

INSTR 2026

Instrumentation for Colliding Beam Physics

October 12–16, 2026, Hefei, China | University of Science and Technology of China

Characterization of 4H-SiC implanted LGADs after 23 MeV Proton Irradiation

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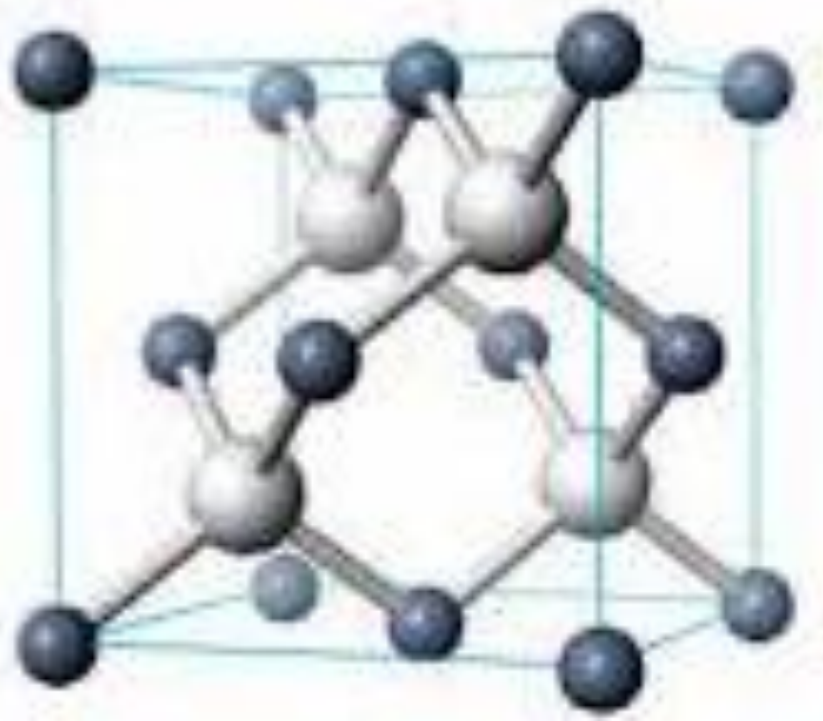


Silicon Carbide: why?



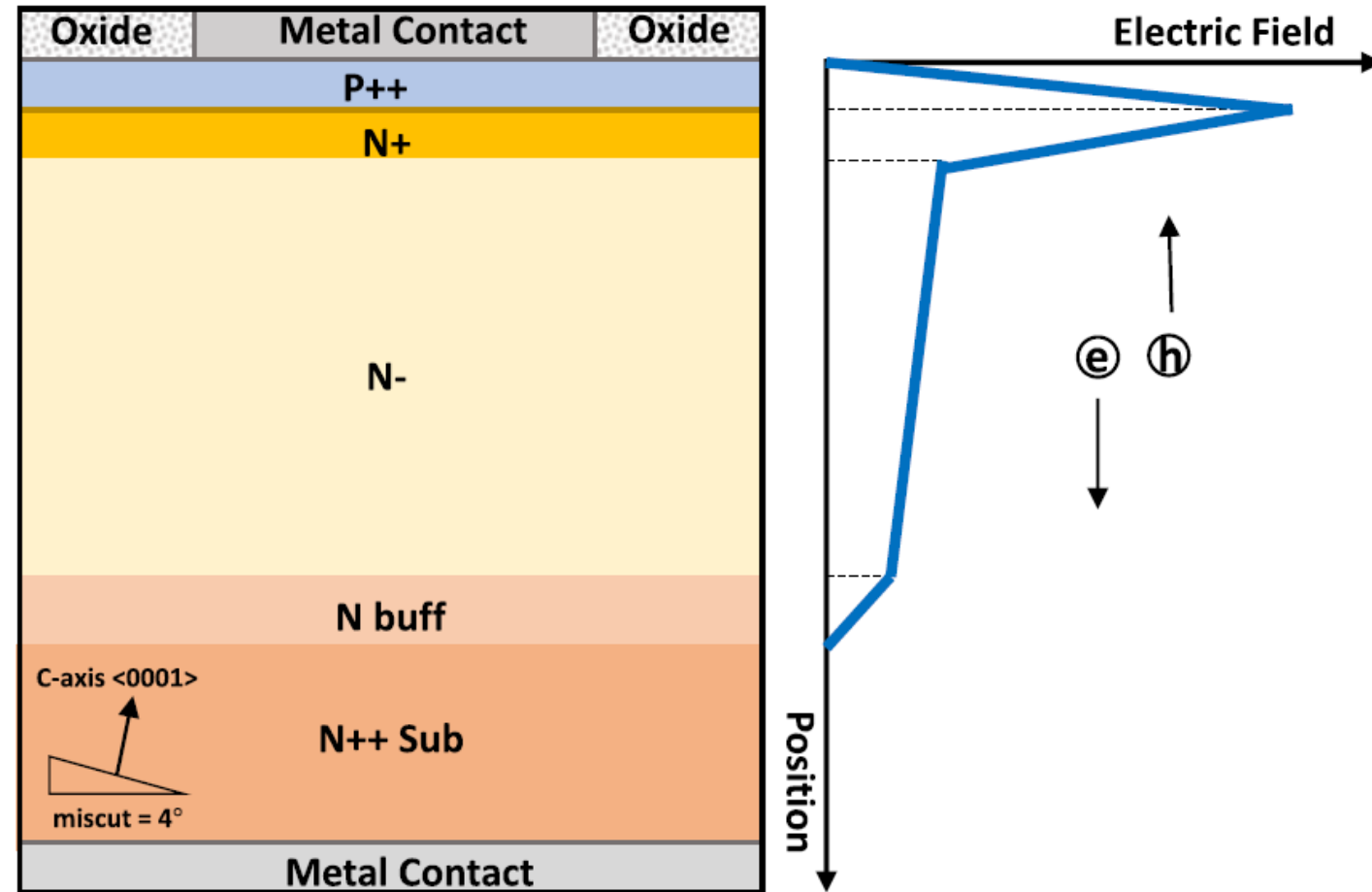
- Attractive for power electronics & automotive industry ⇒ Increased availability and lower costs
- **Higher Saturation velocity** of the charge carriers, beneficial for timing
- Lower leakage current and high thermal conductivity **can mitigate the cooling requirements.**
- Although SiC an higher displacement energy (~35 eV) and wide bandgap (3.26 eV) **radiation hardness seems lower than silicon**^[1, 2].
- MIP generates only ~0.4 fC in a 50 μm-thick SiC device ➡ **gain needed**

Properties	4H-SiC	Si
E _{gap} [eV]	3.23	1.12
E _{breakdown} [V/cm]	3–4 × 10 ⁶	3 × 10 ⁵
μ _e [cm ² /Vs]	800	1450
μ _h [cm ² /Vs]	115	450
V _{saturation} [cm/s]	2 × 10 ⁷	0.8 × 10 ⁶
Z	14/6	14
ε _r	9.7	11.9
E–h energy [eV]	7.6–8.4	3.6
Density [g/cm ³]	3.22	2.33
Displacement E [eV]	30–40	13–15
Thermal Conductivity [W/cm·K]	4.9	1.5



[1] F.Moscatelli et al., IEEE T.Nucl.Sci. 53 (2006) 1557, doi:10.1109/TNS.2006.872202
[2] A.Gsponer et al., JINST 18 (2023) C11027, doi:10.1088/1748-0221/18/11/C11027

SiC Low Gain Avalanche Diodes



There are three LGAD in SiC in literature:

- **Implanted LGAD** from **Onsemi** (Czech Republic) [3]
- **Epitaxial and implanted LGAD** from **IHEP** (China) [4, 5]
- **Epitaxial LGAD** from **NC State University (USA)** [6]

[3] P.Švihra et al., NIMA 1080 (2025) 170742, doi:10.1016/j.nima.2025.170742

[4] Sen Zhao et al, TNS 2025, 10.1109/TNS.2025.3635073

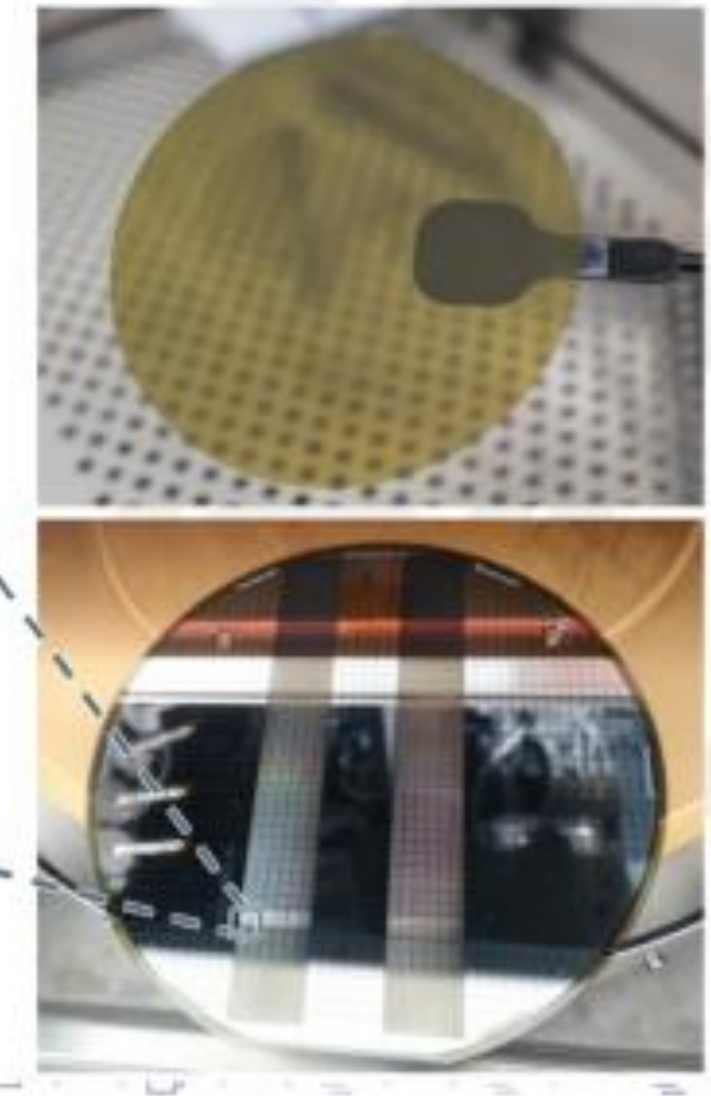
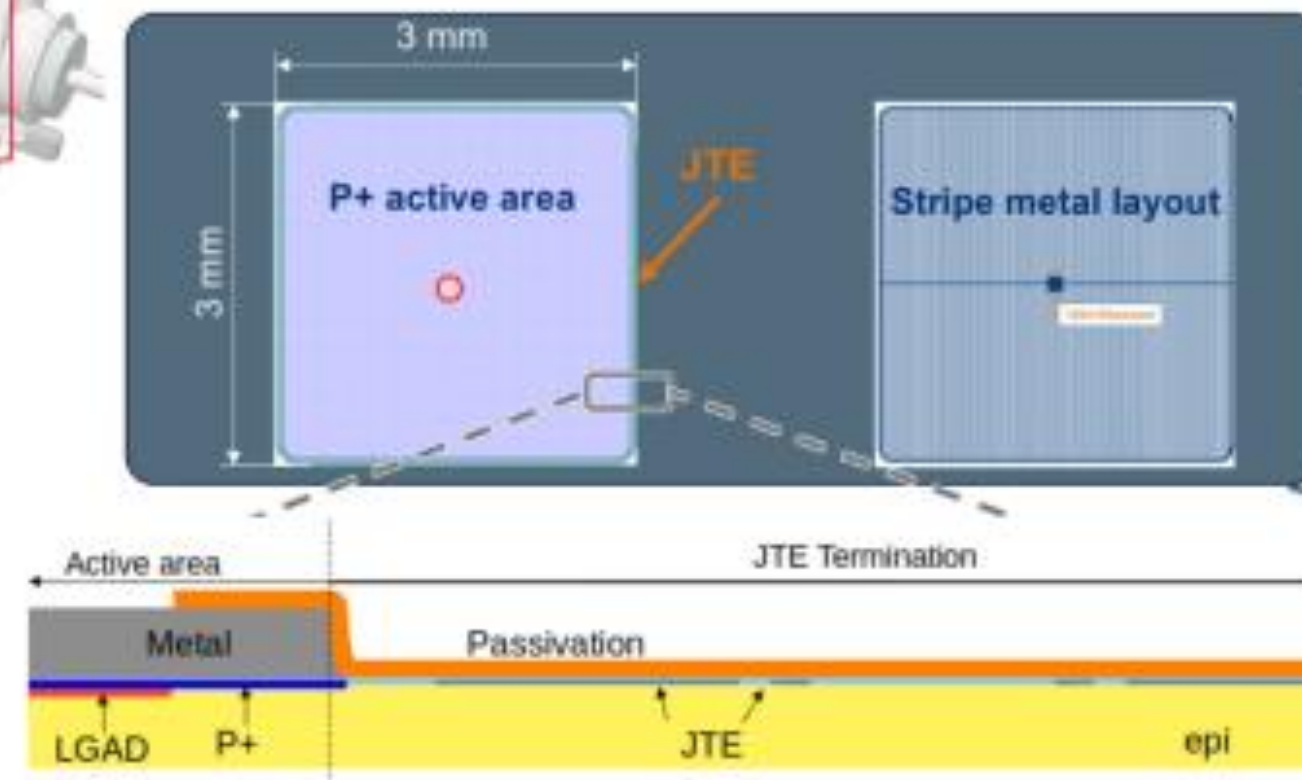
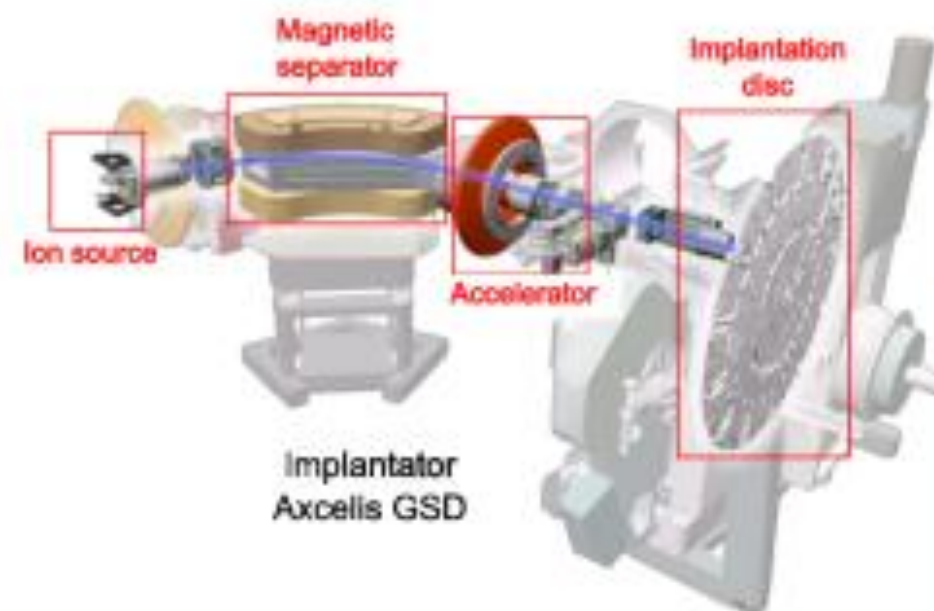
[5] Xiyuan Zhang et al, Development of the SICAR 4H-SiC Radiation Detector, DRD3 week at Bucharest, July 2026

[6] Y. Satapathy et al 2025 JINST 20 P12008



4H-SiC PN and LGAD sensors prepared by Onsemi

- Sensors consist of 6" N-type substrate ($1e19 \text{ cm}^{-3}$) + 30 – 100 μm epitaxial N-type layer ($5e13 - 1e14 \text{ cm}^{-3}$) + **implanted structures** (N^+ Low Gain Avalanche Diode LGAD, P^+ side, etc.) + oxidation + metalization (PECVD, PVD)
 - N-type impl. (**nitrogen**, phosphorus), P-type impl. (**aluminum**, boron)
- Production of LOT 1, 2, and 3 was finished, 1st wafer from LOT-4 was produced and is under investigation - individual samples with dimensions of $3 \times 3 \text{ mm}^2$



