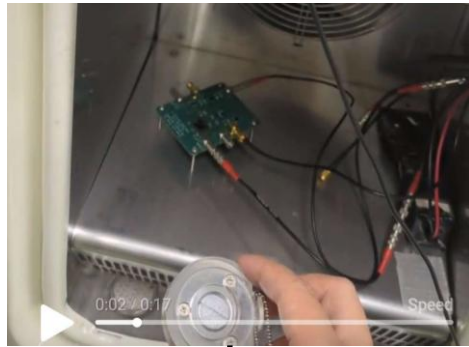


Development of Semiconductor Detector From Sensor Physics to Readout

LIAO CHUAN, KEK/QUP

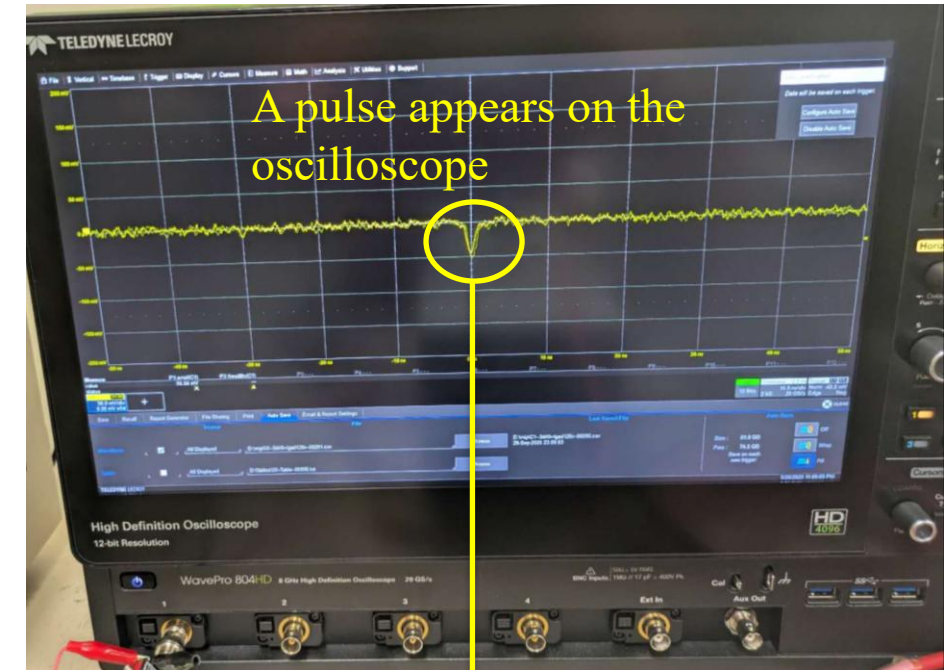
How can I tell the story of my past ten years? Let's start with a pulse



^{90}Sr source



When the source close to detector



Particle physics
(A question for Jesus, the Buddha, or perhaps nature itself)

← 1. What does this pulse represent?

PMT(光电倍增管), Gas detectors
Semiconductor detectors (today's seminar)
Low Temperature Detector

← 2. How can we observe it?

My Journey

Research Background

Research background

Postdoctoral Researcher (Feb. 2024–Present) — KEK, Japan

Research: Fast-timing readout systems, front-end electronics, and multi-channel readout

Ph.D. (Jan. 2020–Sep. 2023) — University of Hamburg & DESY, Germany

Research: Radiation damage and defect evolution, semiconductor defect engineering, and radiation-hardening studies

M.Sc. (Jun. 2016–Sep. 2019) — Xiangtan University, China

Research: TCAD simulation and detector design

B.Sc. (Jun. 2012–Sep. 2016) — Xiangtan University, China

Major: Materials Physics

My journey

TCAD simulation
2016.06-2019.09



Defect engineering
2020.01-2023.09



High-Speed readout
2024.02-present



Multi-Channel Readout Electronics
2024.02-present

Detectors-Materials-Electronics

Outline

1. Brief Introduction to Semiconductor Detectors

(半导体探测器简介)

2. TCAD Simulation for Detector Design

(TCAD仿真)

3. Crystal Defects and Defect Engineering

(晶体缺陷与缺陷工程)

4. Detector Readout Electronics

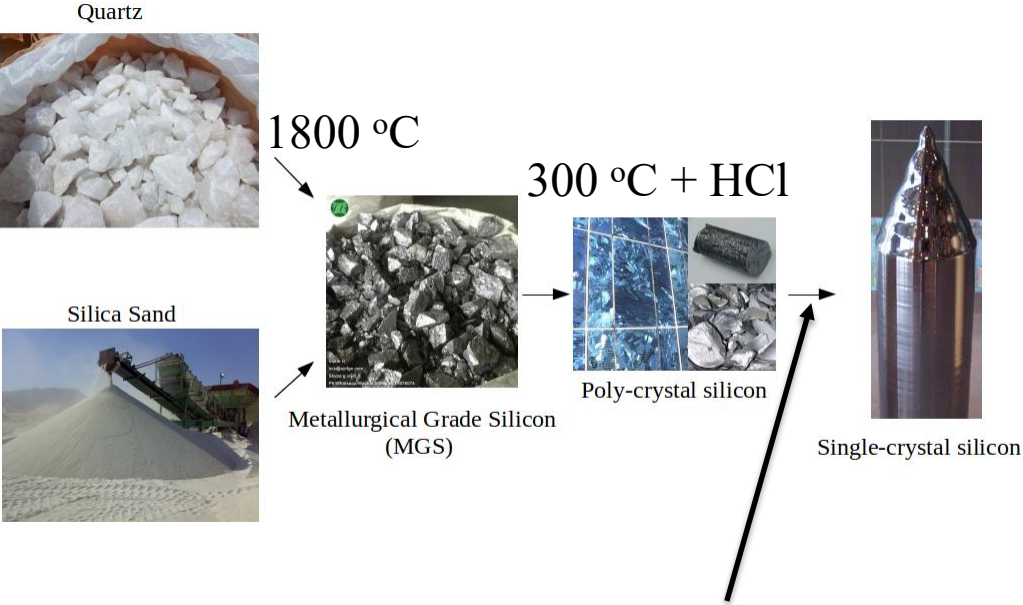
(探测器读出电路)

5. Perspectives on Future Detector Technologies

(未来辐射探测技术浅谈)

Brief Introduction of Semiconductor Detectors (Silicon as an Example)

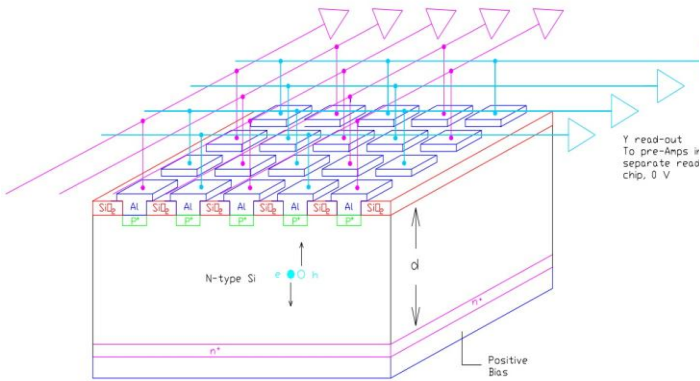
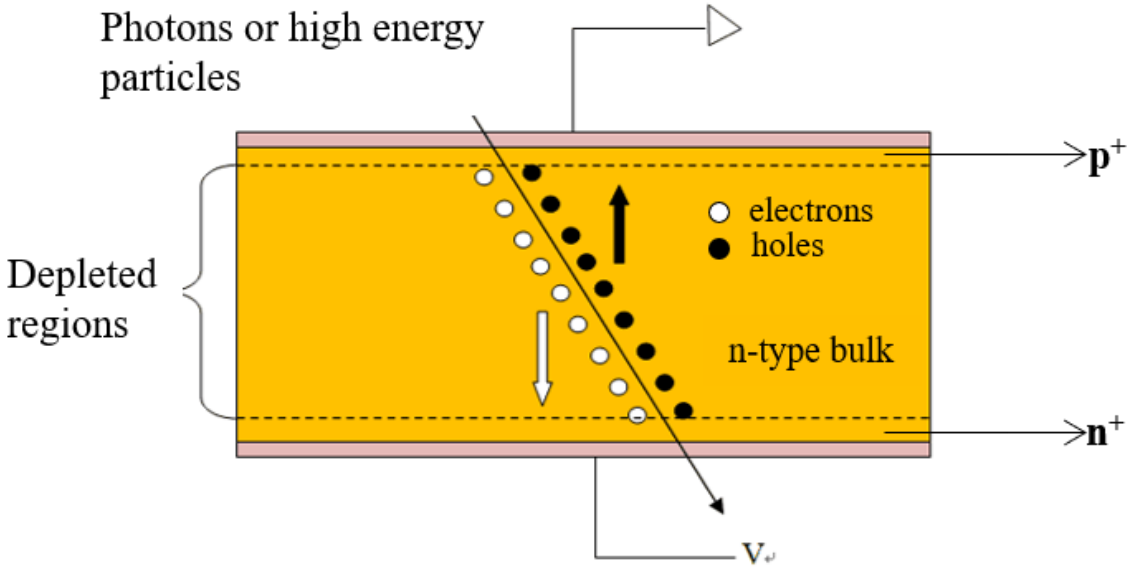
Basic principles of silicon detector



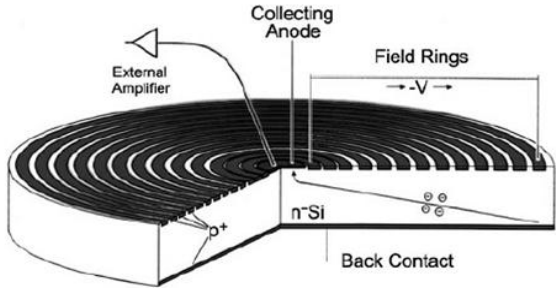
- 1.Czochralski method
- 2.Float zone method
- 3.Epitaxial method

Table 2.1: Impurities information (Epitaxial wafer is growth on Czochralski)

Growth Techniques	Czochralski (Cz)	Float Zone (FZ)	Epitaxial (EPI)
Oxygen [O _i] (cm ⁻³)	1 × 10 ¹⁸	5 × 10 ¹⁵	1 × 10 ¹⁷
Carbon [C _i] (cm ⁻³)	1 × 10 ¹⁶	5 × 10 ¹⁵	2 × 10 ¹⁵



Pixel detector

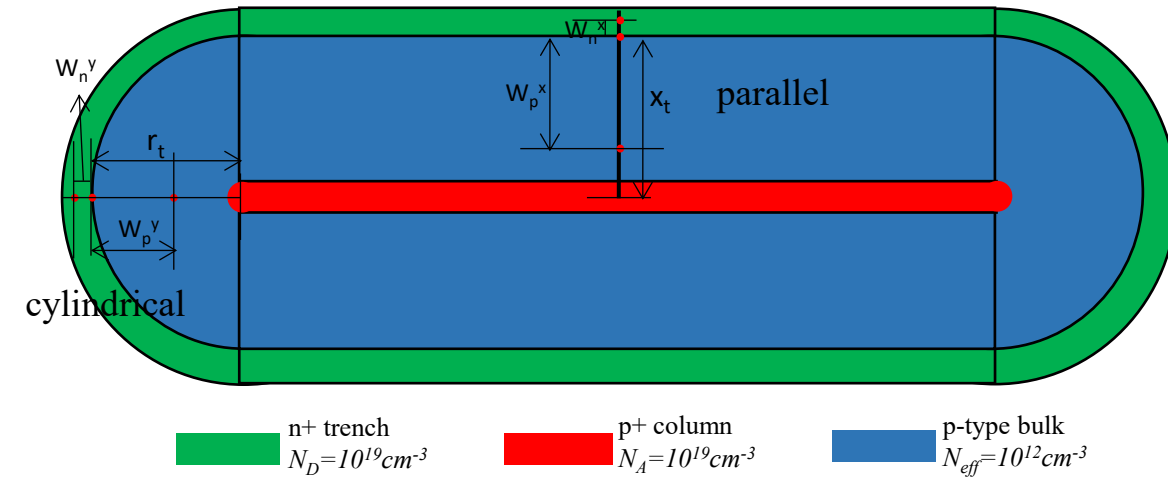
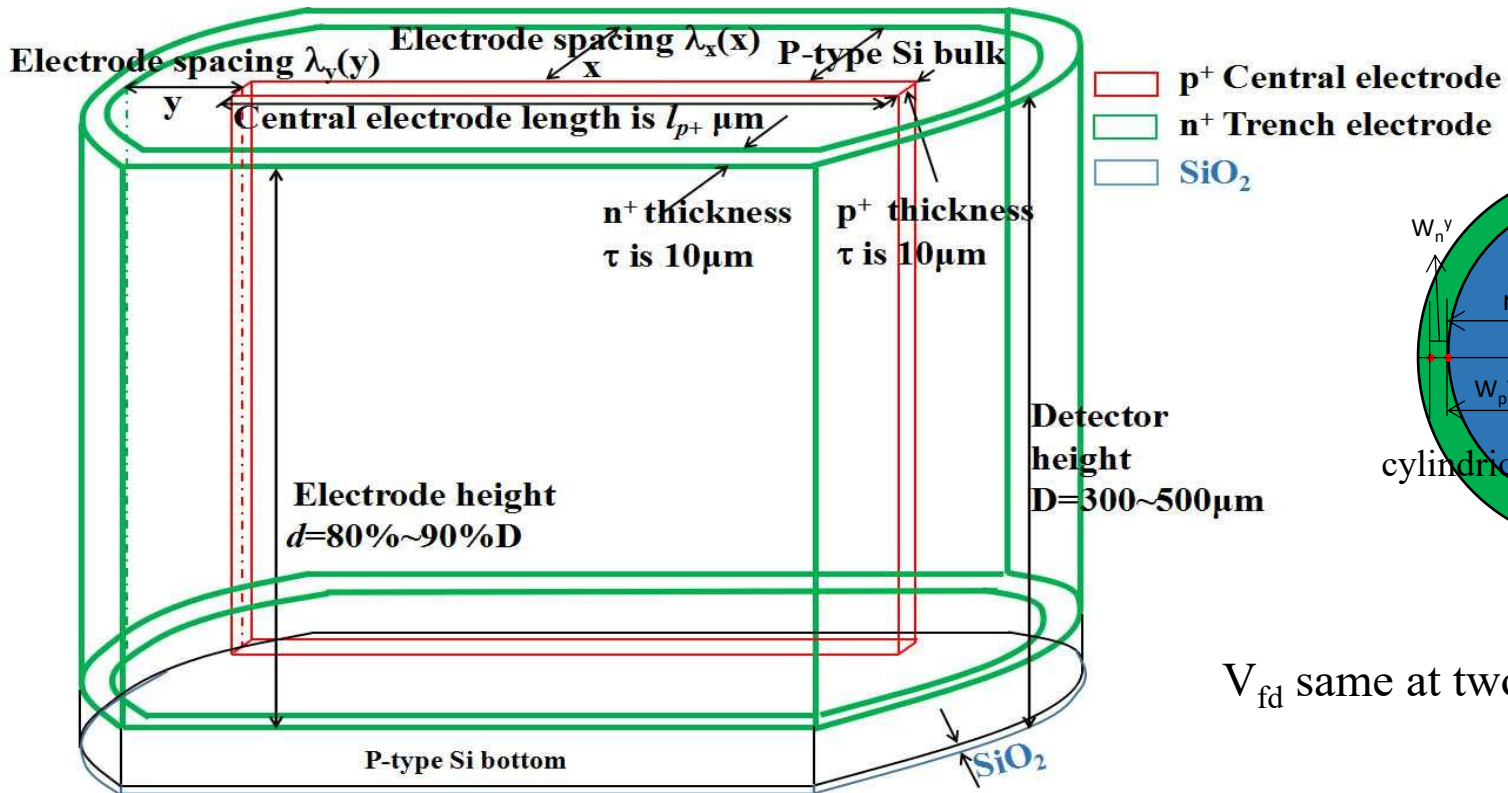


