R&D and applications of low-gain avalanche diodes

Jennifer Ott

Summarizing many others' work

ottjenni@hawaii.edu

US Muon collider workshop, August 7-8, 2025

LGAD sensor technology and challenges

COLLEGE OF ENGINEERING
UNIVERSITY of HAWAI'I at MĀNOA

HL-LHC: separate LGAD timing layers in CMS ETL and ATLAS HGTD

Future colliders: 4D / 5D tracking

LGAD sensors

- ‘standard’ DC-LGAD
- AC-LGAD
- TI-LGAD
- DJ-LGAD
- LGAD-CMOS
- iLGAD
- LGADs in other semiconductors: SiC, diamond

Factors to be considered in application

- Radiation hardness
- Timing resolution
- Spatial resolution
- (Energy resolution)
- Fill factor
- Cost; production at-scale
- Purpose: pileup rejection, tracking, particle ID…

Radiation hardness

- **The main challenge for silicon tracking sensors in the LHC and HL-LHC era**

Benchmarks: radiation hard to...

- >1e14 $n_{eq}cm^{-2}$ for LHC
- 2e16 $n_{eq}cm^{-2}$ in pixel sensors of Phase-2 upgrades in ATLAS and CMS
- Showstopper for monolithic active pixel sensors / CMOS pixels so far

Shift in constraints at lepton colliders: fluence at LHC levels or below; material budget and spatial resolution have higher priority

Fundamental R&D – potentially towards FCC-hh – is approaching fluences of 1e17 cm^{-2}

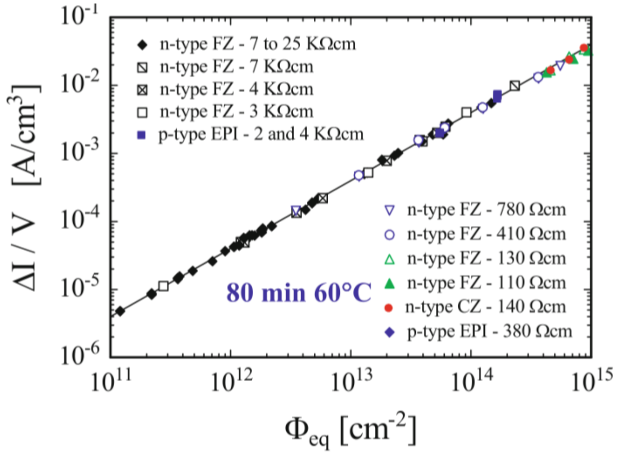
Radiation damage in LGADs

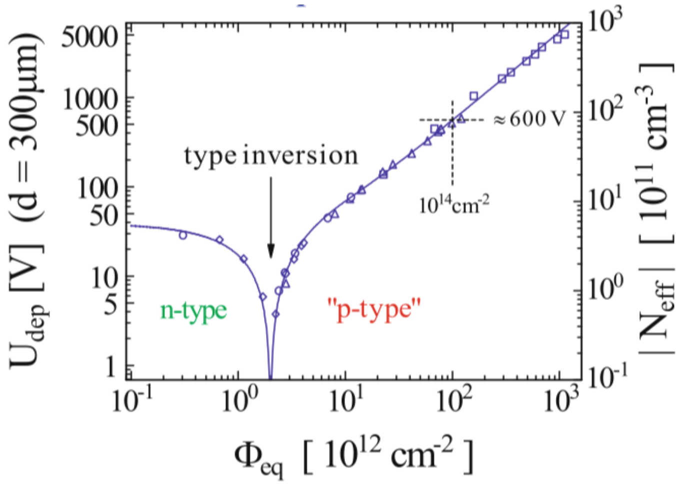
LGADs (regardless of what structural variant) suffer from degradation of the gain due to deactivation of acceptors

Radiation damage has traditionally been quantified through non-ionizing energy loss: generation of bulk defects, increase in leakage current, increase of depletion voltage

- *Not the most relevant definition for LGADs*
- *Prior scaling factors do not apply*

- *Increased leakage current and all other phenomena in silicon bulk will still be present!*