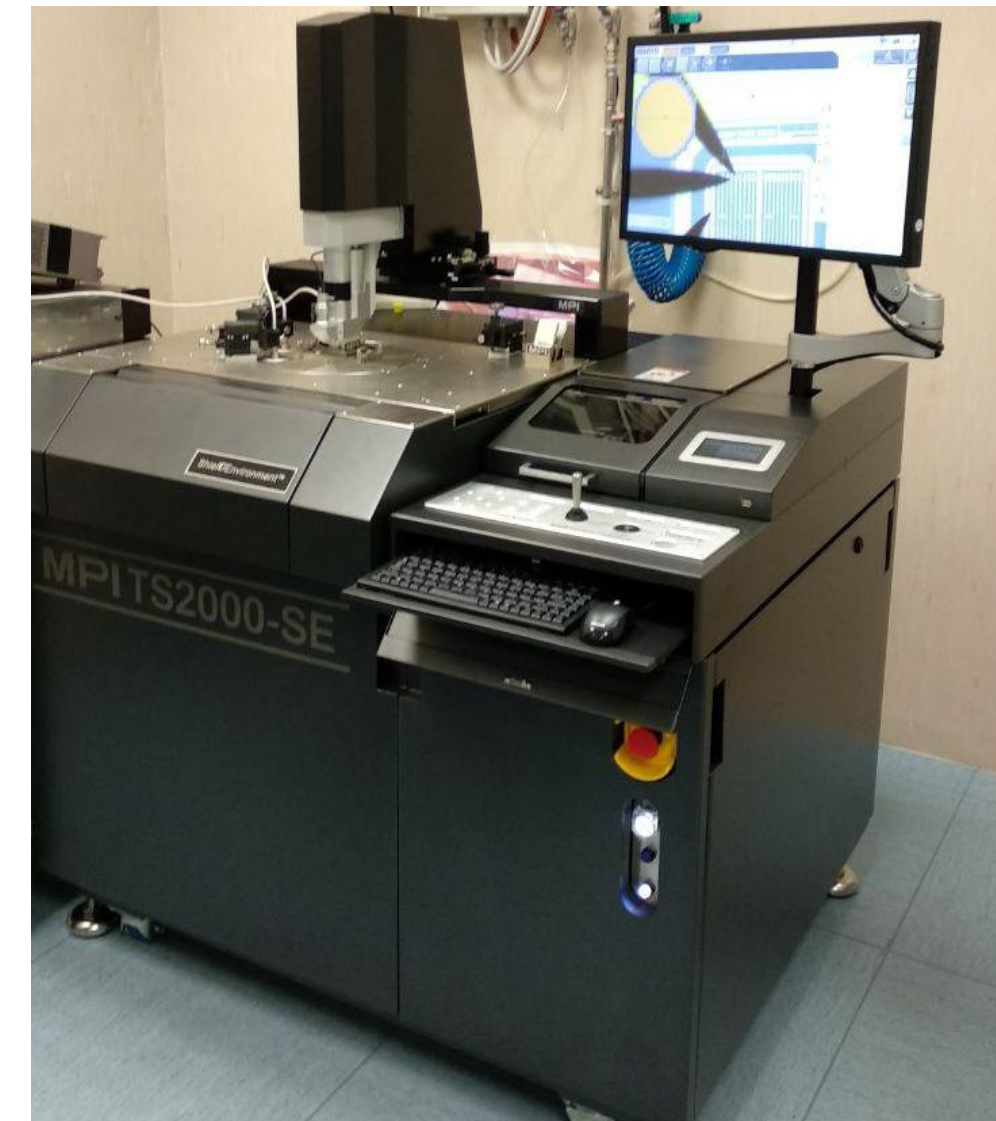
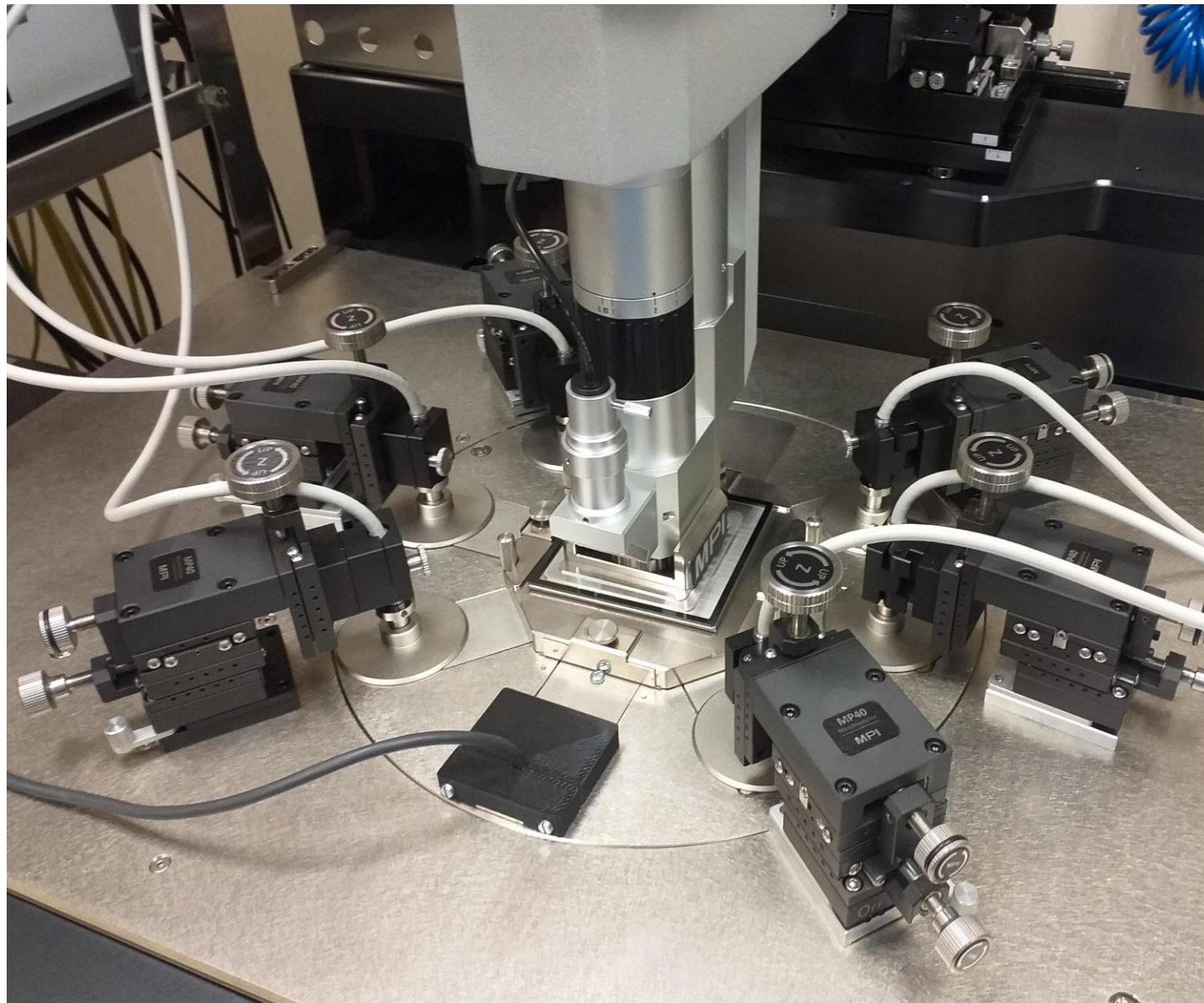
From «Radiation effects in 4H-SiC PN diodes, LGAD sensors, and MOSFET transistors», J. Kroll, HSTD14, Taipei, Nov 2025.

IV and CV measurements

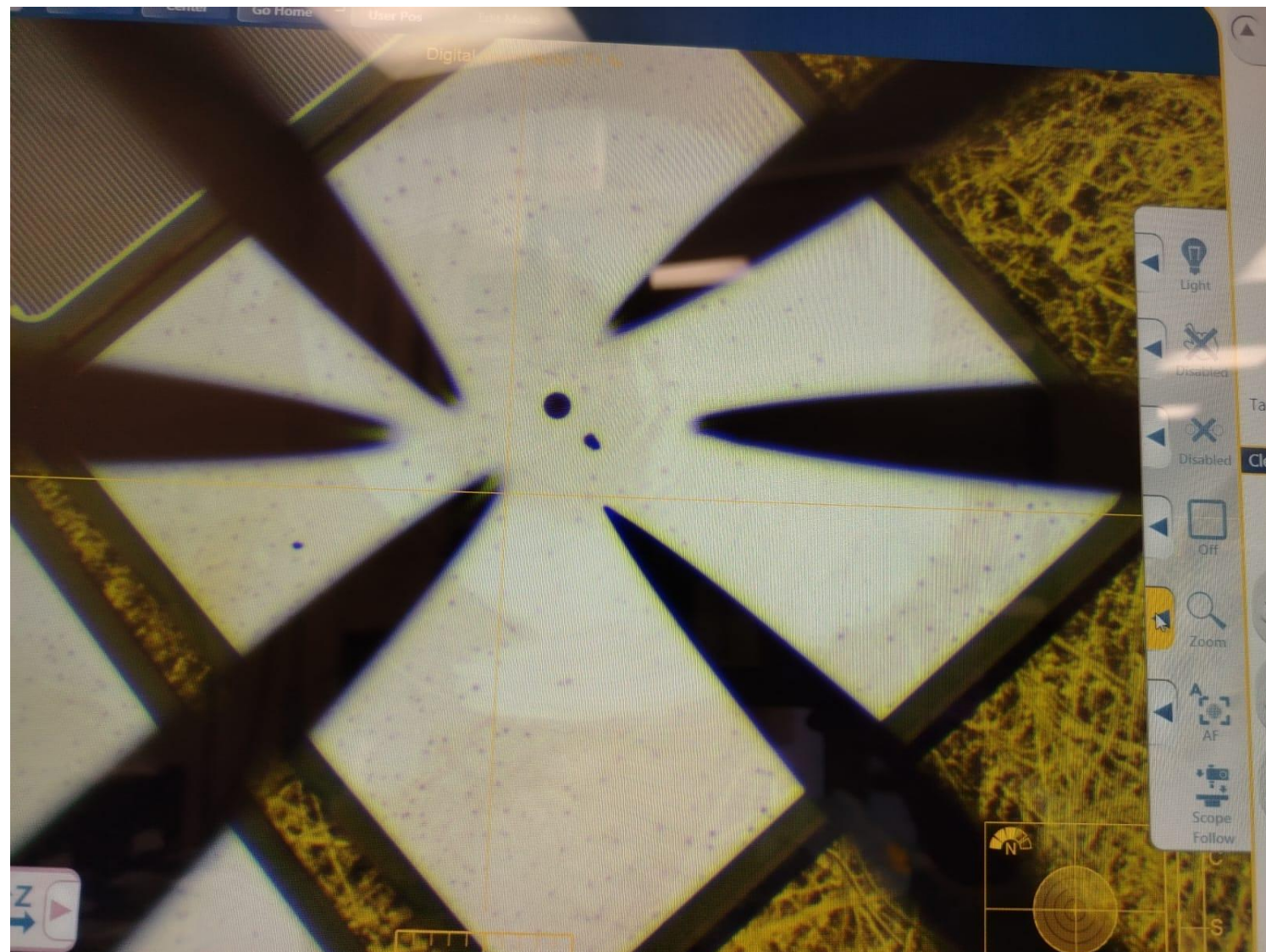
IV and CV measurements carried out
at MPI probe station in the INFN
clean room of Perugia (Italy)

Temperature range: $-60^{\circ}\text{C} \div 200^{\circ}\text{C}$
(possibility to upgrade up to 300°C)

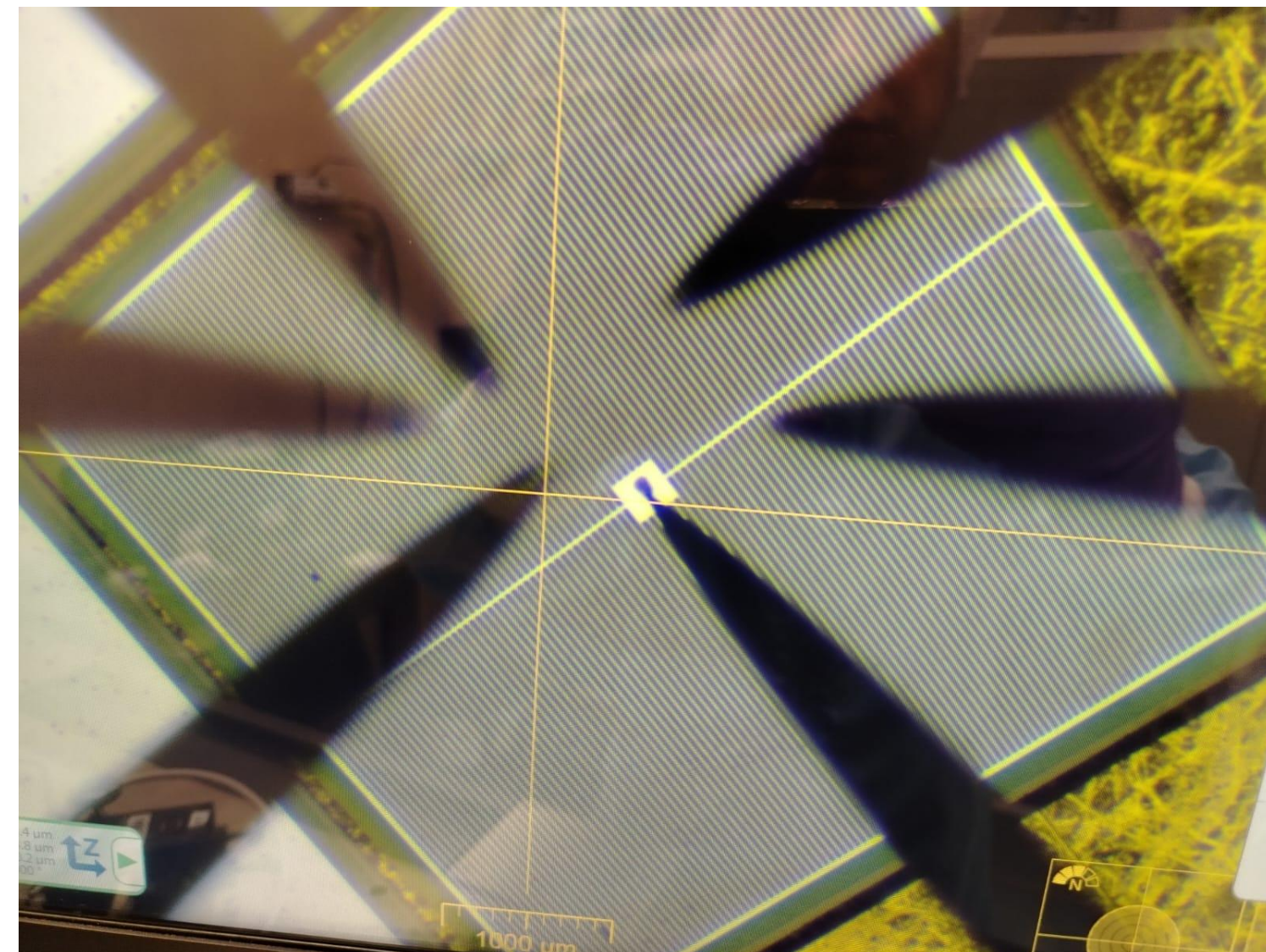
Keithley 237
Keithley 236
LCR meter 4284 A
(20 Hz $\div$ 1 MHz)



Onsemi Lot3 Wafer 2: two different flavours



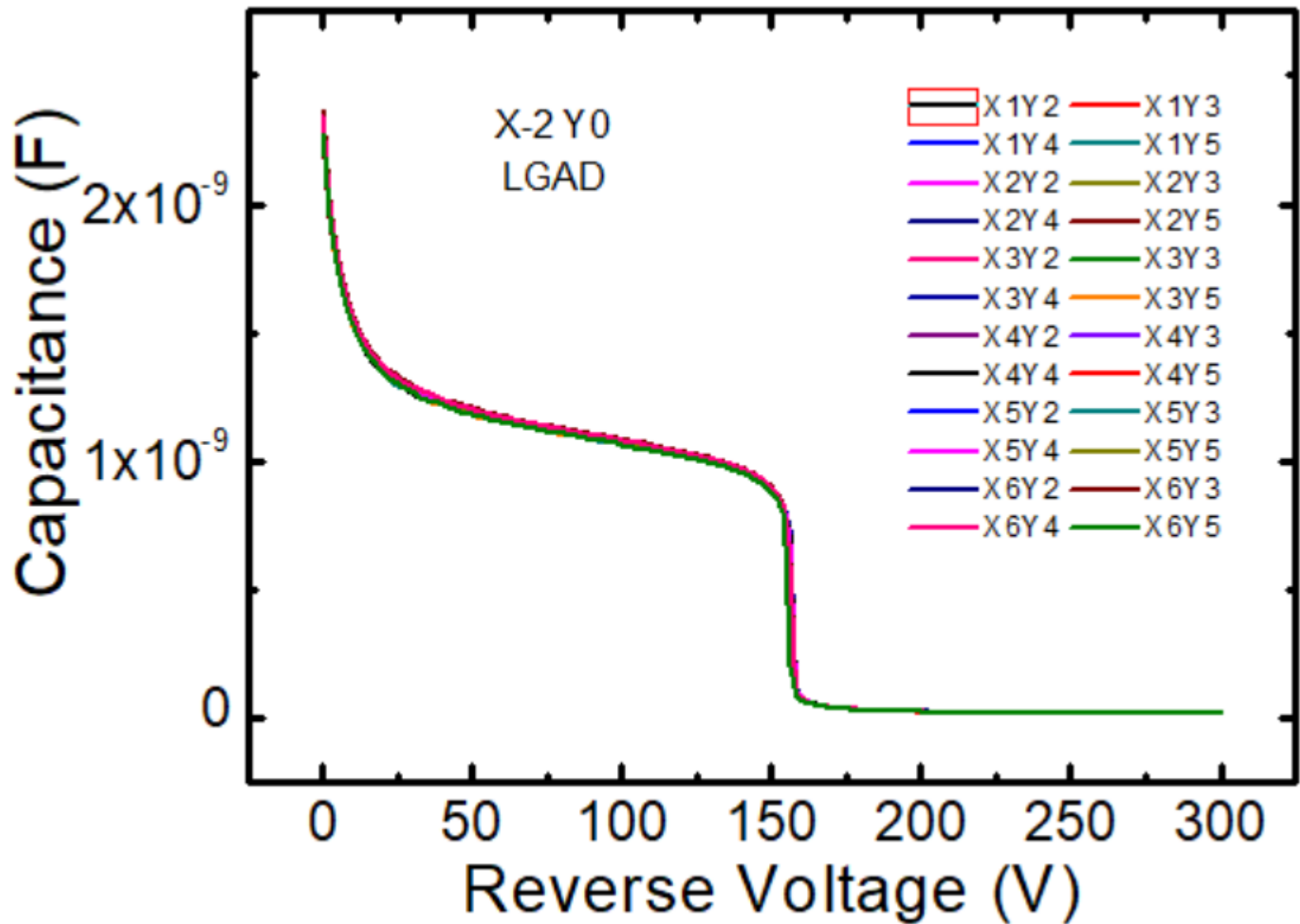
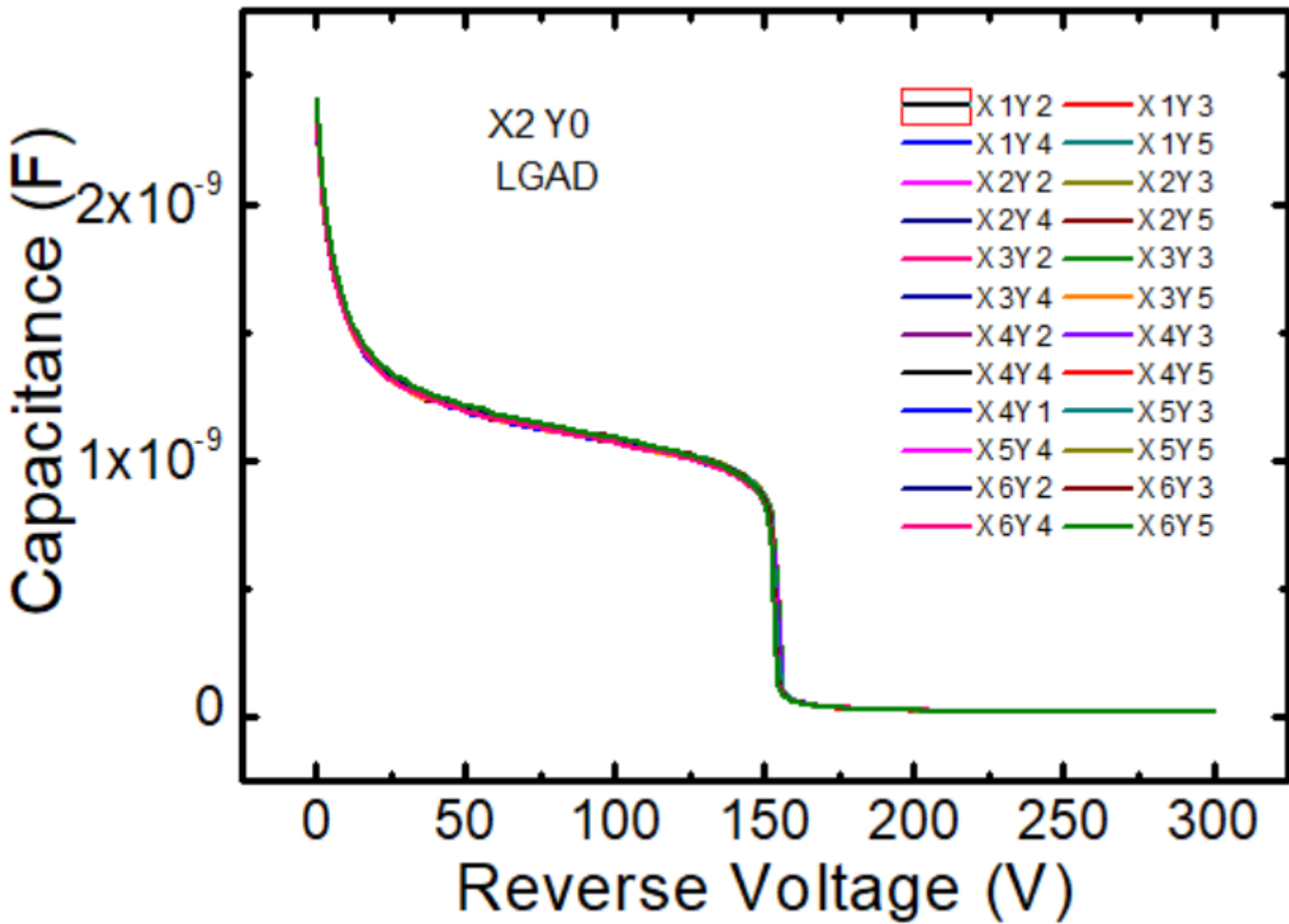
Single pad with a 100 μm hole
 epi 50 μm – $N_D = 5 \times 10^{13} \text{ cm}^{-3}$
 30 LGAD
 30 PIN