Silicon drift detector

Journey of TCAD Simulation (Silicon and wideband-gap semiconductor)

TCAD simulation (Silicon)

Arraying strategy for pixel detectors



V_{fd} same at two regions:

parallel regions:

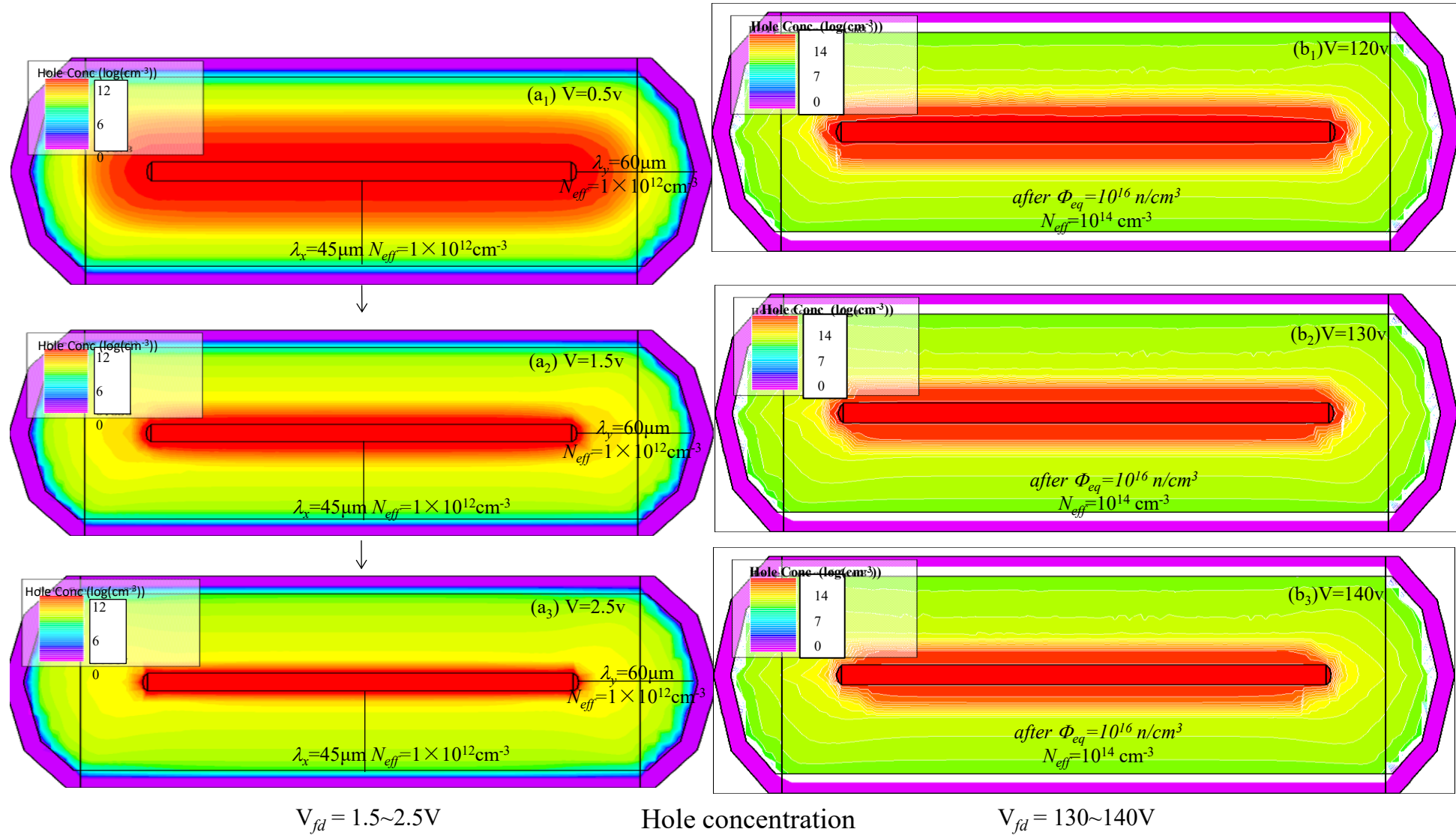
$$V_{fd} \cong \frac{eN_{\text{eff}}\lambda_x^2}{2\epsilon\epsilon_0} - V_{bi} \cong \frac{eN_{\text{eff}}\lambda_x^2}{2\epsilon\epsilon_0}$$

cylindrical regions:

$$V_{fd,y} \cong \frac{eN_{\text{eff}}}{4\epsilon\epsilon_0} \left[\left(\lambda_y + \frac{\tau}{2} \right)^2 - \left(\frac{\tau}{2} \right)^2 \right] - \frac{eN_{\text{eff}}}{2\epsilon\epsilon_0} \left(\frac{\tau}{2} \right)^2 \ln \left(\frac{\lambda_y + \frac{\tau}{2}}{\frac{\tau}{2}} \right) - V_{bi}$$

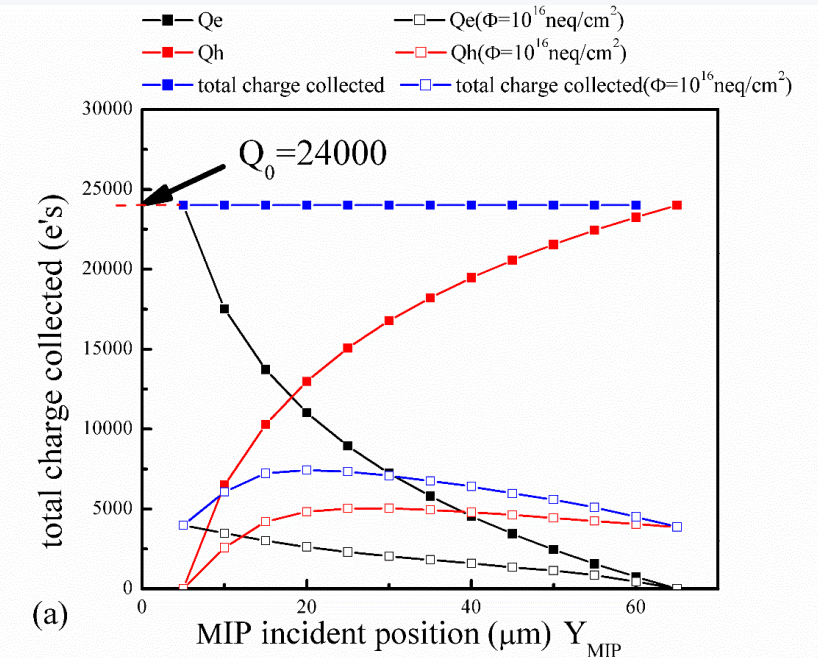
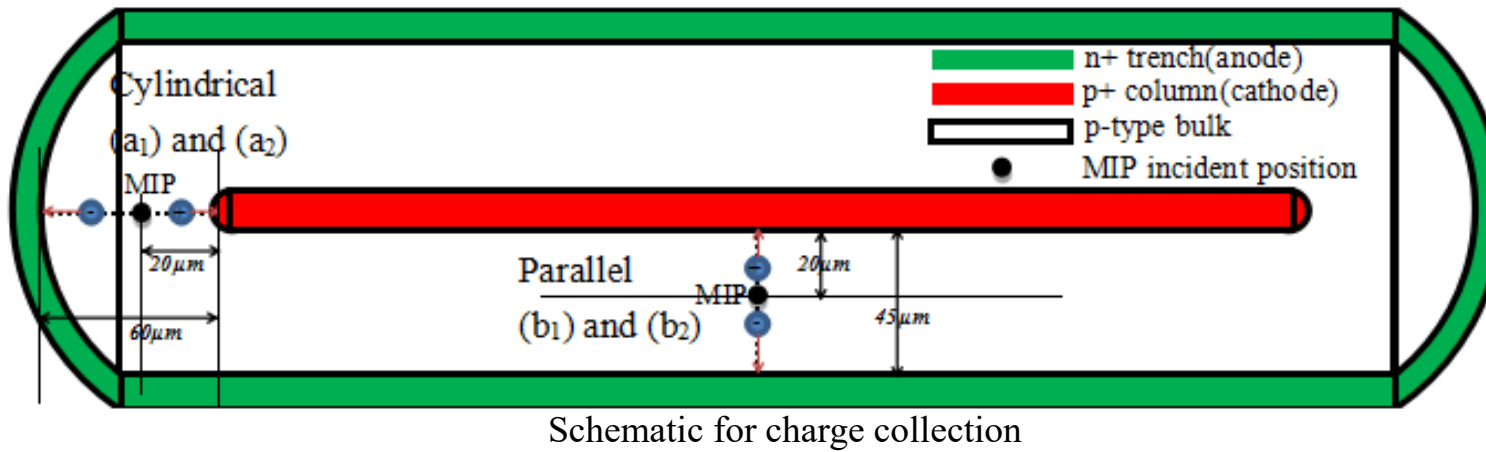
$$\lambda_x = \sqrt{\frac{1}{2} \left[\left(\lambda_y + \frac{\tau}{2} \right)^2 - \left(\frac{\tau}{2} \right)^2 \right] - \left(\frac{\tau}{2} \right)^2 \ln \left(\frac{\lambda_y + \frac{\tau}{2}}{\frac{\tau}{2}} \right)}$$

TCAD simulation



TCAD simulation (radiation damage)

How does the defect affect charge collection efficiency?



Defects affection:

$$i = Q \cdot \vec{E}_w \cdot \vec{v} \text{ and } Q = Q_0 \cdot \exp(-t/\tau)$$

$$i = Q_0 \exp(-t/\tau) \cdot E_w \cdot v \quad \text{Induce current}$$

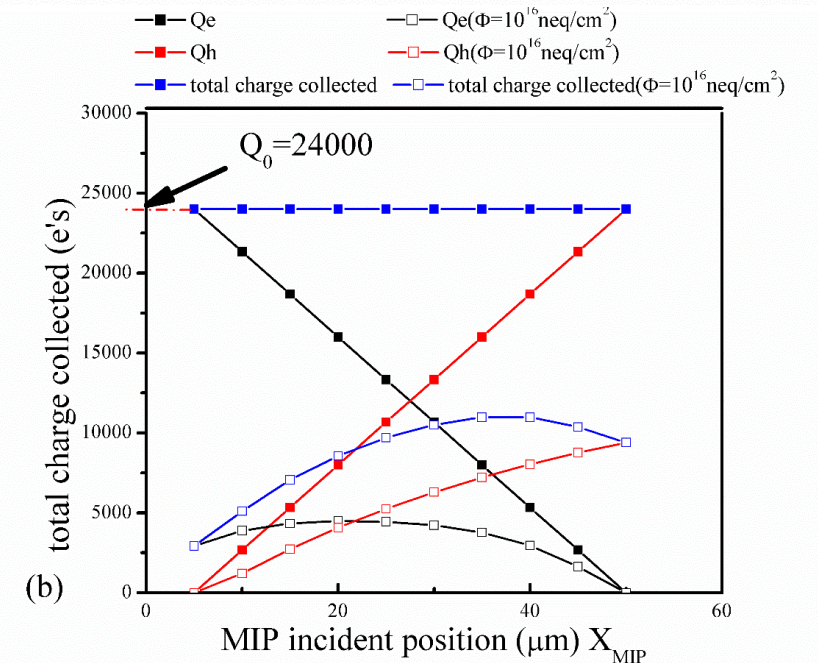
CCE

$$\tau_{te,h}^{-1} = \eta_{e,h} \phi_n$$

$$\begin{cases} E_w^{\text{parallel}} = \frac{1}{\lambda_x} \\ E_w^{\text{cylindrical}} = \frac{1}{r \ln \frac{r_t}{r_i - \lambda_y}} \end{cases}$$

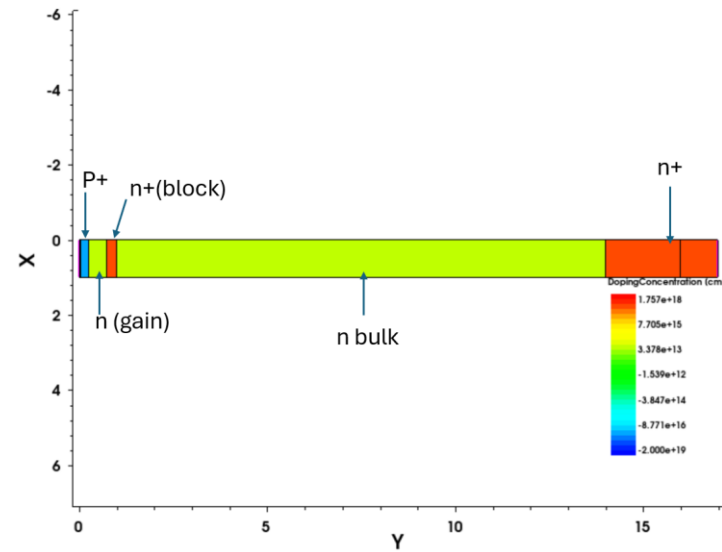
$$\begin{cases} Q_e = \int_0^{t_e} i_{r_i}^e(t_e) dt \\ Q_h = \int_0^{t_h} i_{r_i}^h(t_h) dt \end{cases}$$

$$v_{dr}^{e,h} = \frac{u^{e,h} E(r^{e,h})}{1 + \frac{u^{e,h} E(r^{e,h})}{v_s}}$$



TCAD simulation procedure (wide-bandgap semiconductor GaN)

1. Device structure establish



2. Material parameter input

Ionization {

Species("pMagnesiumActiveConcentration")

