LGAD Development for the LHC's High-Luminosity Upgrade at Teledyne e2v

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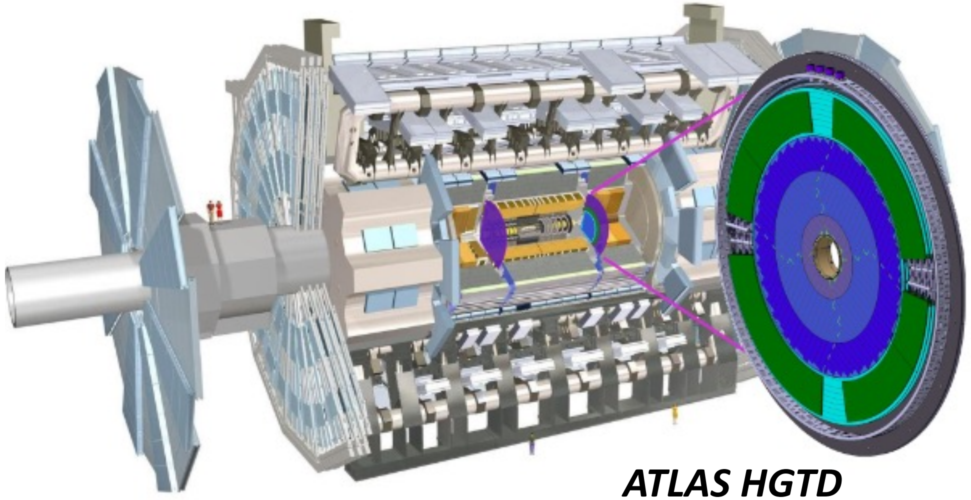
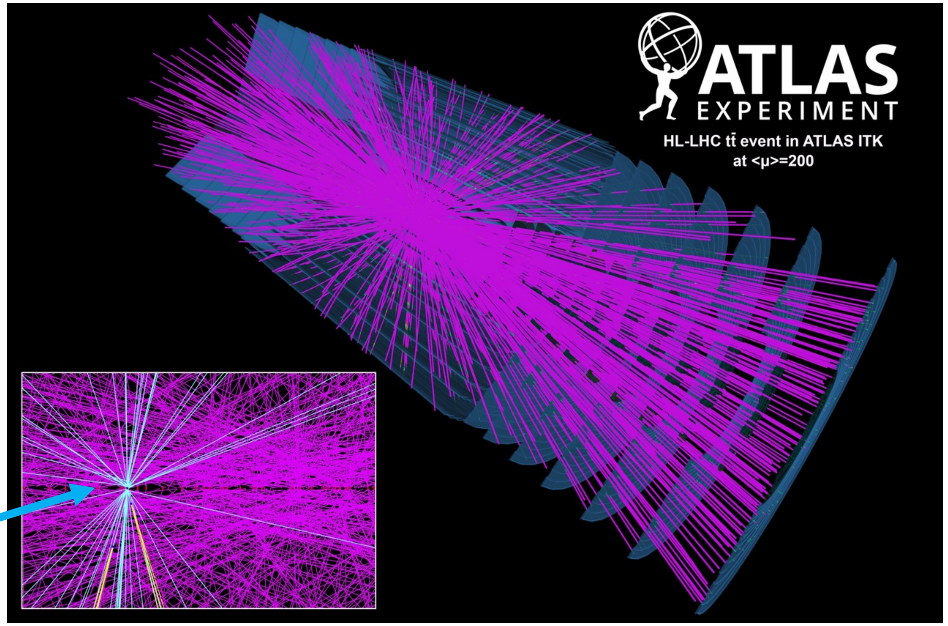
TELEDYNE e2v

Outline

- Introduction: Ultra Fast Silicon Detectors
- Project overview: LGADs manufactured by Teledyne e2v
- Wafer characterization
- Dicing and post-dicing treatment
- Charge gain measurement
- Preliminary jitter measurements
- Future plans and Summary

The need for Ultra Fast Silicon Detectors



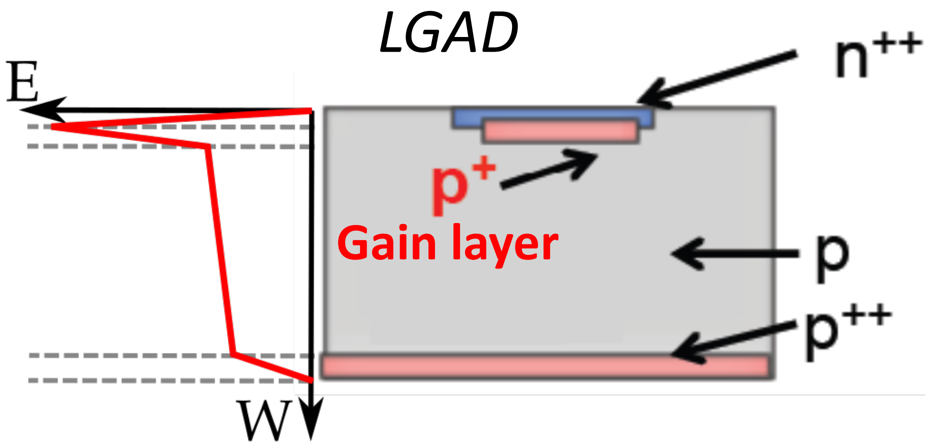


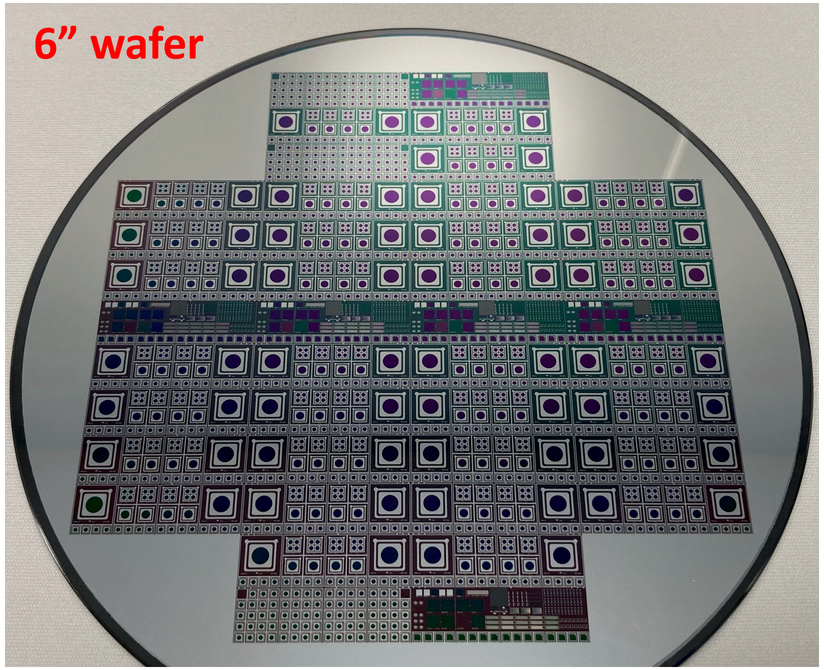
1 pp interaction amongst 200

- Pile-up is one of the major challenges for tracking at the HL-LHC
- Timing information used to disentangle overlapping events
- ATLAS High-Granularity Timing Detector placed outside the ITk

Teledyne e2v LGAD project

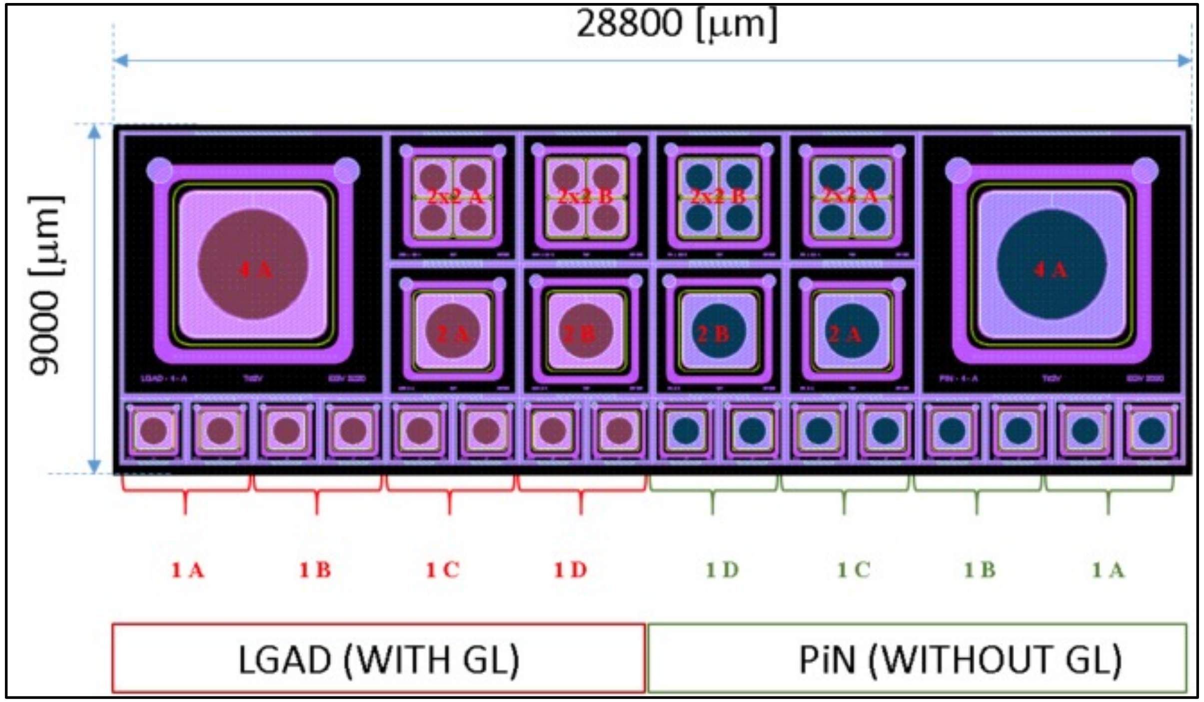
- LGAD: Low Gain Avalanche Detector
- Targeting track timing resolution of approx. 30-50 ps over detector lifetime
  - Time resolution benefits from high slew rate -> increased by introducing internal gain
  - Impact ionization in gain layer -> boron implantation (p^+)
- Pre-manufacture simulation done in TCAD
- University of Oxford, University of Birmingham, Open University, Rutherford Appleton Laboratory