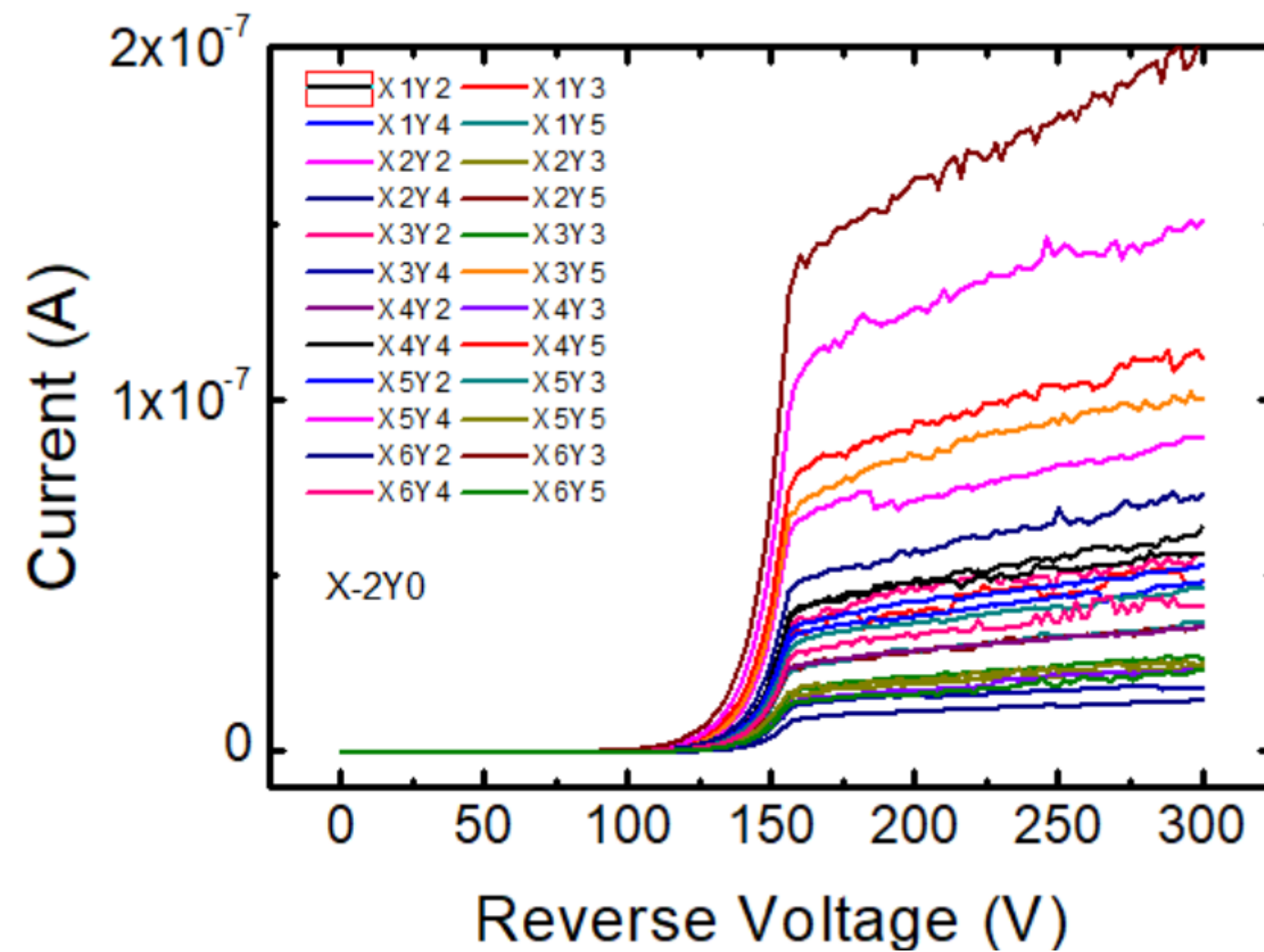
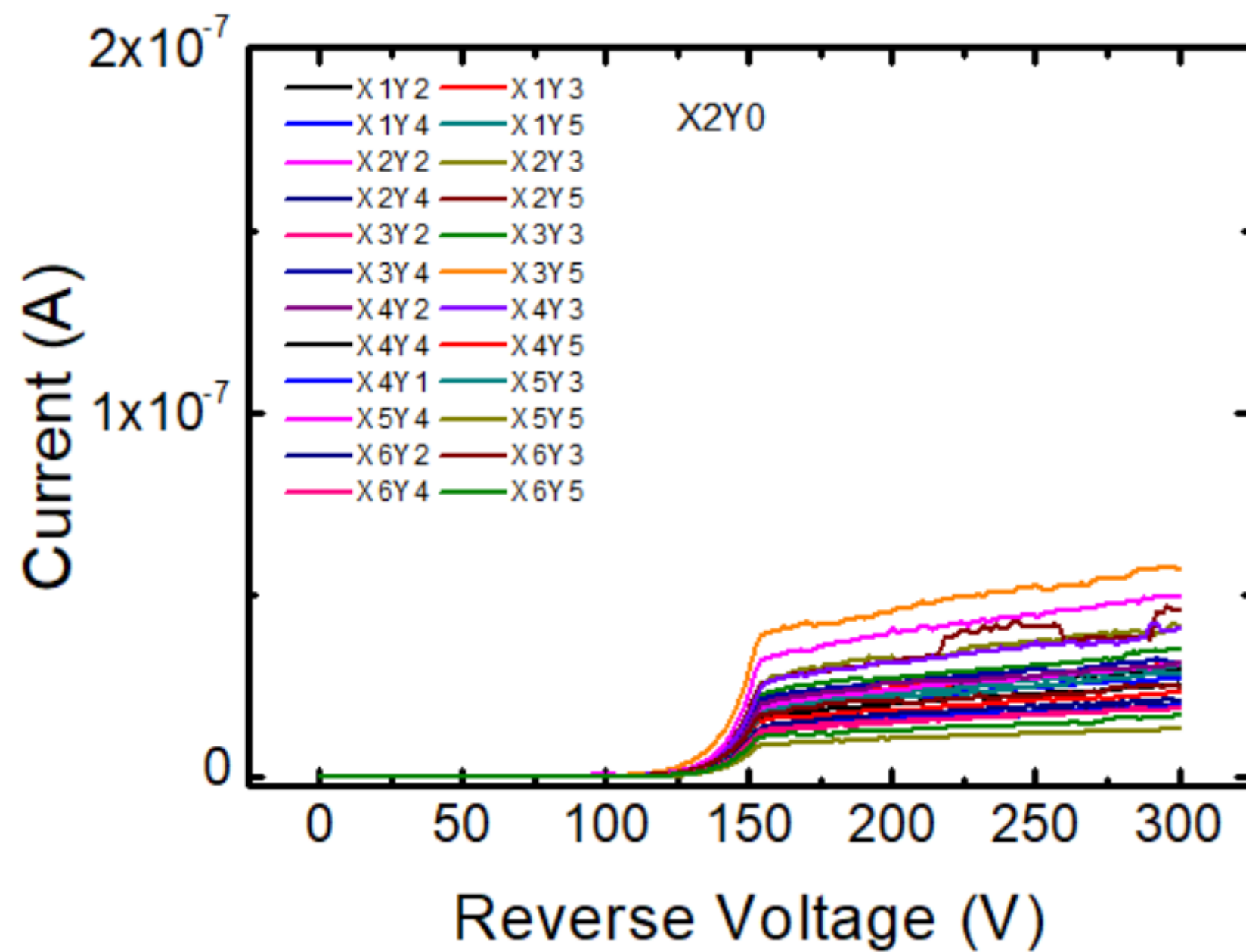
Metal grid on top
 epi 50 μm – $N_D = 5 \times 10^{13} \text{ cm}^{-3}$
 30 LGAD
 30 PIN



LGAD CV 20°C, 500 Hz



LGAD IV 20° C



KIT irradiation



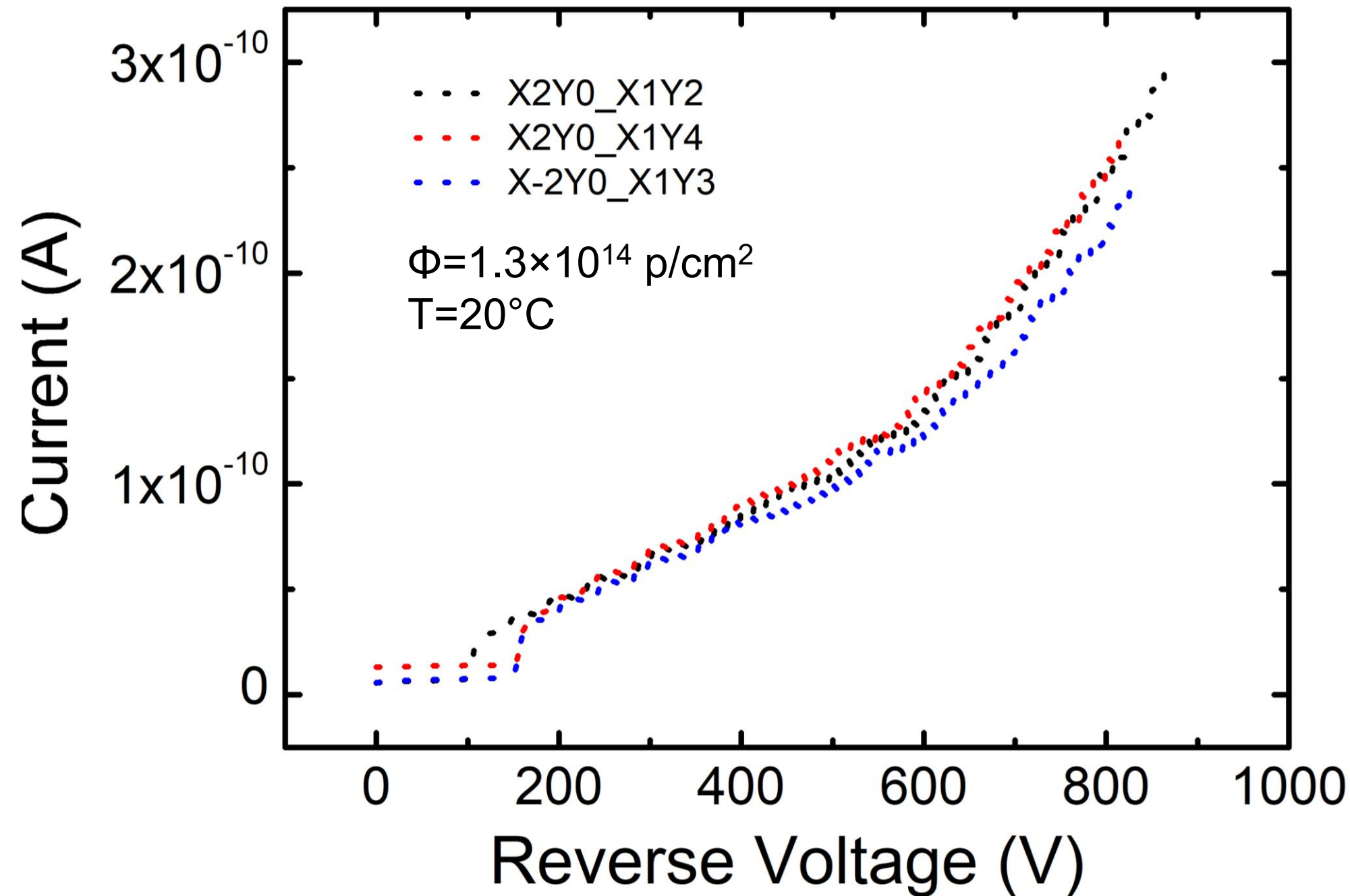
KIT: 5 irradiations with 23 MeV protons:
1.3E14, 3E14, 5.5E14, 1E15, 1.9E15 p/cm².

The devices are 3x3 mm², and for each fluence:

8 Onsemi LGADs

8 Onsemi diodes

IV LGAD REV 1.3×10^{14} p/cm²

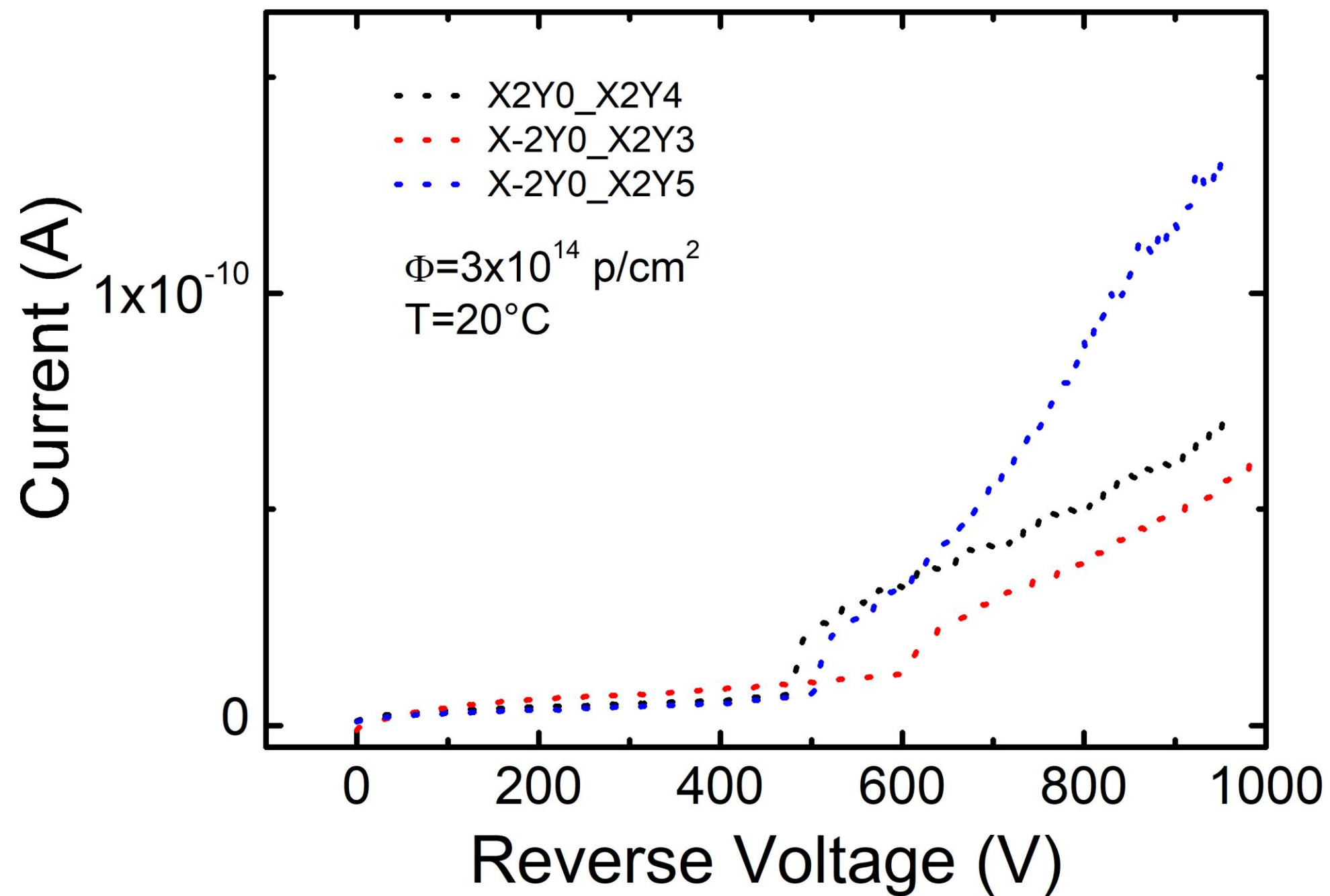


Good uniformity after irradiation.

After a fluence of 1.3×10^{14} p/cm², the current decreases due to compensation and gain reduction, but a low level of multiplication occurs beyond 150-180 V



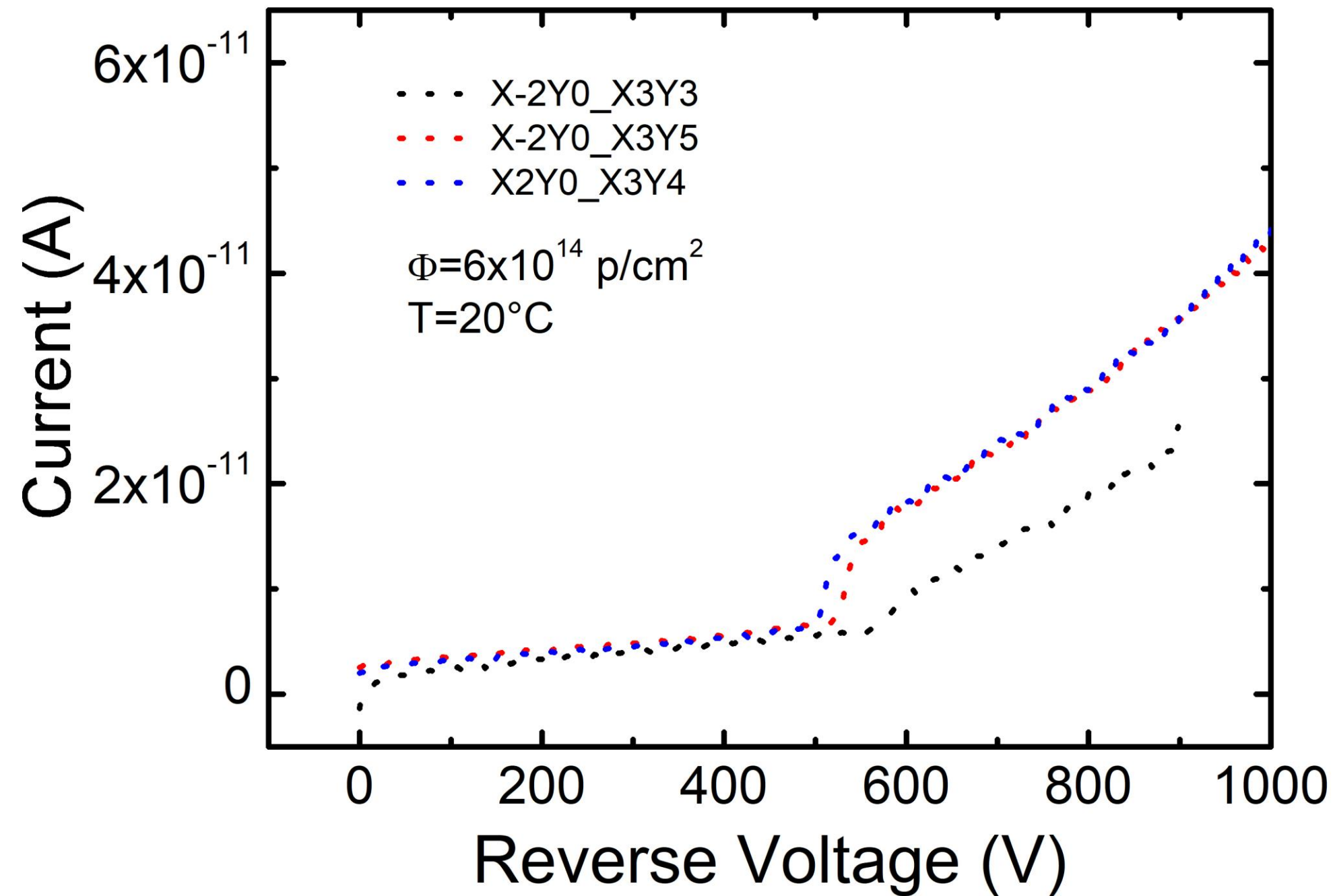
IV LGAD REV 3×10^{14} p/cm²



As the fluence increases, multiplication occurs at progressively higher reverse-bias voltages.