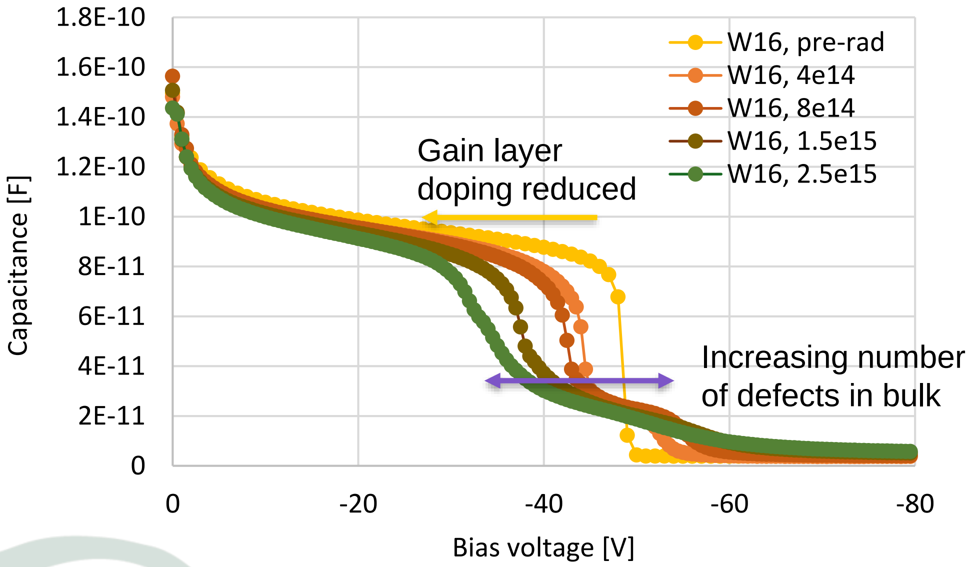
M. Moll, 1999

Radiation damage in LGADs

LGADs (regardless of what structural variant) suffer from degradation of the gain due to deactivation of acceptors

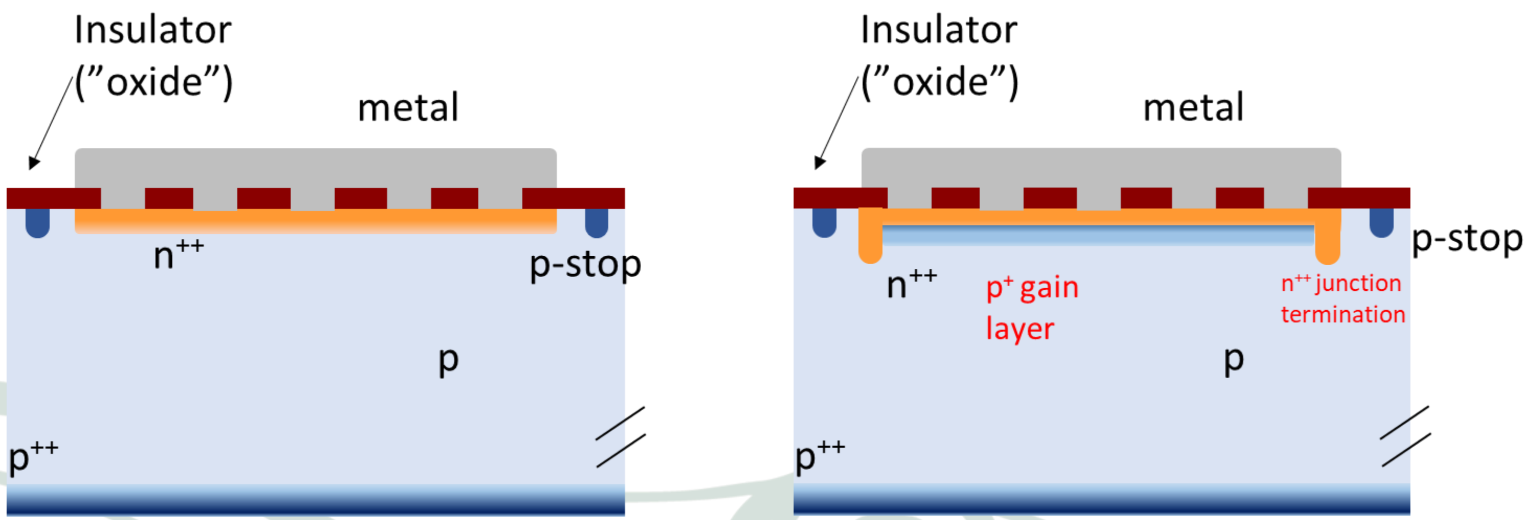
Can be addressed to some extent by gain layer and defect engineering

- Different dopant: e.g. Ga instead of B
  - Not successful
- **Carbon co-doping**
  - **Successful at reducing gain layer deactivation**
- Partially activated boron
  - More recent; very mixed results for different vendors