Teledyne e2v LGAD project

- Epitaxial layer: 50 um thick, high resistivity
- 8 different combinations of manufacturing parameters (only 3 shown below)
- Each field contains LGADs and PiN diodes of the same layout (4 mm, 2 mm, 1 mm)



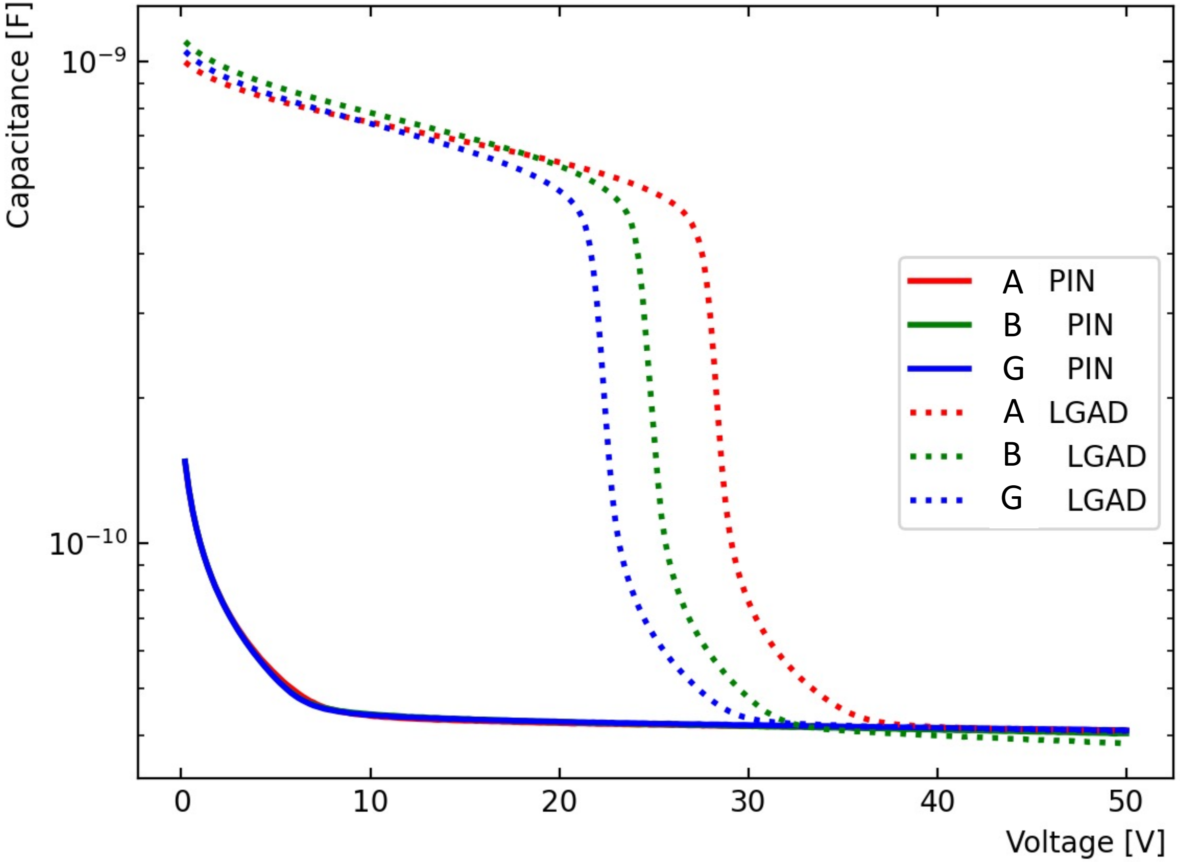
Wafer code	Implant dose (normalised*)	Implant energy (normalised*)
A	1.07	1.11
B	1.07	1.05
G	1.00	1.05

*values normalised to a reference wafer which is not included in the table

Characterization of wafers

T = 21°C, f = 100kHz

4 mm devices

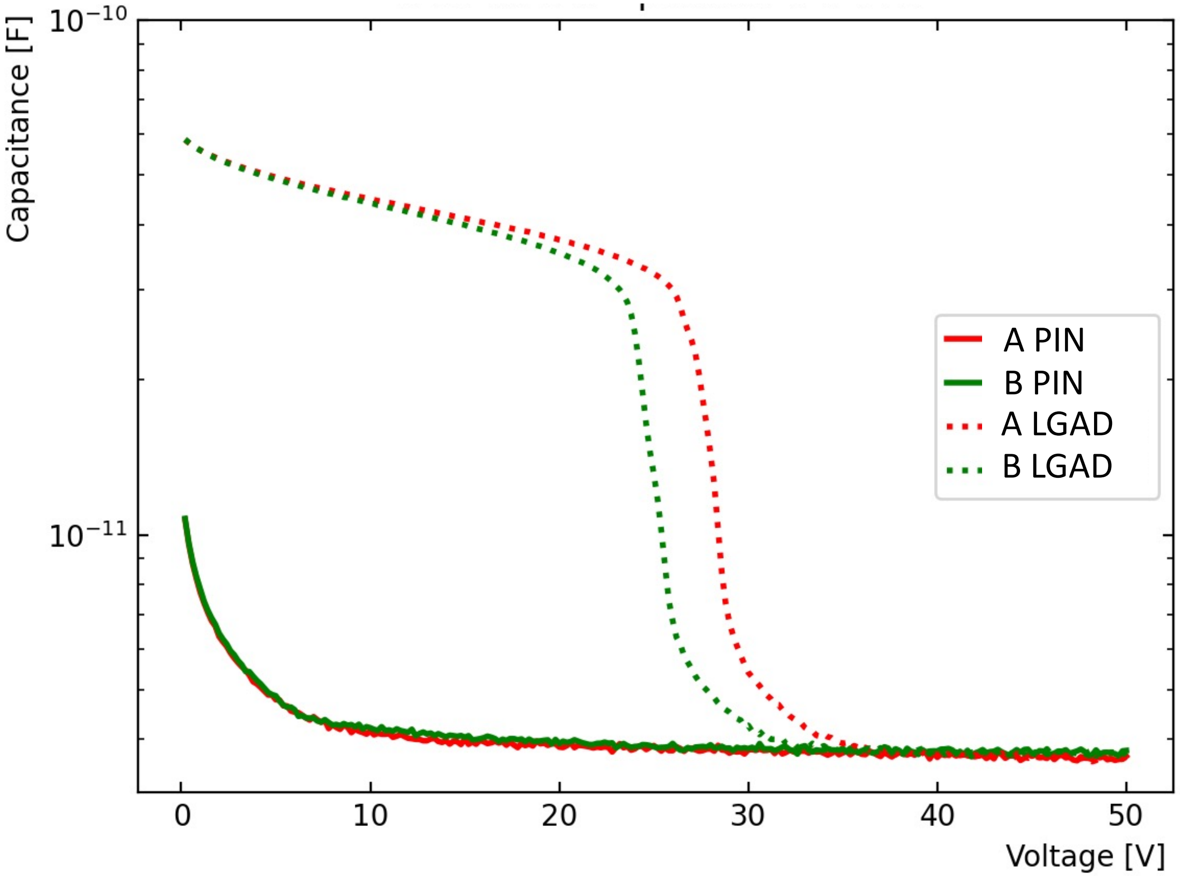


Wafer code	A	B	G
Implant dose (normalised)	1.07	1.07	1.00
Implant energy (normalised)	1.11	1.05	1.05
GL depletion voltage	~ 30 V	~ 25 V	~ 22 V
Breakdown voltage	~ 220 V	~ 420 V	~ 540 V (soft)
Leakage current	0.2-0.4 nA (before breakdown)		