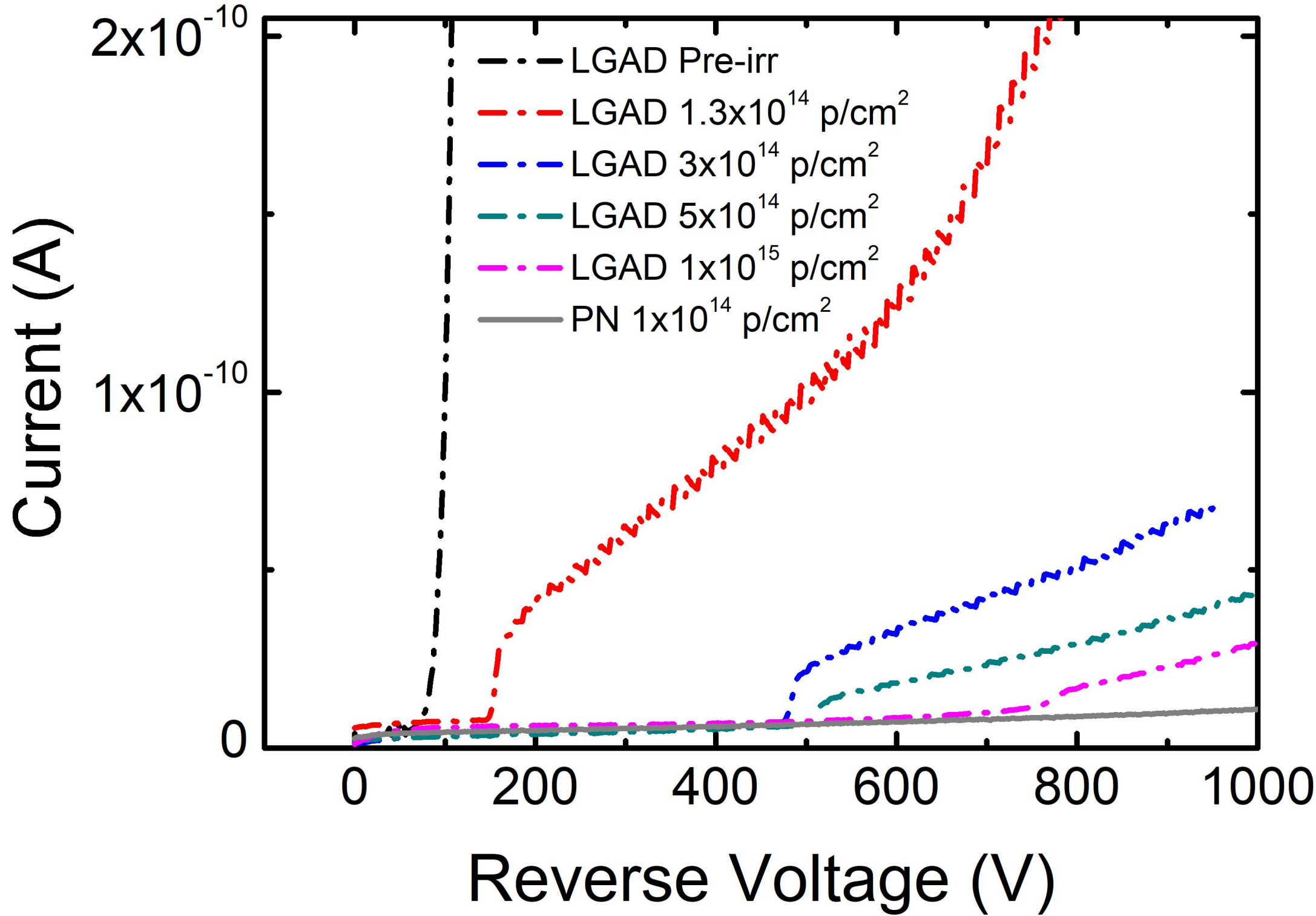
IV-REV $5.5 \times 10^{14} \text{ p/cm}^2$



Two of these three devices are very similar. A low level of multiplication occurs beyond 450-480 V

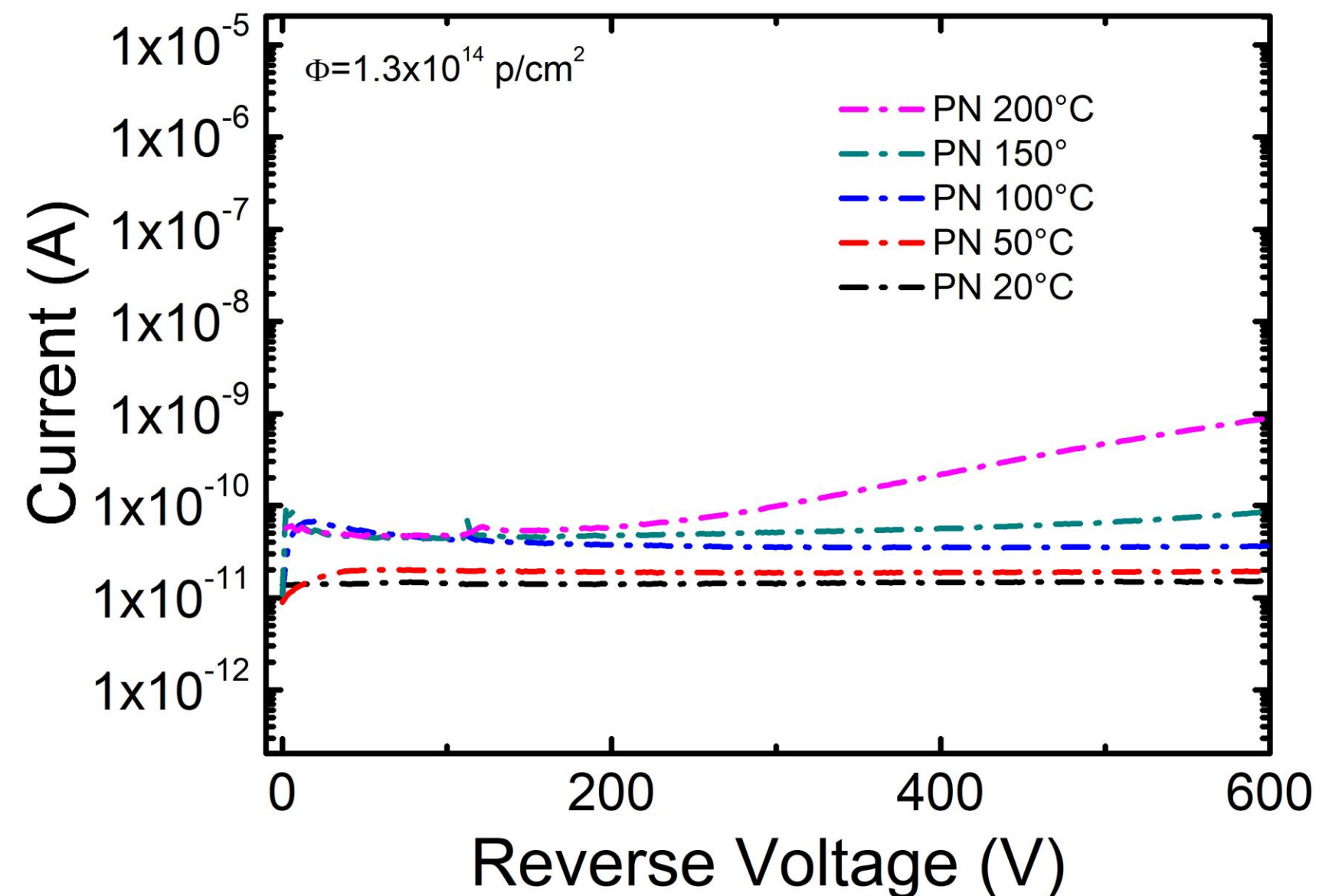
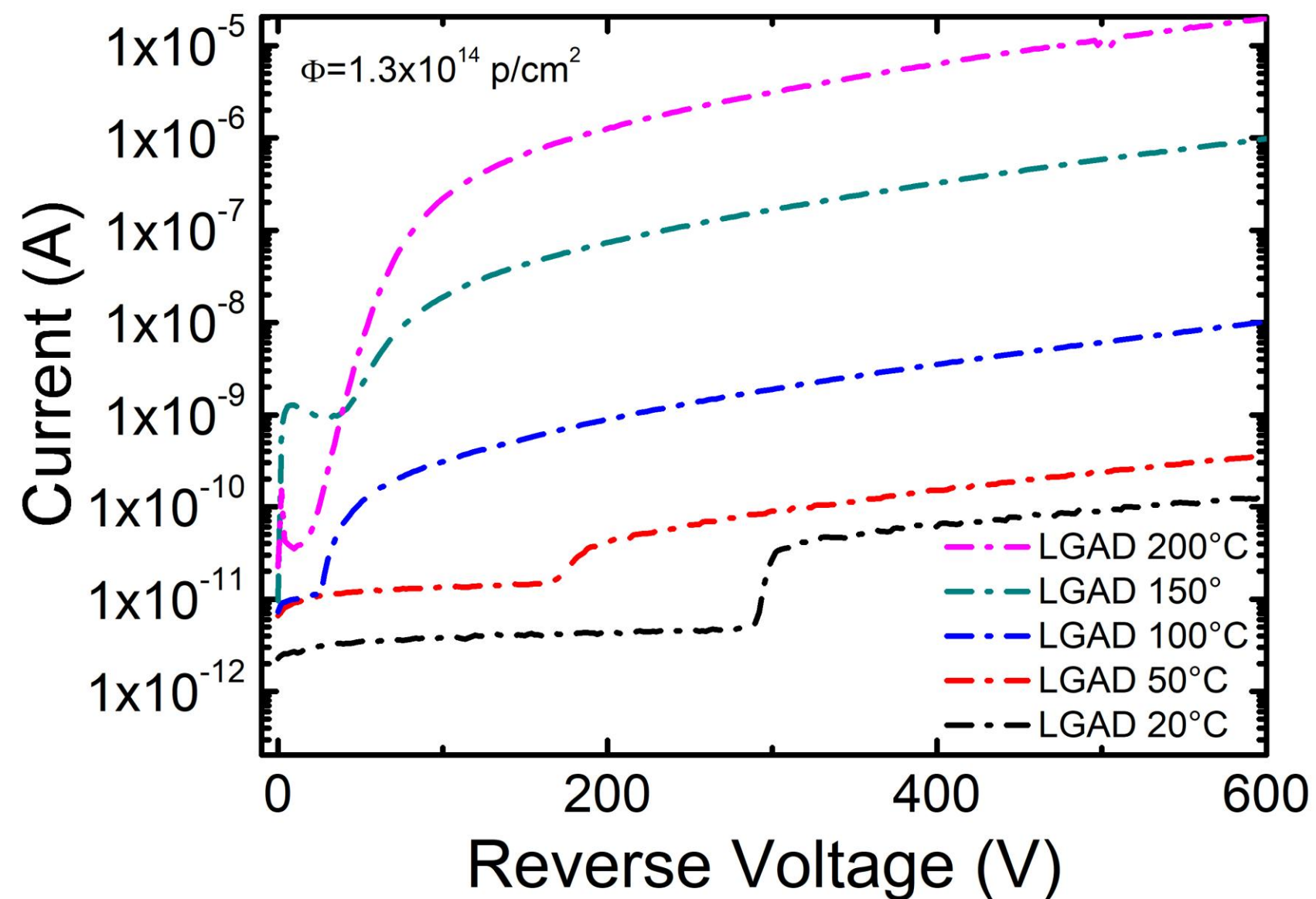


IV LGAD vs Fluence: comparison



IV LGAD and PN at different T

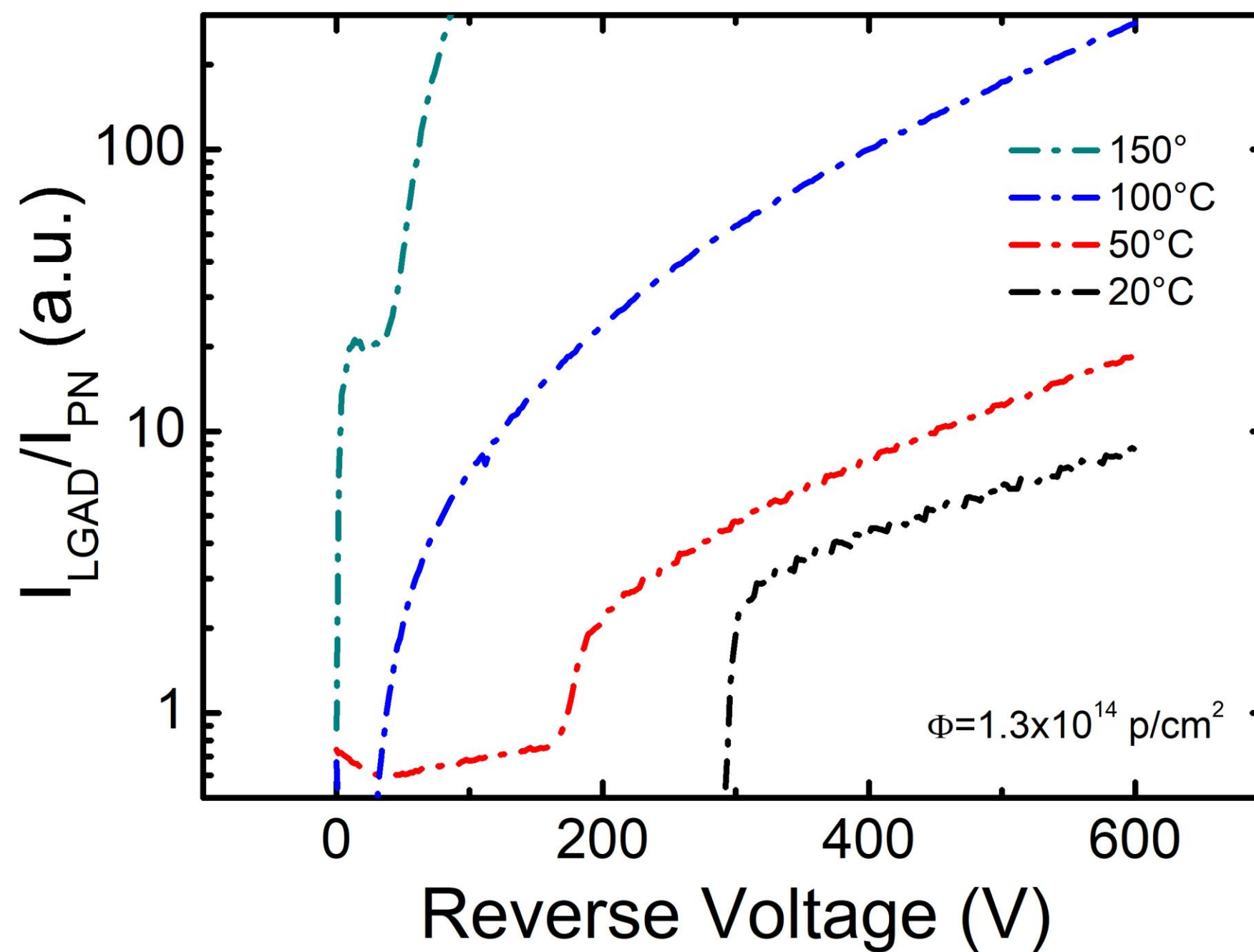
$1.3 \times 10^{14} \text{ p/cm}^2$



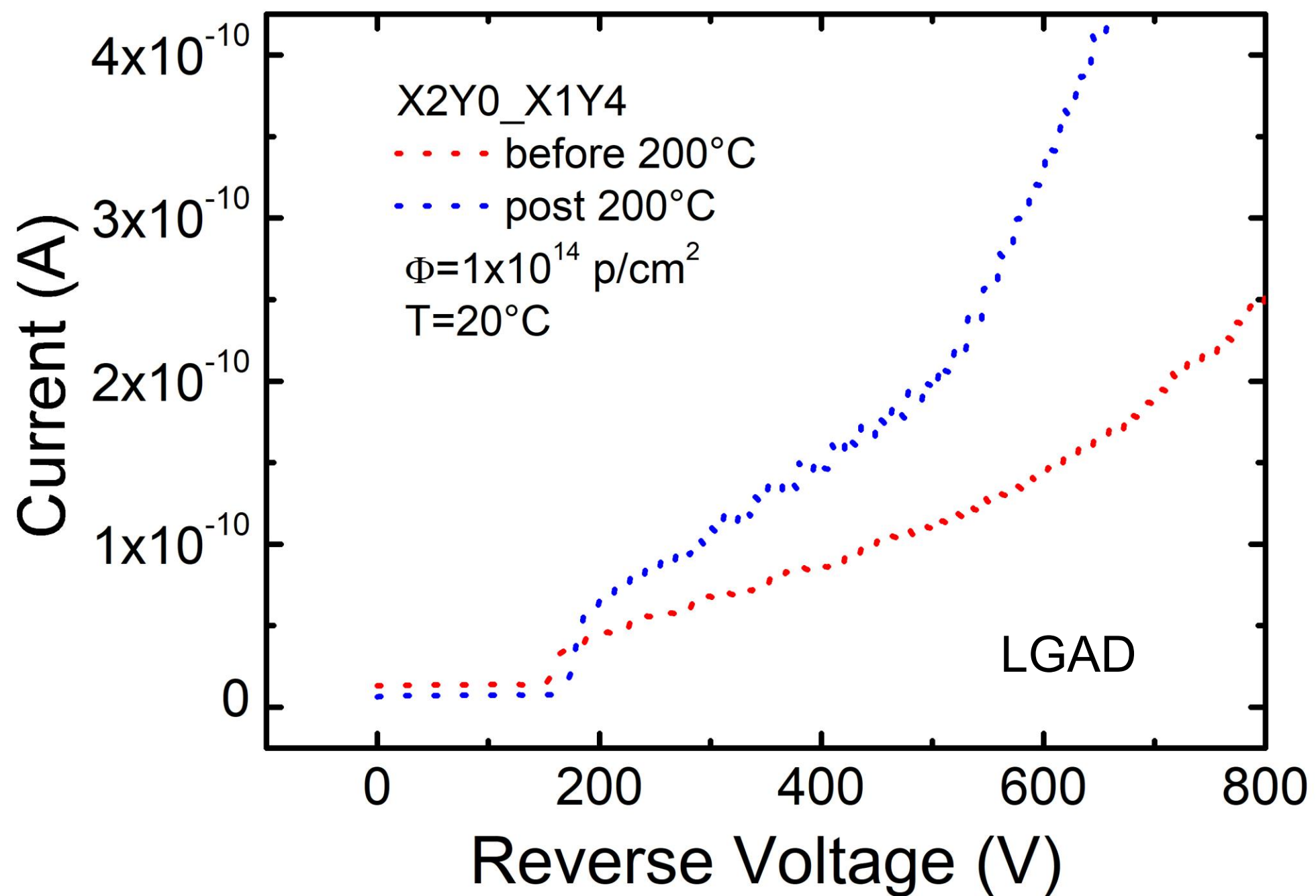
Multiplication increases increasing temperature. In the range 50-100°C there is a multiplication effect for the reverse current.