{

Type = Acceptor

E_0 = 0.17

alpha = 0.0

g = 4

Xsec = 1.0e-13

}

Species("nSiliconActiveConcentration") {

Type = Donor

E_0 = 0.02

alpha = 0.0

g = 2

Xsec = 1.0e-13

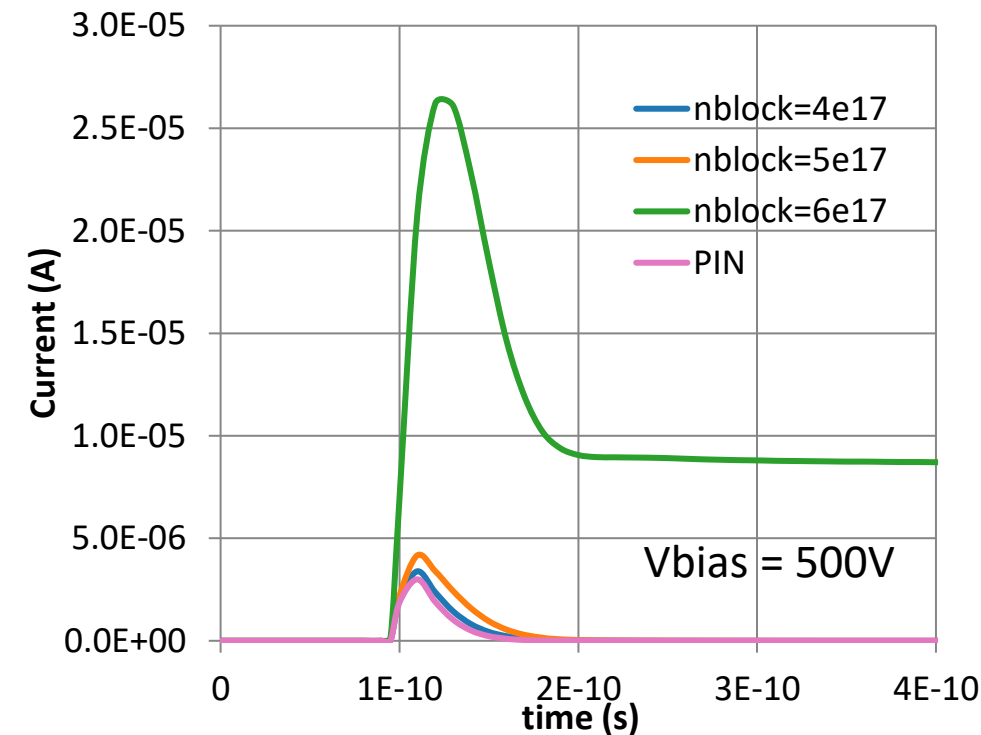
}

}

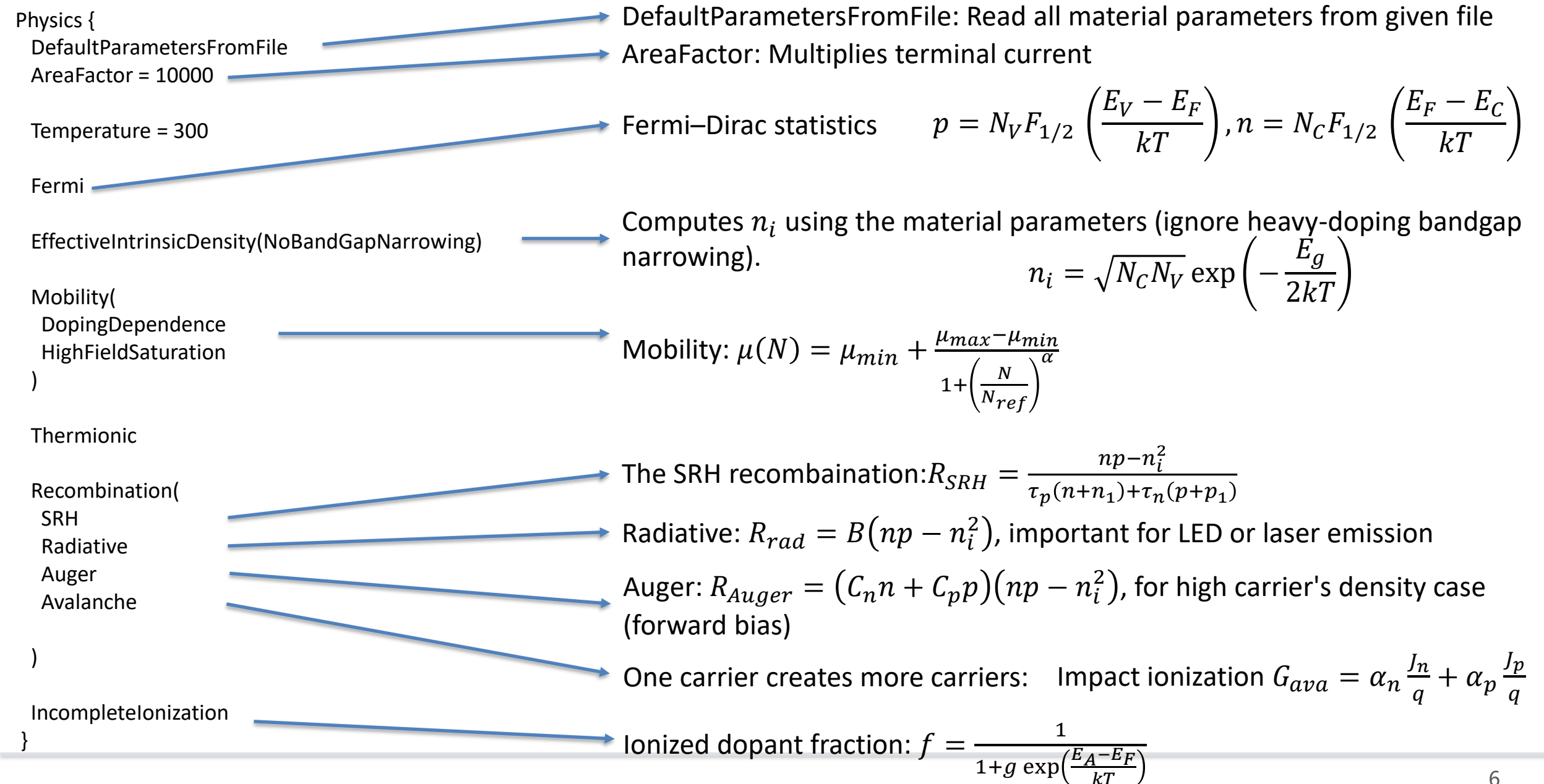
3. Simulation methods:

- I-V:
- C-V:
- Pulse simulation: heavy ions, light injection

heavy ions:



TCAD simulation (essential model for simulation)



Defects in Simulation

```

Physics (Region="Ndrift") {
  Traps(
    * Defect 1: midgap trap, mainly SRH low-bias generation
    (
      Donor Uniform fromMidBandGap
      EnergyMid  = 0
      EnergySig  = 0.01
      Conc      = @conc_mid@
      eXsection  = @eXsec_mid@
      hXsection  = @hXsec_mid@
      PooleFrenkel
    )
    * Defect 2: shallow trap, mainly PF/TAT field-assisted leakage
    (
      Donor Uniform fromMidBandGap
      EnergyMid  = @traplevel@
      EnergySig  = @DE@
      Conc      = @conc@
      eXsection  = @eXsec@
      hXsection  = @hXsec@
      TrapVolume = 6e-4
      HuangRhys  = 10
      PhononEnergy = 0.0912
      eBarrierTunneling(
        Nonlocal="TAT_from_n"
        Nonlocal="TAT_from_p"
      )
      hBarrierTunneling(
        Nonlocal="TAT_from_p"
        Nonlocal="TAT_from_n"
      )
      PooleFrenkel
    )
  )
}

```



Carrier’s lifetime is affected by deep defect:

$$\tau_n = \frac{1}{\sigma_n v_{th} N_t}$$

$$\tau_p = \frac{1}{\sigma_p v_{th} N_t}$$

Leakage current:

$$I_{leak} \propto \frac{1}{\tau} \propto \sigma N_t$$

Poole Frenkel effect (lower the barrier of conduction/valence band):

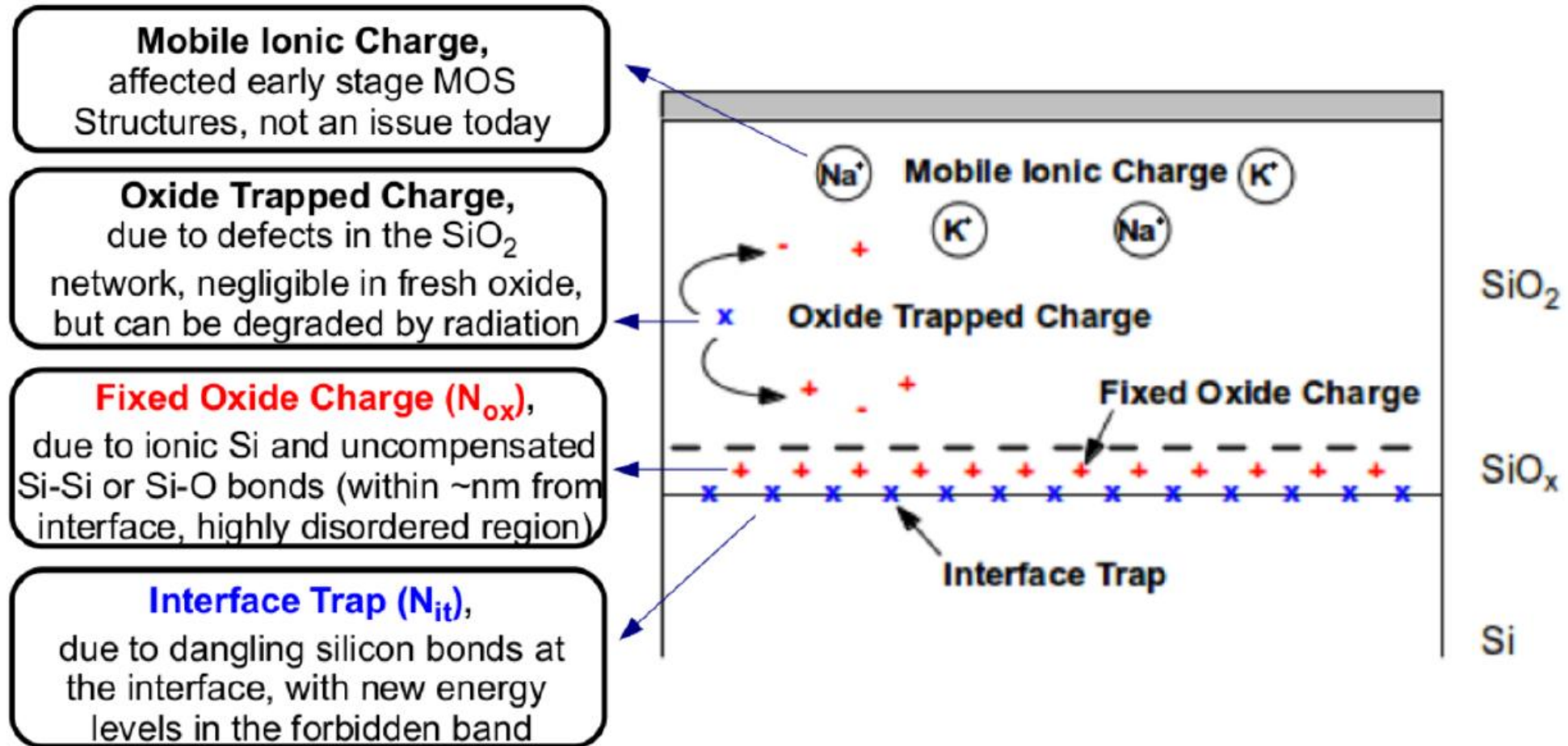
Barrier lowering: $\Delta E_{PF} = \sqrt{\frac{q^3 E}{\pi \epsilon}}$

Increases emission rate: $e(F) = e(0) \exp\left(\frac{\Delta E_{PF}}{kT}\right)$

TAT is a tunneling model, main describe the high field effect (close to breakdown field)

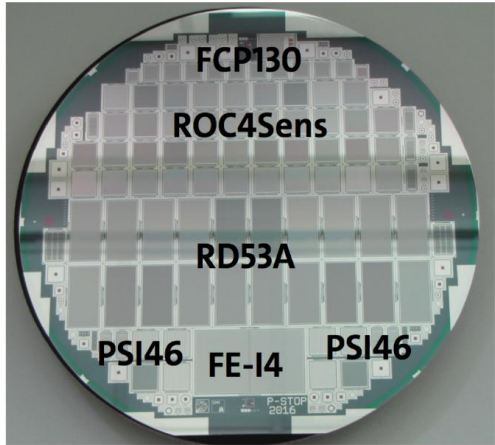
Journey of Defects (Surface) (Bulk)

Surface damage

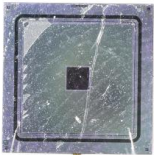


Surface damage

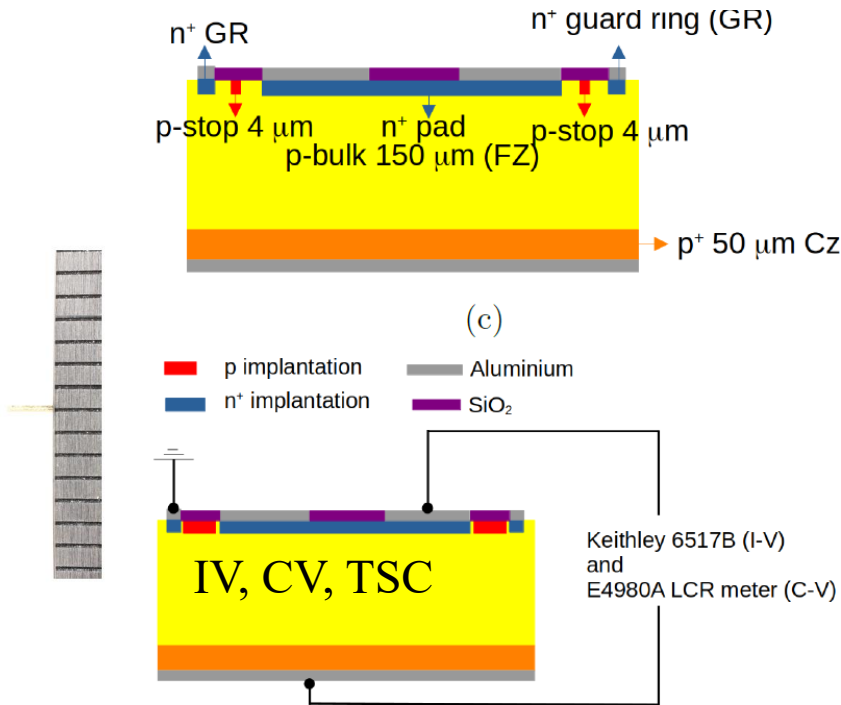
My journey



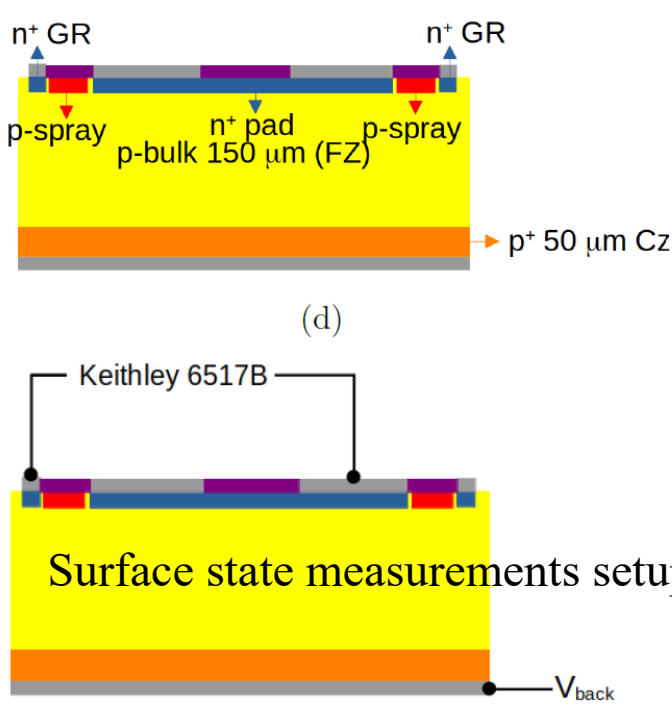
(a)



