Characterization of Ultra-Fast Silicon Detectors (UFSD) for High Energy Physics Application

F. Zareef[a], A. Obłąkowska-Mucha[a], N. Cooke[b], A. Docheva[b], N. Moffat[c], T. Szumlak[a], D. Maneuski[b], R. Bates[b], M. Bullough[d]

[a]Department of Particle Interaction and Detection, AGH University of Krakow, Poland
[b]School of Physics and Astronomy, University of Glasgow, Scotland
[c]Centro Nacional de Microelectrónica, Barcelona, Spain
[d]Micron Semiconductors Ltd, Lancing, England

Introduction

Challenges

- Detectors for Phase II upgrades (HL-LHC) ~ 30ps resolution
- Greater pile-up ~ 200

Ultra-Fast Silicon Detectors

- Low Gain Avalanche Detector (LGAD) based technology.
- Thin-detectors (for fast signal processing
- Suitable candidate for 4D tracking
- CMS-ETL and ATLAS-HGTD will be using these detectors
- Applications in Particle Physics (particle identification), as well as in medical facilities (Positron Emission Tomography)

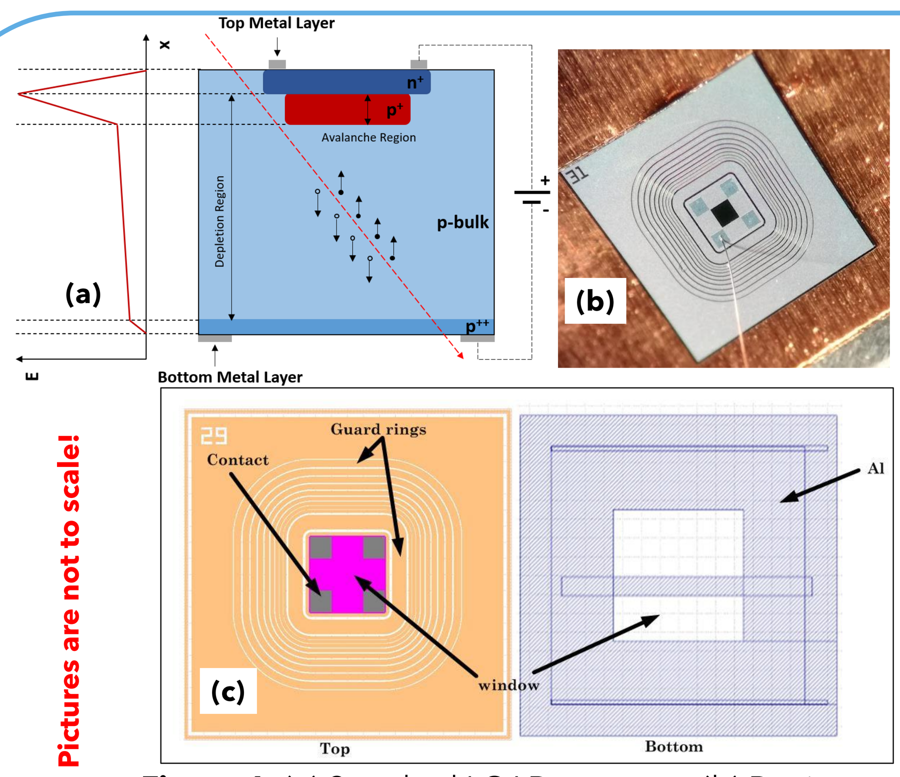

Figure 1: (a) Standard LGAD structure, (b) Device under test (16-31), (c) Top and bottom mask of the DUTs

Devices Under Test (DUT)

- LGADs and PINs used in this worked are from 3331 wafer of **MediPix3** mask, manufactured by **Micron Semiconductors Ltd.**
- Difference in LGAD as compared to PIN is the additional **p^+-implant (gain layer).**
- Device parameters are given in Table 1.

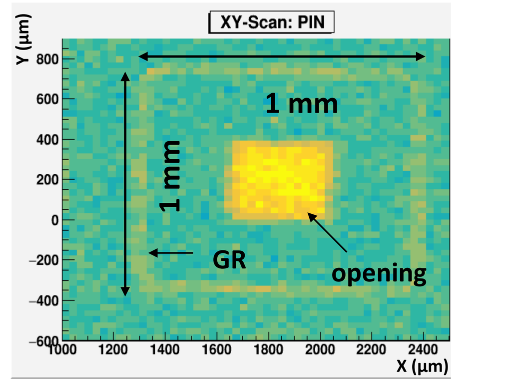

Figure 2: 2D scan (xy) of the PIN confirming the dimensions of the device.