Spatial & timing resolution

- **Spatial resolution is related to the fill factor of the sensor**
- **Standard DC-LGADs feature a junction termination extension n-type implant to terminate the high electric field at the edges of each pad**
  - Plus p-spray and p-stop insulation between pads
- ➢ **Reducing the sensor's active area, limiting the pad size**



n-in-p normal diode *n-in-p LGAD*

Spatial & timing resolution

- **Spatial resolution is related to the fill factor of the sensor**
- **Standard DC-LGADs feature a junction termination extension n-type implant to terminate the high electric field at the edges of each pad**
  - Plus p-spray and p-stop insulation between pads
- ➢ **Reducing the sensor's active area, limiting the pad size**

- **Timing resolution: adjustment of gain layer; thinning of sensors to lower Landau fluctuations**
- ***Electronics play a large role as well***

- ➢ **HL-LHC LGAD sensors have pad lengths of 1.3 mm**
- ➢ **Need different sensor variants to improve this for future colliders**

Optimizing the fill factor

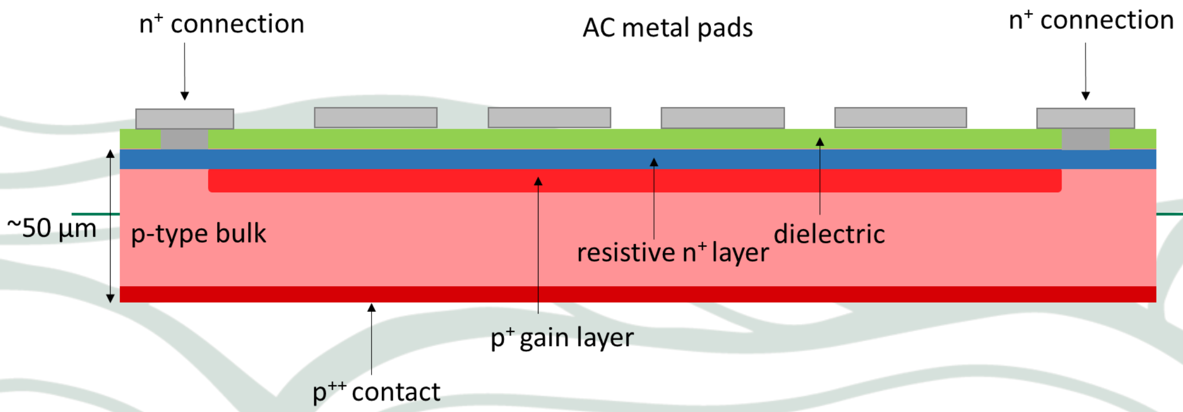
COLLEGE OF ENGINEERING
UNIVERSITY of HAWAI'I at MĀNOA

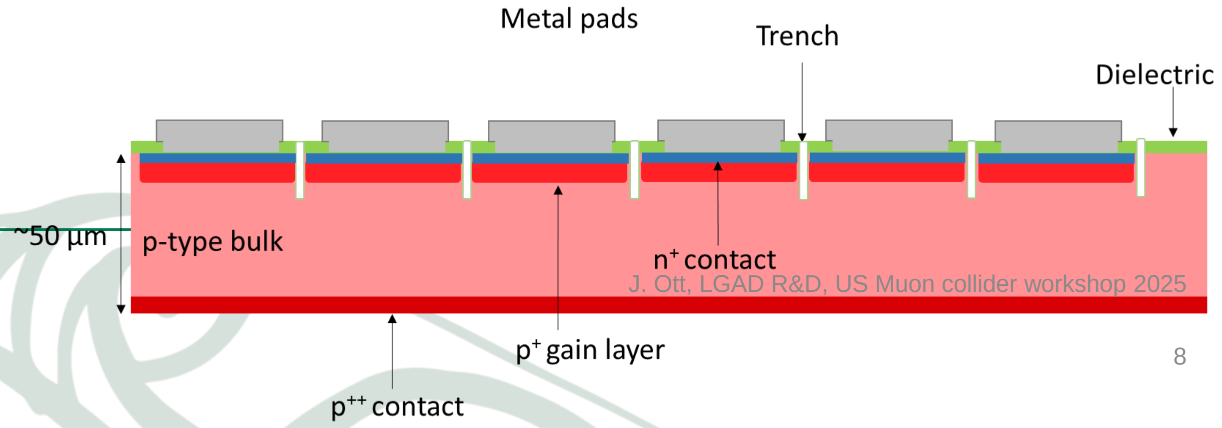
AC-LGADs (Resistive Silicon Detectors)