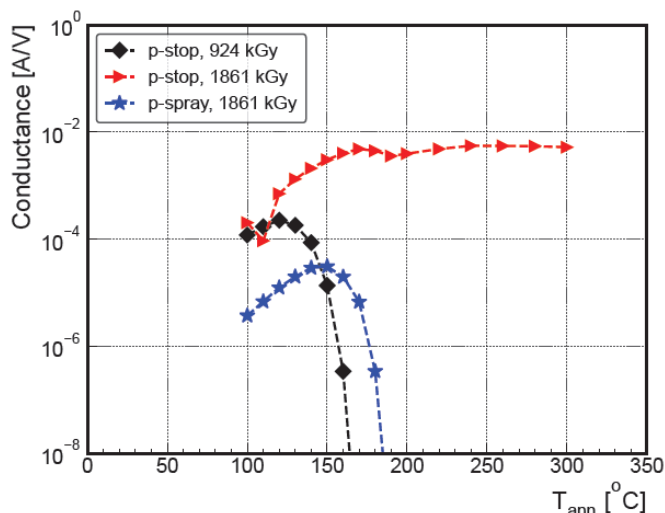
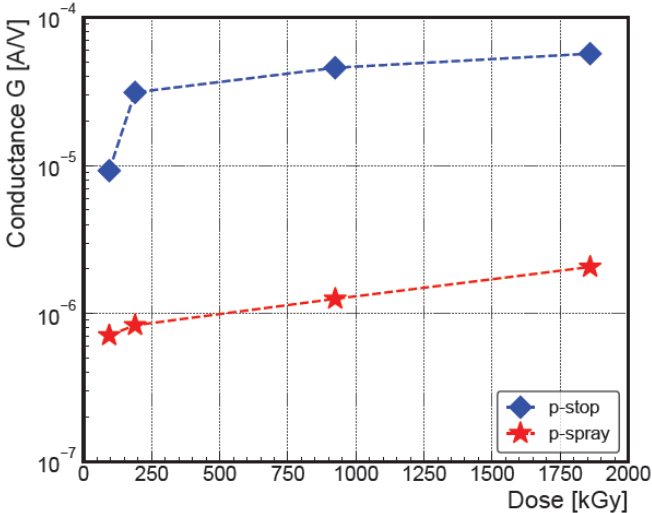
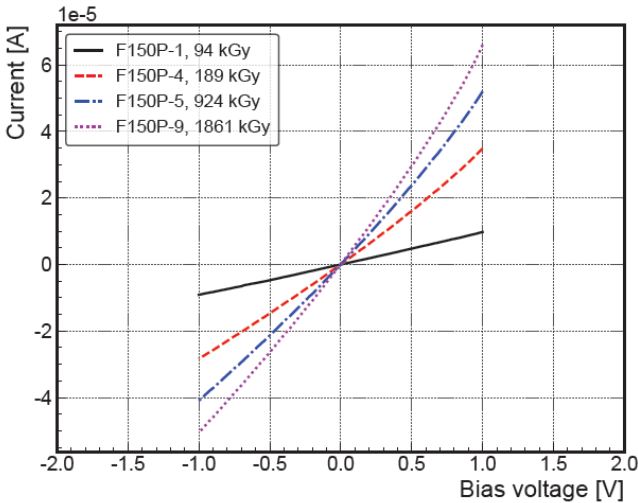
(b)



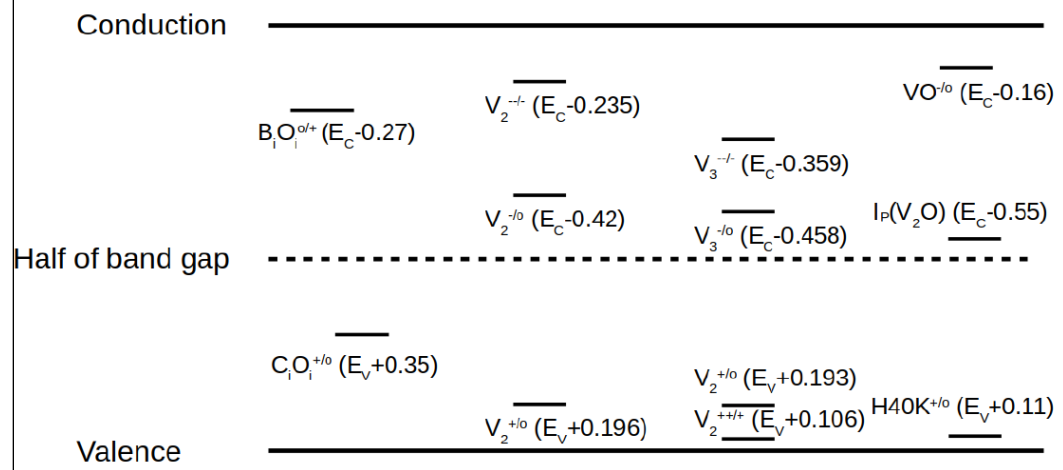
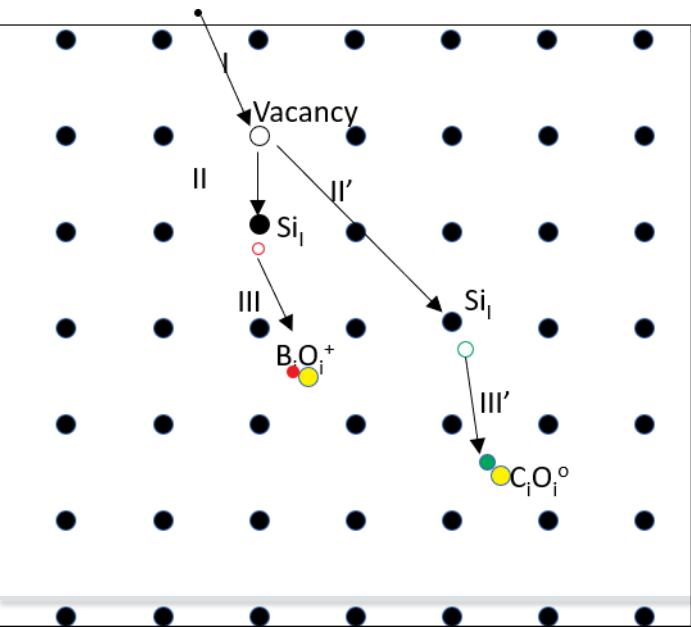
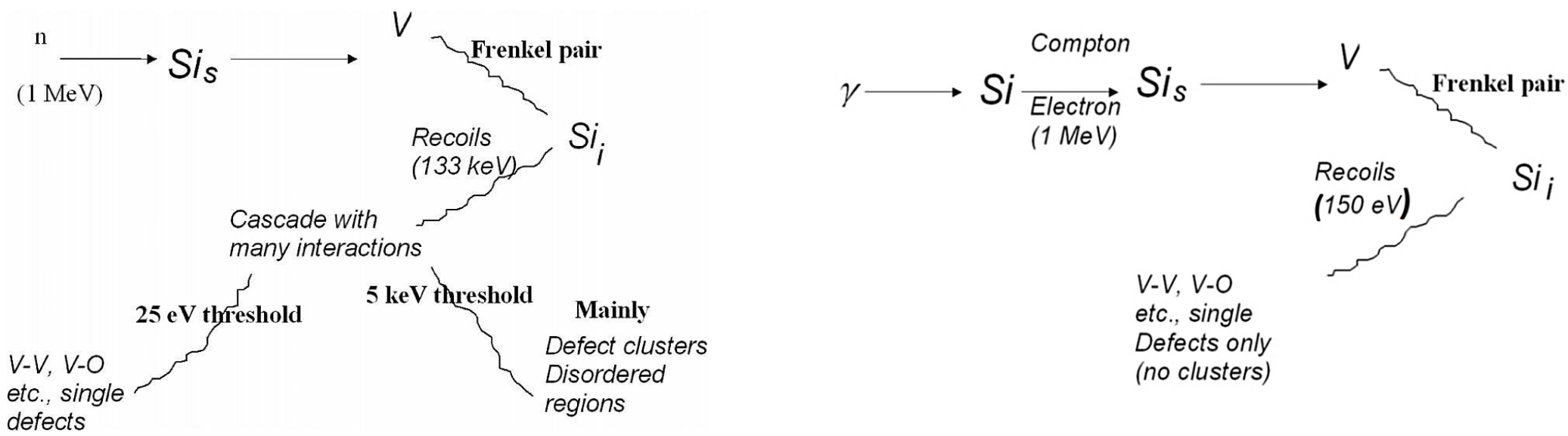
(e)



(f)

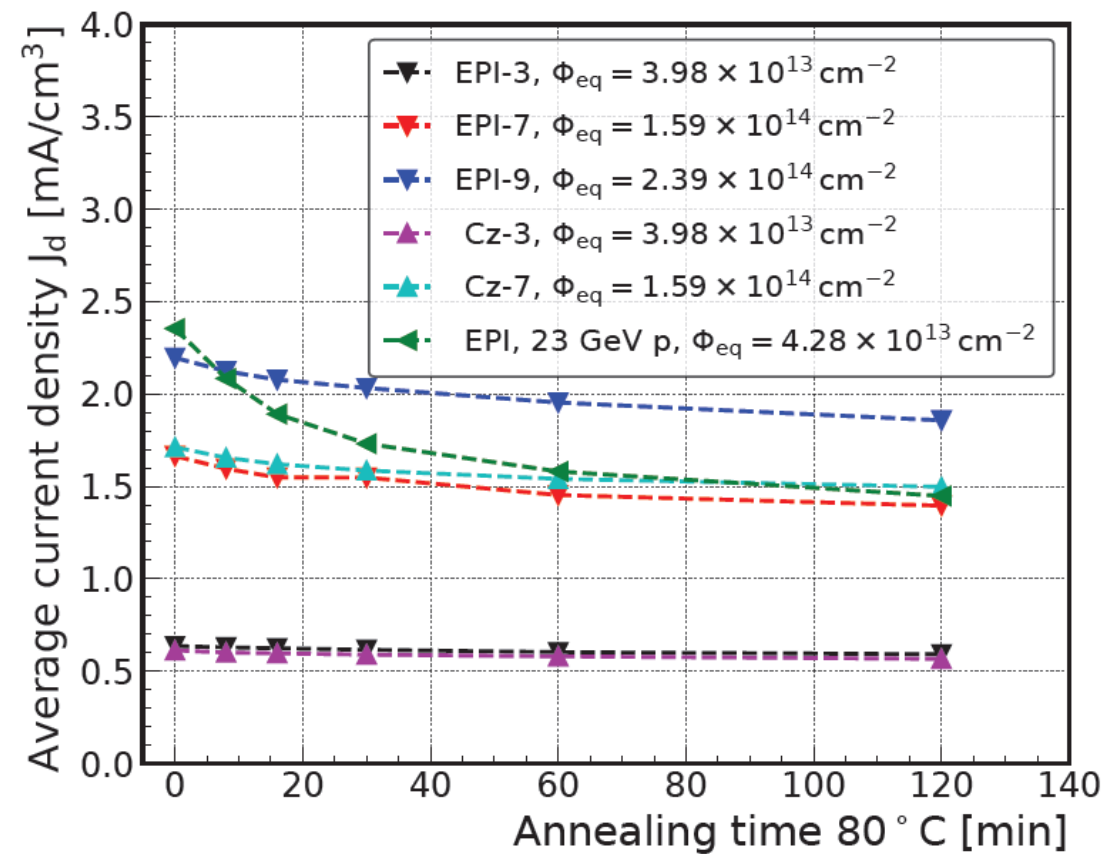


Bulk Defects

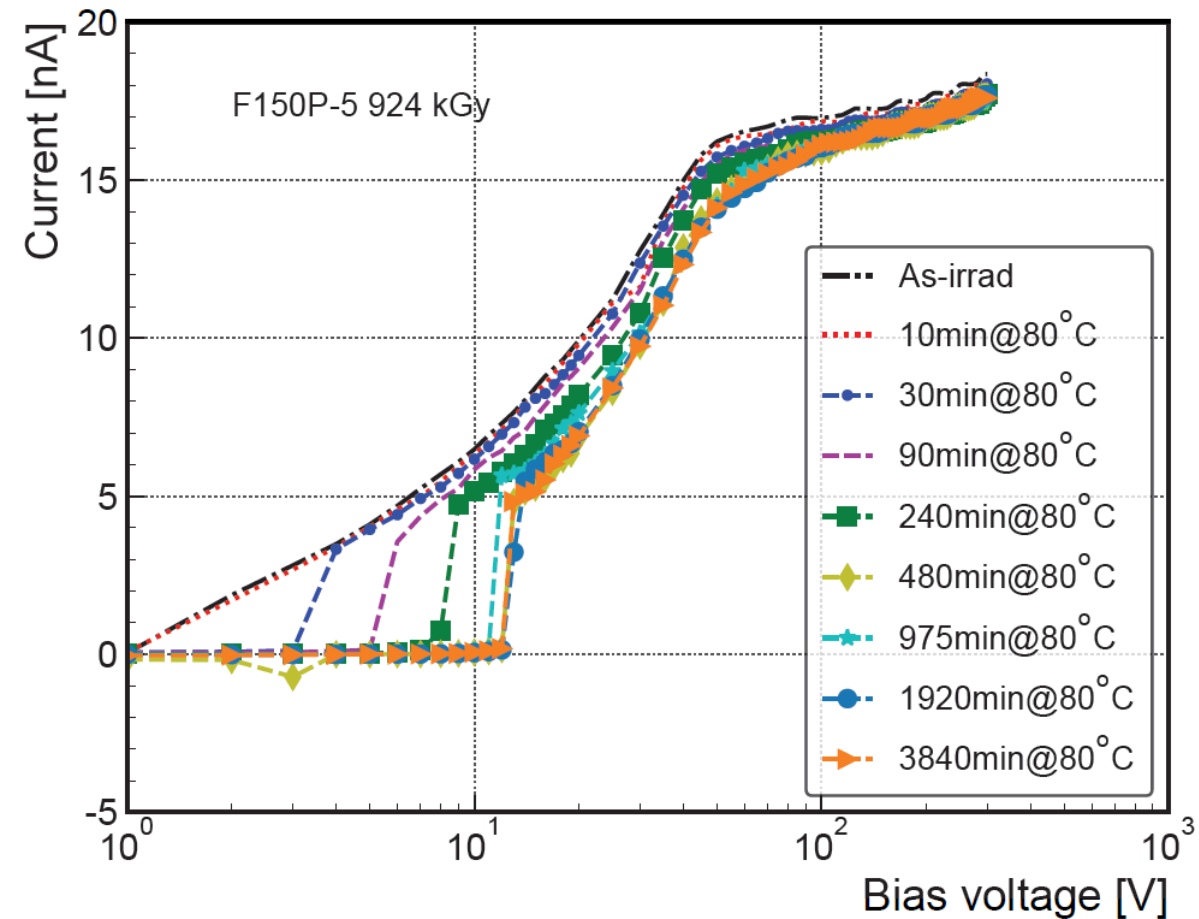


- Macroscopic behaviour:**
- Increase of leakage current (dark current)
 - Change of effective space charge density
 - Decrease of charge collection efficiency
 - Decrease of gain value in LGADs