Table 1: Details of the devices used in this work

Name	Type	Thickness (μm)	Gain Doping (cm^{-3})	Pixel Size (mm)
3331-16-30	PIN	50	-	1x1
3331-16-31	LGAD	50	$1.2x10^{13}$	1x1
3331-19-04	LGAD	50	$1.3x10^{13}$	0.5x0.5

Electrical Characterizations: I-V

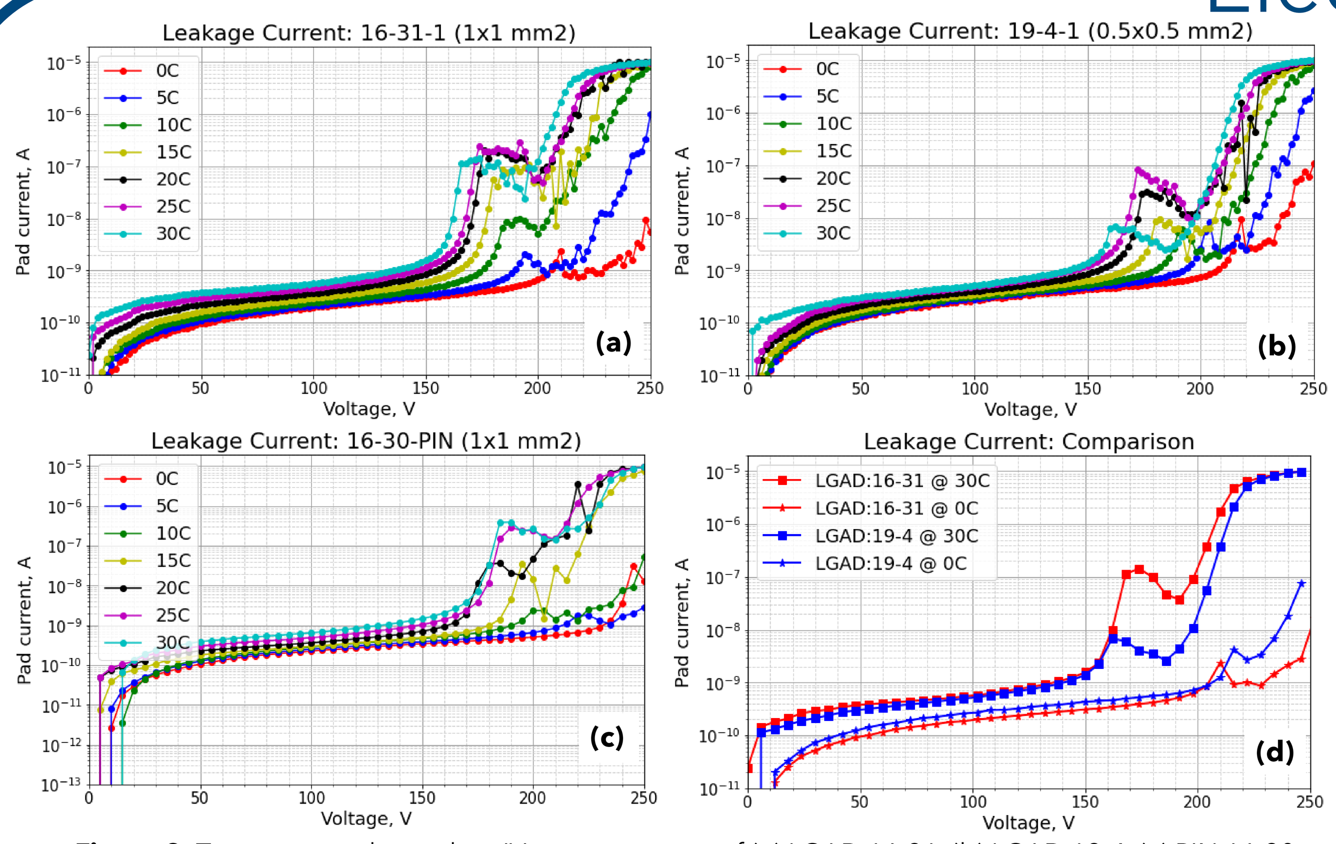

Figure 3: Temperature dependent IV measurements of (a) LGAD 16-31, (b) LGAD 19-4, (c) PIN 16-30, and (d) shows the comparison of 16-31 and 19-4 at 0°C and 30°C.

