University of Glasgow | Department of Physics & Astronomy

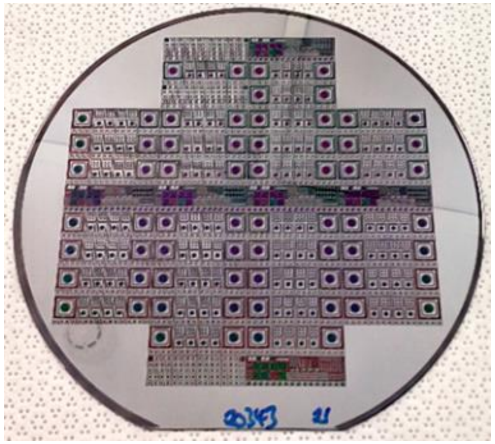
Small Pixel Low Gain Avalanche Detector (LGAD)

Contents

- LGAD experience
  - Teledyne e2v
  - Micron

- Proposal - Techniques to increase the fill-factor
  - AC coupled
  - Trench Isolated (LGAD and iLGAD)
  - Deep Junction

Te2v LGAD project

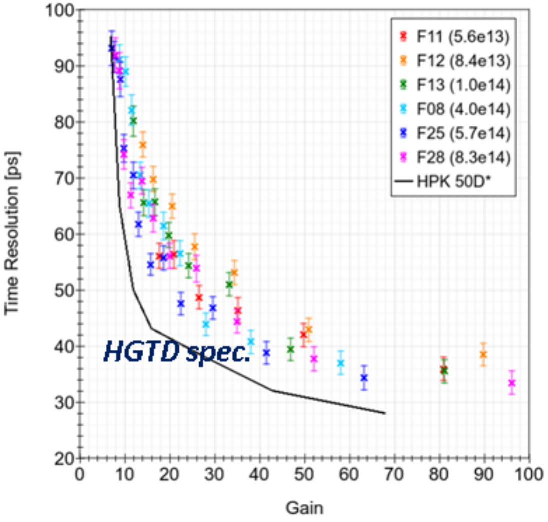


First Te2v LGAD 6'' wafer

Second Te2v LGAD 6'' wafer

1st ru

2nd ru

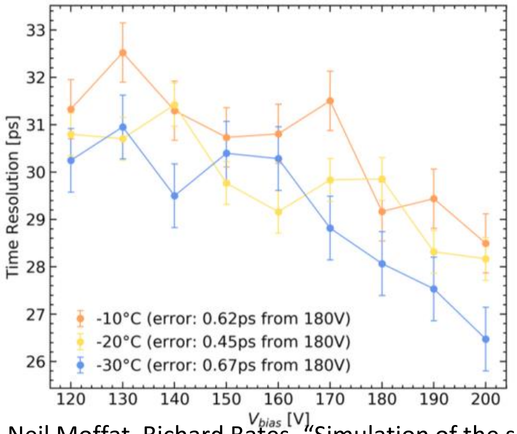


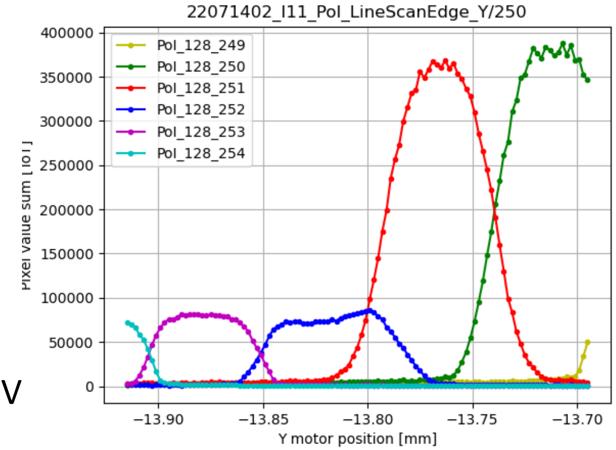
A Rutherford Appleton Laboratory, Oxford, Birmingham and Open University project in collaboration with Teledyne e2v foundry for LGAD production

- Design on 6'' wafers 50 µm HR epitaxial thickness
- Two fabrication runs:
  - First run of eight LGAD flavors (GL) and PiN diodes of the same layouts, 2021
  - Second run for ATLAS High Granularity Timing Detector (HGTD)
- Single pad time resolution (jitter) around 10 ps using IR source, 35 ps using MIP

Micron Projects – Gain and timing

- Glasgow, Edinburgh, Manchester and Krakow, supported by CNM
- Developed small pixel devices
  - LGADs, iLGADs, and trench isolated LGADs
  - 200µm FZ, 50µm FZ, 50µm epi
- Bonded to TimePix3 and TimePix4
- Gain of 5-20 obtained – depends on processing details
- Timing resolution of ~30ps on 1mm^2 pad 50µm thick devices
  - Sr90 MIP measurement
- iLGAD Small 55µmx55µm pixels with uniform gain
  - Simulated [1] and measured @ Diamond Light Source with TimePix3
  - Measured @ CERN with TimePix3 and TimePix4





Uniform Gain
iLGAD, 55µm, 250V

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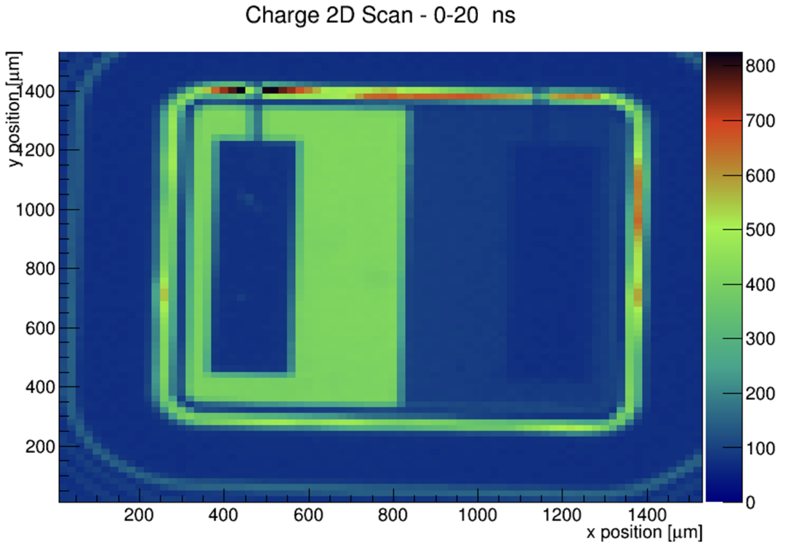
[1] Neil Moffat, Richard Bates, "Simulation of the small pixel effect contributing to a low fill factor for pixellated Low Gain Avalanche Detectors (LGAD)", NMA, Vol 1018, 2021, 165746, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2021.165746.