Defect properties identification (different particles)



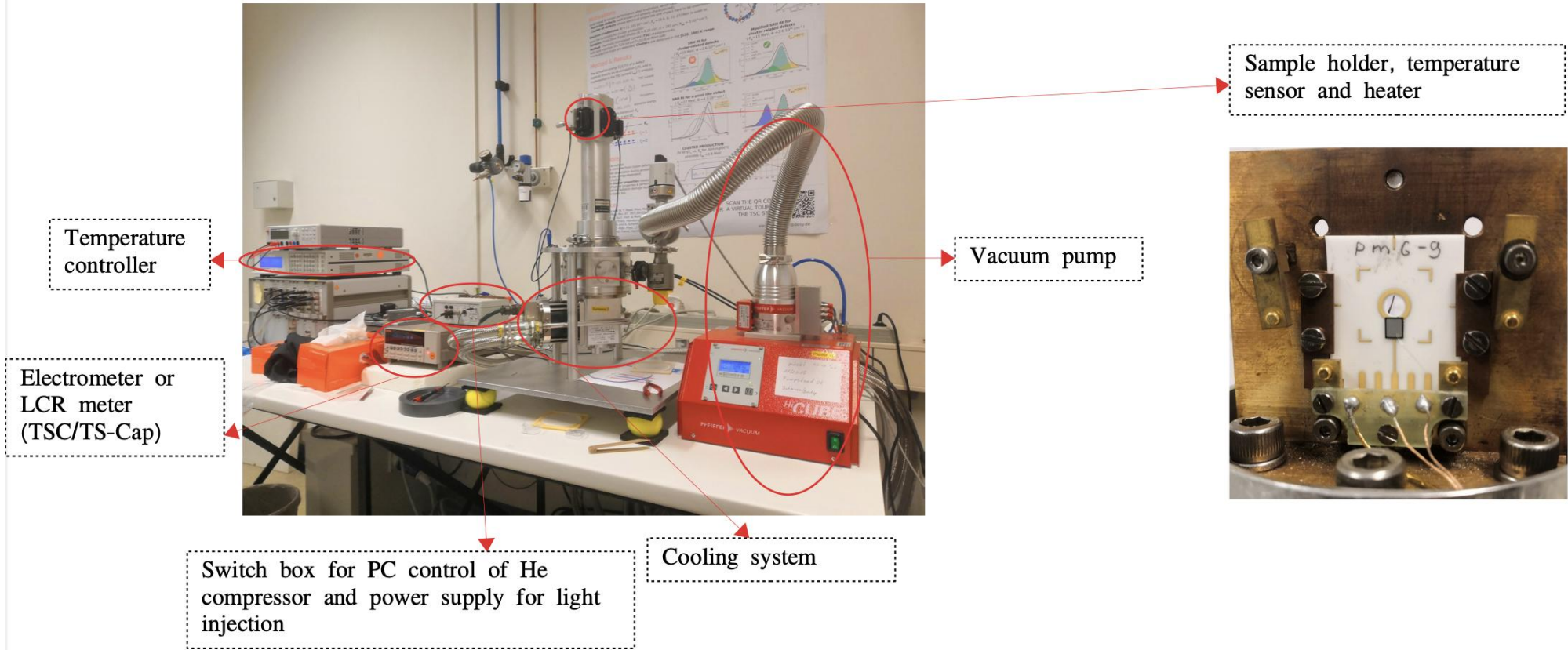
Particle irradiation



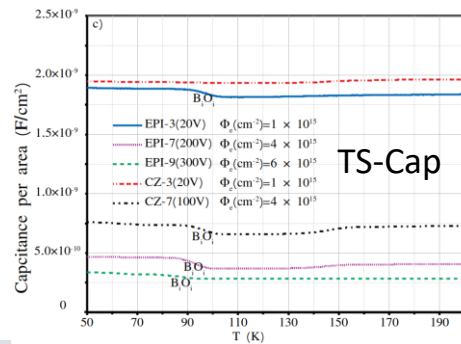
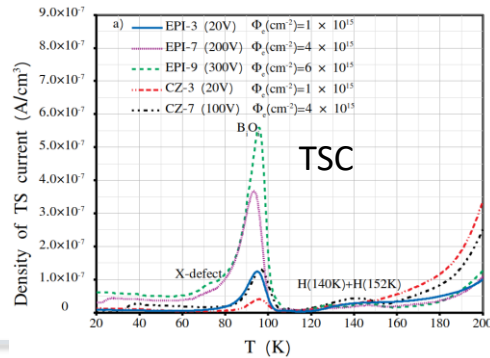
⁶⁰Co gamma-ray

Defects engineering

Thermally Stimulated Current or capacitance – TSC or TS-Cap:



Measurements:

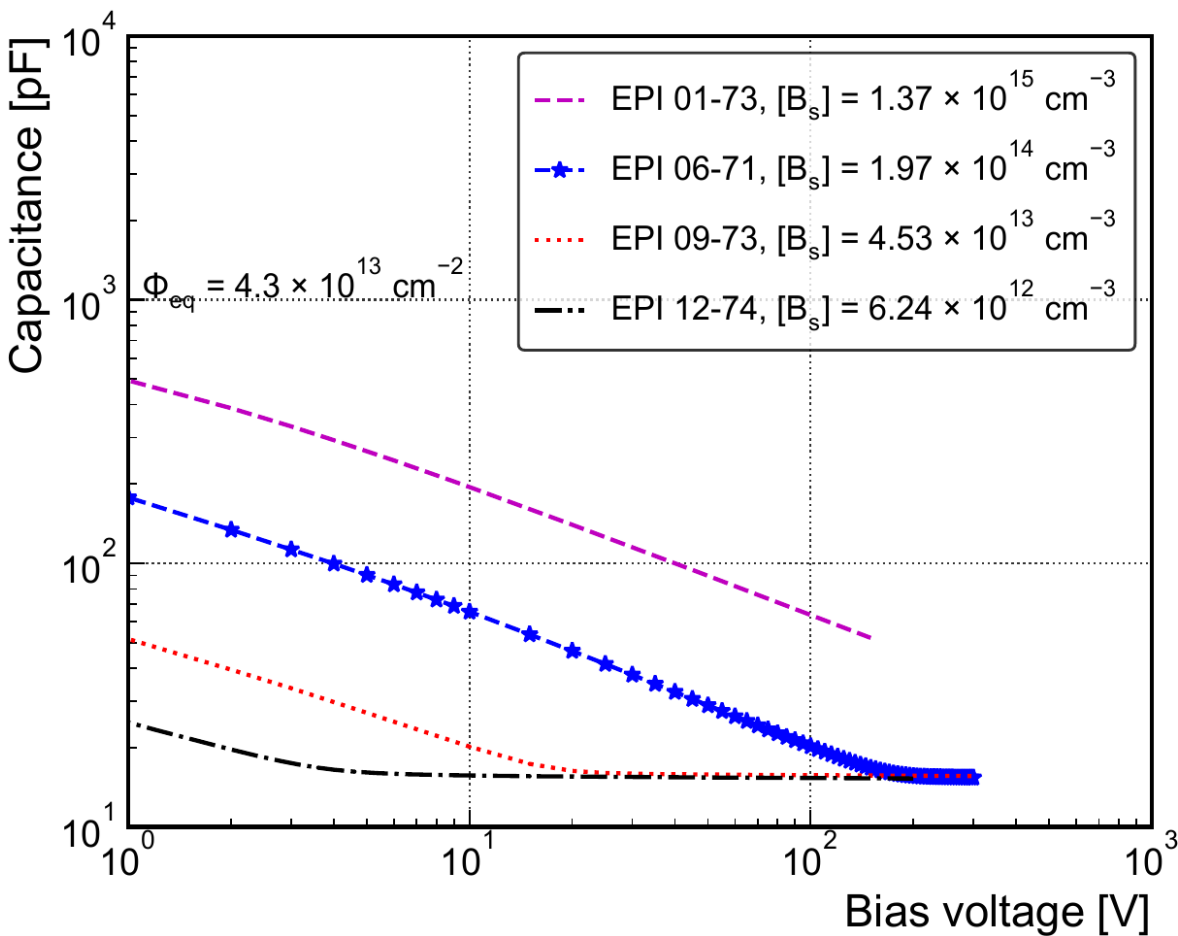


→ $E_t, N_t, \sigma_{e,h}$

By studying the defects formed by different elements, the detector fabrication process can be improved.

← Variation in doping elements, radiation type, and dose

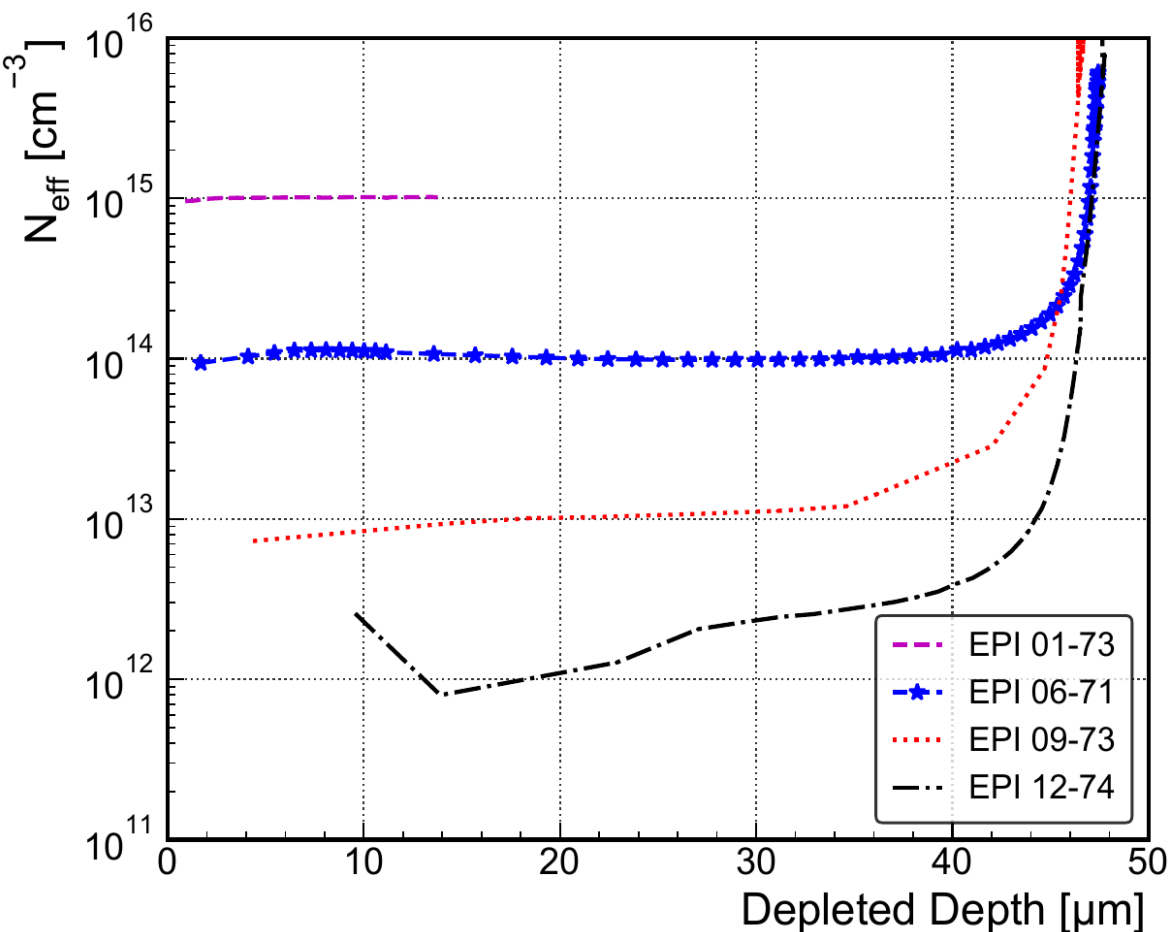
Defect properties identification (Space charge density or effective doping)



C-V. Measurement parameter: T=20 °C, Freq = 10 kHz

N_{eff} extracted from C-V:

$$N_{eff} = \frac{2}{\epsilon_0 \epsilon_r A^2 q_0} \frac{d(1/C^2)}{dV}$$



N_{eff} profile extracted from the figure shown on the left

Depleted depth $W(V)$:

$$W(V) = \frac{\epsilon_0 \epsilon_r A}{C(V)}$$

Defect properties identification (Defect information extraction)

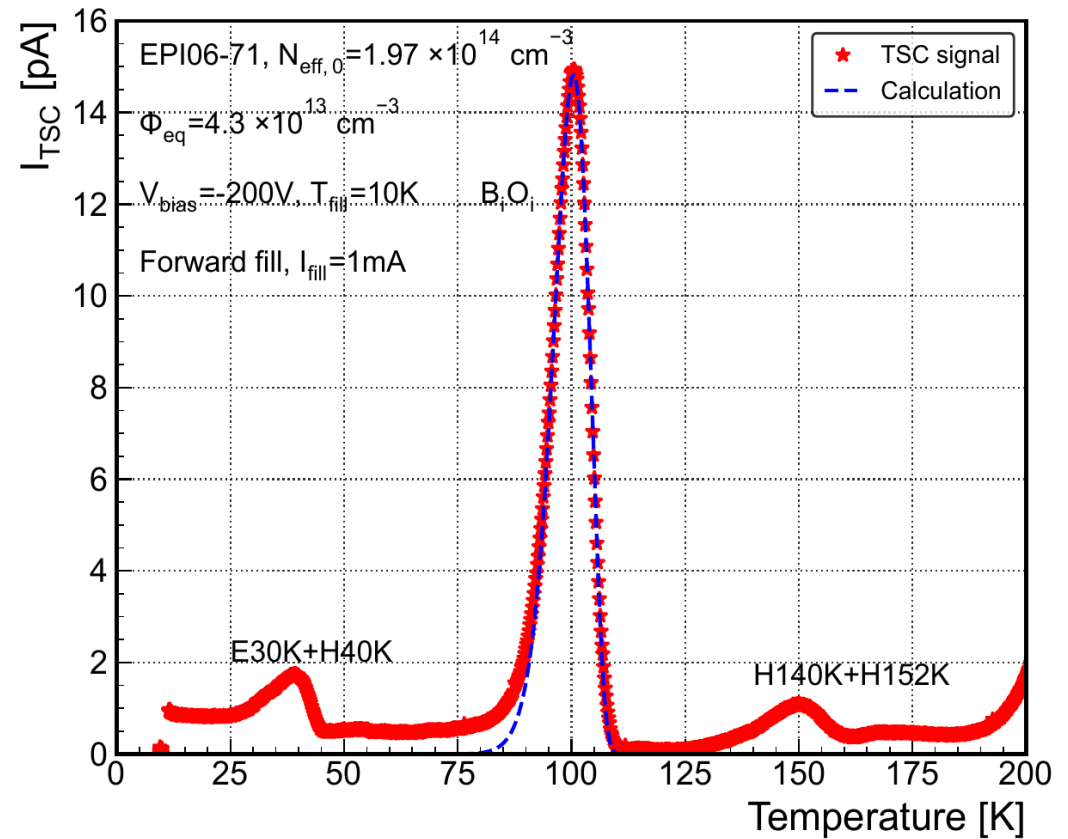
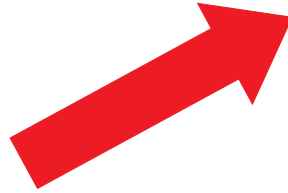
$$I_{tsc} = \frac{1}{2} q_0 A d N_t e_n \exp\left(-\frac{1}{\beta} \int e_n(T) dT\right)$$

$$e_n = \sigma_n v_{th,n} N_c \times \exp\left(\frac{-E_a}{k_B T}\right)$$

$$E_a = E_C - E_T$$

N_t is defect concentration; β is heating rate; σ_n is capture cross section; E_a is activation energy; A is diodes area; d depleted thickness; [1, 2]

$$\begin{aligned}\sigma_n &= 1.05 \times 10^{-15} \text{ cm}^2 \\ E_a &= 0.25 \text{ eV} \\ N_t &= 3.5 \times 10^{13} \text{ cm}^{-3}\end{aligned}$$