- IV measurements of the devices are carried out inside a temperature-controlled climate box.
- Figure 3 (a), 3 (b) and 3 (c) shows the temperature dependent IV measurements of LGAD 16-31, LGAD 19-4, and PIN 16-30.
- A temperature dependent study of the devices is carried out in the temperature range of **0 - 30° C**.
- Leakage current before the breakdown voltage is even less than **nA's** for both the LGADs and PIN.
- A decrease of almost **1 order in magnitude** in leakage current is observed with the decrease in temperature.
- **Significant increase in the V_{BD}** is observed with the decrease in temperature. This behavior is quantified in Figure 4.
- As it is seen in Fig. 3 that the V_{BD} ha[s] significantly increased with th[e] decrease in temperature, we tried t[o] quantify it in Fig. 4.
- The effect of temperature on V_{BD} for a[ll] the devices is same.
- The temperature difference of 0 to 30 C caused **33-34%** increase in th[e] breakdown voltage as seen in Fig 4 (d).
- Increase in V_{BD} is more like **exponential**, which means that at lower temperatures V_{BD} increases **rapidly** as seen in Fig. 3 and 4.

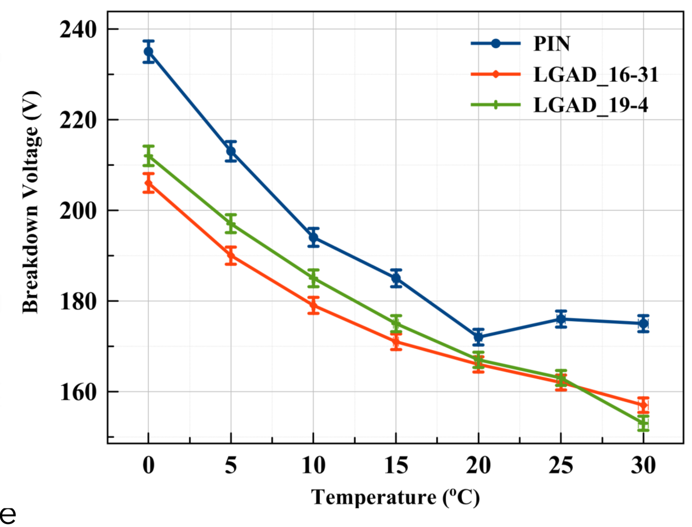

Figure 4: Breakdown voltage (V_{BD}) of the devices as a function of temperature.

Electrical Characterizations: C-V

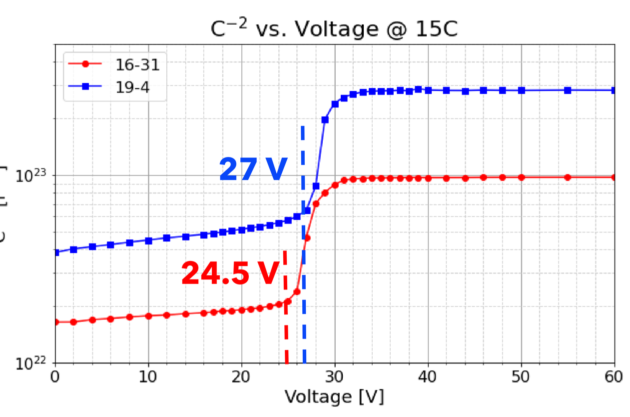

Figure 5: Inverse squared capacitance of LGADs 16-31 and 19-4 at 15°C. The red and blue dashed lines show gain layer depletion voltage (V_{GL}).

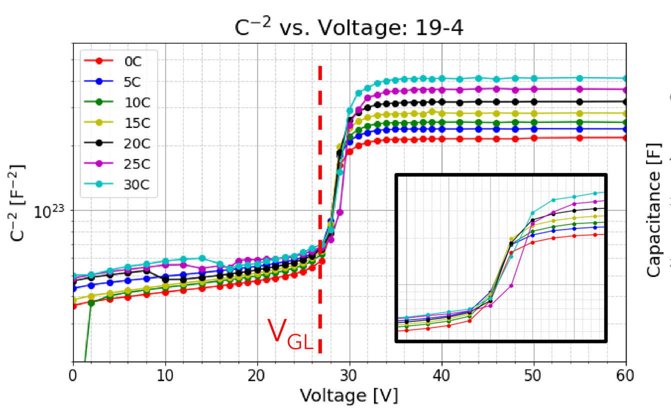

Figure 6: Inverse squared capacitance of LGAD 19-4 at different temperatures. The red dashed lines show gain layer depletion voltage (V_{GL}).