Ratio IV LGAD and PN at different T

$1.3 \times 10^{14} \text{ p/cm}^2$



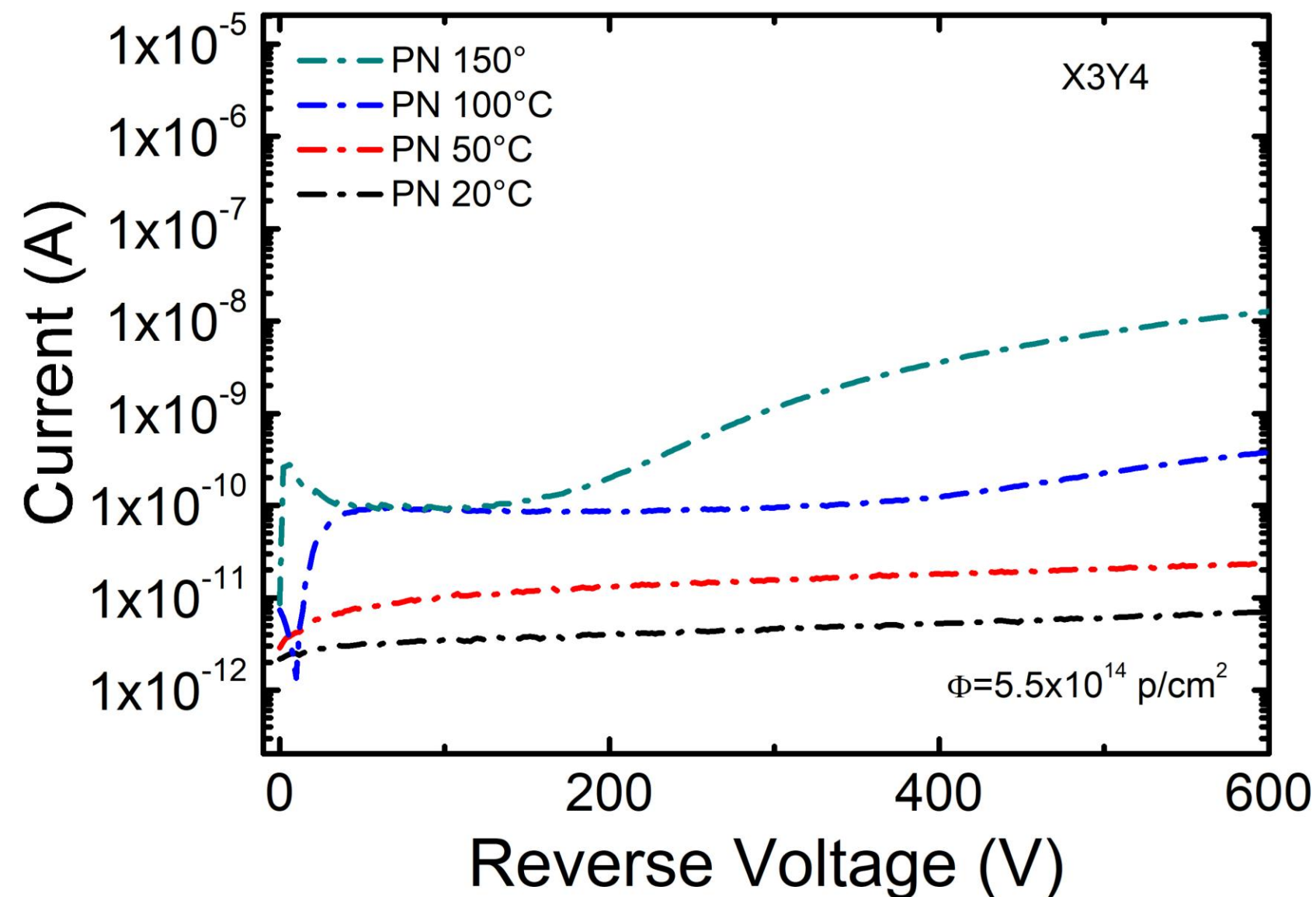
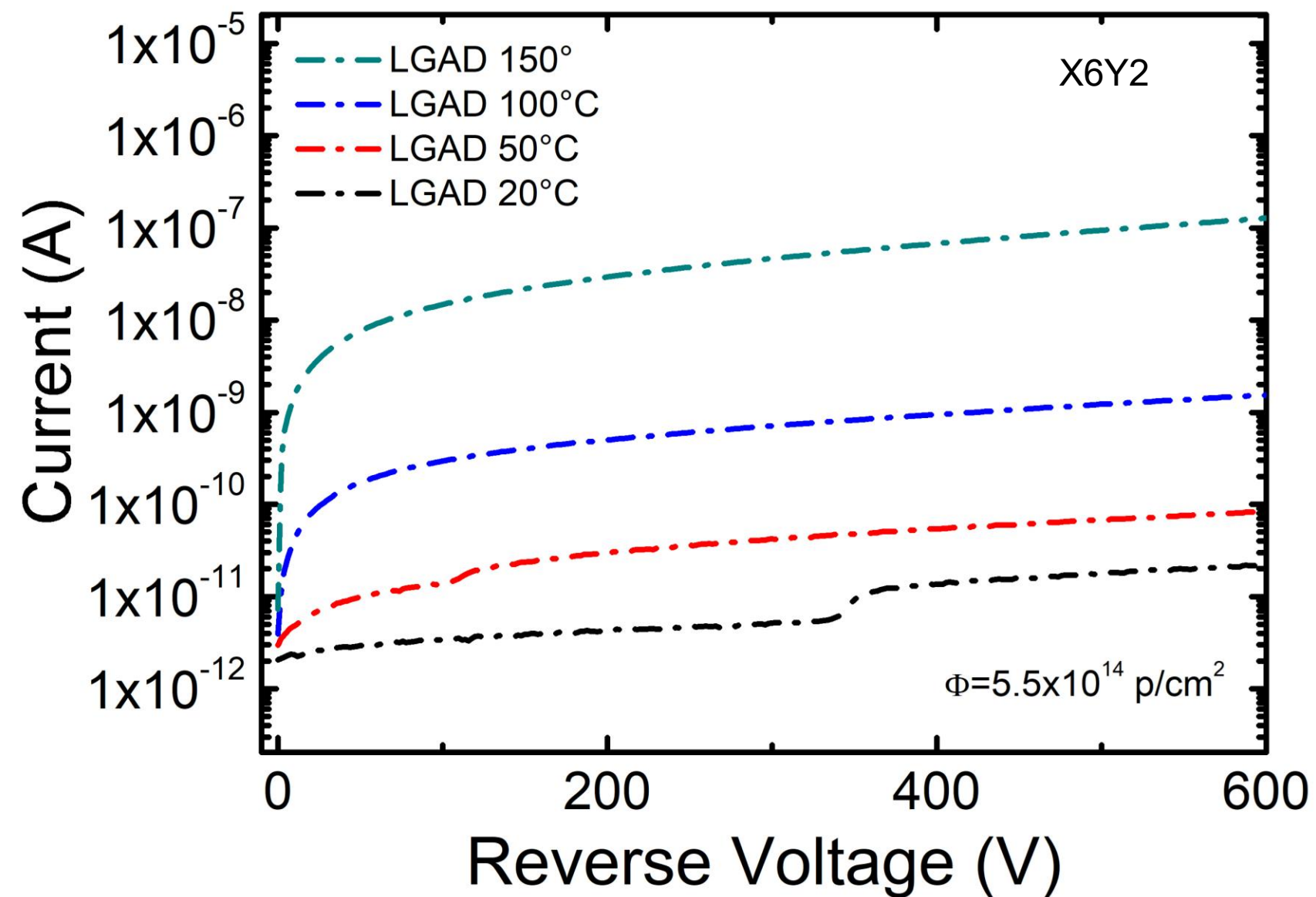
200°C annealing effect on LGAD device (80 minutes)



Annealing
effect after
80 minutes
at 200°C

IV LGAD and PN at different T

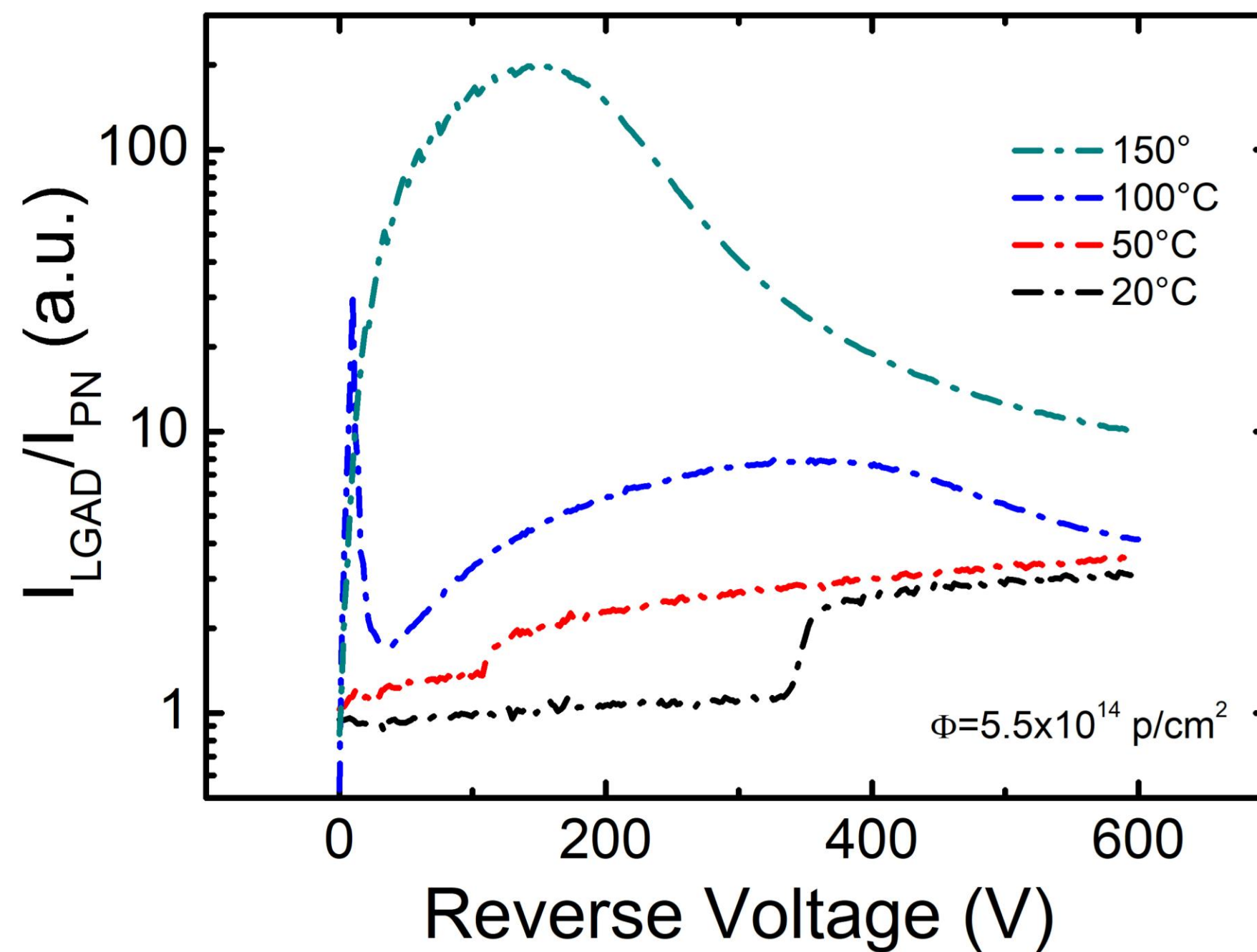
$5.5 \times 10^{14} \text{ p/cm}^2$



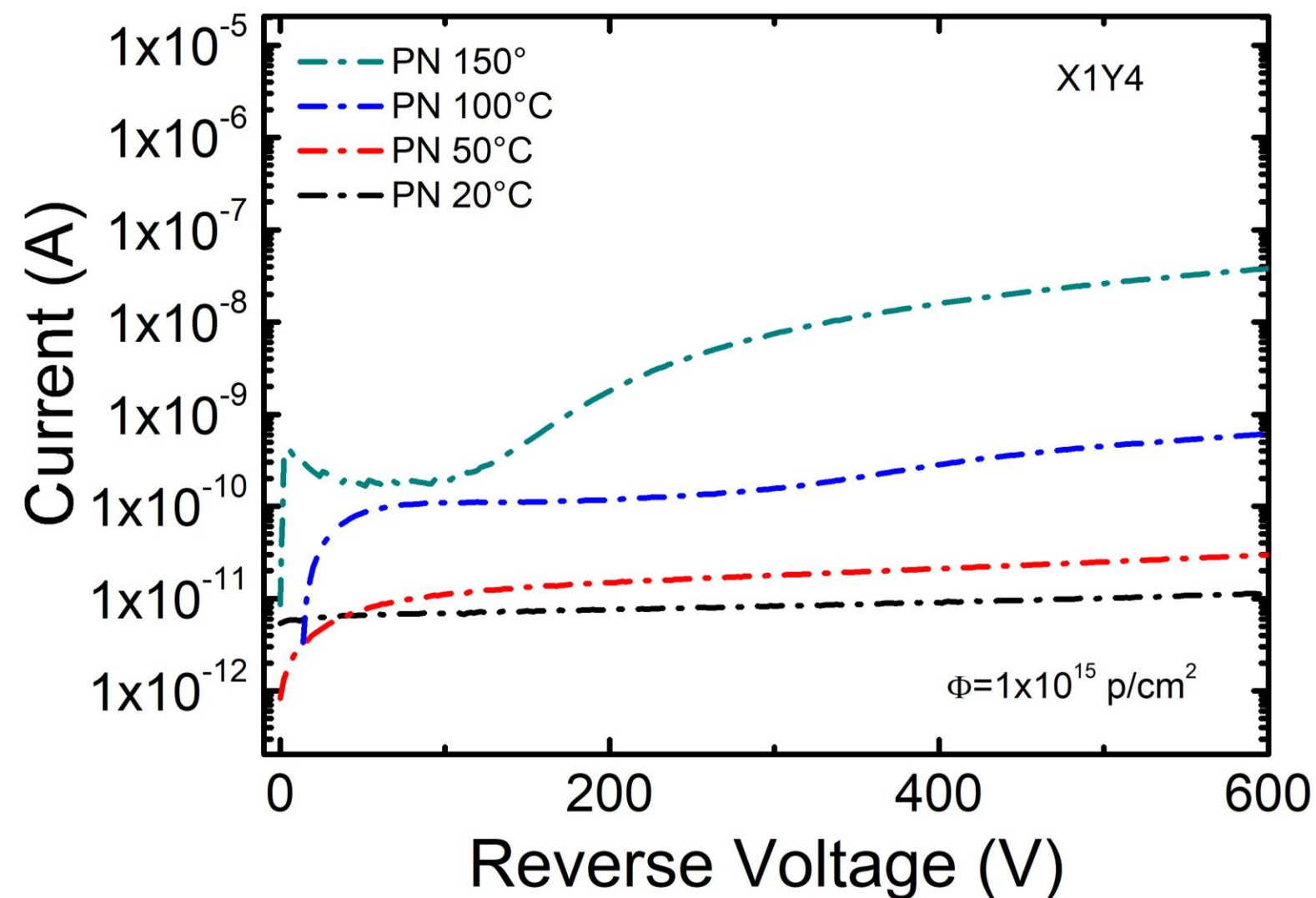
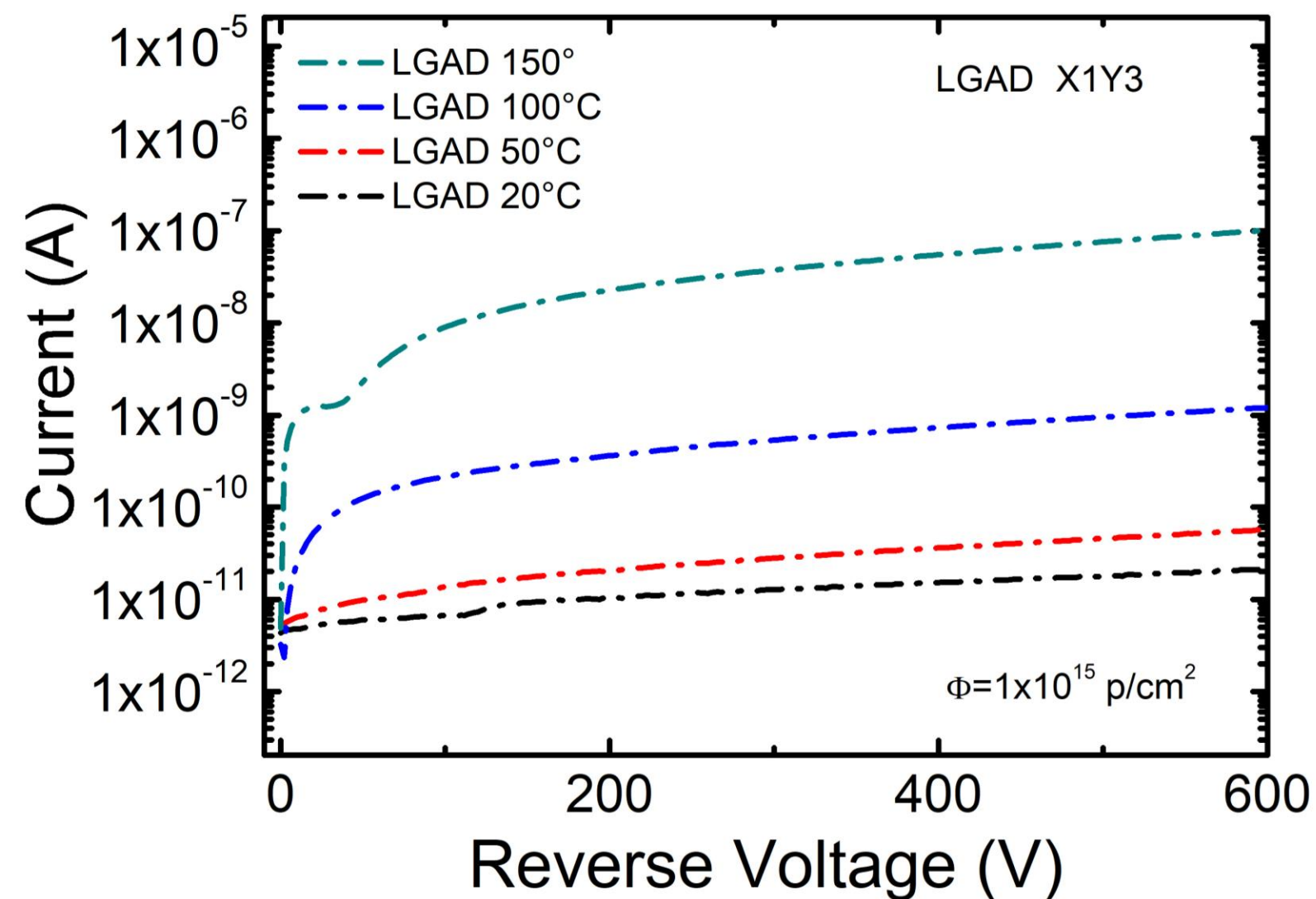
Multiplication increases increasing temperature. At 100-150°C LGAD has an higher current than the diode.