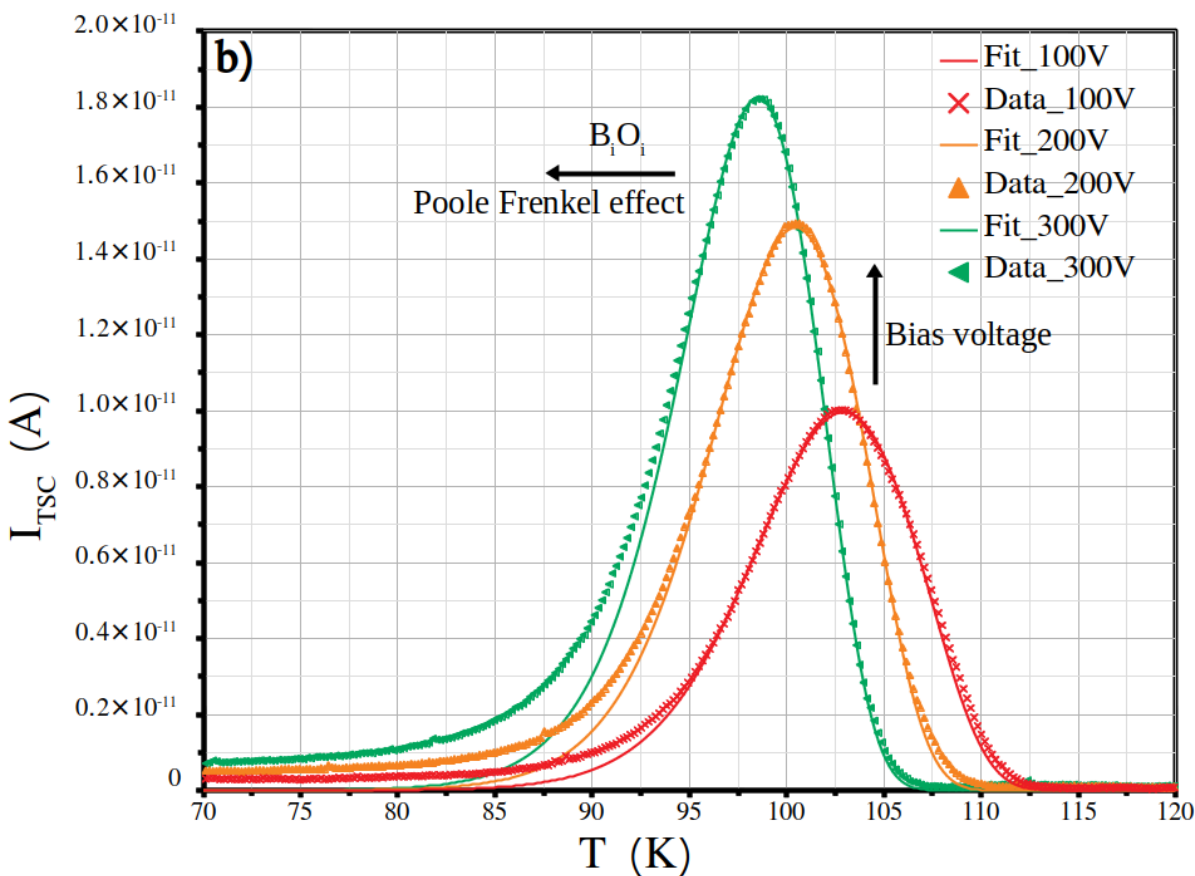
Example of calculated BiO_i peak

$$N_t \approx n_t(T_{fill}) \text{ or } p_t(T_{fill}) = \frac{2 \int_{T_s}^{T_e} I_{TSC}^{e,h}(T') dT'}{q_0 A d}$$

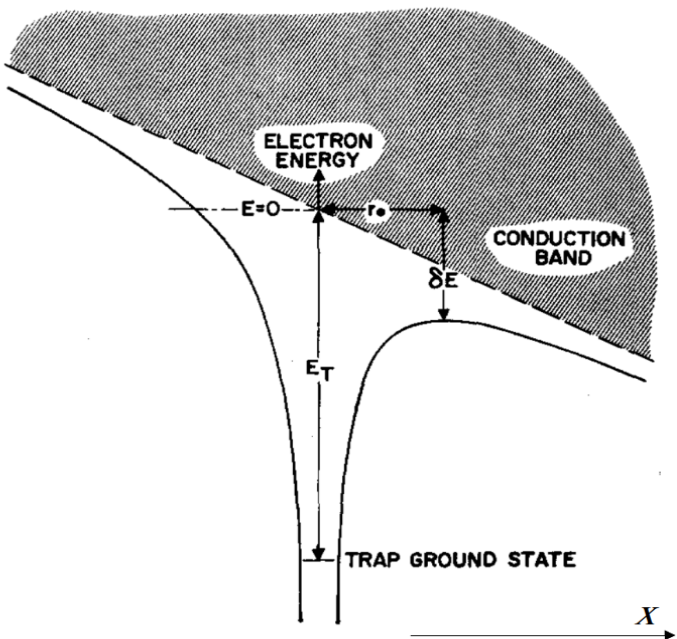
[1] C. T. Sah et al., Solid State Electron, vol. 13, no. 6, pp. 759-788, 1970.

[2] M. G. Buehler, vol. 15, no. 1, pp. 69-79, 1972.

Defect property identification (identifying point defect – Poole Frenkel effect)



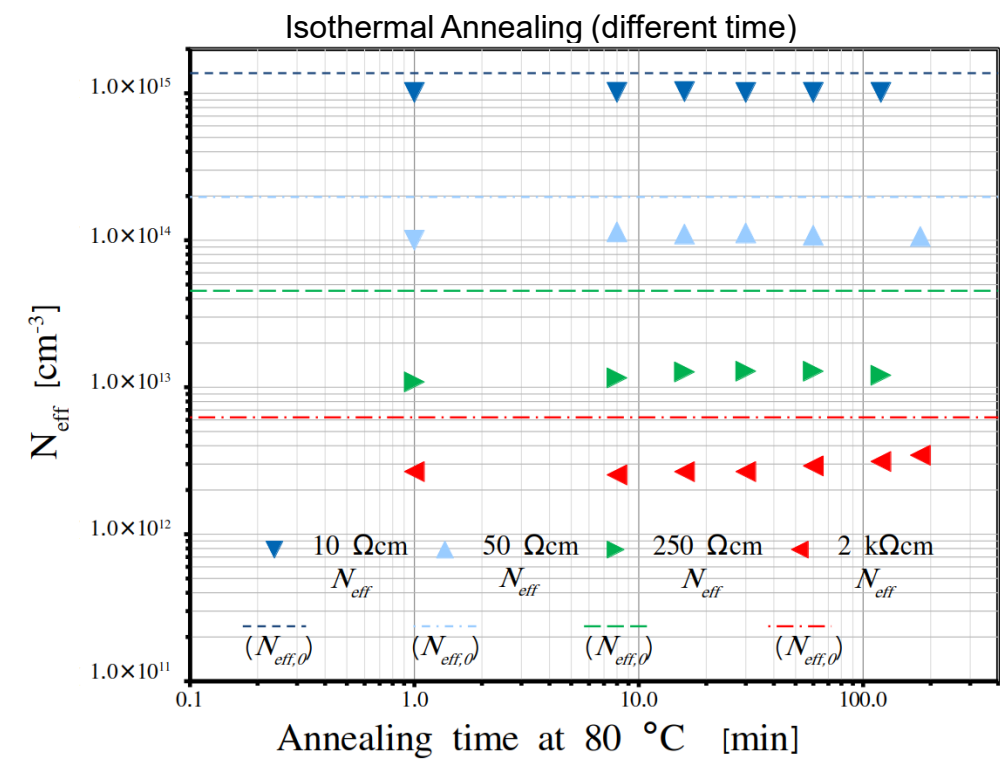
TSC spectra with forward bias filling (10 V) and $T_{fill} = 10$ K
different V_{bias}



- Shift of peak maximum with V_{bias} → Poole Frenkel effect [1]
- Peak amplitude increases with bias voltage due to increase of depleted volume [2]
- The extracted zero field $E_a \rightarrow E_{a,0} \approx \mathbf{0.27-0.275}$ eV [2]

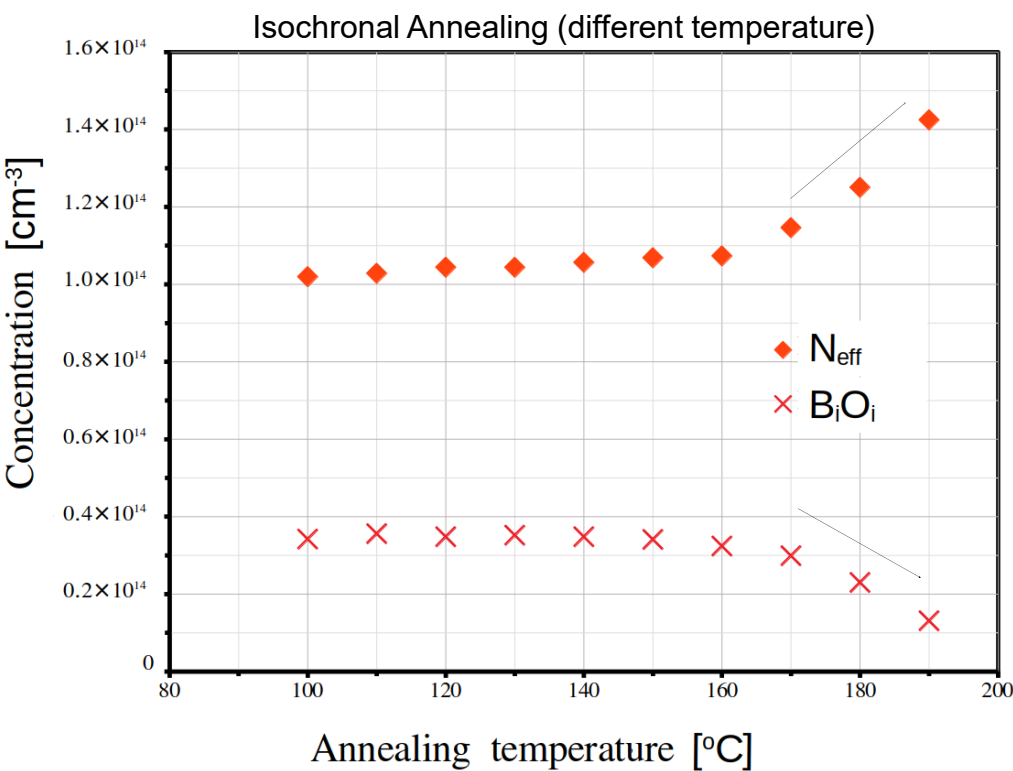
[1] J. L. Hartke, J. Appl. Phys. 39, 4871 (1968).
[2] C. Liao et al., IEEE Trans. Nucl. Sci, vol. 69, no. 3, pp. 576–586, 2022.

Defect properties identification (defects analysis)