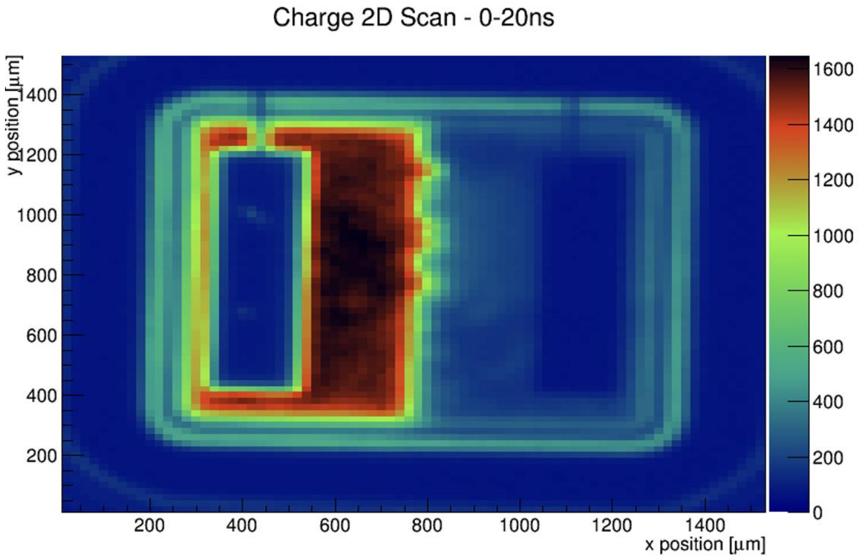
Micron – trench isolation [2]

- Frist trench devices
  - LGAD processing at Micron
  - Trench etching at Scottish Microelectronics Centre, SMC, Edinburgh
  - 2 process runs performed
- Issues with surface planarity
  - Leading to metal in the trench
  - Reduced isolation/hot spots
- One Pad connected to Readout
  - Blue shows good charge isolation
  - IR shows High charge spots in the trench might be due to high field in the trench.
    - Observed with blue laser as well, but less intense.

Blue Laser



IR Laser

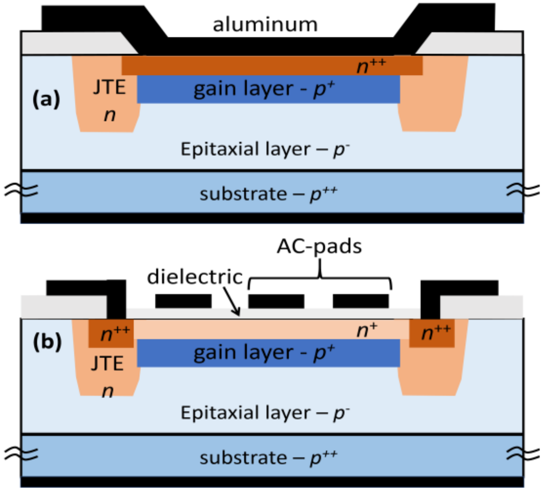


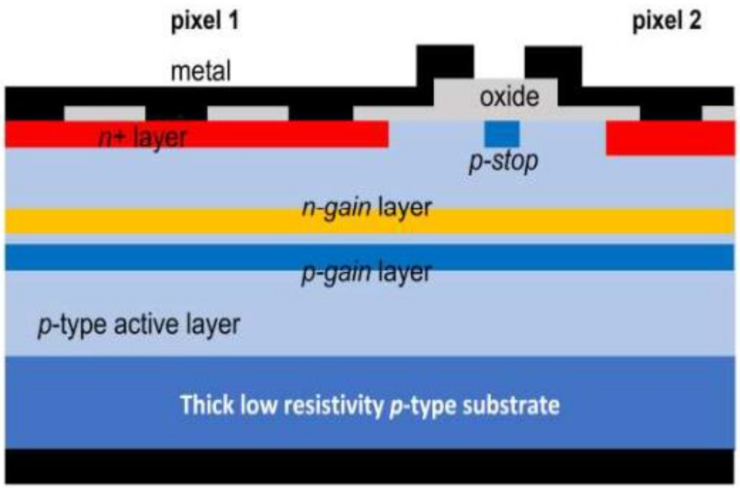
[2] G. Paternoster, G. Borghi, M. Boscardin et al., *Trench-isolated low gain avalanche diodes (ti-lgads)*, IEEE Electron Device Letters 41 884-887, 2020.