Characterization of wafers

T = 21°C, f = 100kHz

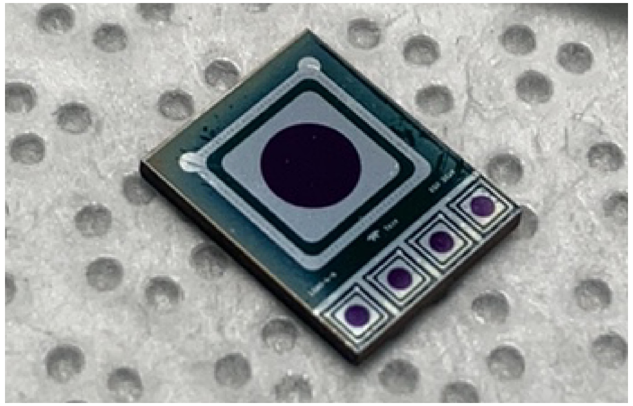
1 mm devices



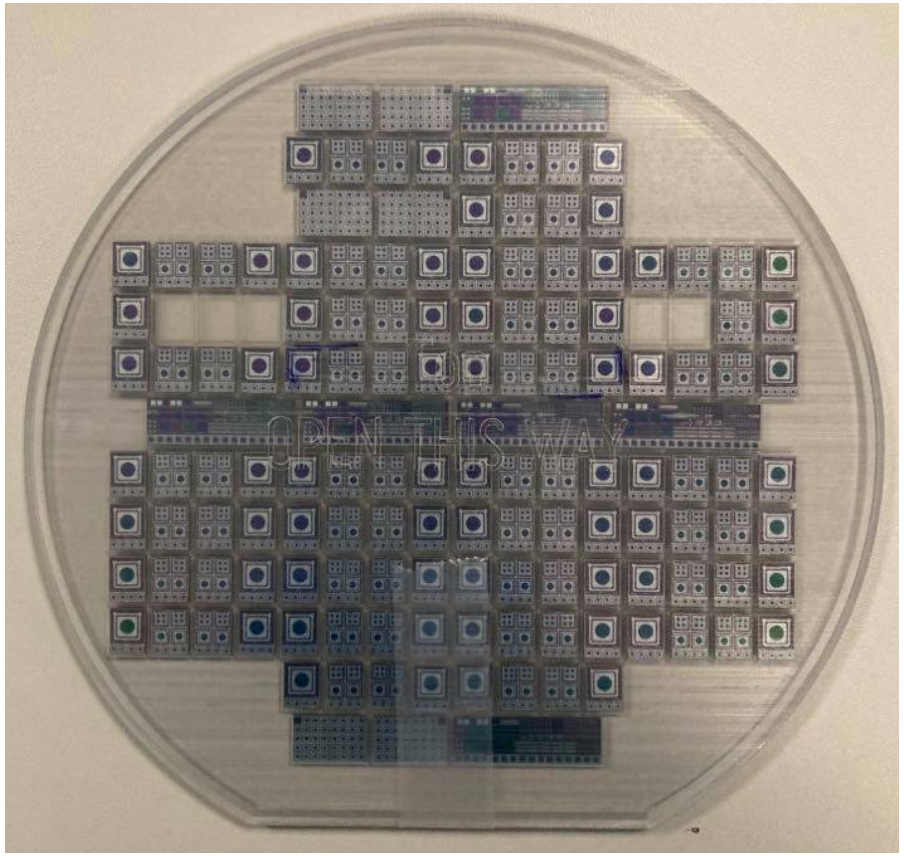
Wafer code	A	B
Implant dose (normalised)	1.07	1.07
Implant energy (normalised)	1.11	1.05
GL depletion voltage	~ 30 V	~ 25 V
Breakdown voltage	~ 240 V	~ 440 V
Leakage current	0.01-0.03 nA (before breakdown)	

Laser dicing of wafers

- Laser dicing
  - Laser wavelength λ = 1028 nm
  - Power: 10 W
  - Beam size: 25 x 25 um^2
- Measurable effects of dicing on the leakage current
  - Further investigation needed to see if saw dicing produces the same effect

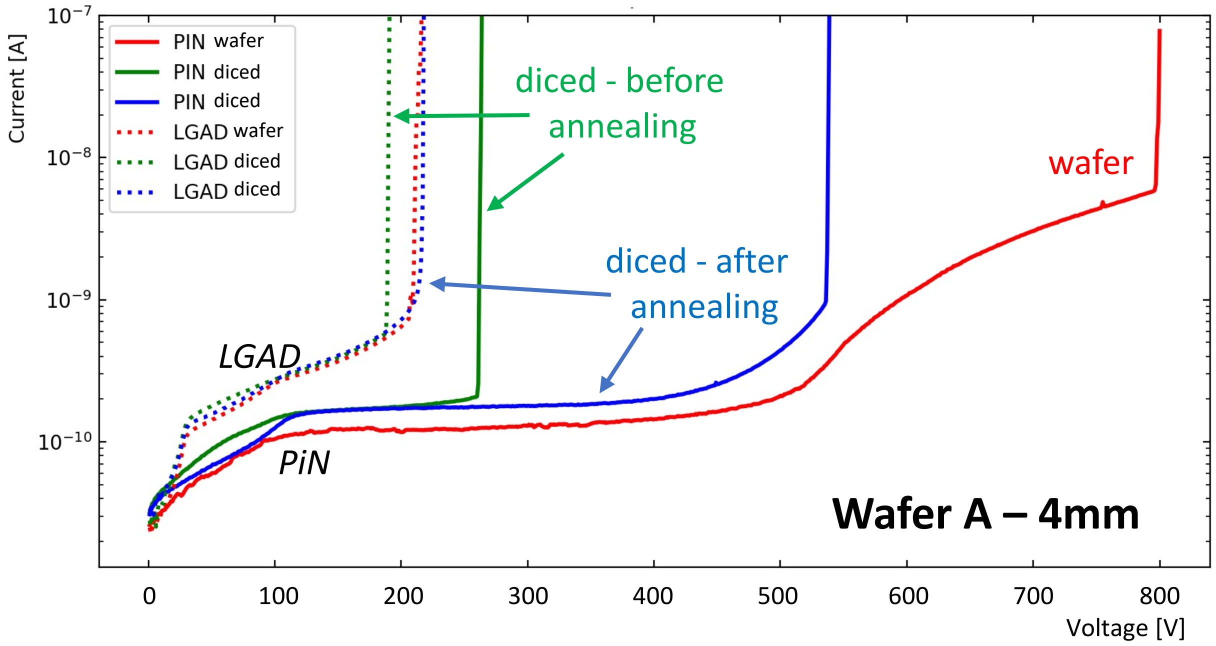


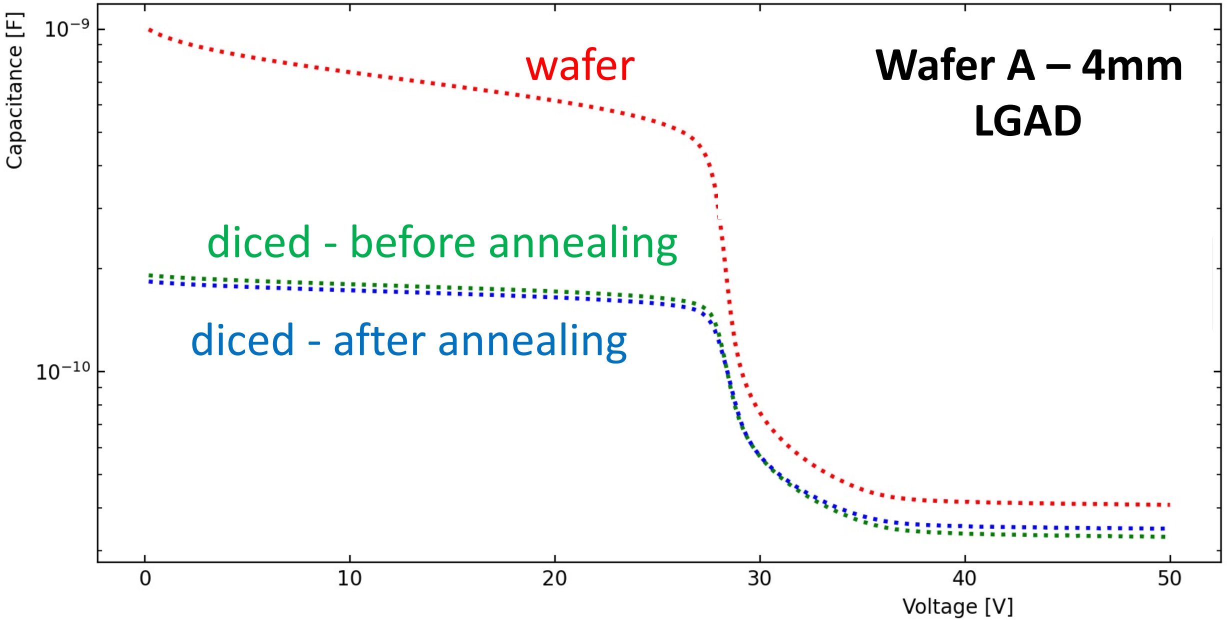
Custom-made 3D printed frame to keep sensors in place and allow for direct comparison pre- and post-dicing



