective
Sensor and ASIC Temporal resolution

\[ \sigma_t^2 = \left( \frac{\text{Noise}}{dV/dt} \right)^2 + (\Delta \text{ionization})^2 + (\Delta \text{shape})^2 \]

"Jitter" term

Small noise ==> choice of electronic technology

LGADs, having a larger signal, decrease the jitter component

Amplitude variation ==> corrected offline (time walk)

Non-homogeneous energy deposition ==> signal change variation. Cannot be corrected, =minimized by design

Signal shape is determined by Ramo's Theorem

\[ i \mu q v E_w \]

Saturated drift velocity \( v \)
everywhere in the sensor volume

Well-designed LGAD sensors (sometimes called UFSD) optimize the temporal resolution