Small Pixel LGAD – AC Coupled & Deep Junction (DJ) LGAD

Standard LGAD

AC coupled LGAD

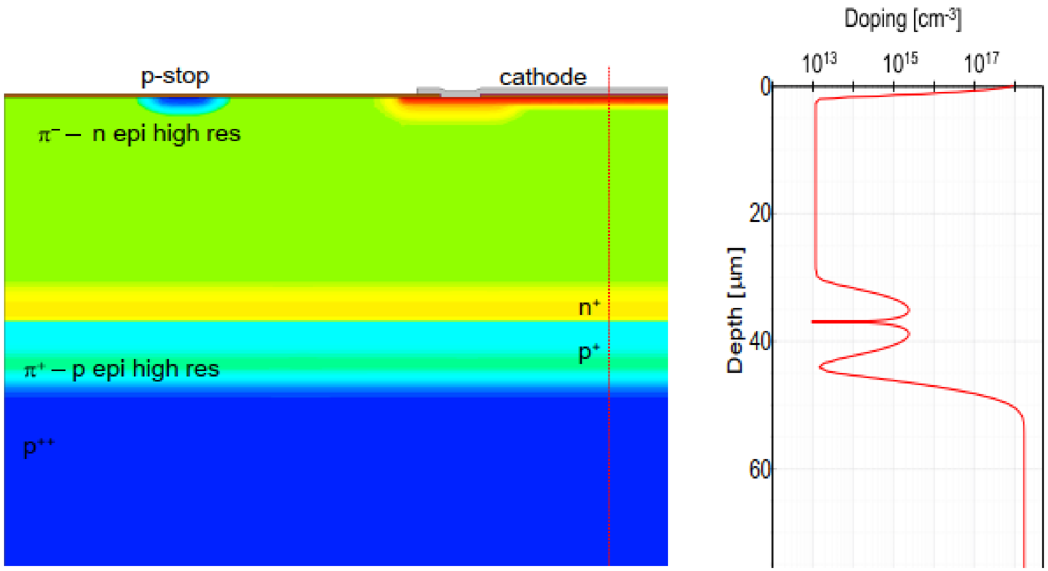




- AC-coupled LGADs [3] n^{++} implant well is replaced by a more resistive n^{+} layer, with electrodes that are AC coupled to it via a thin dielectric layer.
- Another approach is the deep-junction (DJ-LGAD) [4]. A deep junction, made by a large area of uniform n^{+} and p^{+} gain implants, sits a few microns from the surface where n^{+} DC coupled electrodes are placed.
- The buried GL is obtained either by abutting two wafers onto each other after gain layer implantation or by implanting it on a base wafer and then adding an epitaxial deposition to form the avalanche region.

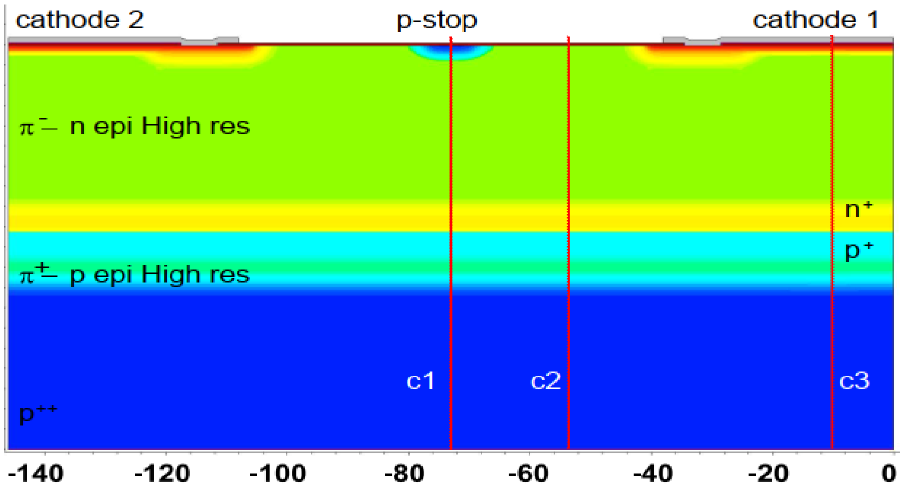
[**3**] G. Giacomini, W. Chen, G. D'Amen, A. Tricoli, *Fabrication and performance of AC-coupled LGADs*, https://doi.org/10.1088/1748-0221/14/09/P09004, 2019.
[**4**] Y. Zhao, S. Ayyoub, W. Chen et al., *A new approach to achieving high granularity for silicon diode detectors with impact ionization gain*, J. Phys. Conf. Ser. 2374, 012171, 2022.

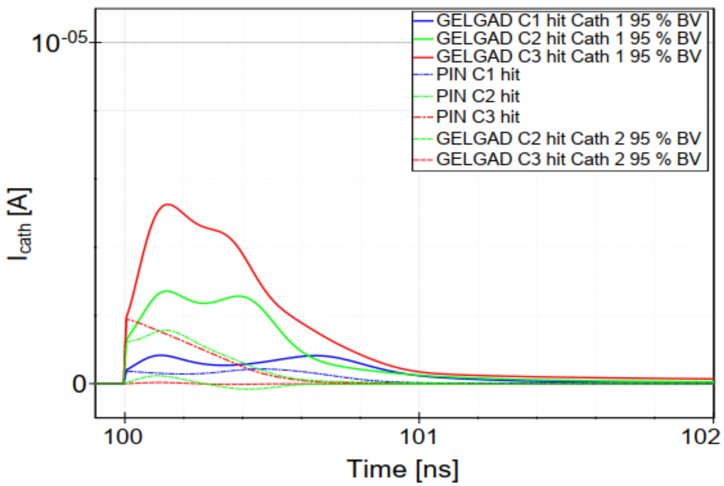
Small Pixel LGAD – **Deep Junction (DJ) LGAD**

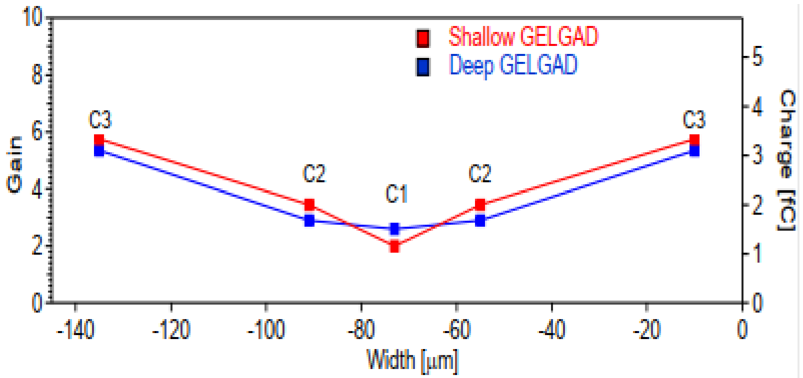


- The proposed method to obtain a deep-junction is via epitaxy. The buried GL is again a $n^+ p^+$ junction located within the epitaxial layer at some depth. The GL is obtained during the epitaxial growth. The GL formation via graded epitaxy should also avoid issues related to defects in the epitaxial created by implantation. A foundry has been identified and technical aspects have been discussed. A quote is already available for the purchase of 6’ wafers.