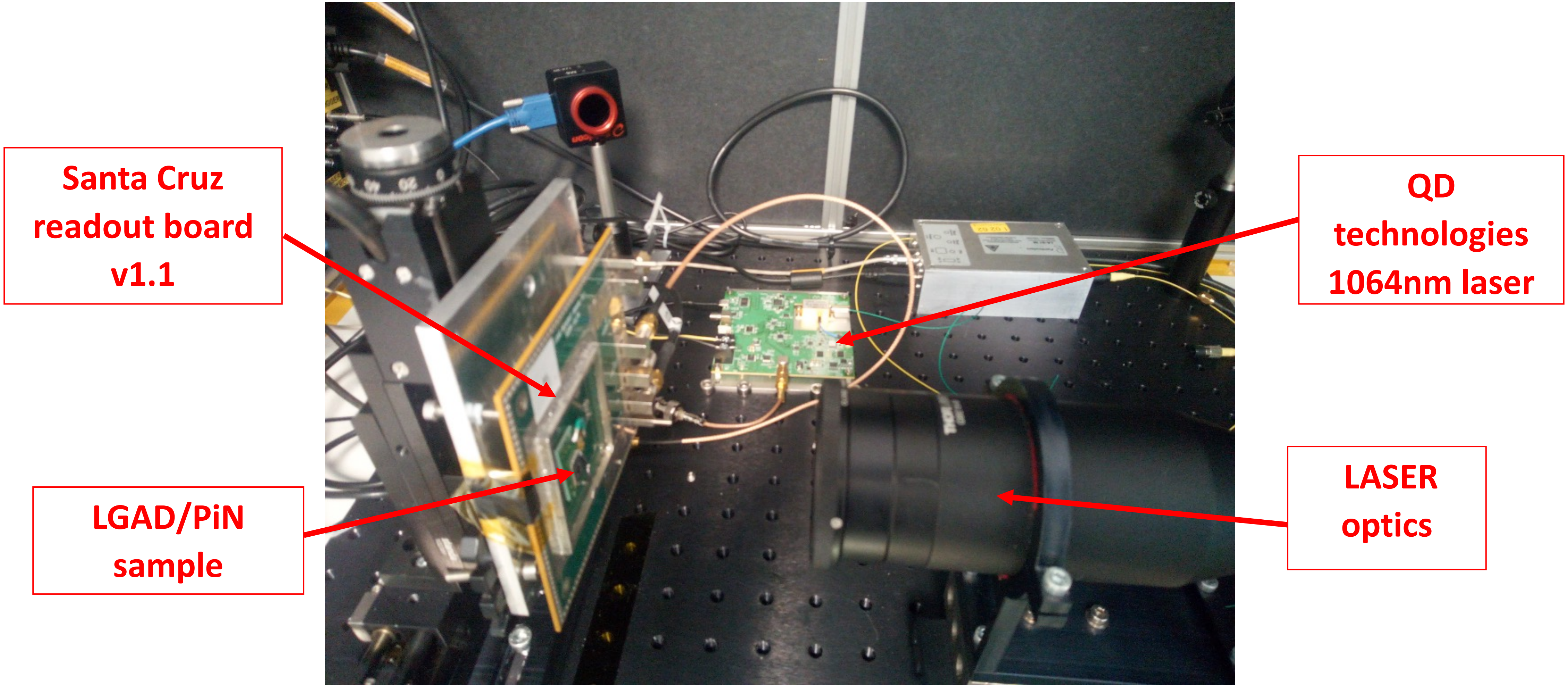
Post-dicing treatment - thermal annealing

- Suspected surface states formed after wafer dicing
  - Detrimental effects of laser dicing: lower breakdown voltage, soft-breakdown behaviour (gradual breakdown over a longer voltage range, often starting relatively soon)
- Thermal annealing at 150°C applied for 2 hours





Charge gain measurement laser setup



Santa Cruz readout board v1.1

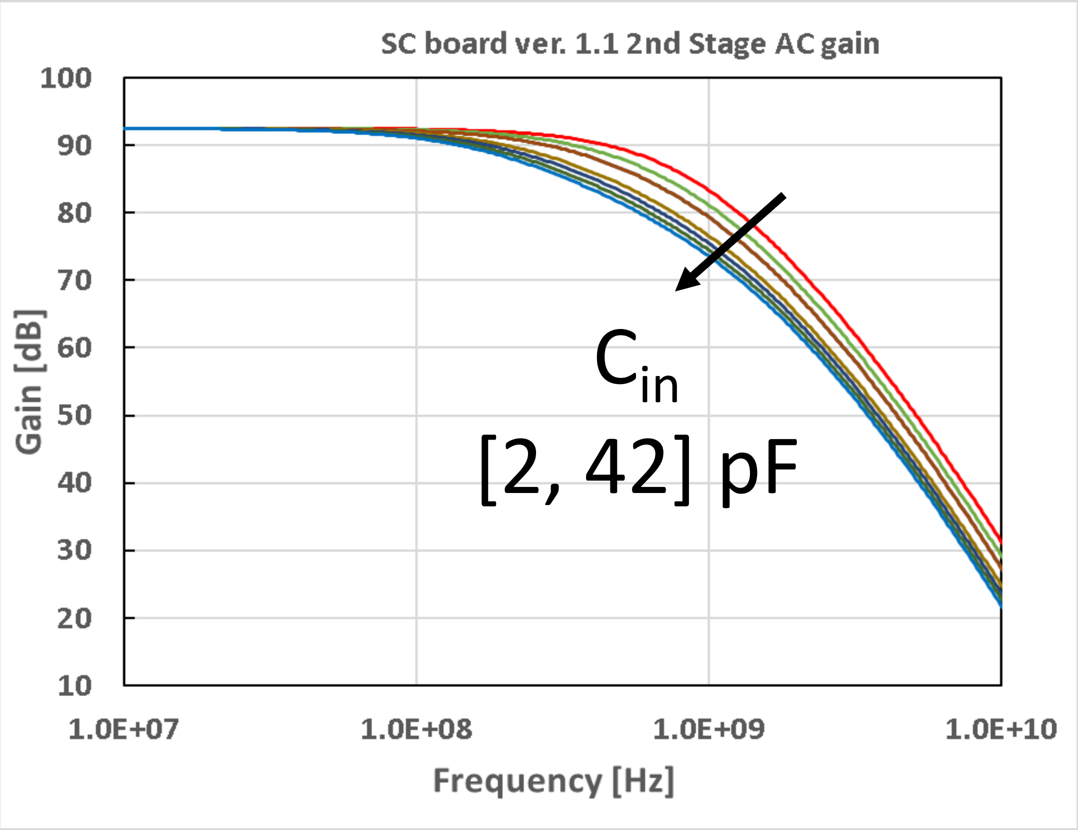
QD technologies 1064nm laser

LGAD/PiN sample

LASER optics

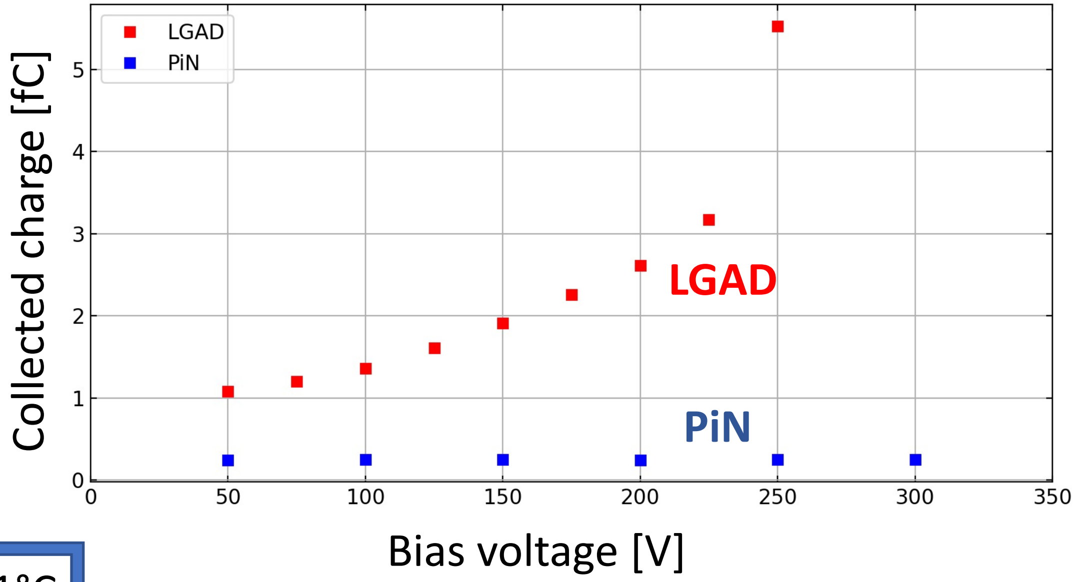
Charge gain measurement – laser and amplification