- Common n+ electrode, gain layer and insulation: signal charge is capacitively coupled to metal readout electrodes
- **Interpolation of hit by exploiting signal sharing between electrodes**
- Combination of two new concepts: resistive n+ layer, AC-coupling of signal
  - ***Could also separate these aspects: 'DC-RSD' with resistive n+ layer, but direct contact***

Trench-insulated LGADs

- Insulation between pads is provided by an etched trench, which can be 'filled' with a dielectric
- Similarly to 3D sensors: gas phase process, reactive ion etching
  - *Balance density of trenches with respect to wafer thickness to avoid instabilities*
- First large(r) sensors of >1 cm strip length are being fabricated





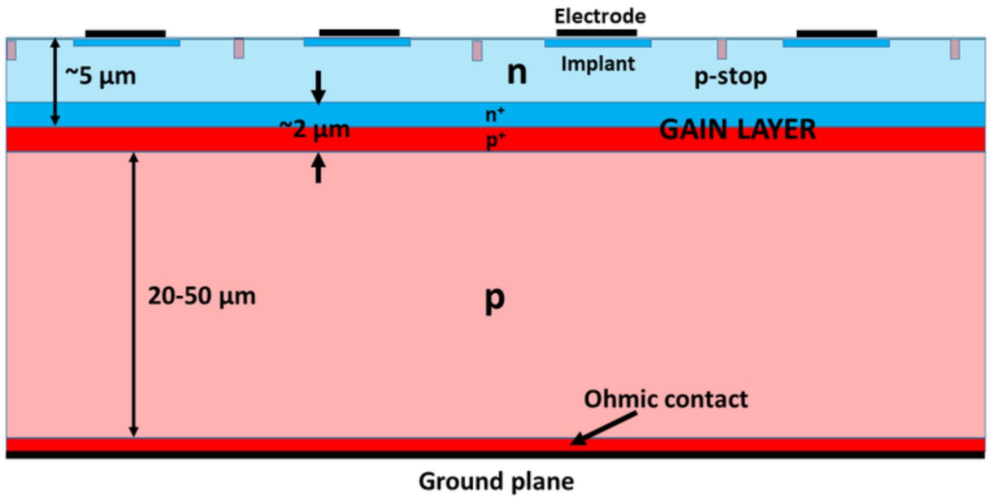
J. Ott, LGAD R&D, US Muon collider workshop 2025

LGADs in industrial Si processes

Integration of gain layer into silicon CMOS process

- **Successfully demonstrated by University of Geneva PicoAD detector: IHP 130 nm SiGe process**
  - Long and extensive work together with manufacturer
  - *Beginning efforts for industry-scale silicon CMOS integration in the US by FNAL and SLAC*

- **Deep-junction LGADs: uniform gain layer situated deeper in the bulk – no need for junction termination extension, less sensitive to radiation effects**
  - Challenge: very deep implant or wafer-wafer bonding, not trivial to find industrial partner



Summary

- **Considering the muon collider baselines, requirements, aspirations: neither spatial resolution nor timing resolution are overly strenuous**
  - 30-60 ps are being achieved with DC-LGADs developed for the HL-LHC, assuming high radiation levels!
- **Using precision timing to identify vertices and reconstruct tracks, separate collision data from beam backgrounds is tempting (required) – but keep in mind that this is being done in software, the detector itself will still experience the full hit rate**
  - E.g. resistive silicon detectors will not do well in a high-occupancy environment

➢ ***Consider the big picture and operational constraints: availability of detector process lines, uniformity of large sensors, ...***

➢ ***Further specify (through simulations and modelling) critical performance parameters to select or develop the optimal semiconductor sensor technology***