Small Pixel LGAD – **Deep Junction (DJ) LGAD**

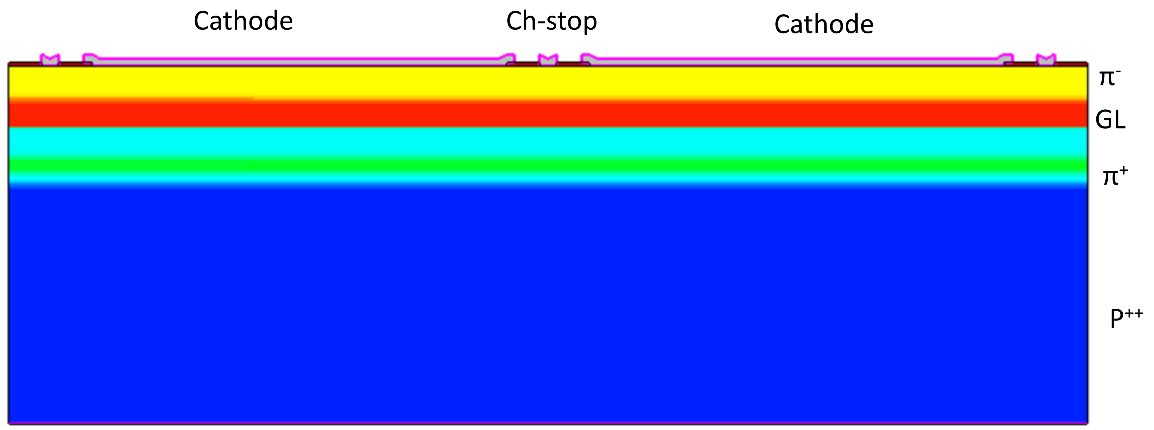






- Some TCAD simulations on GE-LGAD
- Additional simulations to investigate guard ring effects near the cutting-edge, to reduce leakage

Small Pixel LGAD – **Deep Junction (DJ) LGAD**



- An alternative approach uses Schottky barriers to make the cathode and the channel stop
- This would eliminate the need for implantation, reducing the cost and, possibly, improve the device performance:
    - no drive-in leads to a tighter GL profile, leading to a thinner active region
    - no dead region below the cathode would improve soft X-ray detection
    - No JTE

Small Pixel LGAD project

- Develop with CNM, Teledyne and Micron
- Pixel arrays
  - 55µm pixels arrays
  - Couple to TimePix4 and RAL 28nm LGAD chip

Technologies

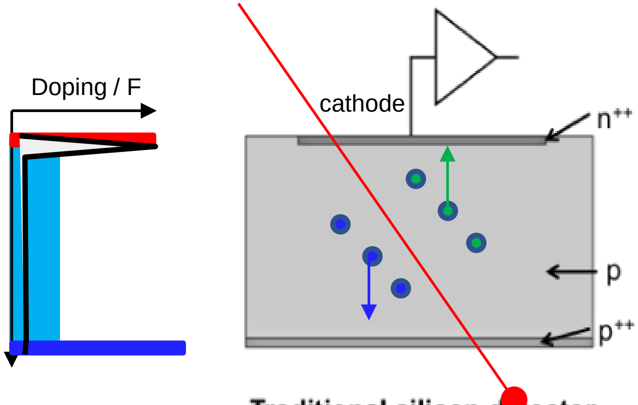
- Trench isolation – prefect the process & apply to iLGAD
- AC Coupled – take from lab to factory with Teledyne e2v
- Buried gain layer – new process architecture

Applications

- PPE – timing resolution
  - Lab characterization & CERN based beam tests
- EM – timing resolution & low energy detection
  - Rosalind Franklin Institute
  - Lab & microscopy characterization
- Synchrotrons – timing resolution & low energy detection
  - Diamond Light source
  - Light source characterization with micro-focused Xray beams

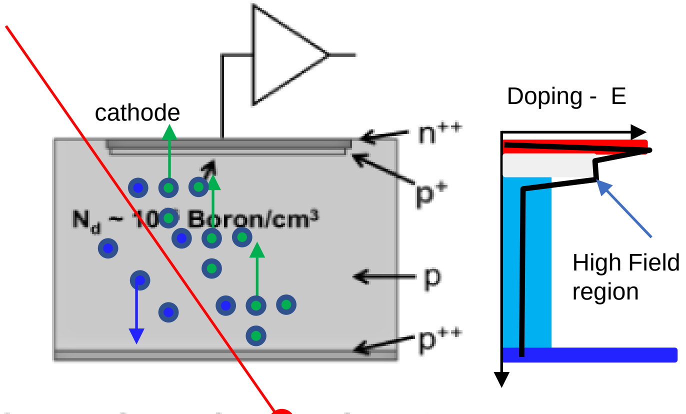
Thank you for your time

LGAD



Traditional silicon detector

$Q_{coll} <= Q_{gen}$

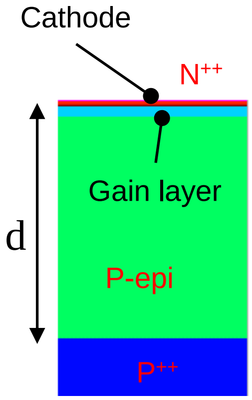


Low gain avalanche detectors

$Q_{coll} > Q_{gen}$

- **An LGAD is a detector which provides signal gain by exploiting impact ionization (= solid state equivalent of proportional counter)**
- A Silicon n-in-p LGAD implements an additional p^+ layer placed below the n^{++} of the cathode. Once this layer is depleted its ionized dopants create an electric field of magnitude that depends on the dopant concentration
- The effect of the electric field due to the additional p^+ layer is to increase the energy of electrons drifting towards the cathode
- If the energy acquired is high enough, they can create additional charge by ***impact ionization***. In this case **$Q_{coll} > Q_{gen}$** , leading to ***signal amplification which allows to obtain high timing resolution***

LGAD timing characteristics

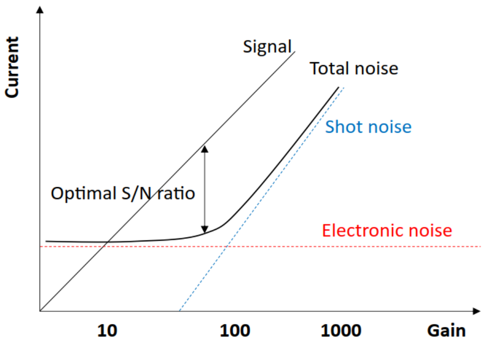


LGAD

$$I_{pk} \propto n_{eh} \cdot d \cdot G \cdot e \cdot \frac{1}{d} \cdot v_{sat} = n_{eh} \cdot G \cdot e \cdot v_{sat}$$

$$dI \propto v_{sat} \cdot dt \cdot G^* \cdot e \cdot \frac{1}{d} \cdot v_{sat} \propto \frac{G^*}{d} \cdot (v_{sat})^2 dt$$