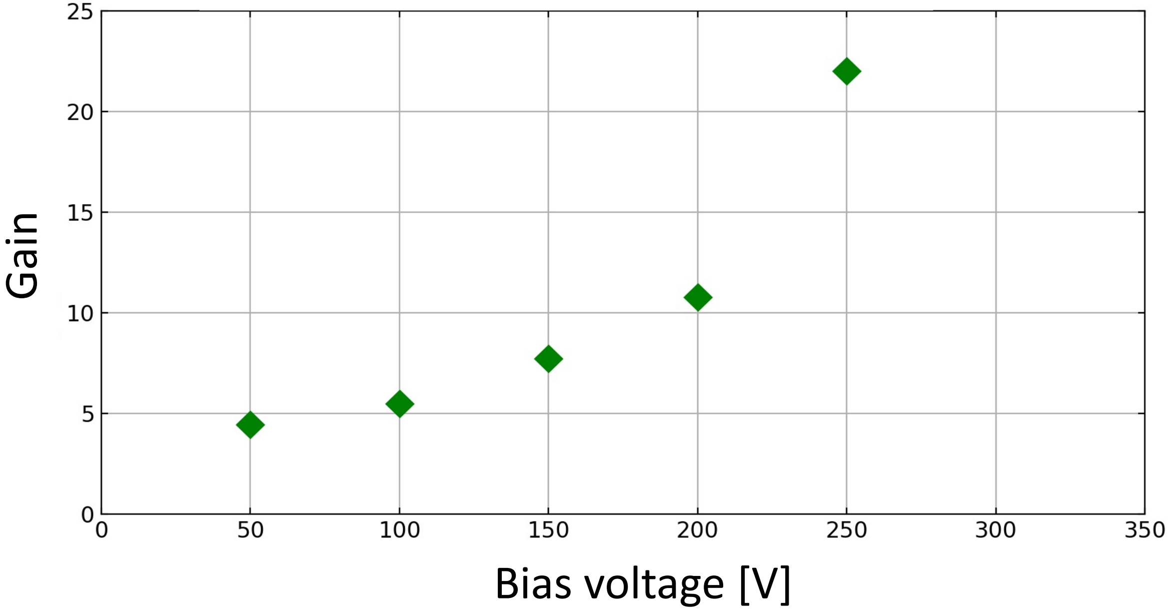
- First stage amplifier: Santa Cruz Readout v1.1
- Second stage amplifier: RF amplifier FEMTO HSA-X-2-40, 40 dB – 2GHz
- Impedance matched to 50 Ohm
- The combined effect of the chain of amplifiers simulated in SPICE
  - Estimate the gain of the chain
- Laser wavelength: 1064 nm
  - average energy: 77.9 fJ
  - pulse width 69.5 ps



Charge collected and gain - LGAD vs PiN (1mm)

- Conversion from the amplifier output to collected charge is achieved by estimating the gain of the chain of amplifiers from a SPICE simulation (92.5 dB or 42,170 for C_{in} of 2 pF)
- The gain is estimated as the ratio of the charge collected by LGAD and PiN
- Small additional correction (approx. 2.2%) due to the bandwidth limitation of the amplifier chain not included yet

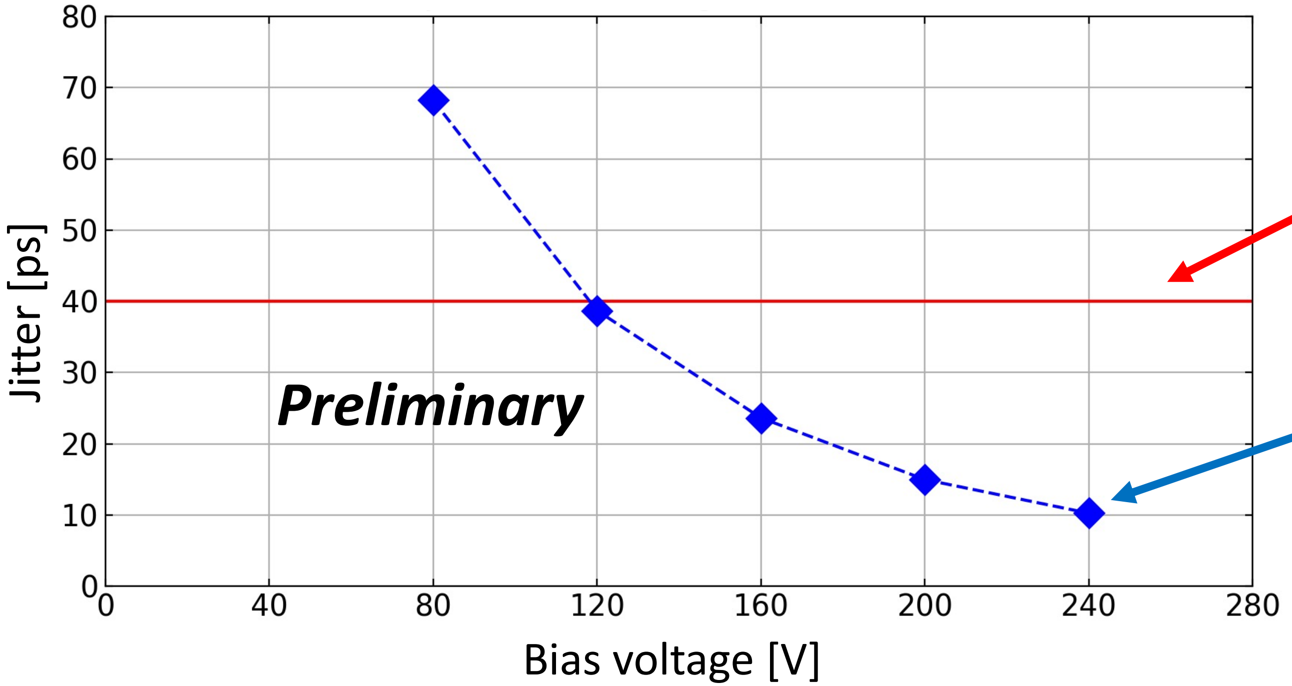




T = 21°C

1mm LGAD jitter measurement – preliminary results

- Jitter - the spread (standard deviation) of time delay between 50 % of trigger signal amplitude and 50 % of LGAD signal amplitude
- Average energy of the laser pulse lowered below 79 fJ
- Low pass filter applied at 1 GHz – noise issues
- Unirradiated device; No subtraction of other contributions



initial HGTD requirement (40 ps)