N_{eff} is given by average value of N_{eff} profile in the bulk

- N_{eff} stable

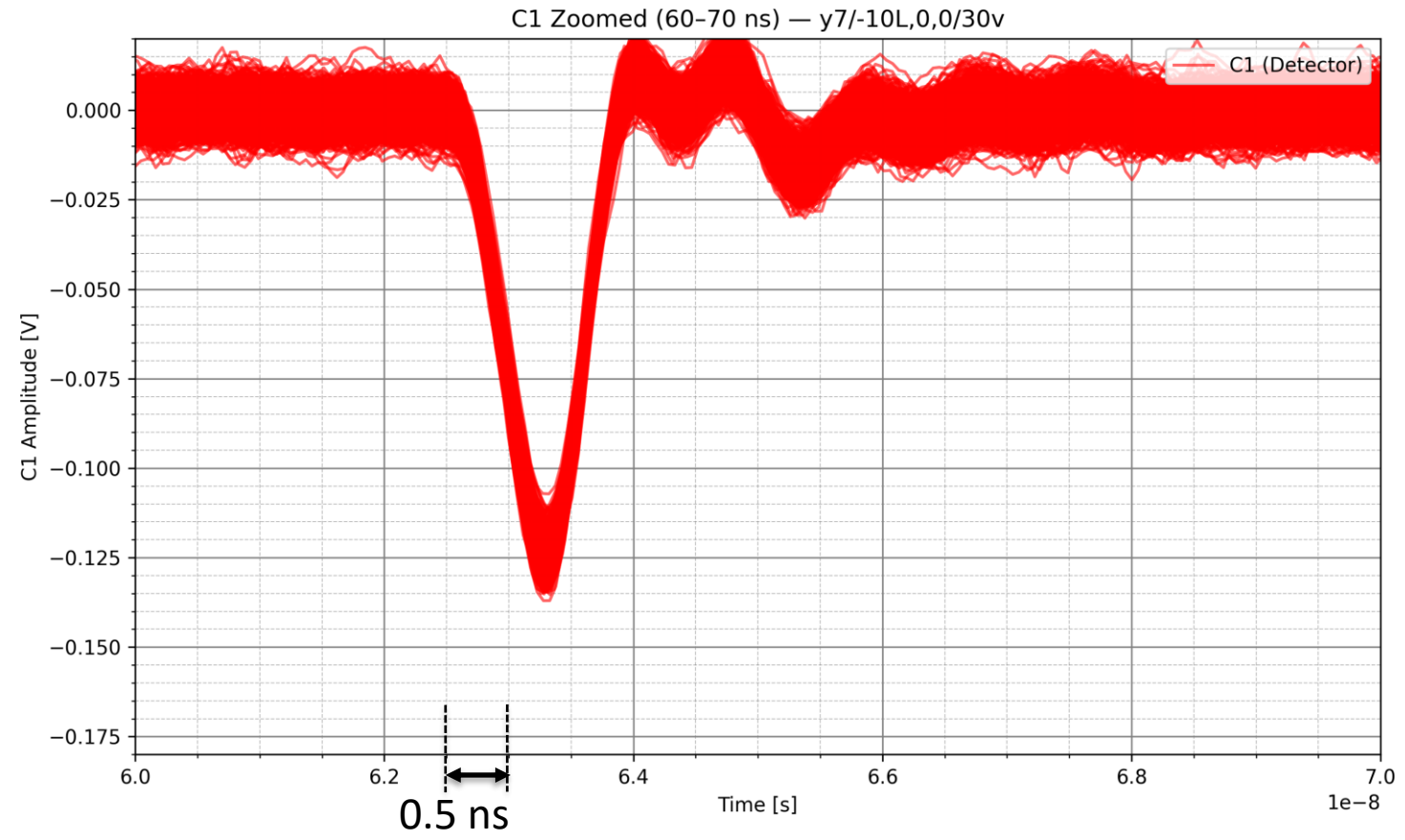
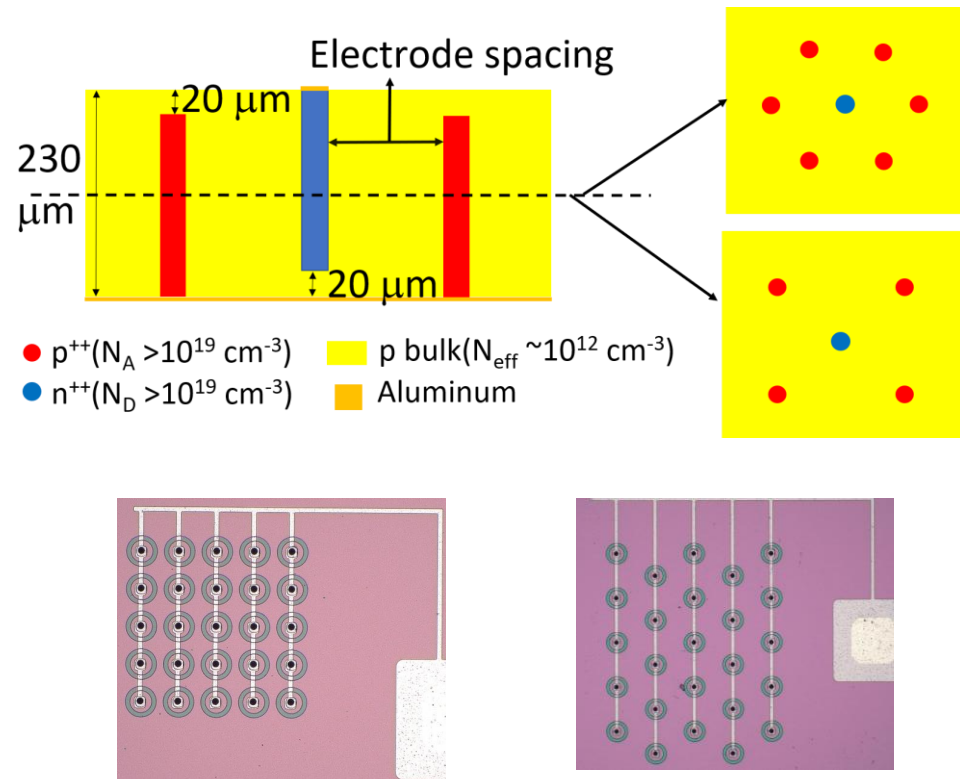


N_{eff} and B_iO_i concentration vs. T_{ann} measured on 50 Ωcm diodes

- If $T_{ann} > 150$ °C, B_iO_i concentration decrease
- $\Delta N_{eff} \approx 2 \times \Delta N_t (B_iO_i)$ as expected from $B_s(-) \rightarrow B_iO_i(+)$

Journey of Detector Readout

Fast readout for 3D silicon detector

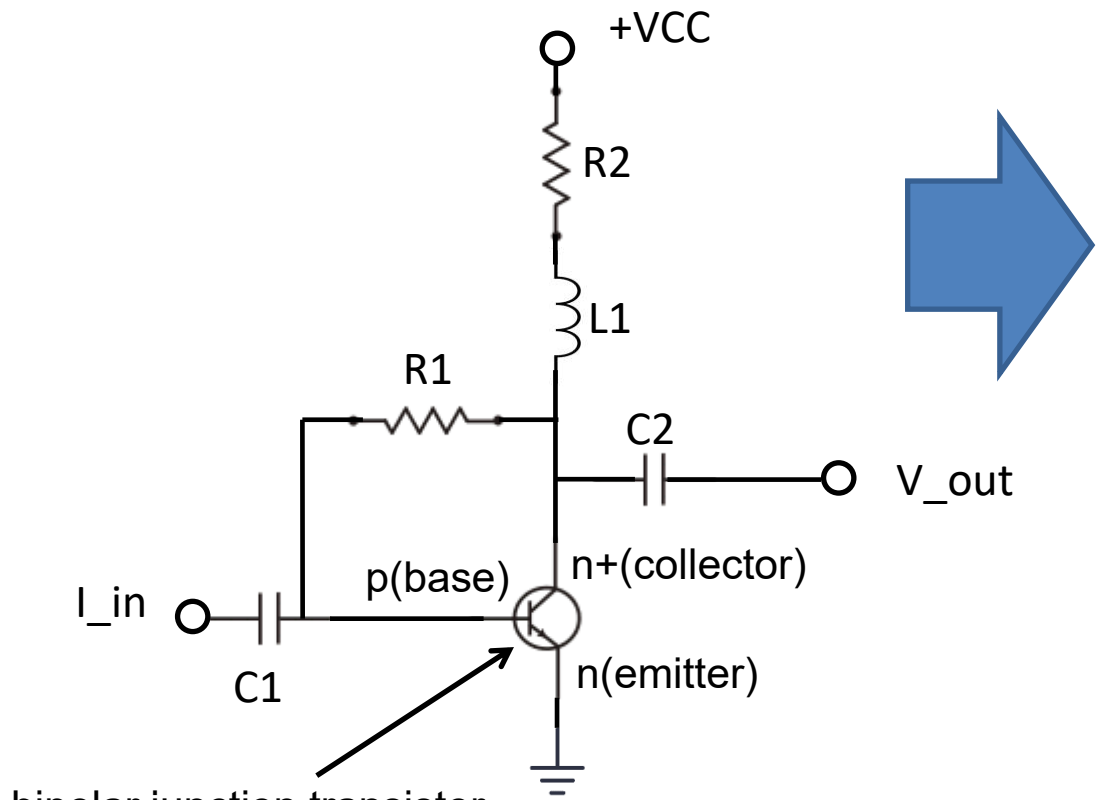


3D detector(depends on the design):

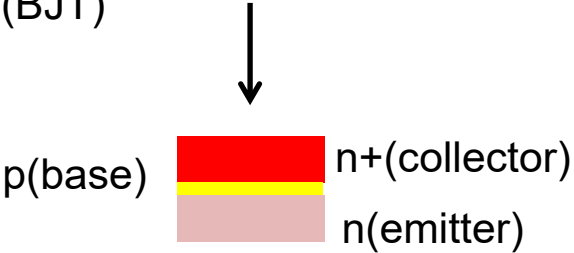
- Tiny current: 0.1-1 μA
- Fast ramp up: 200-400 ps

3D detector IR laser test results

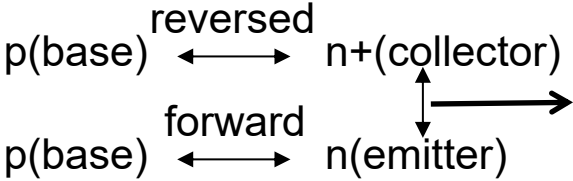
BJT based Transimpedance amplifier



bipolar junction transistor (BJT)



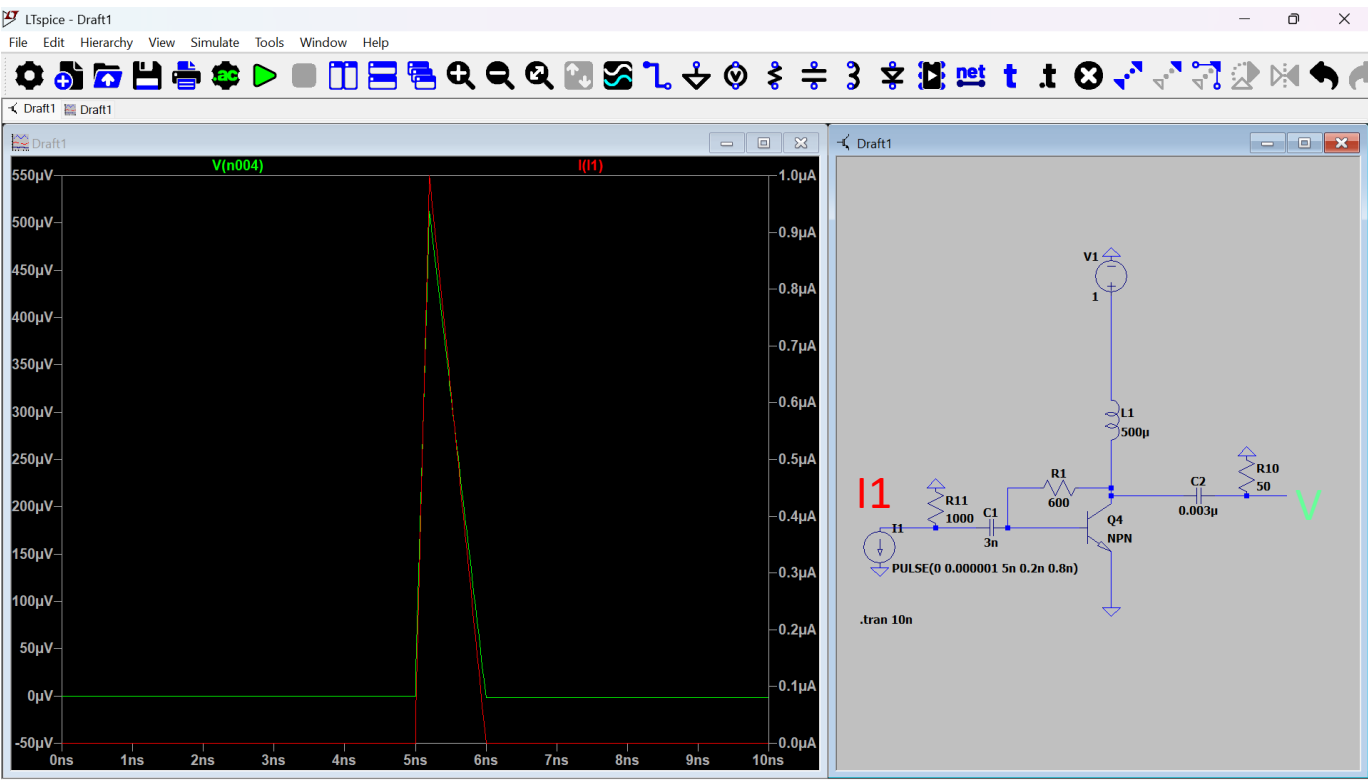
Positive Vcc on p-base (~0.7 V):



If "p" is thin enough, it will short

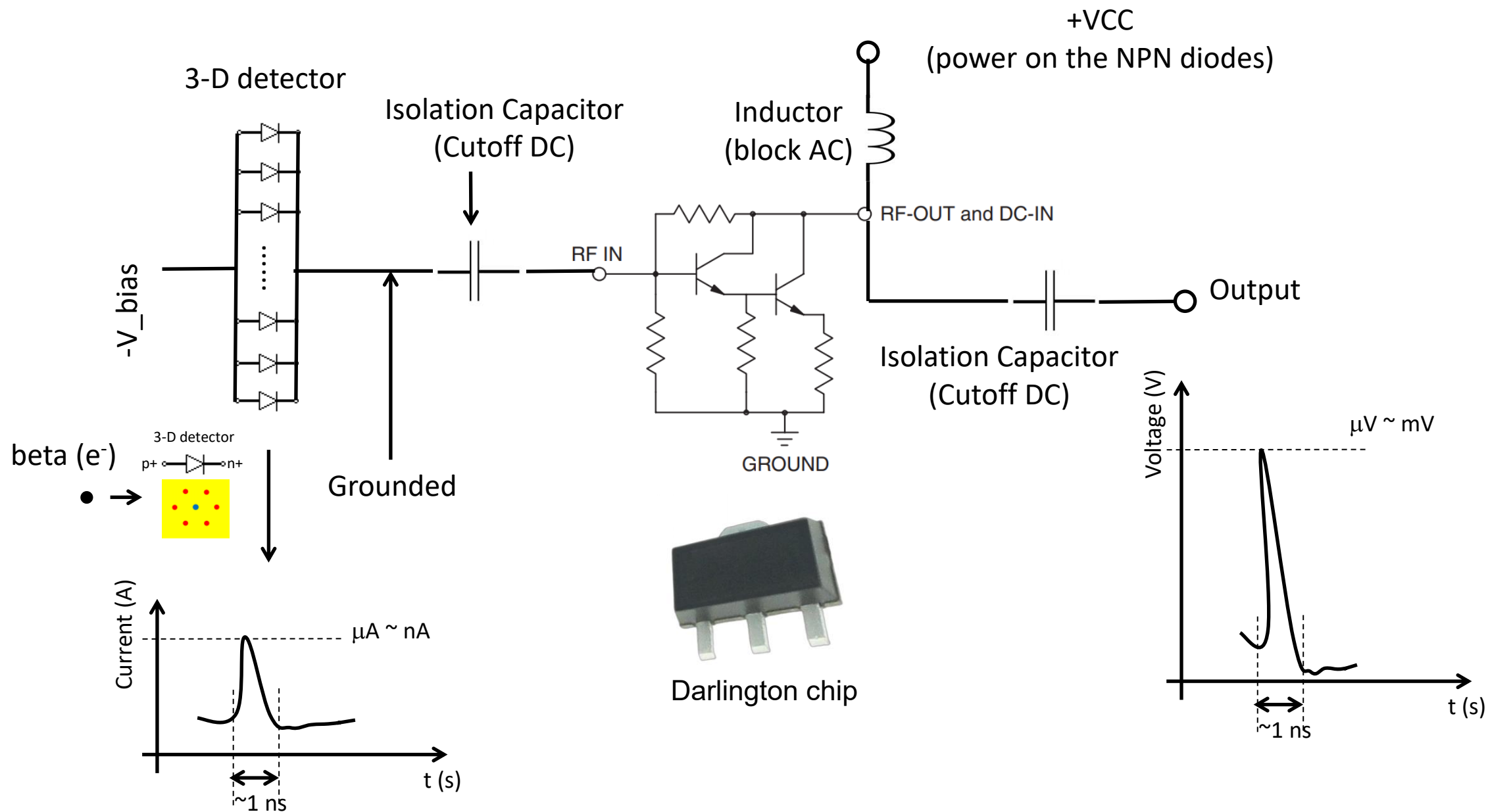
If:
 C_{pn+} is 0
 $R_{pn} \gg R1$

$V_{out} \approx R1 \cdot I_{in}$



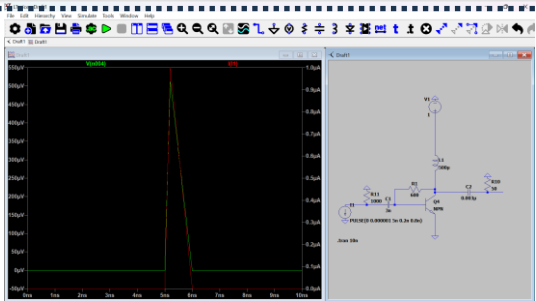
LTspice simulation of the default NPN transistor (For details, please refer to the backup)