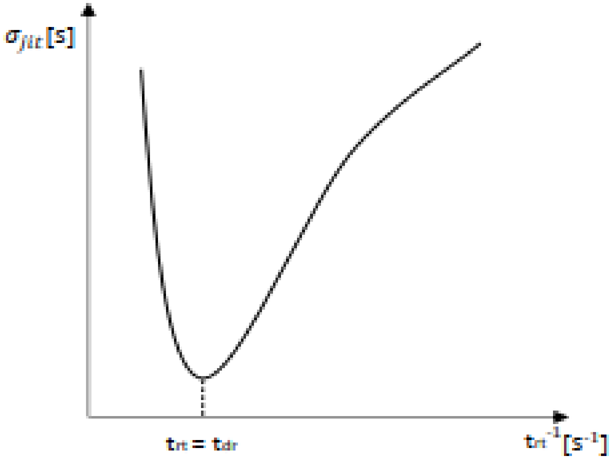
$$(dI/dt)_{SR_{LGAD}} \propto \frac{G^*}{d} \cdot (v_{sat})^2$$



- An increase of the signal, due to internal gain *G (assuming G* = G when dt$\simeq$ 0)*, ***increases the current signal slew rate*** **(SR)**
- Thinning the detectors (small d) also increases the SR but increases capacitance, ***which leads to a decrease of the S/N and reduced SR of the Read Out***
- Simulations and experiments on Si-based devices suggest ***a thickness of ~50 µm and G ~20 for optimal S/N***

➢ Material of higher v_{sat} could also be beneficial in terms of SR

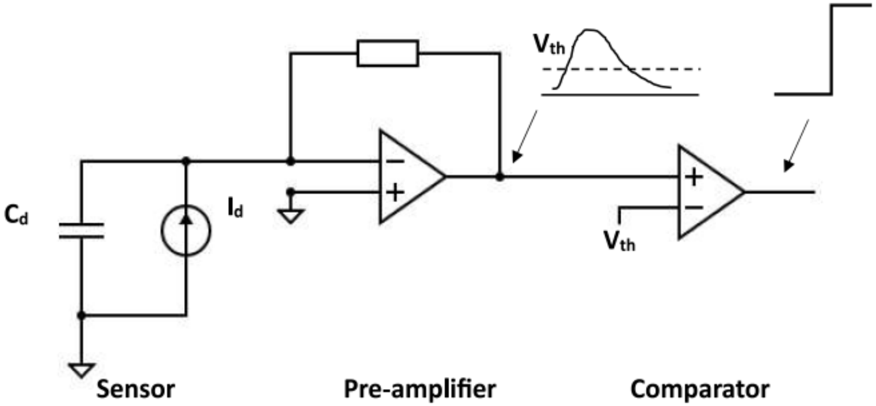
LGAD timing characteristics



$$\sigma_{jit} \propto \frac{t_r}{\frac{S}{N}} = \frac{e_n C_s}{Q_{inj}} \sqrt{\frac{t_{rt}^2 + t_{dr}^2}{2t_{rt}}}$$

- To minimise the jitter, a low C_s, a large Q_{inj} and small t_{dr} are required, in combination with optimised characteristics of the amplifier for the specific sensor
- Minimum jitter is achieved when rise time t_{rt} of amplifier = drift time t_{dr} of sensor

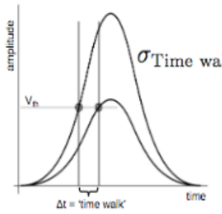
LGAD timing characteristics



- Time-tagging: sensor signal output is shaped (filtered) and compared to a threshold to determine time of arrival of a particle

- Time resolution can be expressed as:

$$\sigma_t^2 = \underbrace{\sigma_{ionis}^2}_{\sim\left(\frac{t_{rise}N}{S}\right)} + \sigma_{dist}^2 + \underbrace{\sigma_{jit}^2}_{\sim\left(\frac{t_{rise}N}{S}\right)} + \sigma_{TDC}^2$$



$$\sigma_{\text{Time walk}} \propto \left[\frac{N\sigma_n}{\mathrm{dV/dt}}\right]_{RMS}$$

- **Time resolution *improves with high Slew Rate and high amplitude signal***

LGAD developments

- The motivation behind proposing LGAD devices in HEP was precise timing resolution for MIP through internal charge amplification.

- The first planned application of LGADs is for the High Luminosity LHC (HL-LHC), in the ATLAS timing layer HGTD [1] and CMS End-Cap timing layer [2], to suppress the pile-up which would lower the efficiency in tracking and vertex reconstruction.

- The standard segmentation technique includes JTE and p-stop. Whilst this is effective, it has the downside of decreasing the fill factor, i.e. it reduces the gain area of the device, as the region between the pads provides no gain. This currently limits the achievable spatial granularity of these devices to a millimetre scale.

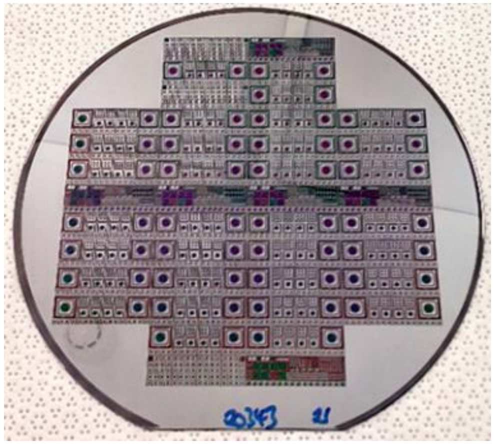
- Future HEP applications would however benefit from devices [3,4] achieving a granularity of 100 μm or less. The next generation of light sources would also require X-ray imaging of similar granularity. There are also potential applications in low LET particle detection and clinical dosimetry.