breakdown onset around 240 V for this device

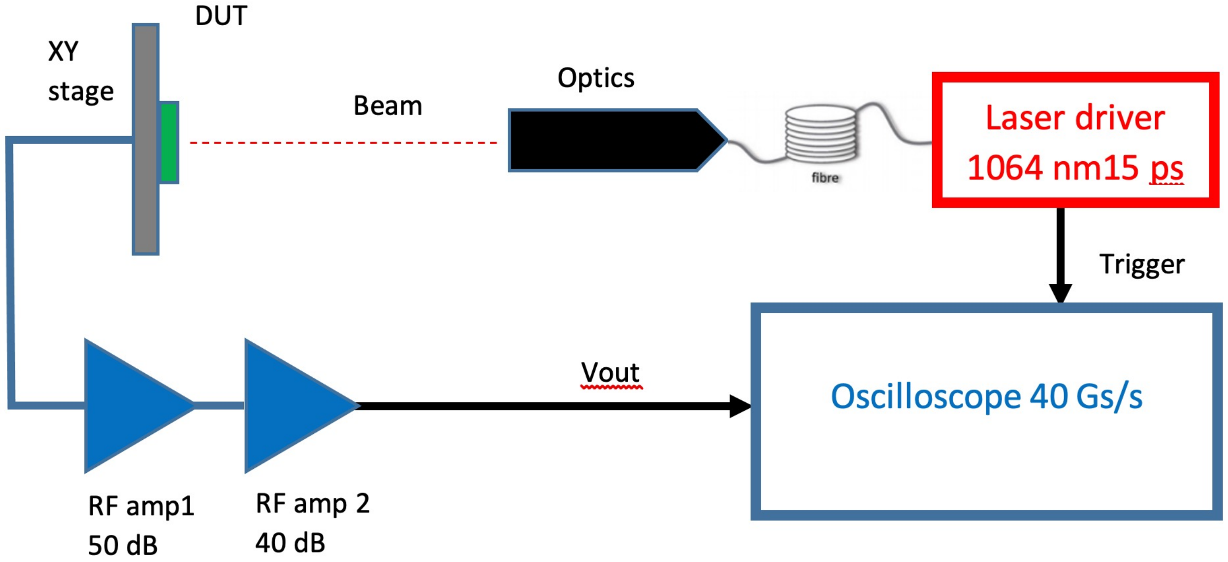
T = 21°C

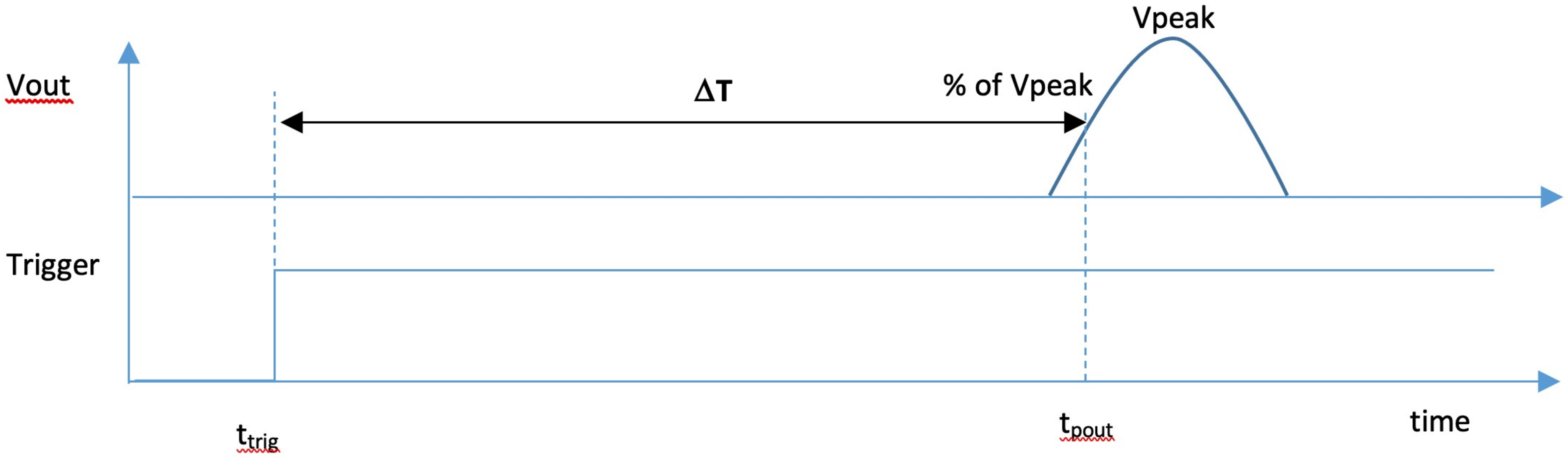
Summary and Future Plans

- First batch of LGAD devices manufactured by Teledyne e2v, currently being tested at Oxford, Birmingham, Open University and Rutherford Appleton Laboratory
- Post-dicing treatment required (thermal annealing) – laser dicing
- Wafer A 1mm: gain of around 25 at voltage of 225 V,
  preliminary measurement of jitter <20 ps for bias voltages above 200 V

- Test wafers with other manufacturing parameters
- Quantify saw dicing effects on wafers (currently using laser dicing)
- Further timing measurements with fast laser
- Prepare for second wafer batch from Teledyne e2v
  - Larger arrays produced, possibility for individually diced devices
  - Implementation of observations from the first batch

Backup – Timing Measurement setup





Backup – Timing Measurement uncertainties

$$\sigma_{\Delta t}^2 = \sigma_{trig}^2 + \sigma_{Laser}^2 + \sigma_{DUT}^2 + \underbrace{\sigma_{Amp1}^2 + \sigma_{Amp2}^2}_{\text{Jitter of the amplifiers}} + \sigma_{TW}^2 + \sigma_{TDC}^2$$

Jitter term of trigger output

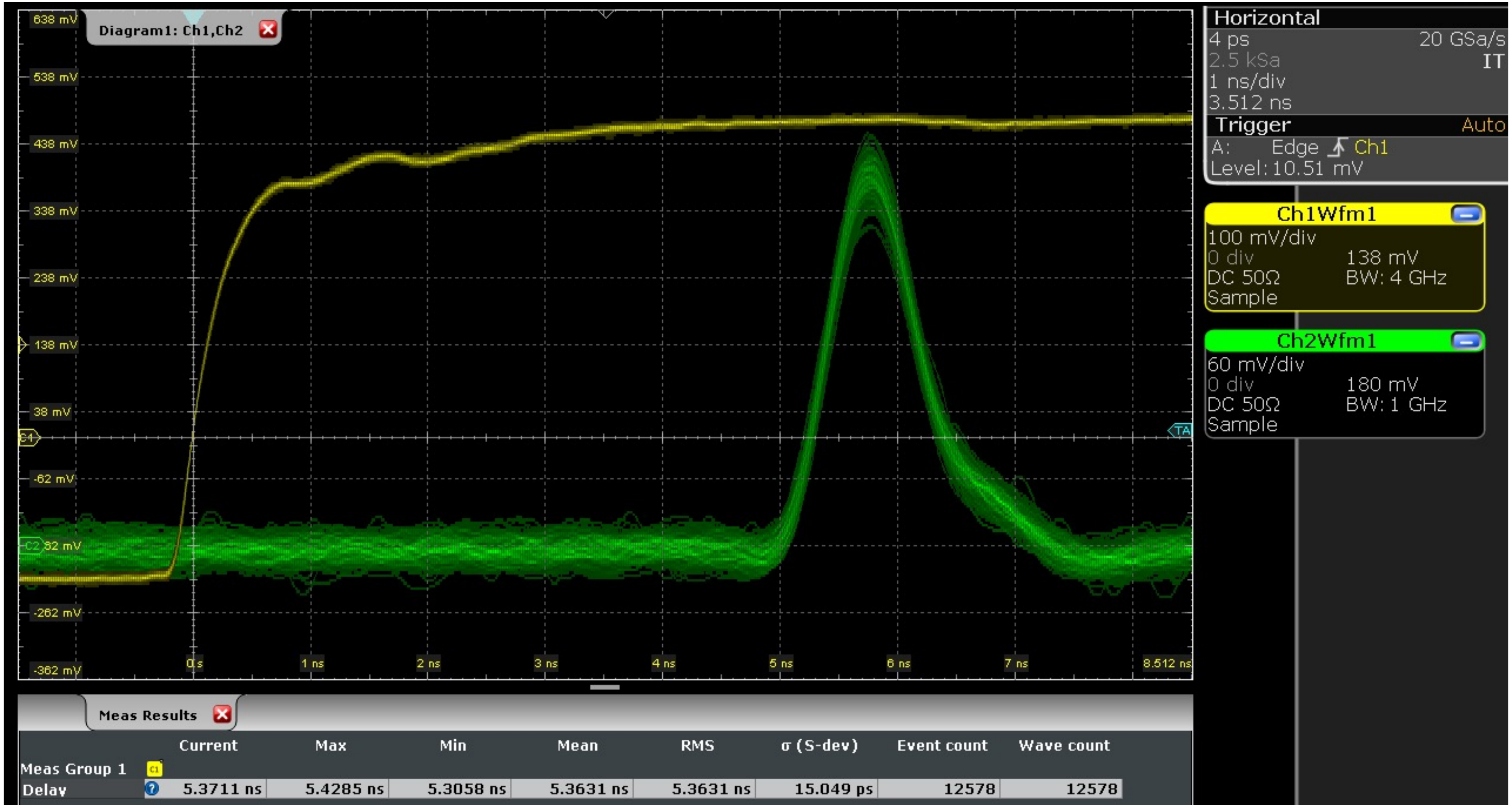
Jitter term due to the laser pulse fluctuations

Intrinsic jitter of the DUT (+ distortion and Landau)

Time-walk term

Time quantization noise of the scope (negligible)

Backup – LGAD 1mm, 200 V



Horizontal
4 ps 20 GSa/s
2.5 kSa IT
1 ns/div
3.512 ns

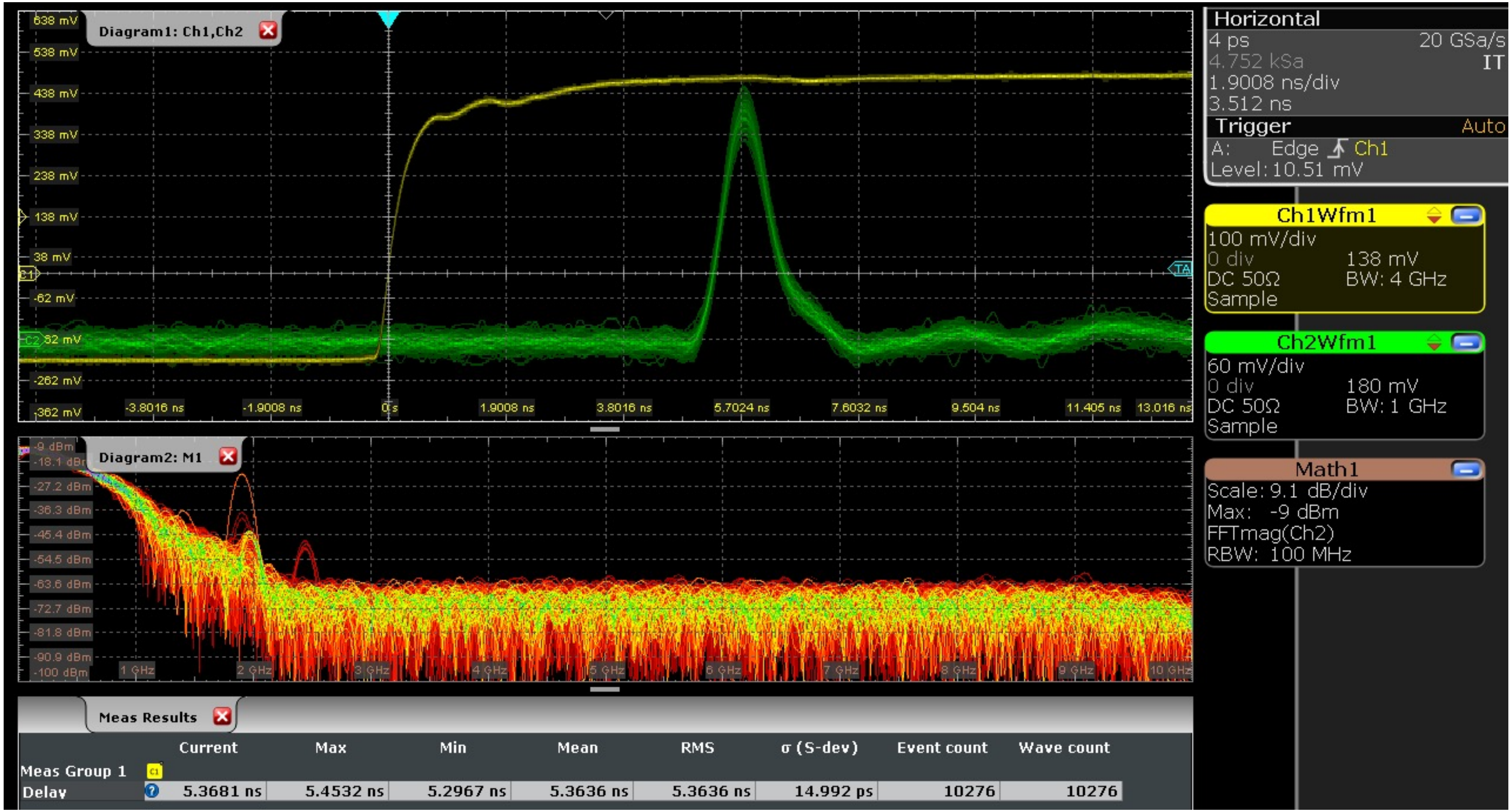
Trigger Auto
A: Edge Ch1
Level: 10.51 mV