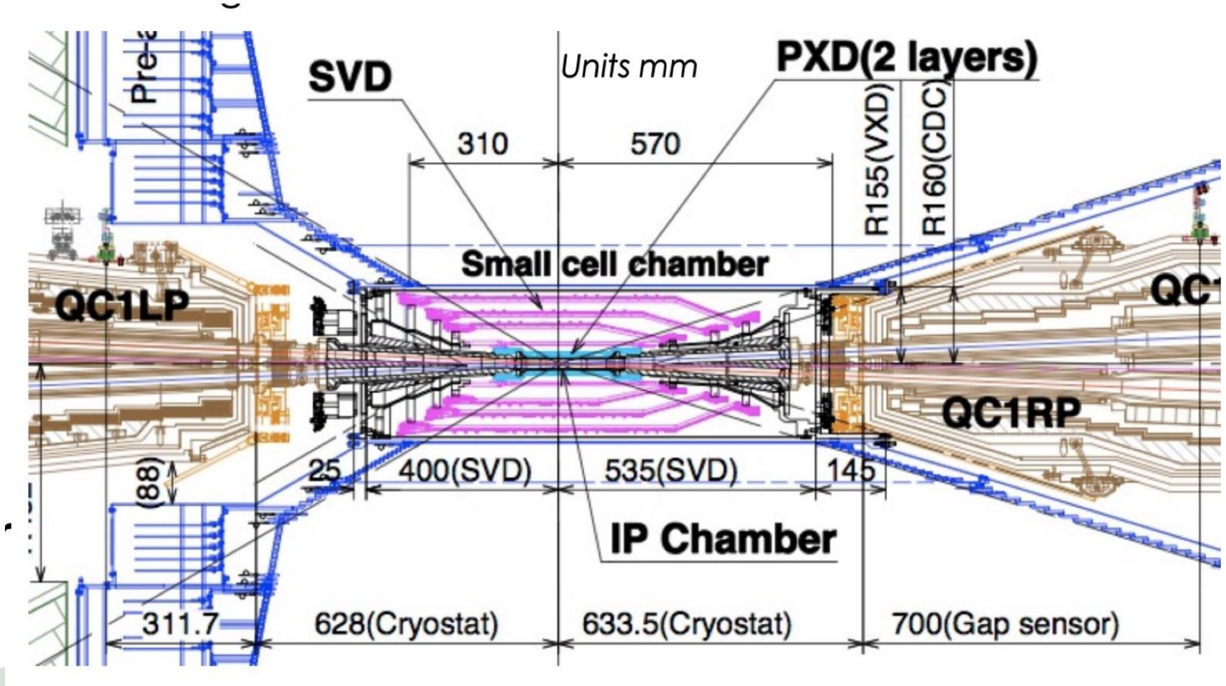
Timing layer for Belle II?

With Yubo Han and Peter Lewis (UH)

- **The Belle II detector employs DEPFET pixels and a drift chamber**
- **The drift chamber is likely to be retreating to larger r because of high backgrounds**

➢ **new volume available between ca. r = 17cm and 34 cm**

Could add a TOF detector for triggering and particle ID??



A timing layer for Belle II?

With Yubo Han and
Peter Lewis (UH)

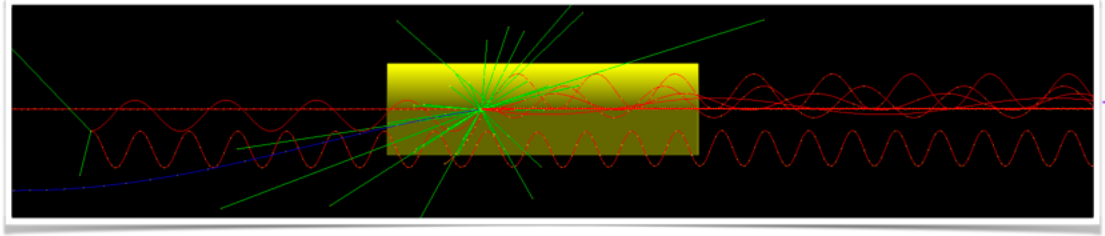
Could add a TOF detector for triggering and particle ID??

VERY PRELIMINARY RESULTS

Assuming e.g. 30ps resolution:

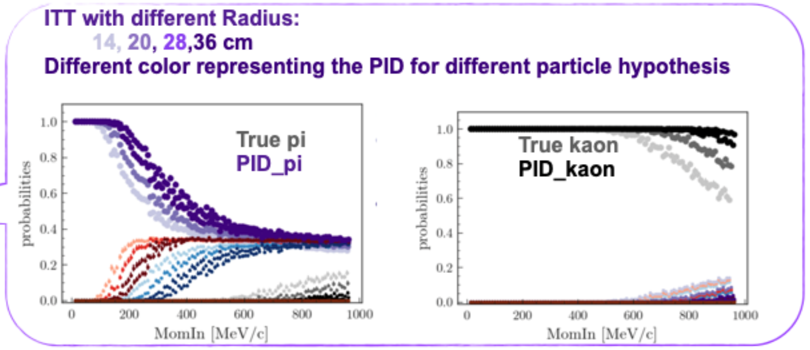
- Allows PID down to pT~100MeV for muons instead of ~500MeV, increasing effective luminosity for many analyses that use low-p tracks
- Could replace triggering role of CDC, particularly for small-pT tracks
- ***Separation of beam backgrounds?***

Starting with 1 layer of LGAD
Timing resolution: 30 ps
Radius: 24cm



+

ITT-standalone PID based on TOF



Promising PID performance for low Pt tracks

Thank you

Mahalo