[**1**] ATLAS Collaboration, *Technical Design Report: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, tech. rep. CERN-LHCC-2020-007, CERN, 2020, URL:https://cds.cern.ch/record/2719855.
[**2**] CMS collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, Tech. Rep. CERN-LHCC-2019-003. CMS-TDR-020, CERN, Geneva, Mar, 2019.

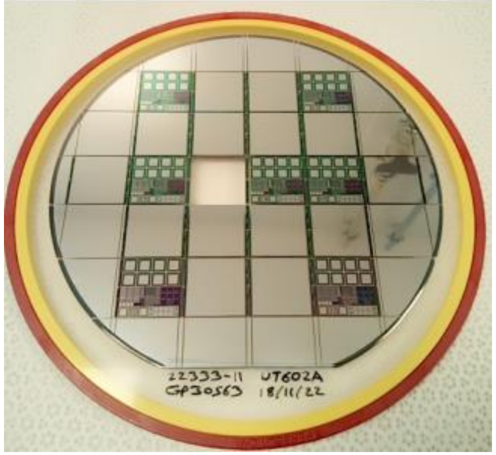
[**3**] H. F.-W. Sadrozinski, A. Seiden and N. Cartiglia, *4d tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 81, 026101, 2017.

[**4**] D. Dutta, *The LHCb VELO Upgrade*, PoS, vol. VERTEX2018, p. 022, 2019.

Te2v LGAD project



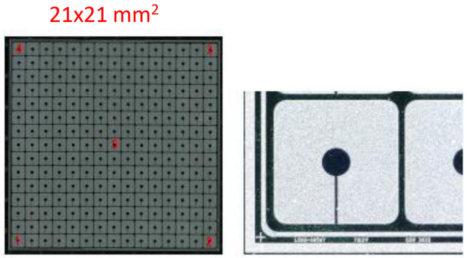
First Te2v LGAD 6'' wafer



Second Te2v LGAD 6'' wafer

1st run

2nd run



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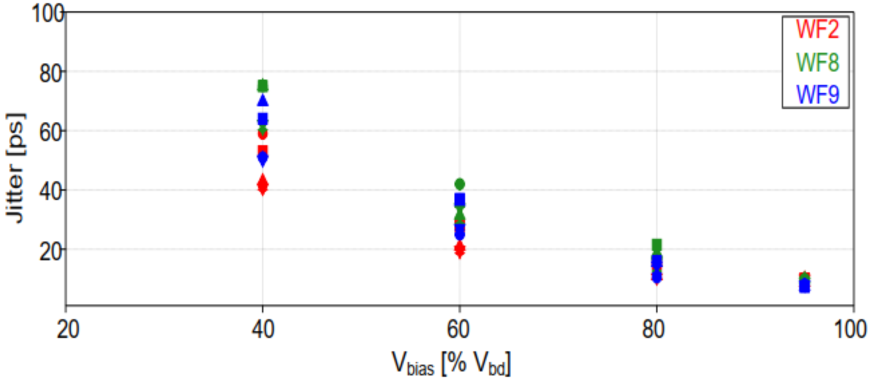
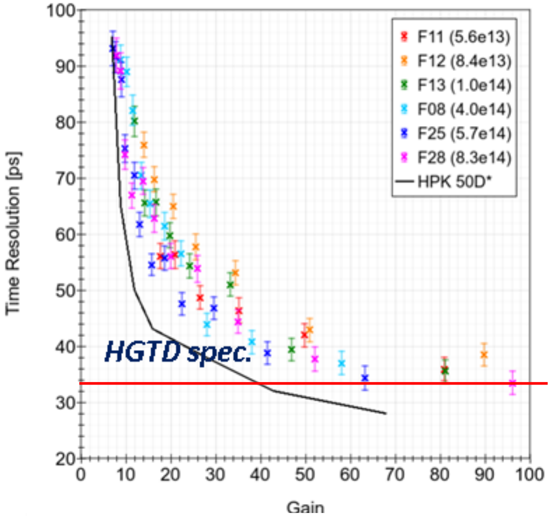
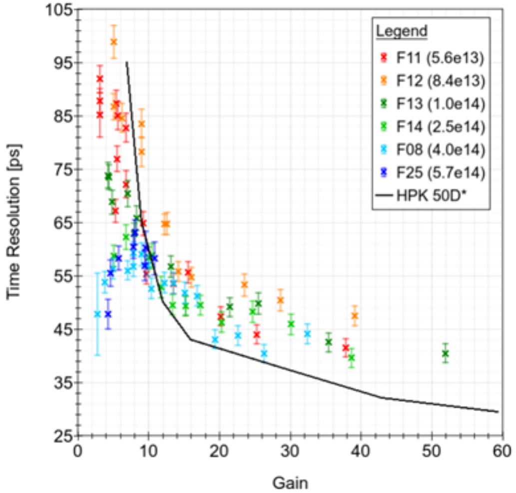
Te2v LGAD project



Jitter of Te2v (WF2, WF8 and WF9) LGAD devices versus bias voltage as a percentage of breakdown voltage V_{bd}.





Pre and post-irradiation time resolution using ^{90}Sr source versus gain (from J. Mulvey, University of Birmingham).

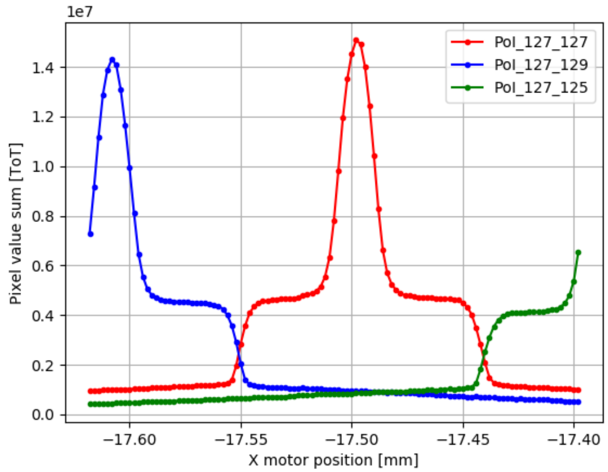
- Single pad time resolution (jitter) around 10 ps using IR source, 35 ps using MIP