Ch1Wfm1
100 mV/div
0 div 138 mV
DC 50Ω BW: 4 GHz
Sample

Ch2Wfm1
60 mV/div
0 div 180 mV
DC 50Ω BW: 1 GHz
Sample

	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Meas Group 1 C1								
Delay	5.3711 ns	5.4285 ns	5.3058 ns	5.3631 ns	5.3631 ns	15.049 ps	12578	12578

Backup – LGAD 1mm, 200 V, FFT



Horizontal
4 ps 20 GSa/s
4.752 kSa IT
1.9008 ns/div
3.512 ns

Trigger Auto
A: Edge Ch1
Level: 10.51 mV

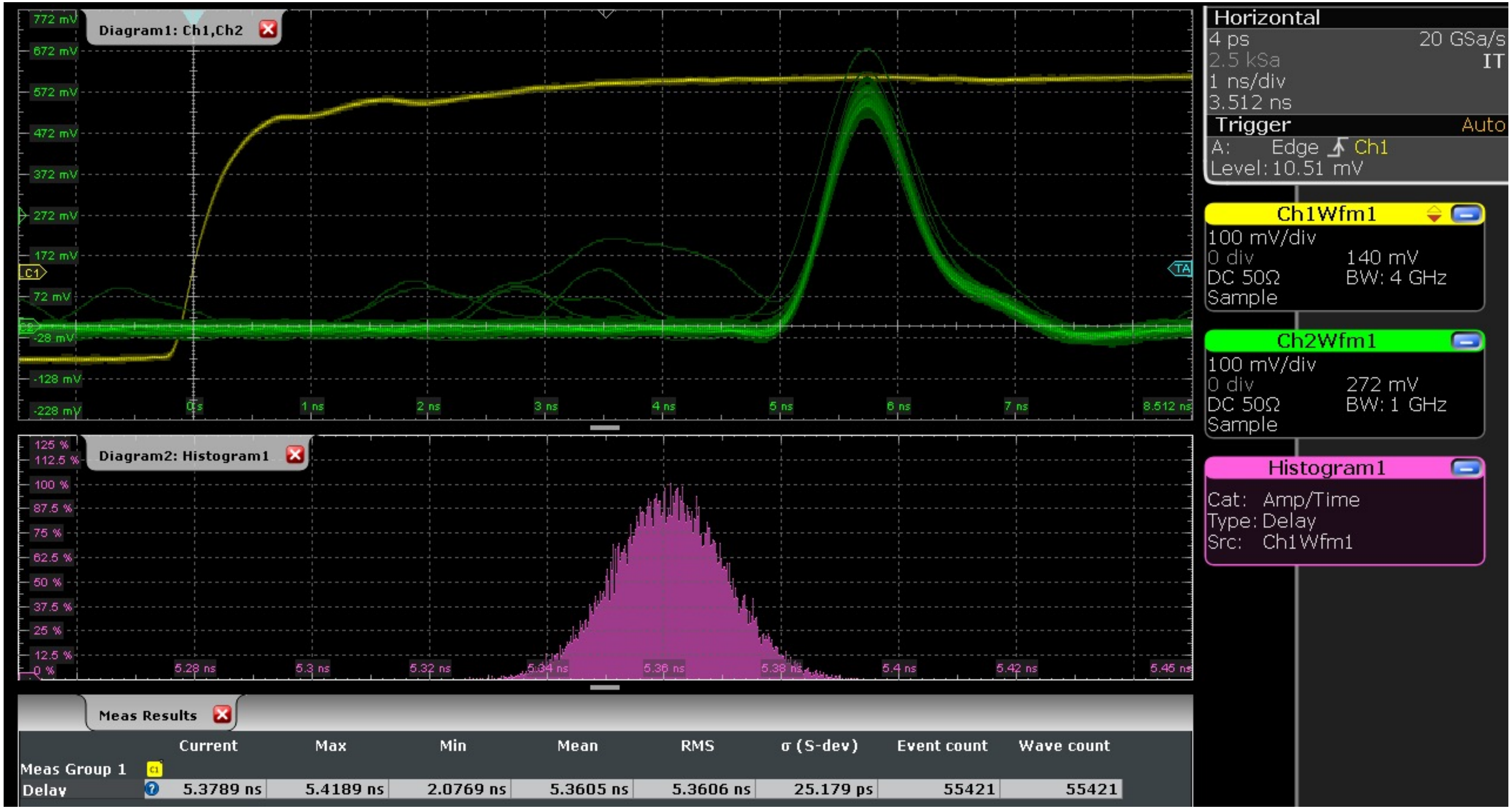
Ch1Wfm1
100 mV/div
0 div 138 mV
DC 50Ω BW: 4 GHz
Sample

Ch2Wfm1
60 mV/div
0 div 180 mV
DC 50Ω BW: 1 GHz
Sample

Math1
Scale: 9.1 dB/div
Max: -9 dBm
FFTmag(Ch2)
RBW: 100 MHz

	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Meas Group 1								
Delay	5.3681 ns	5.4532 ns	5.2967 ns	5.3636 ns	5.3636 ns	14.992 ps	10276	10276

Backup – LGAD 1mm, 240 V, histogram



Horizontal
4 ps 20 GSa/s
2.5 kSa IT
1 ns/div
3.512 ns

Trigger Auto
A: Edge Ch1
Level: 10.51 mV

Ch1Wfm1
100 mV/div
0 div 140 mV
DC 50Ω BW: 4 GHz
Sample

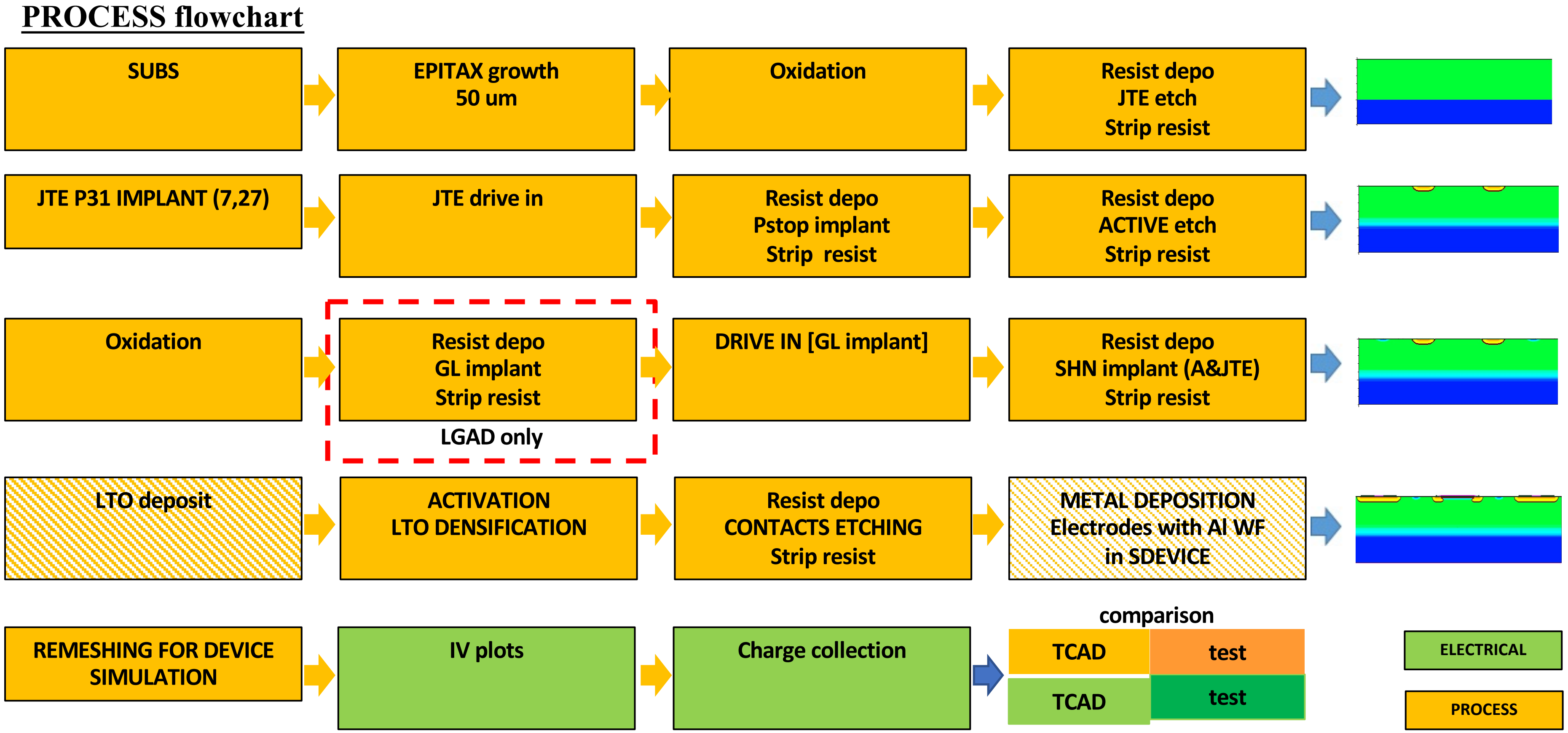
Ch2Wfm1
100 mV/div
0 div 272 mV
DC 50Ω BW: 1 GHz
Sample