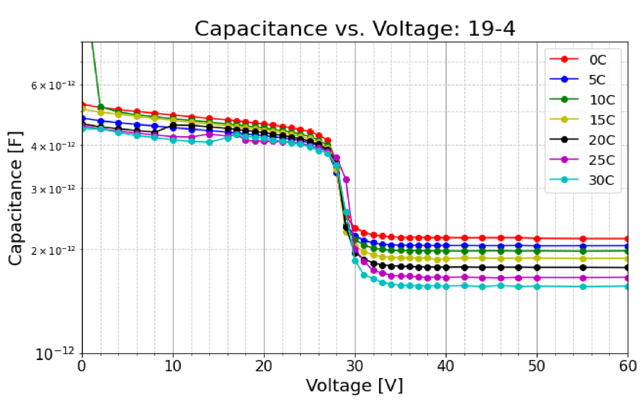

Figure 7: CV curve of LGAD 19-4 at different temperatures.

- Fig. 5 shows the inverse squared capacitance for both the LGADs at 15C.
- V_{GL} for LGAD 16-31 is **~24.5 V**, and for 19-4 is **~ 27 V**.
- Capacitance of LGAD 19-4 is higher due to the higher doping concentration as compared to LGAD 16-31.
- In Fig. 6, the temperature dependent CV measurements are seen, where it is observed that the change in temperature doesn't influence the **V_{GL}** (can be seen in inshot), but the value of End-capacitance changes as seen in Fig. 7.

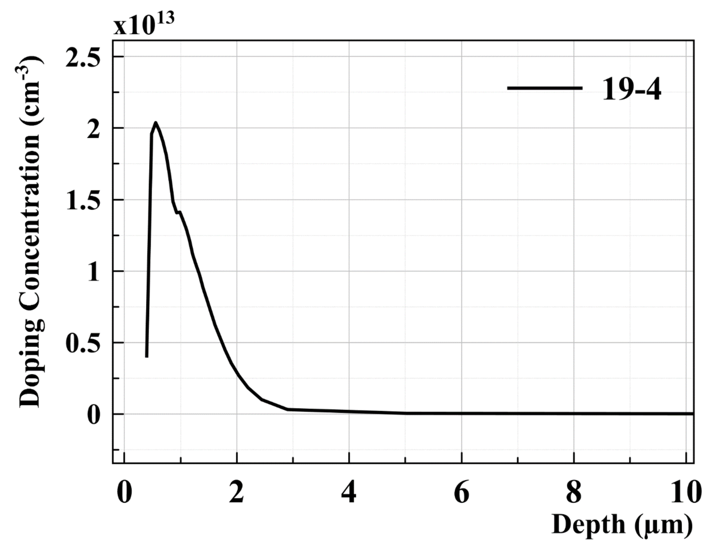

Figure 8: Doping profile of the gain layer of LGAD 19-4 as a function of device thickness calculated from capacitance.