- LGAD array still to be tested

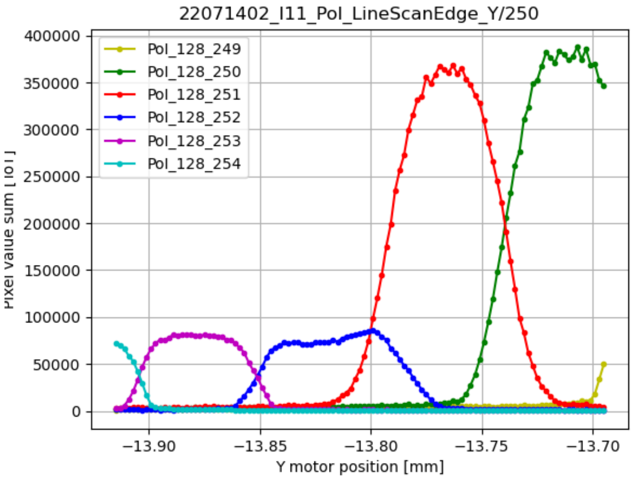
Micron Projects – small pixels

- Small pixels with JTEs subpress gain, close to none for 55µm pixels, small central gain region for 110µm pixels.
  - Simulated [1] and measured @ Diamond Light Source with TimePix3
- Inverse LGADs remove this issue with continuous gain layer
  - Uniform gain for 55µm pixels

Gain suppression
LGAD with JTE, 110µm, 300V



Uniform Gain
iLGAD, 55µm, 250V



[1] Neil Moffat, Richard Bates, “Simulation of the small pixel effect contributing to a low fill factor for pixellated Low Gain Avalanche Detectors (LGAD)”, NMA, Vol 1018, 2021, 165746, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2021.165746.

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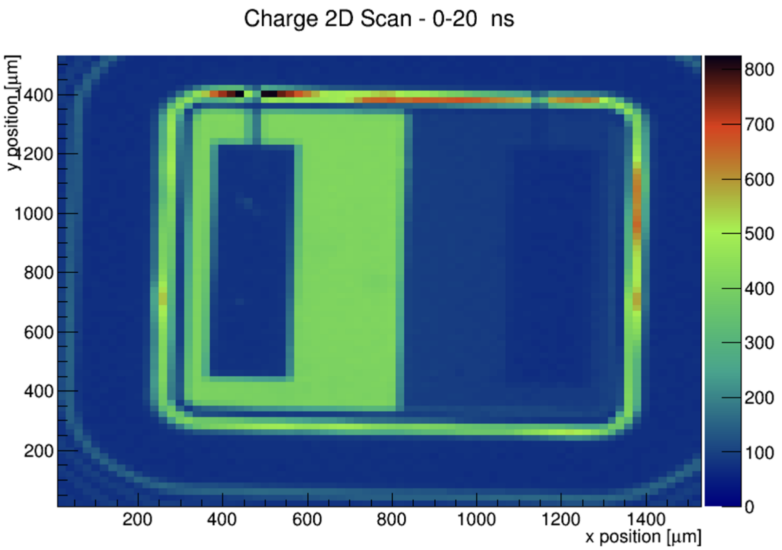
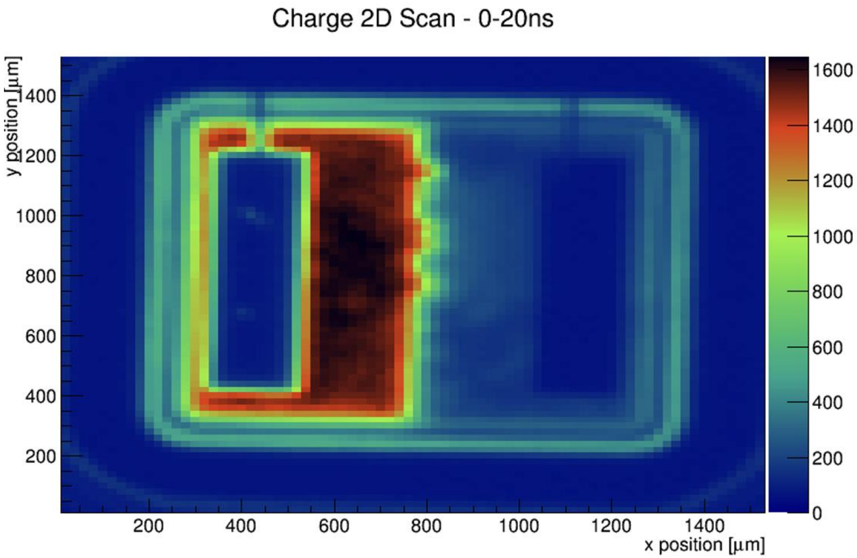
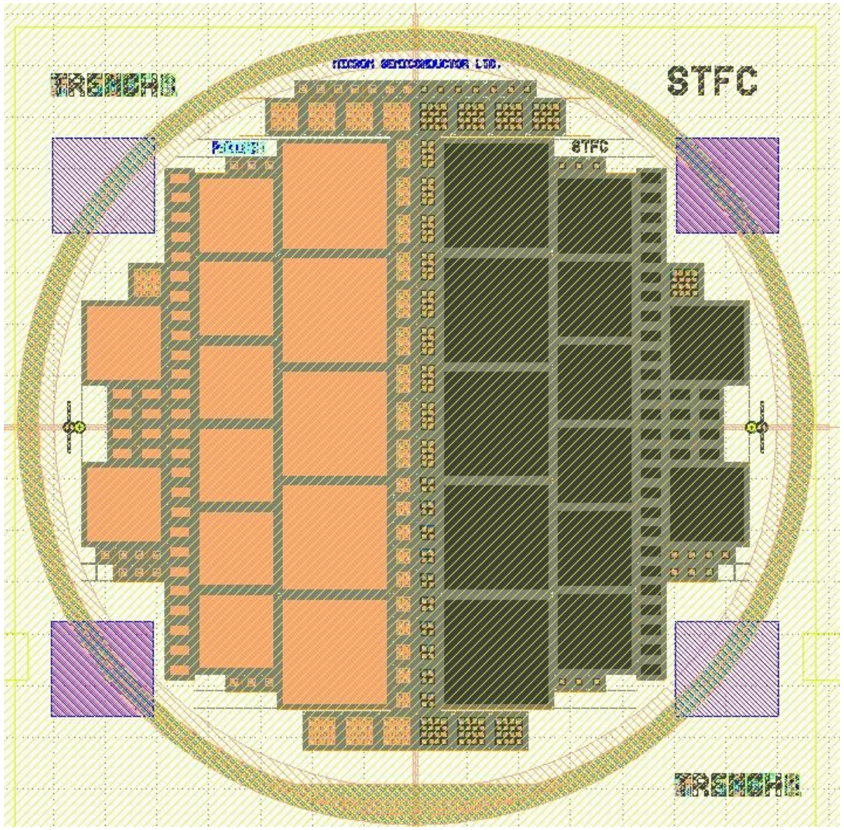
Blue Laser