Ratio IV LGAD and PN at different T

$5.5 \times 10^{14} \text{ p/cm}^2$



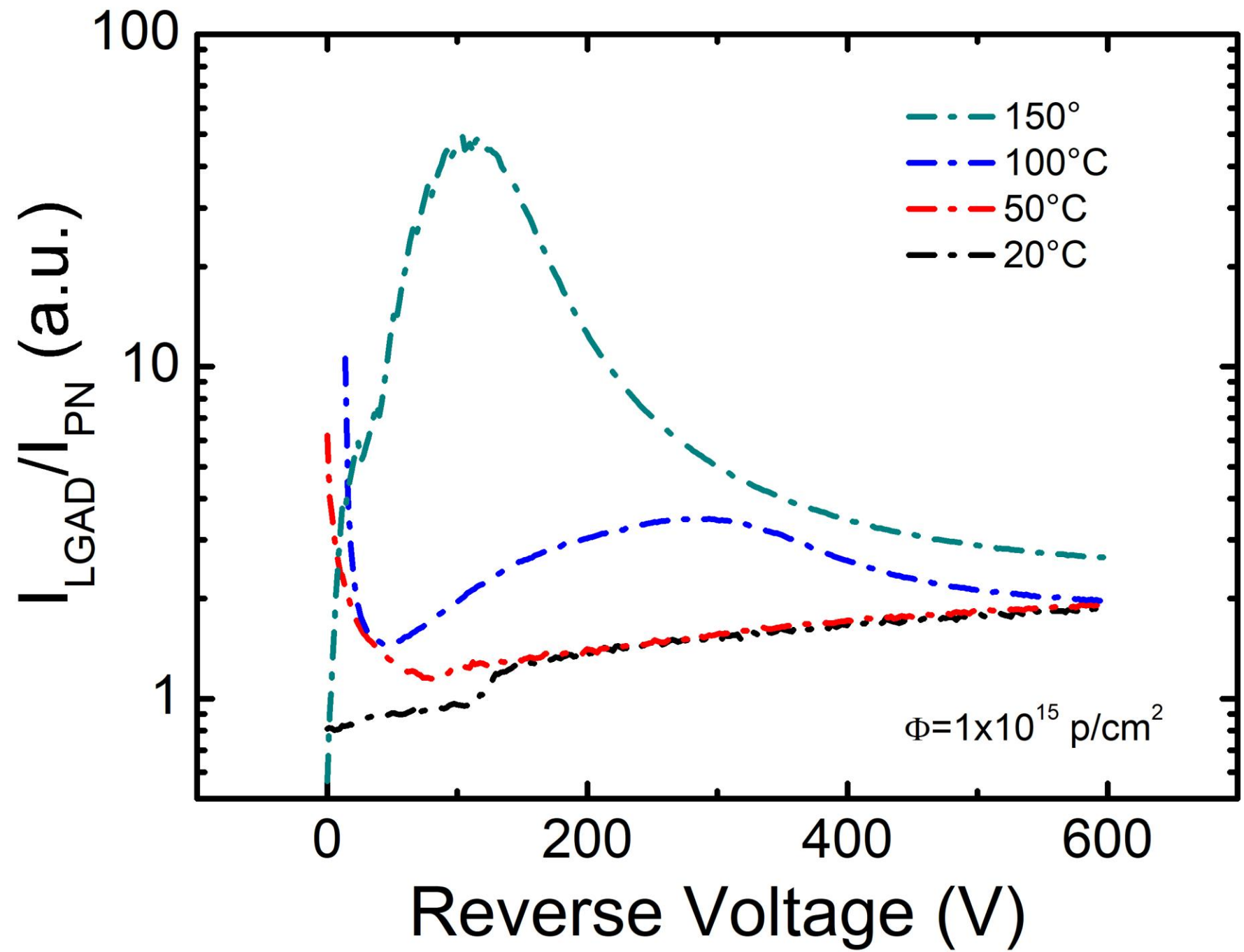
IV LGAD and PN at different T $1 \times 10^{15} \text{ p/cm}^2$



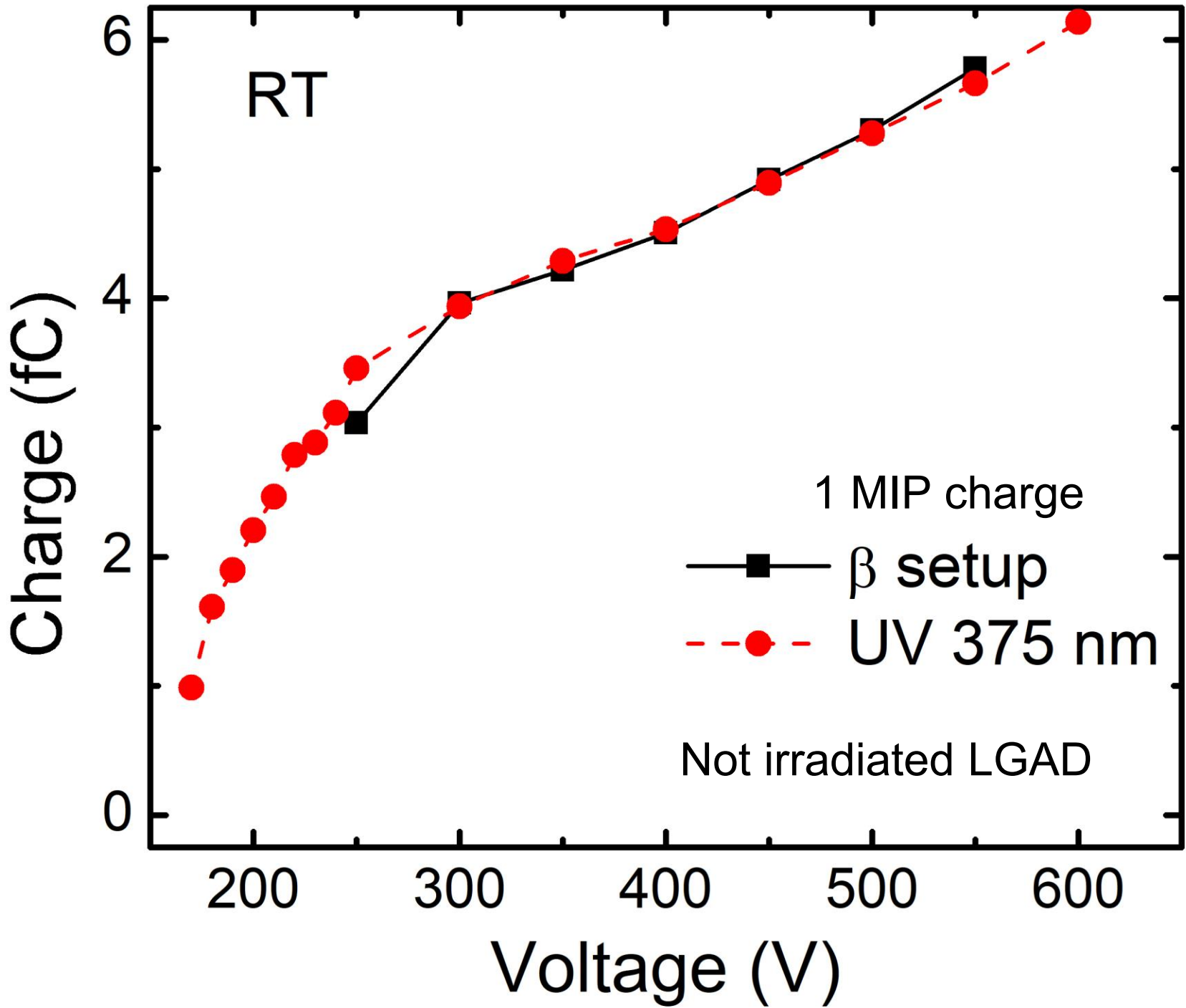
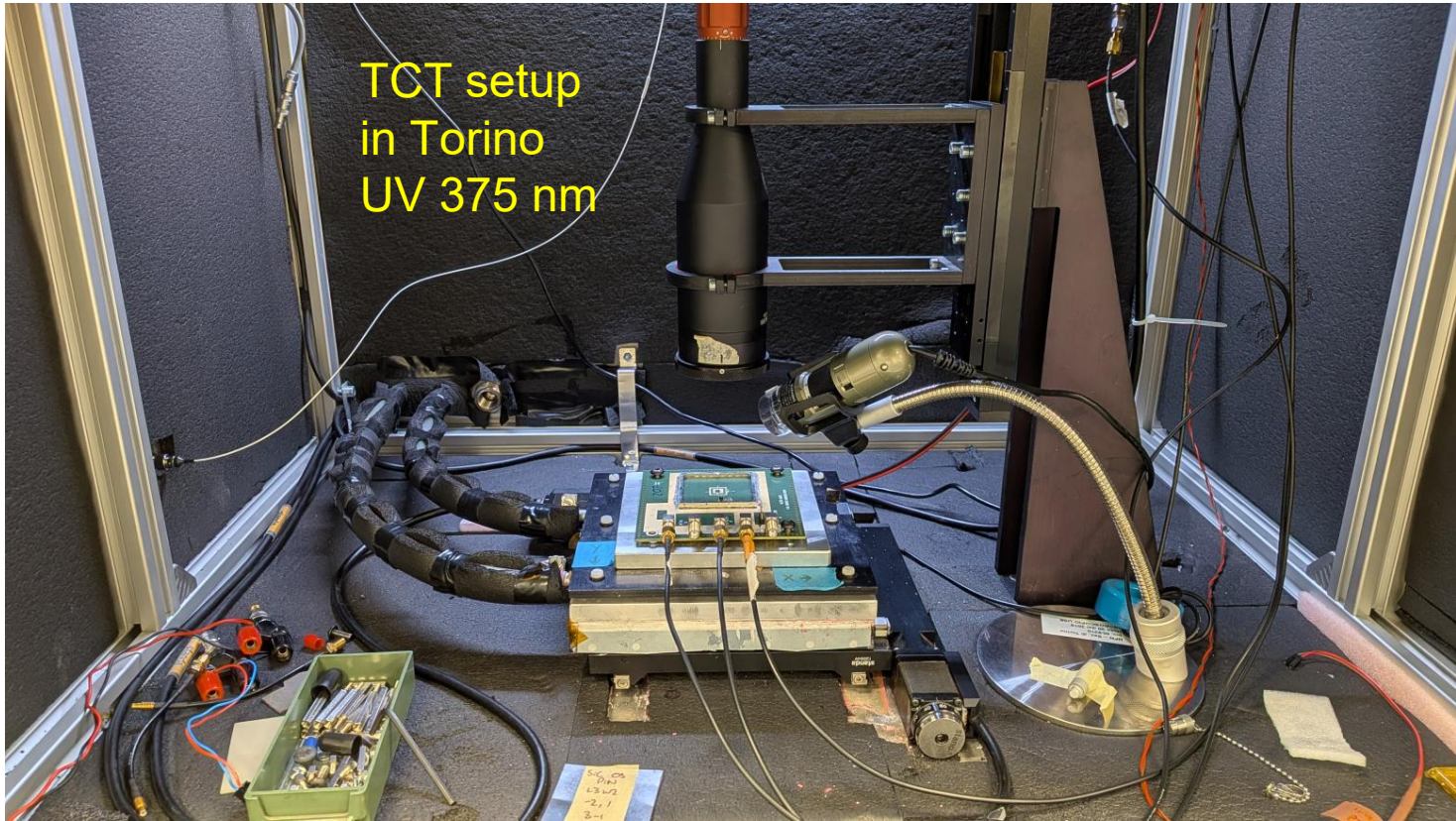
Multiplication increases increasing temperature. At 100-150°C there is a multiplication effect for the current below 250 V.

Ratio IV LGAD and PN at different T

$1 \times 10^{15} \text{ p/cm}^2$

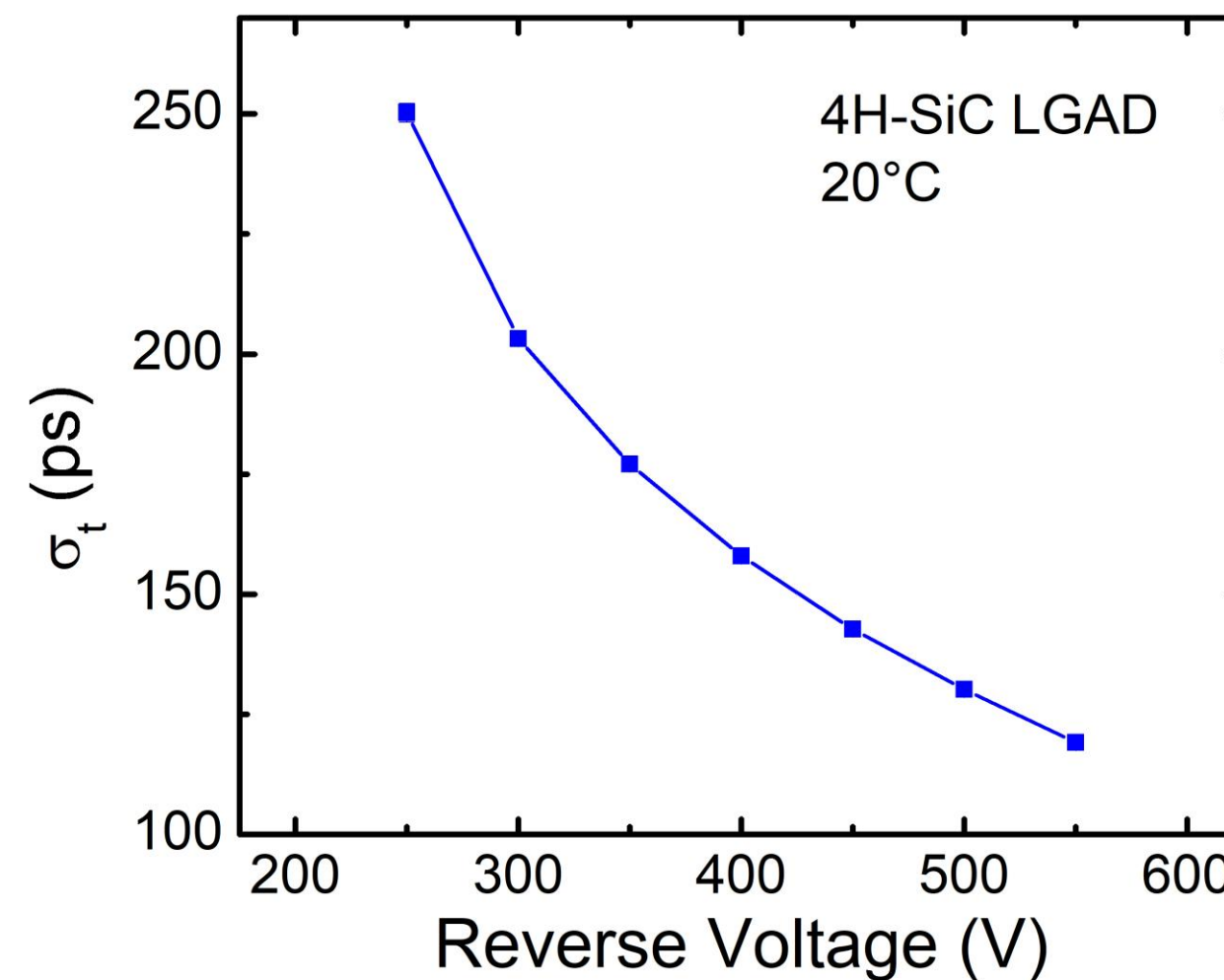
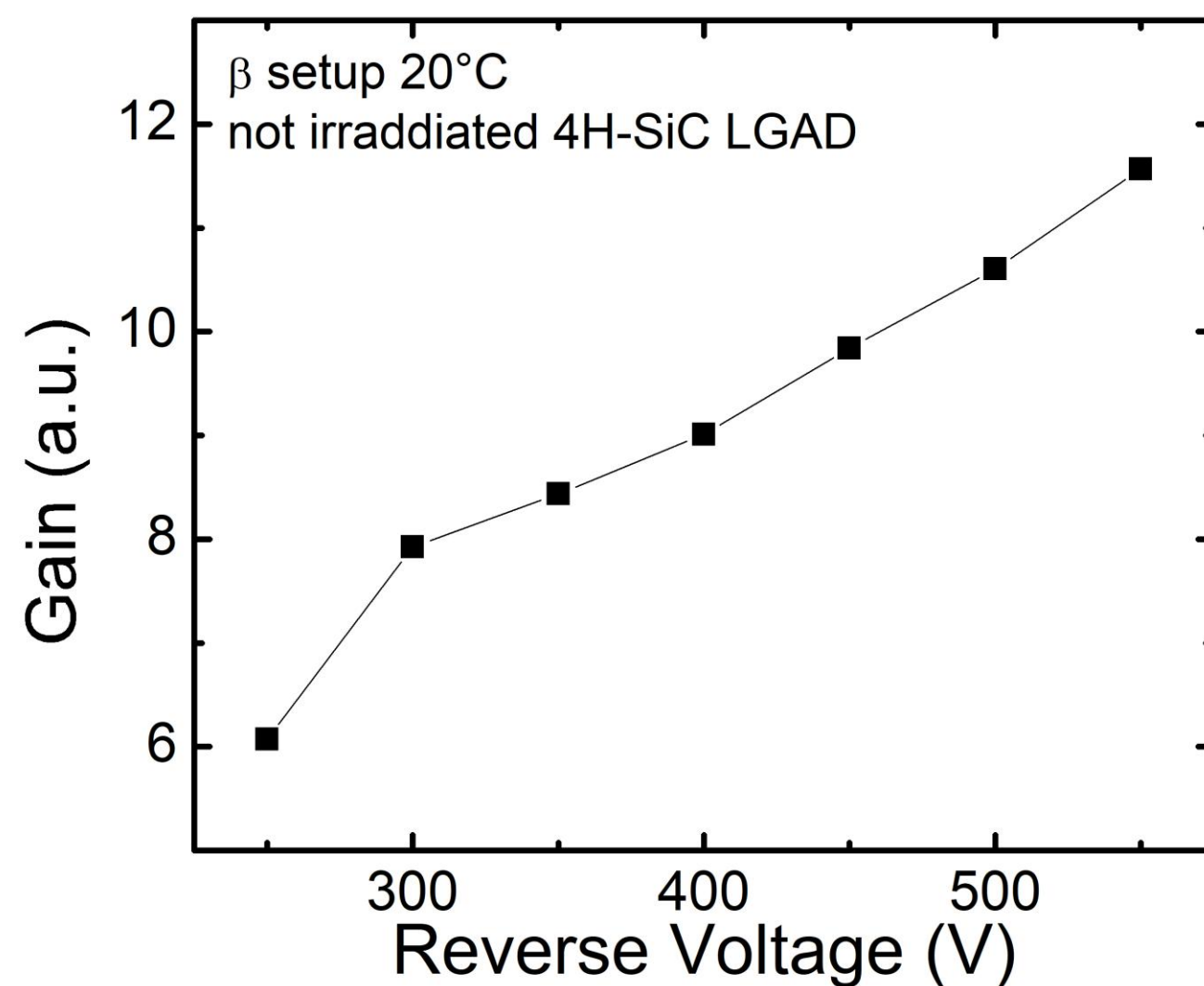


Collected Charge before irradiation with beta and TCT

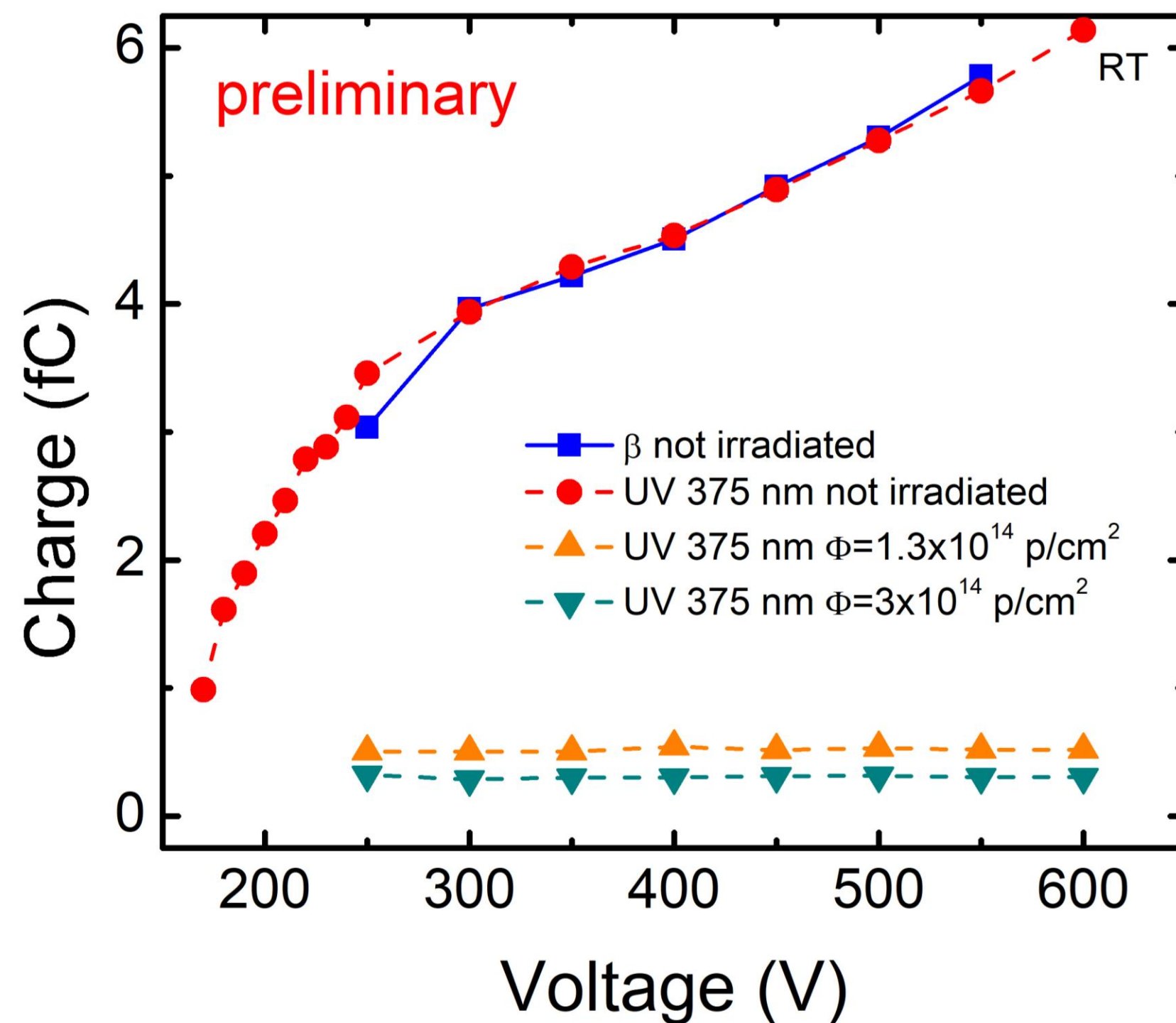


SiC Onsemi LGAD @ β setup (20°C). Not irradiated LGADs

Results on CCE measurements in Torino. Measurements on not irradiated LGADs.