Laser Characterizations

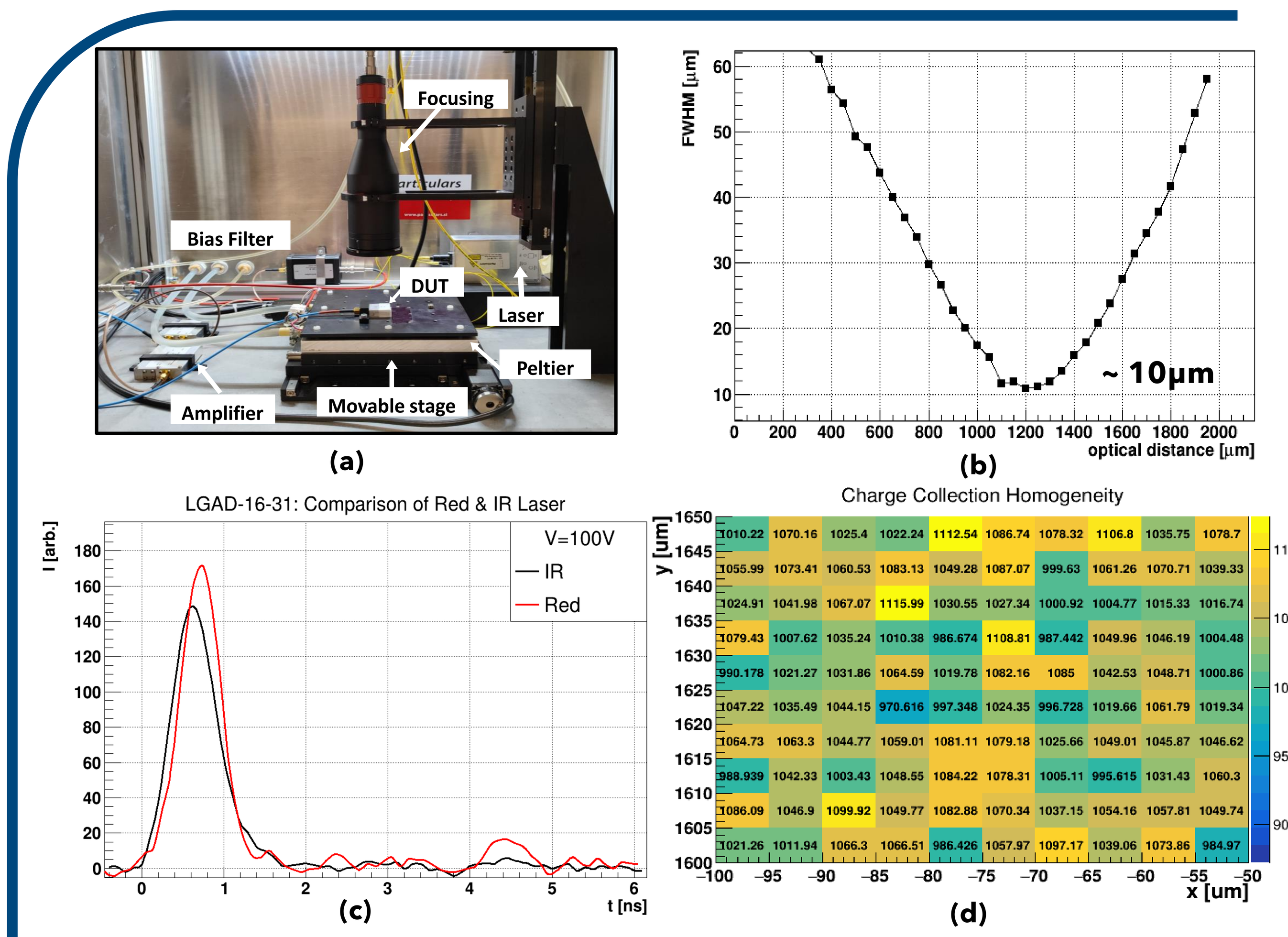

Figure 9: (a) TCT setup at AGH University of Krakow, (b) Focusing of infrared laser (beam spot ~ 10μm), (c) Comparison of TCT waveforms illuminated by Red (658 nm) and IR (1064 nm) lasers, (d) Charge collection homogeneity in 50μm^2.

- **IR Laser (1064 nm)** is used for the gain measurements. All measurement are carried out at same laser intensity, pulse width, and temperature (20°C).
- Fig. 10 (a) shows the signal formation with bias voltage. After 40V, the signal is significantly faster i.e., charge carriers gets collected **within 2 ns**.
- The collected charge with in 2 ns is shown in Fig. 9 (c), for LGAD 16-31, 19-4 and PIN 16-30.
- Gain of the **LGAD 19-4 is ~5.5**, and for **LGAD 16-31 is ~5** at 150 V. The difference is due to higher gain layer doping in 19-4.

Gain is calculated by:

$$Gain = \frac{Q_{LGAD}}{Q_{PIN}}$$

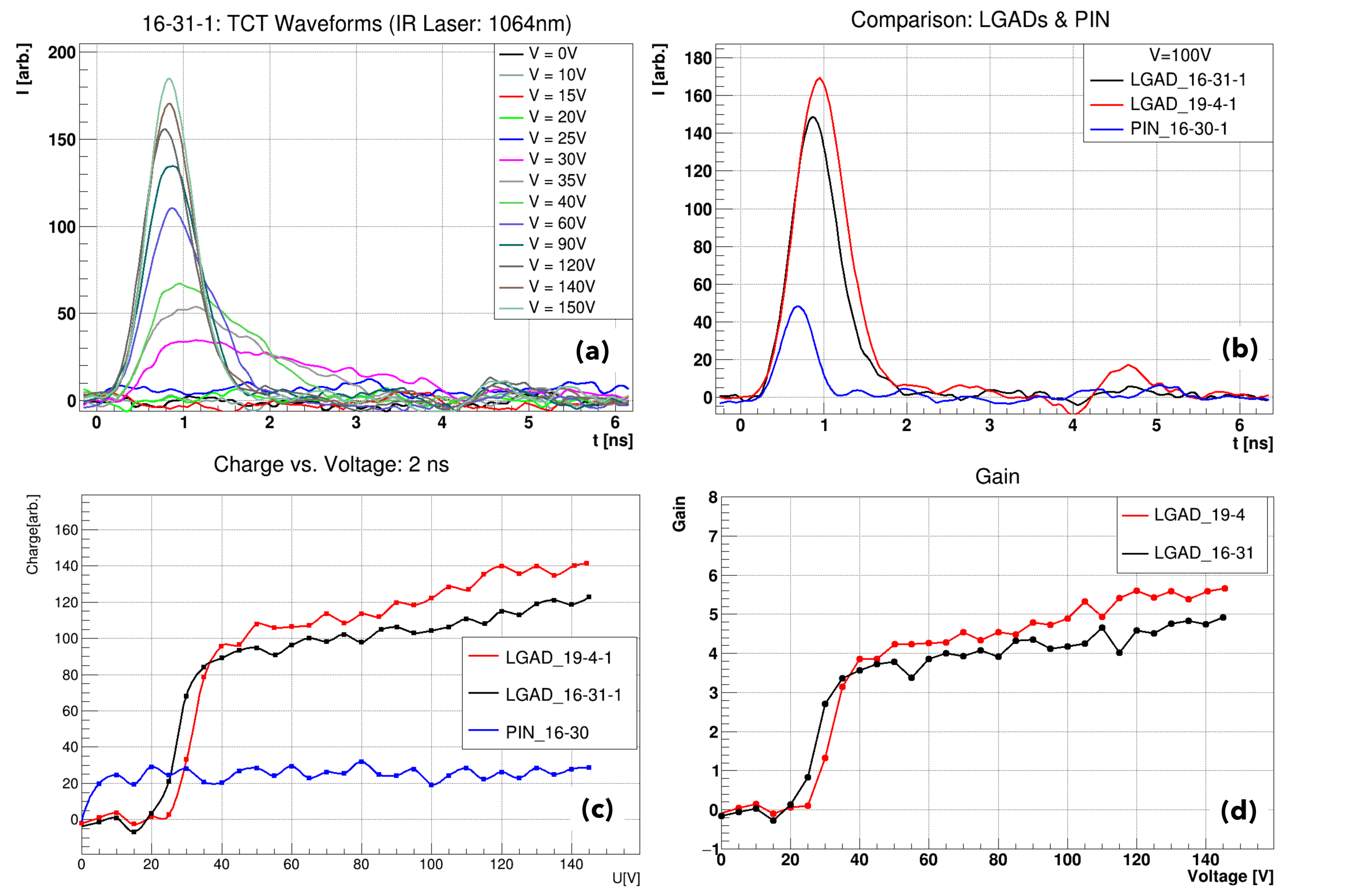

Figure 10: (a) Signal formation as a function of bias voltage of LGAD 16-31, (b) TCT waveform comparison of LGADs and PIN using IR laser, (c) Comparison of charge collection with in 2 ns , (d) Gain calculation as a function of bias voltage.

- We are equipped with TCT system with Red and IR lasers, manufactured by Particulars. The system can be seen in Fig. 9(a). Focused IR laser shows the beam spot **~ 10μm** as seen in Fig. 9 (b).
- A comparison based on the different wavelengths of illumination is made to observe if there is change in the signal shape as seen in Fig. 9 (c). The signal is too fast to show any changes caused by difference in wavelength penetration depth.
- In Fig. 9 (d), **charge collection homogeneity** is observed in 50μm^2 area of the device. The charge collection shows uncertainty within **±7%** of the mean value, referring to a homogenous charge collection.

Summary

Conclusions

- Response of these LGADs are significantly fast (2 ns), which is why they are categorized as ultra-fast silicon detectors.
- Higher gain layer doping leads to higher charge collection, hence higher gain.
- Leakage current decrease by 1 order magnitude and V_{BD} increase with the decrease in temperature.
- No dependence of temperature is observed on V_{GL}.

Future goals:

- Temperature dependent gain measurements and time-resolution measurements with be carried out in near future.
- Irradiation studies on these sensors is planned in future.

We acknowledge the financial support of IDUB Excellence Initiative - University Research # 6275, AGH University of Krakow