IR Laser

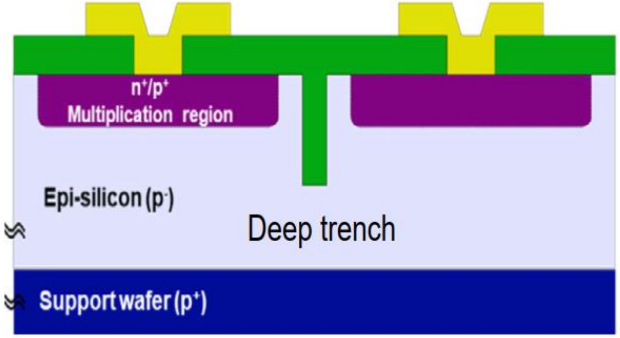


Small Pixel LGAD – **Trench Isolated (TI) LGAD**



- TI LGADs produced on thin (100 um) and thick (300 um) 6’’ wafers for timing and X-ray detection in collaboration with Micron Semiconductor, Glasgow University, Scottish Microelectronics Centre and Rutherford Appleton Laboratory

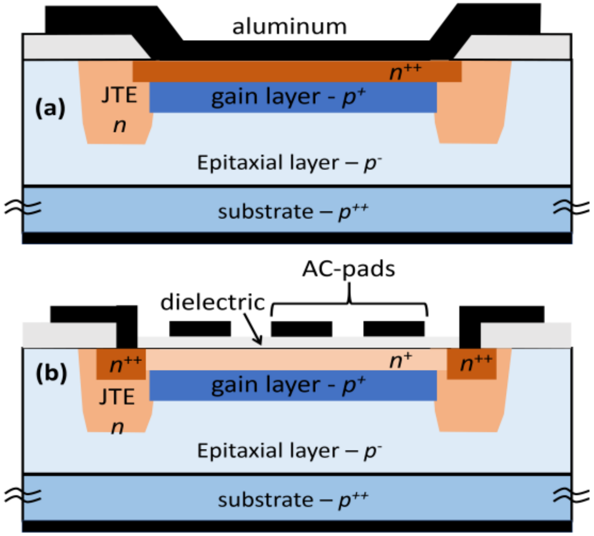
Small Pixel LGAD – **Trench Isolated (TI) LGAD**



- In TI LGADs [2] the GL is the same as in conventional LGAD but the termination and isolation structures (p-stop and JTE) are replaced by a deep trench, less than a μm wide, a process widely used for pixel isolation in CMOS imagers and Silicon Photomultipliers. This isolation reduces the extension of the no-gain region between pads, increasing the fill factor.
- Trench can be applied to iLGAD devices as well
- 2 process runs with Micron + SMC

[**2**] G. Paternoster, G. Borghi, M. Boscardin et al., *Trench-isolated low gain avalanche diodes (ti-lgads)*, IEEE Electron Device Letters 41 884-887, 2020.

Small Pixel LGAD - **AC coupled LGAD**



Standard LGAD

AC coupled LGAD

- In the AC-coupled LGAD design, [3], the n^{++} implant well is replaced by a more resistive n^{+} layer, with electrodes that are AC coupled to it via a thin dielectric layer.
- This eliminates the need for a JTE structure except at the very edge of the sensor, thus providing a non-segmented GL. A fill factor of nearly 100% can be achieved without complicating the fabrication process.
- The AC coupled signal and the intrinsic charge sharing in the resistive n^{+} layer might however make it difficult to achieve a high repetition rate.

[**3**] G. Giacomini, W. Chen, G. D’Amen, A. Tricoli, *Fabrication and performance of AC-coupled LGADs*, https://doi.org/10.1088/1748-0221/14/09/P09004, 2019.

Small Pixel LGAD – **Deep Junction (DJ) LGAD**

- Process flow

- SUBS (p, 0.004 Ω cm)
- EPITAX 1 growth (p, > 300 Ω cm)
- EPITAX 2 growth (p, ~ 1.8 Ω cm)
- EPITAX 3 growth (n, ~ 0.6 Ω cm)
- EPI 4 growth (n, > 300 Ω cm)
- Oxidation 300 nm Thermal Oxide
- Resist depo 1 μm JTE photomask Etch
- JTE implant Strip resist
- JTE drive in
- Resist depo 1 μm PSTOP mask etch
- p-stop B implant Strip resist
- p-stop drive in
- Resist depo 1 μm ACTIVE photomask etch
- Sacrificial oxide Thermal Oxidation 40 nm
- Resist depo 1 μm Shallow n mask etch
- Shallow n implant Strip resist
- LTO depo 500 nm
- Implant activation
- LTO densification
- Resist depo 1 μm VIAs photomask etch
- Aluminium depo 1 μm
- Resist depo 1 μm Contacts photomask etch
- Strip resist
- END of Process

- All the fabrication steps of the devices have been simulated using **TCAD** tool from Synopsys

LGAD project summary and next steps

- A number of LGADs have been produced as a result of collaboration with Te2v and Micron Semiconductor.

- The collaboration with Te2v focused on timing applications for HEP. The collaboration with Micron focuses also on X-ray imaging.

- Additional applications are possible, including low-LET particle detection [8].

- Next development will focus on increasing the fill factor in higher granularity devices. Various options are available. Currently, the DJ using graded epitaxial is not being pursued (as far as we know).

[**8**] Archer, Jay et al. A Two-Dimensional Characterisation of Low Gain Avalanche Diodes for Low-LET Microdosimetry. IEEE Transactions on Nuclear Science. PP. 1-1. 10.1109/TNS.2024.3359249 (2024)..