TCT after irradiation



- After a fluence of 1.3×10^{14} p/cm², the gain is significantly reduced and is just above unity.
- At 3×10^{14} p/cm², there is no longer any gain at room temperature.
- There were problems with the setup for measurements up to 50°C due to fiber and chiller failures.



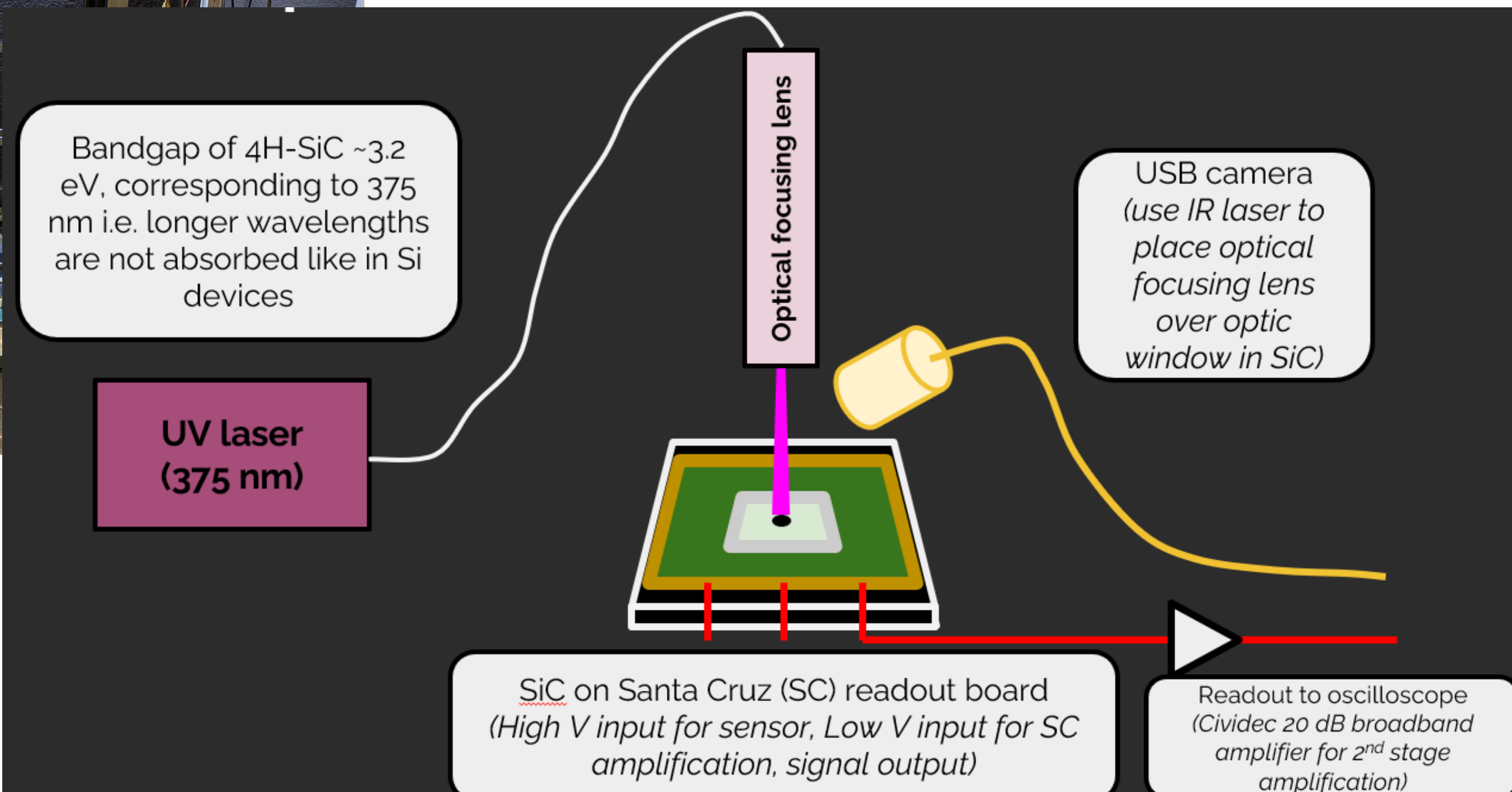
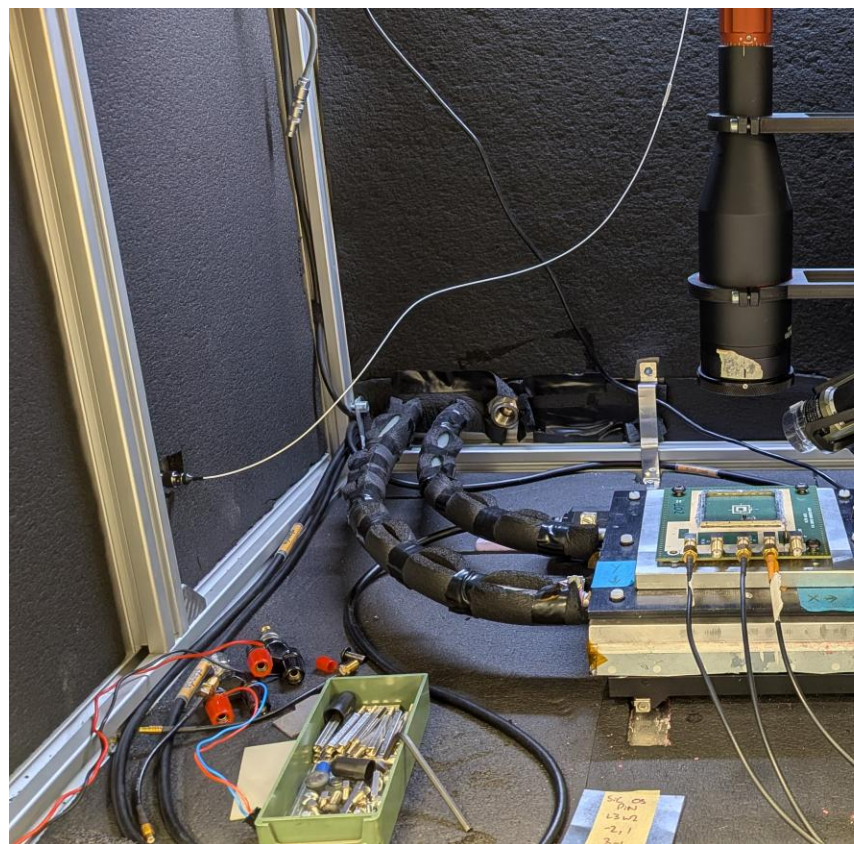
Conclusions and next steps

- **Proton irradiation with 23-MeV proton beam at KIT campus.** 5 fluences have been considered: 1.3×10^{14} p/cm², 3×10^{14} p/cm², 5.5×10^{14} p/cm², 1×10^{15} p/cm², 1.9×10^{15} p/cm². 8 LGAD and 8 PN diodes have been irradiated for each fluence.
- After a fluence of 1.3×10^{14} p/cm², **the current decreases** due to compensation and gain reduction, but **a low level of multiplication occurs beyond 150-180 V**
- **As the fluence increases, multiplication occurs at progressively higher reverse-bias voltages.**
- **Multiplication increases increasing temperature.** In the range 50-100°C LGAD has a high current after 1.3×10^{14} p/cm². At higher fluences it is necessary to further increase the temperature to increase the current of the LGAD.
- CCE and TCT results: Preliminary results on irradiated LGADs show that after a fluence of 1.3×10^{14} p/cm² the **gain is significantly reduced** and is just above unity, while **after a fluence of 3×10^{14} p/cm² there is no gain.**
- **There were problems with the TCT setup** for measurements up to 50°C due to fiber and chiller failures. As soon as the setup is repaired, measurements will be taken to verify whether the gain increases with increasing T.

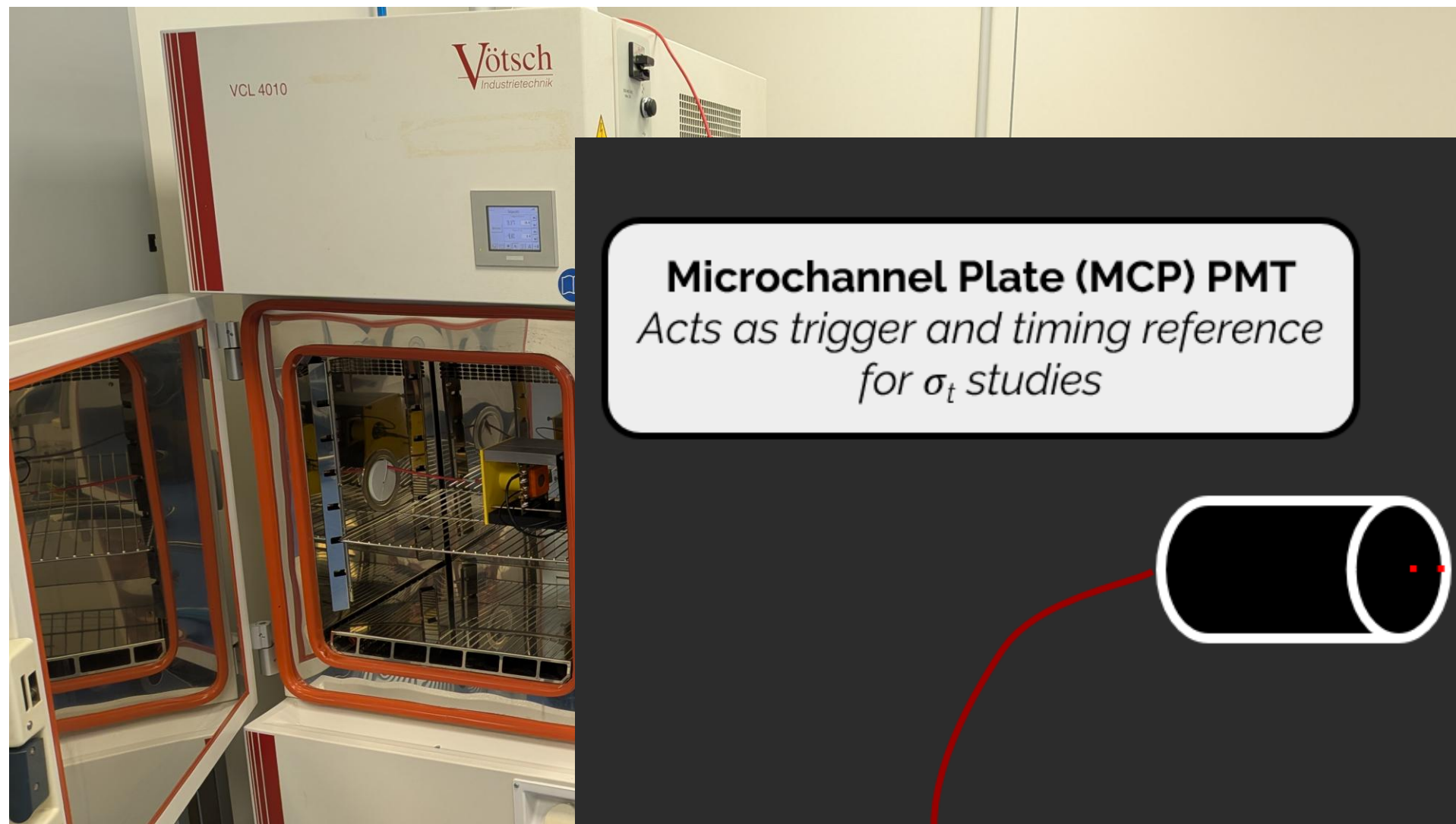
Backup



TCT setup



Beta setup



Microchannel Plate (MCP) PMT
Acts as trigger and timing reference for σ_t studies

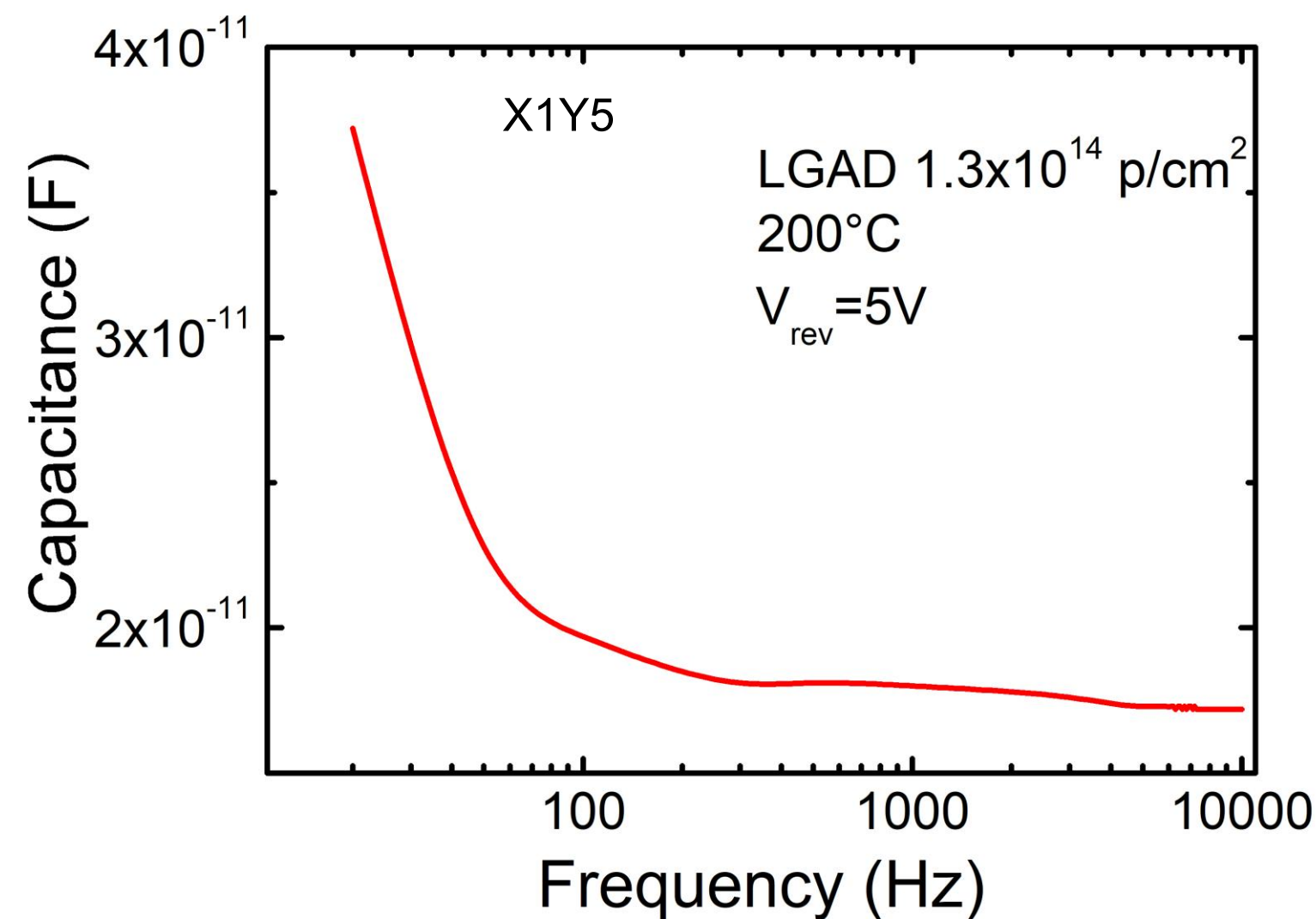
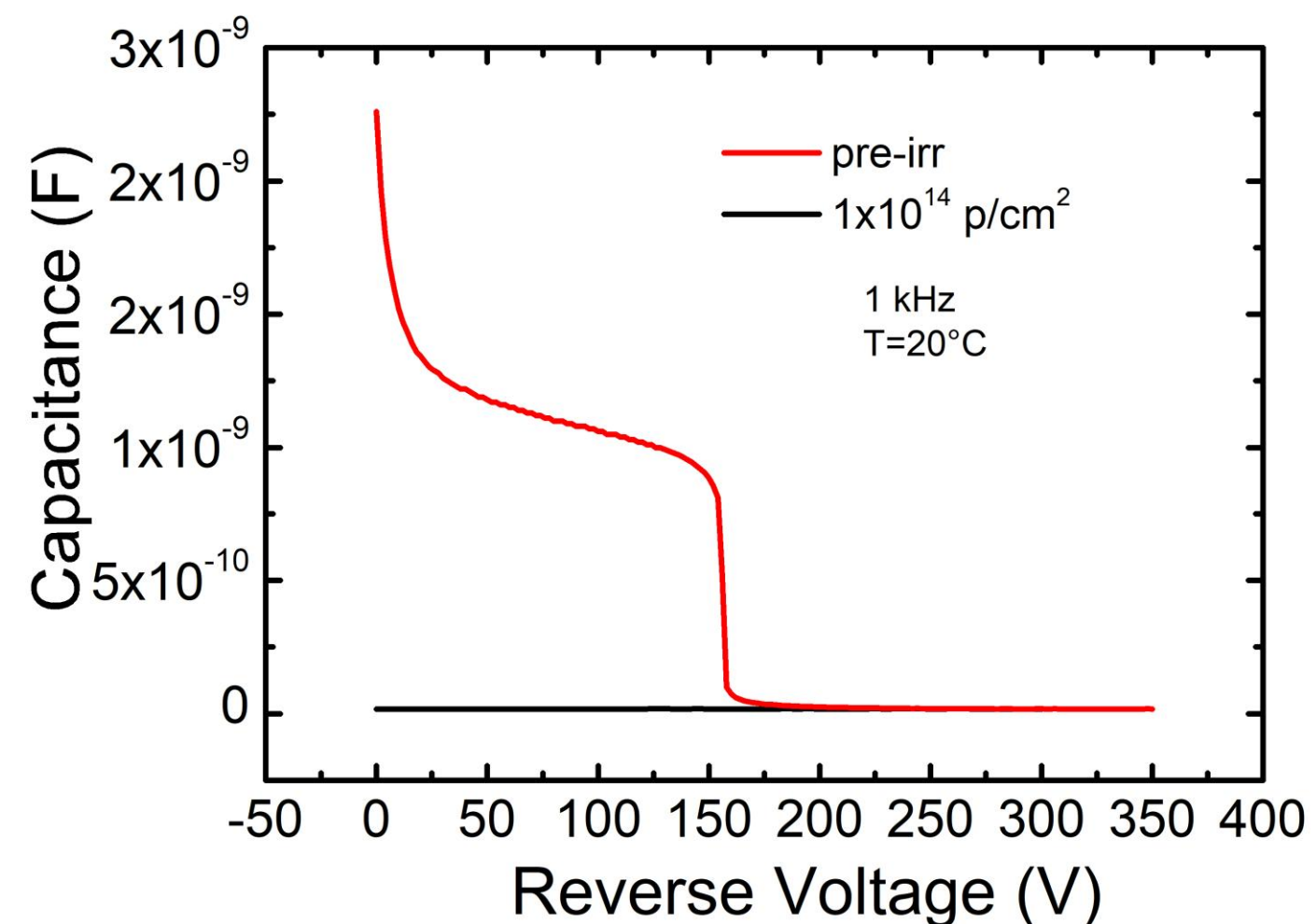
SC board with SiC mounted
Trigger on MCP events, some portion will be coincident with a SiC LGAD signal from the same MIP