Histogram1
Cat: Amp/Time
Type: Delay
Src: Ch1Wfm1

	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Meas Group 1								
Delay	5.3789 ns	5.4189 ns	2.0769 ns	5.3605 ns	5.3606 ns	25.179 ps	55421	55421

Backup - LGAD Simulation I

- Fabrication steps of the devices simulated using TCAD tool from Synopsis



PROCESS flowchart

SUBS → EPITAX growth 50 um → Oxidation → Resist depo JTE etch Strip resist

JTE P31 IMPLANT (7,27) → JTE drive in → Resist depo Pstop implant Strip resist → Resist depo ACTIVE etch Strip resist

Oxidation → Resist depo GL implant Strip resist (LGAD only) → DRIVE IN [GL implant] → Resist depo SHN implant (A&JTE) Strip resist

LTO deposit → ACTIVATION LTO DENSIFICATION → Resist depo CONTACTS ETCHING Strip resist → METAL DEPOSITION Electrodes with Al WF in SDEVICE

REMESHING FOR DEVICE SIMULATION → IV plots → Charge collection →

comparison

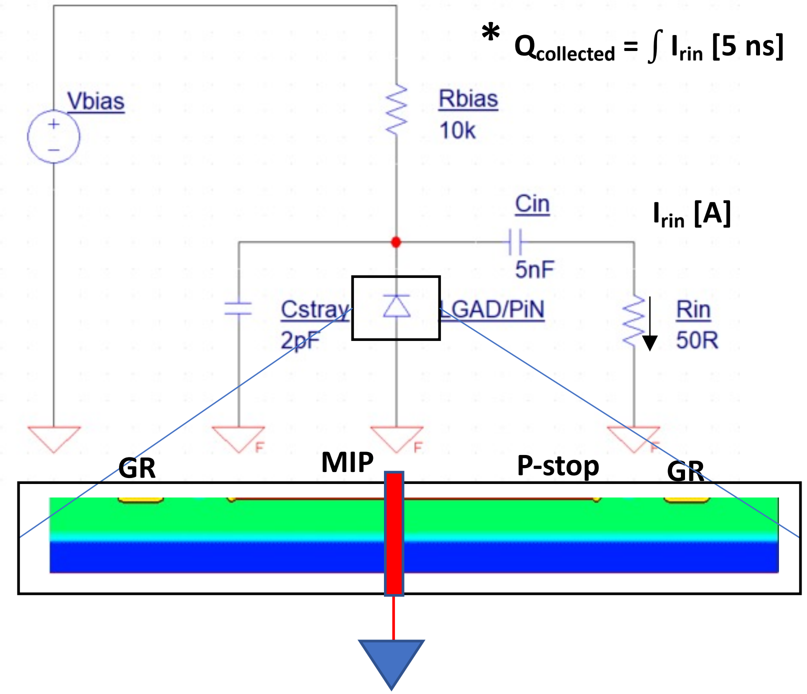
TCAD	test
TCAD	test

ELECTRICAL

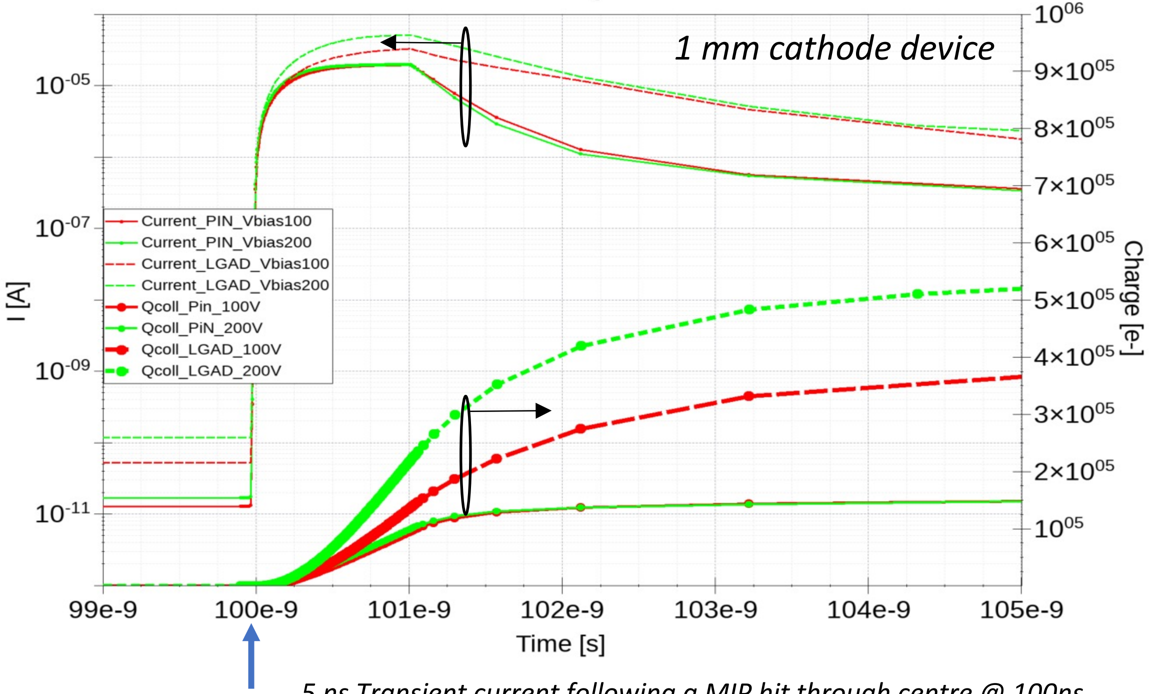
PROCESS

Backup - LGAD Simulation II

- Electrical simulation setup, common to PiN and LGAD, with RC network



Transient I - Qcollected



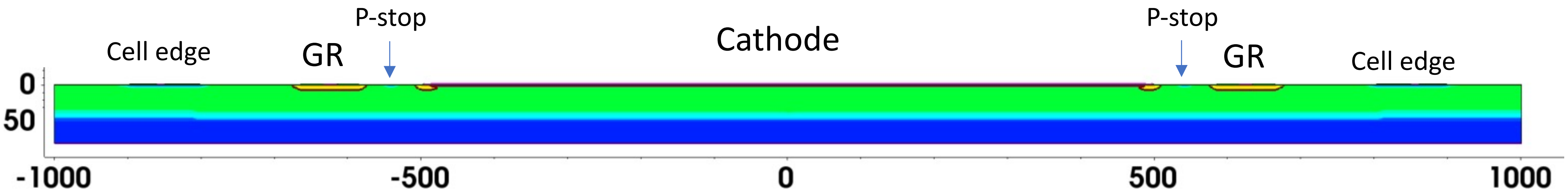
1 mm cathode device

HIT

5 ns Transient current following a MIP hit through centre @ 100ns

- Bulk radiation damage not included in this iteration, but effects of Si-SiO_2 surface states have been modelled

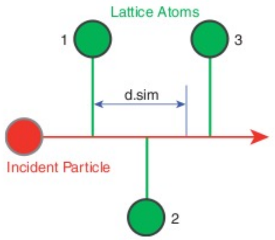
Backup – Simulated cross-section



- **2 implantation models implemented:**
  - **MC (1e5 runs) using BCT with modified parameters**
  - **Pearson IV (analytical)**

$$\frac{\Delta E_n}{E_0} = \frac{4 M_1 M_2}{(M_1 + M_2)^2} \cos^2(bI) \quad \mathrm{x}\alpha$$

E lost by BC by Nucl. Scattering
custom factor α (=1 default)



Multi-body collisions for crystal [0.25,1]
lattice constant assume d=1