^{90}Sr source of β^- particles
 $^{90}\text{Sr} \rightarrow ^{90}\text{Y} + \beta^-$ (0.546 MeV)
 $^{90}\text{Y} \rightarrow ^{90}\text{Zr} + \beta^-$ (**2.28 MeV**)
Clean energy spectrum for MIP detection as primarily have this energy

Readout same as TCT
*Cividec BB amplifier (20dB) for DUT
MCP direct to oscilloscope*

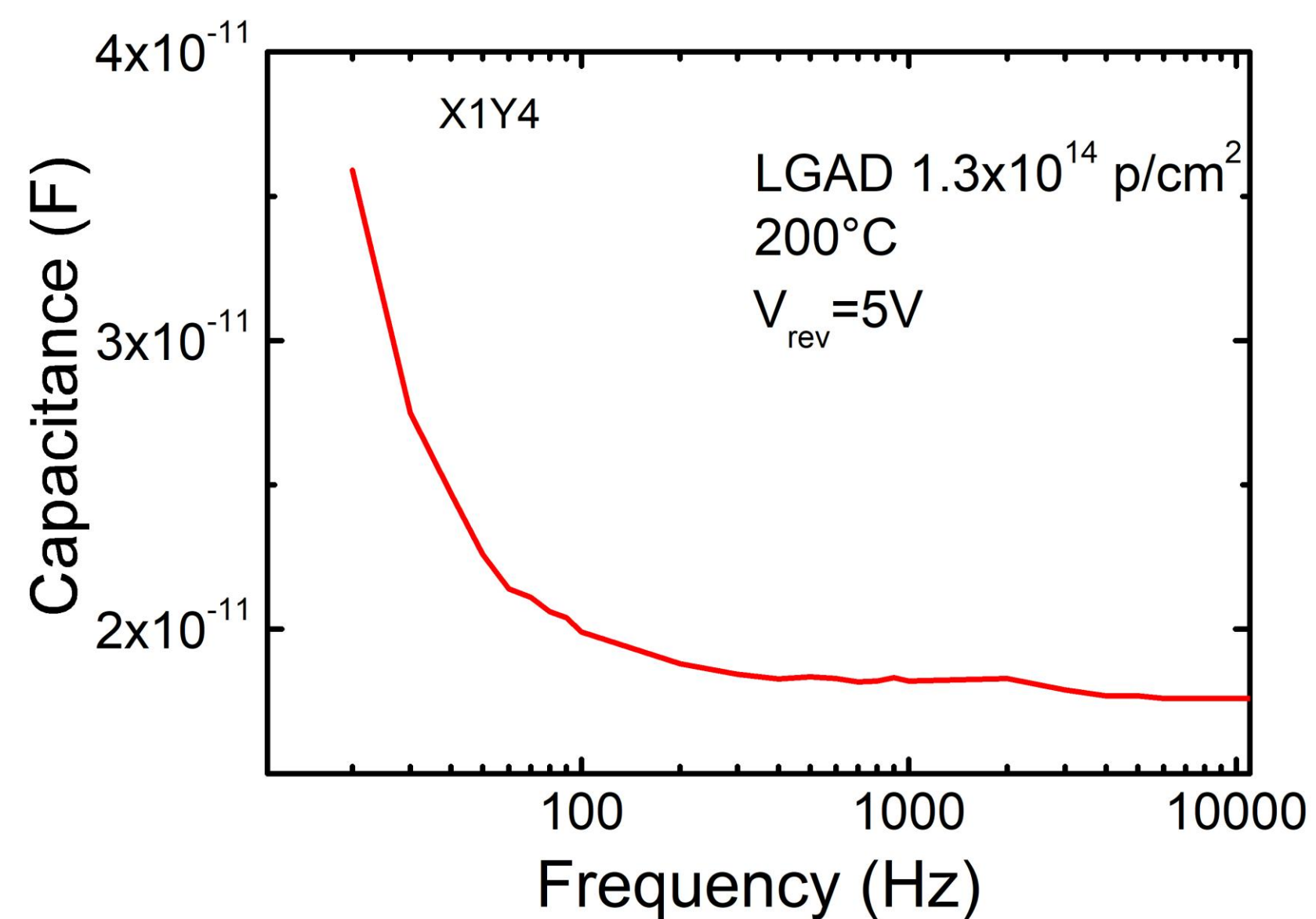
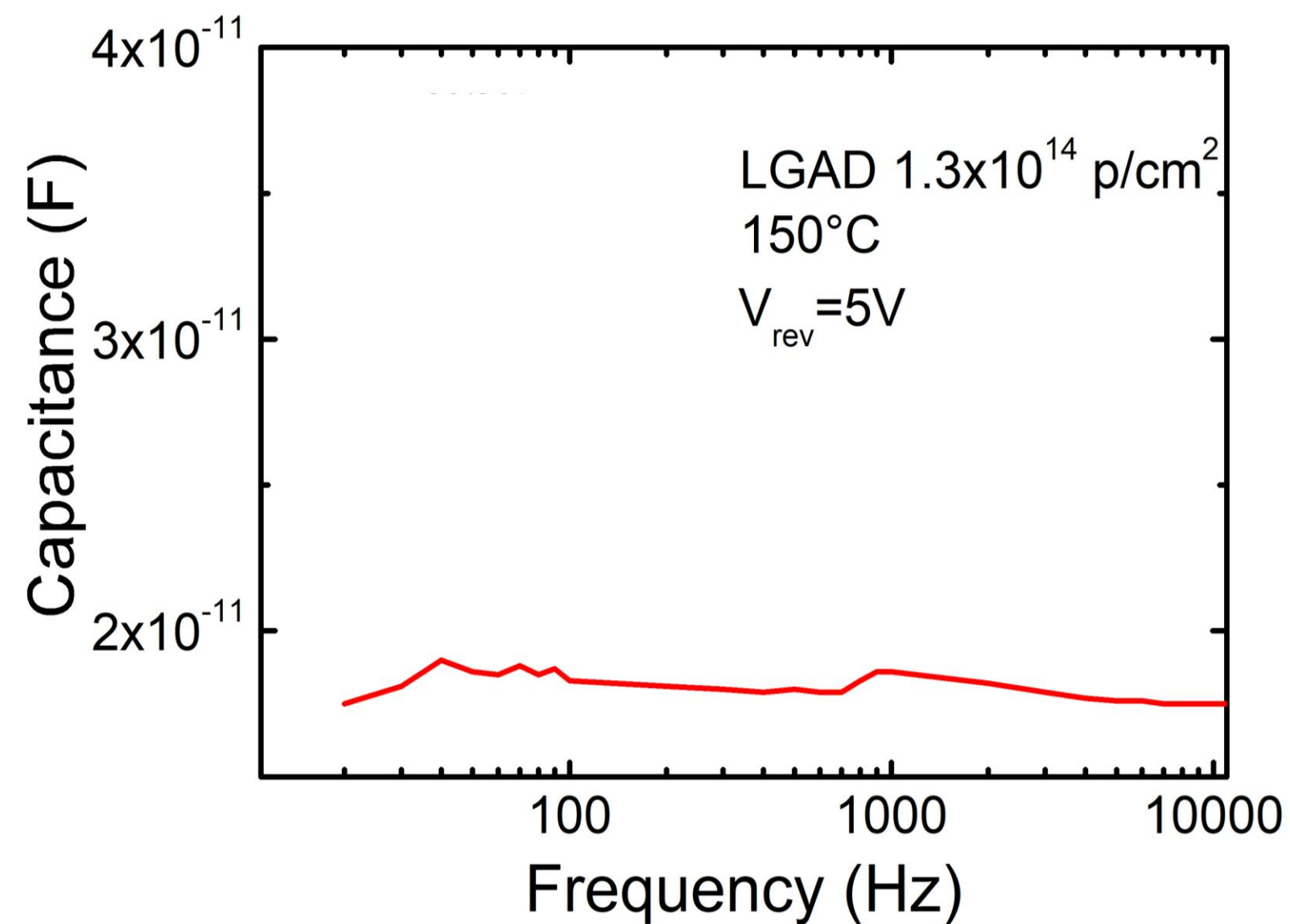


C-V measurements after proton irradiation

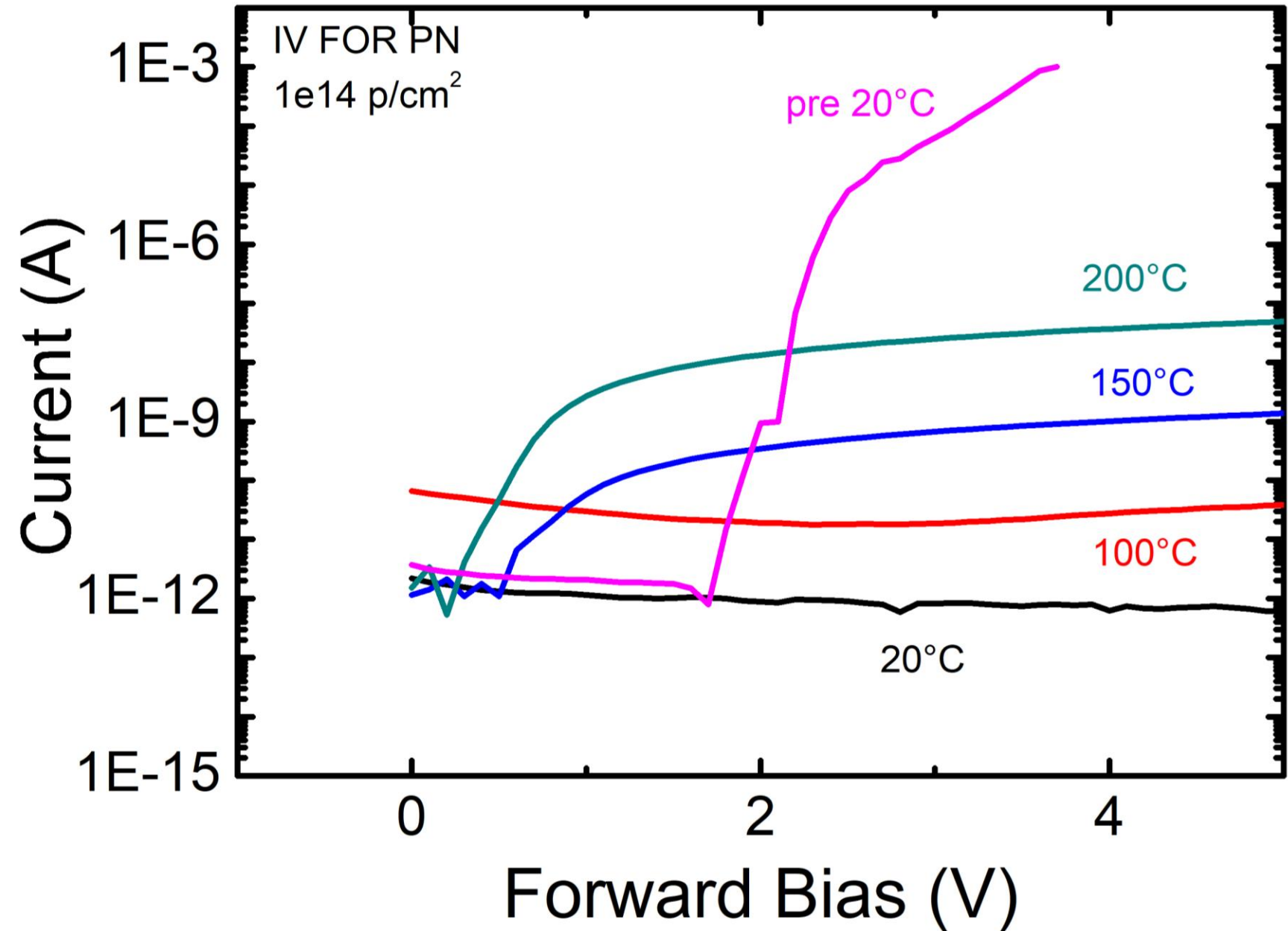
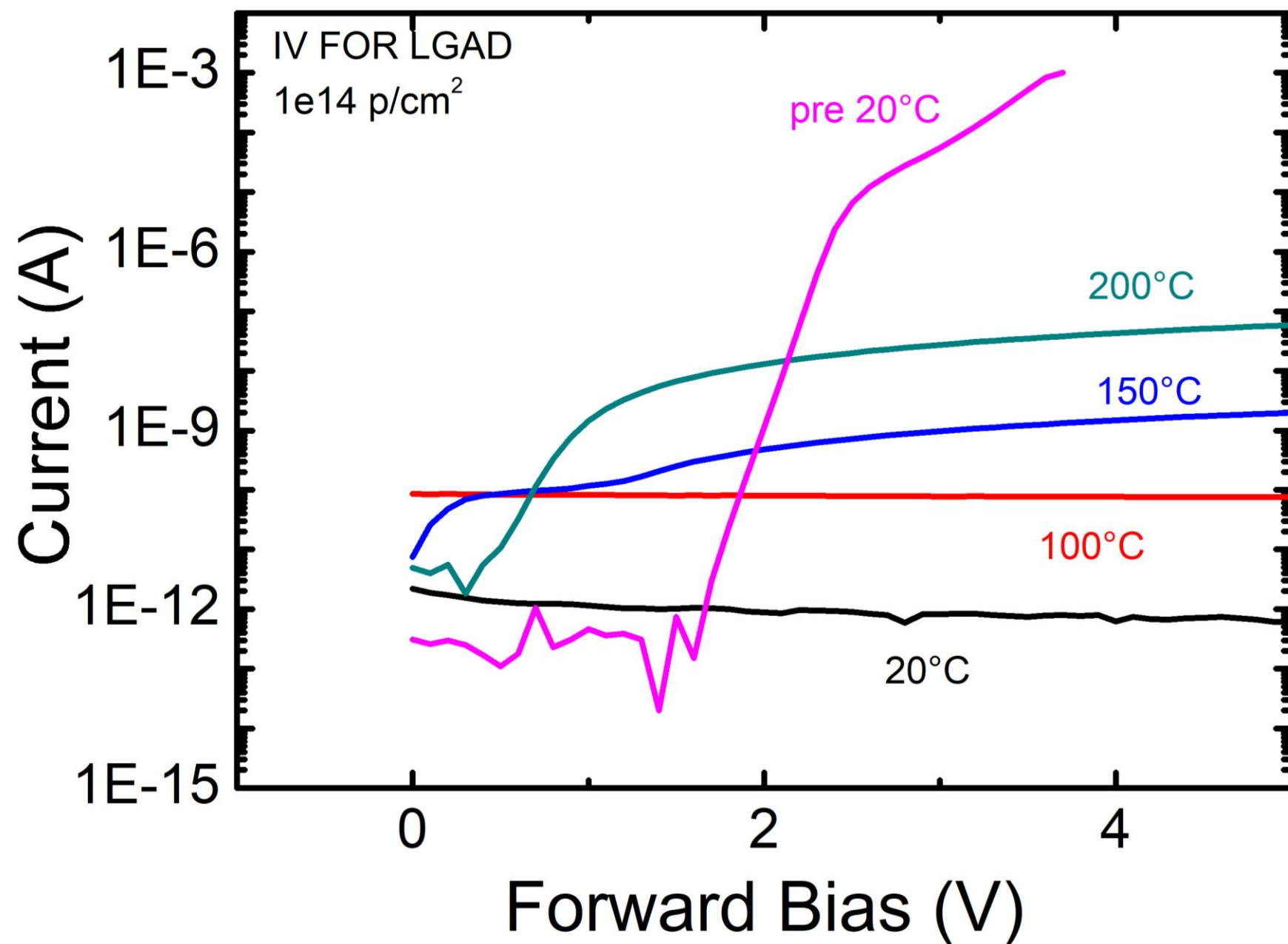


At 200°C for frequencies lower than 100 Hz, the capacitance begins to increase, starting to show the dependence of the defects on temperature and frequency

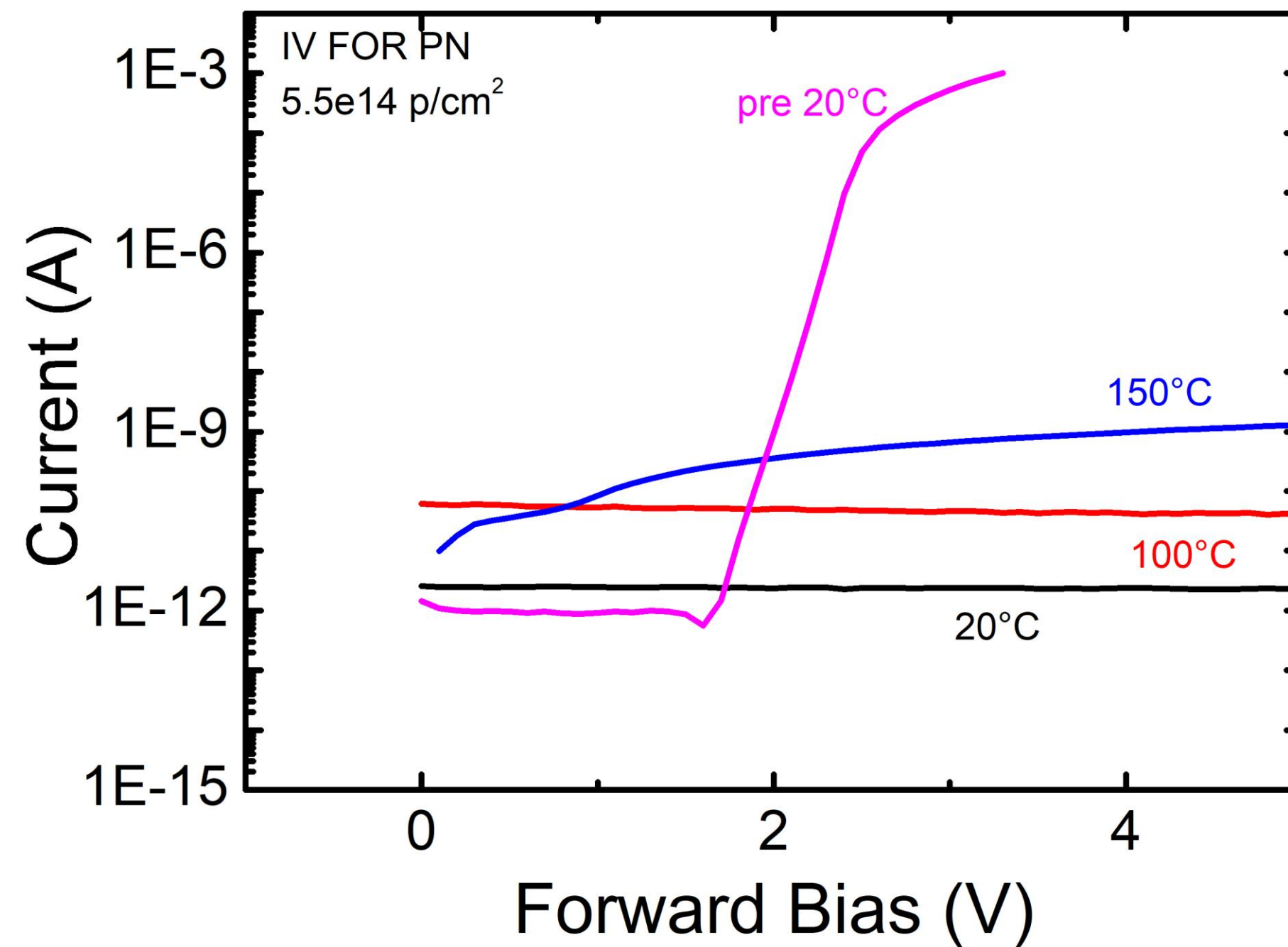
C-V measurements 1.3×10^{14} p/cm² 2nd device



Forward current as a function of temperature



Forward current as a function of temperature $5.5 \times 10^{14} \text{ p/cm}^2$



Onsemi Diodes Forward