Darlington chip



Detector Readout design

Ltspice simulation



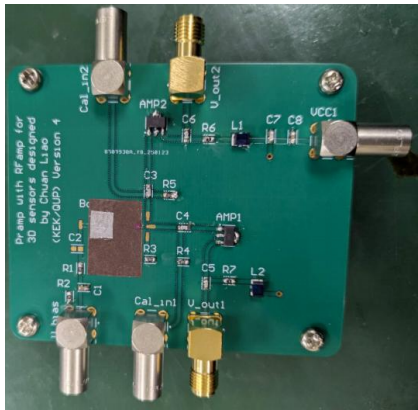
Adjust and feedback



PCB assembly and test



Second stage amplifier



Pre-amplifier

Adjust and feedback

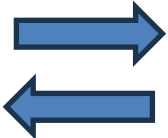


AC signal test



Pulse generator

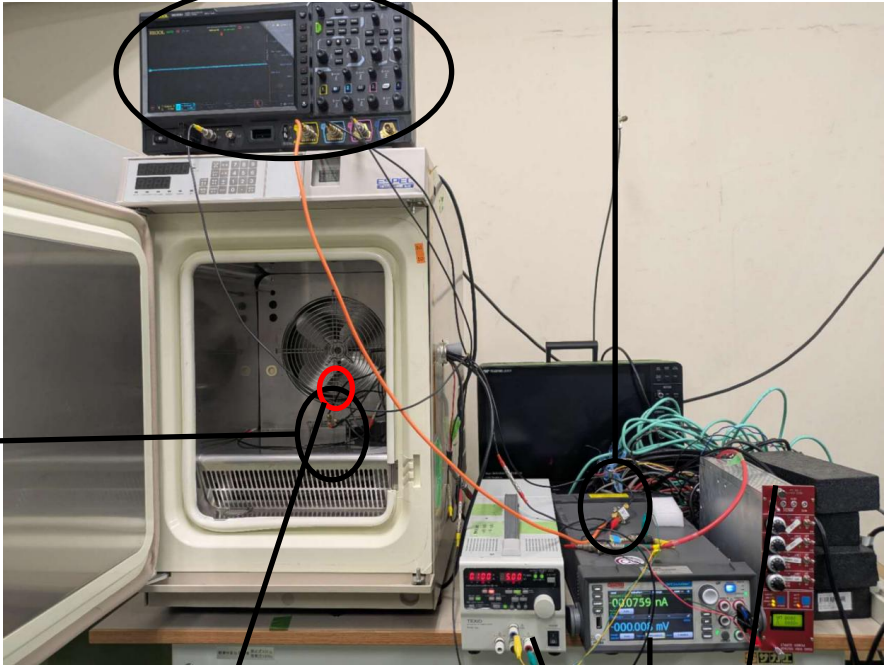
Adjust and feedback



Radiation test

Oscilloscope
MSO8064/600Mhz

2 stage amplifier

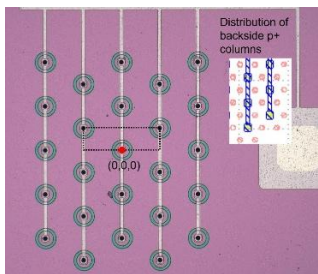


⁹⁰Sr source
(perpendicular to the detector)

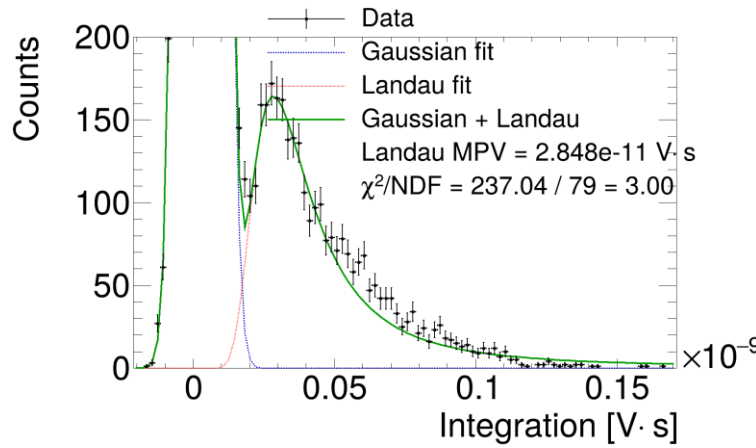
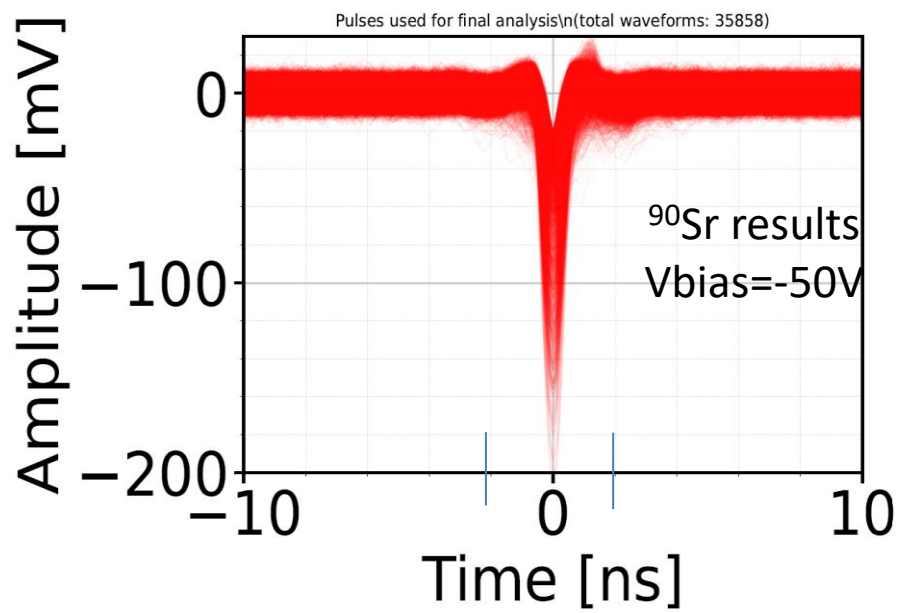
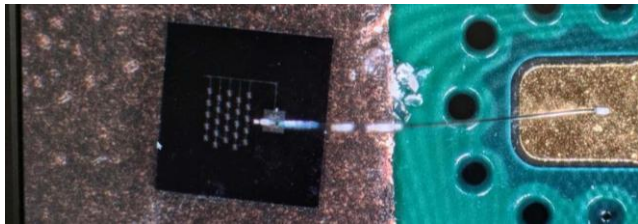
Power supply

MIP test with readout

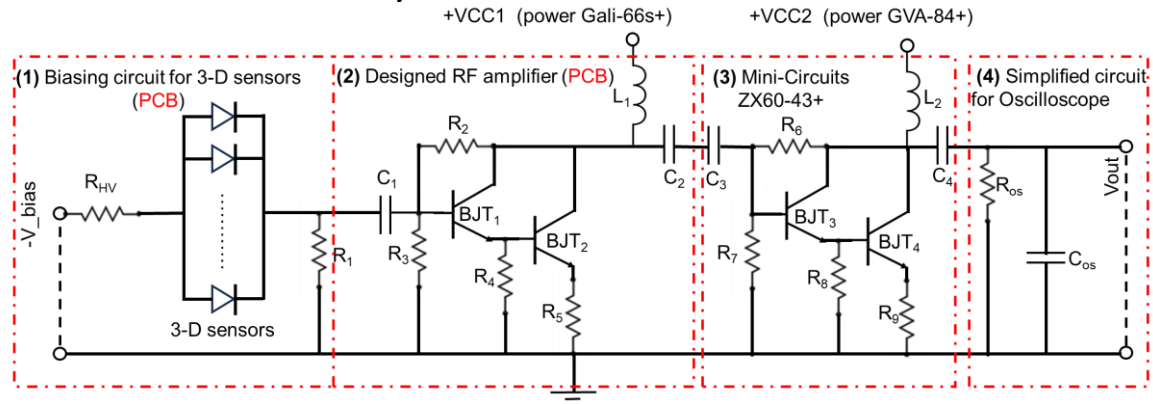
3D sensors from CNM



3D sensors on PCB



Front-end readout system



- Noise σ : $\sim 4 \text{ mV}$
- Bandwidth: $> 4 \text{ GHz}$
- Voltage gain: 200 times larger

Collected charge:

$$Q = \frac{MPV}{13 \cdot R_2 \cdot 1.6 \times 10^{-19}}$$

For all sensors:

$$Q \approx 18000 e$$

The expected value is around **17000** electrons from Bethe.

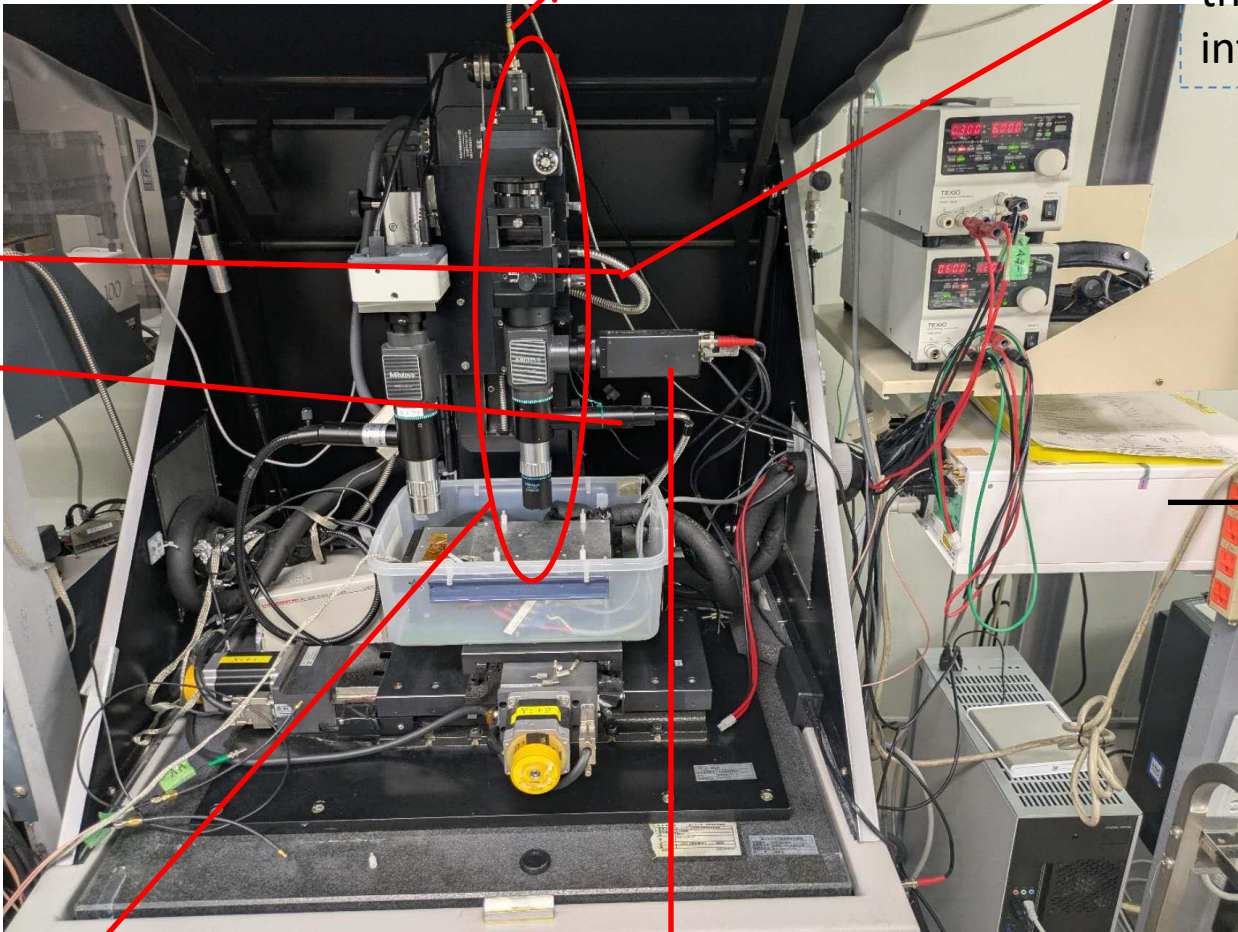
Laser setup

1064 nm IR laser system:



Infrared fiber (connecting the picosecond laser)

Visible laser (indicates the position of the infrared laser)



NTK photonics, Katana LP (picosecond laser , 1064 nm)

Focusing optical path tube (spot size down to 2 microns)

Optical microscope



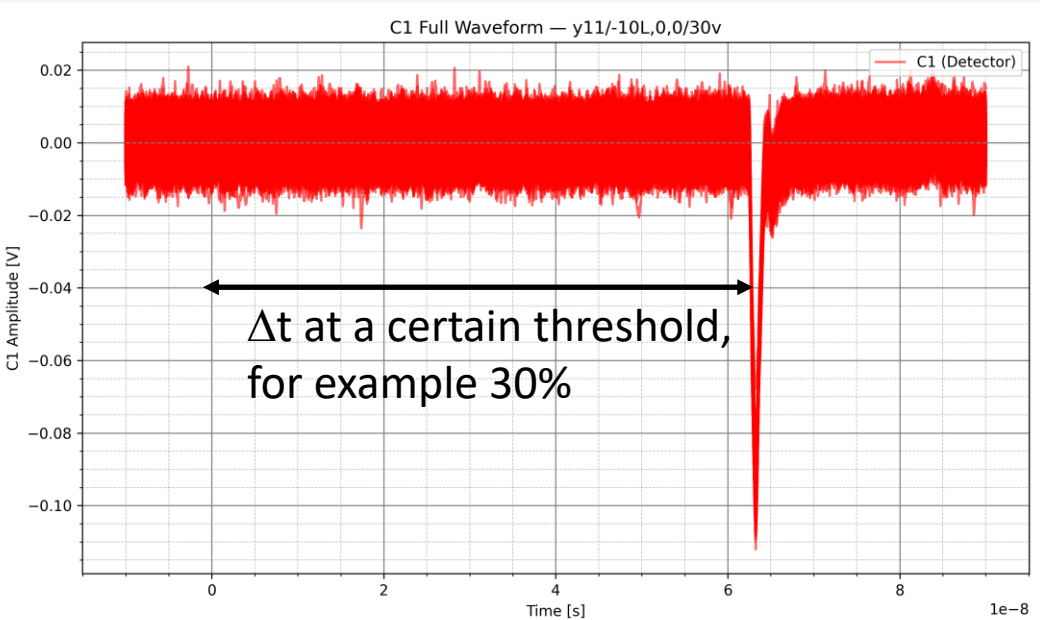
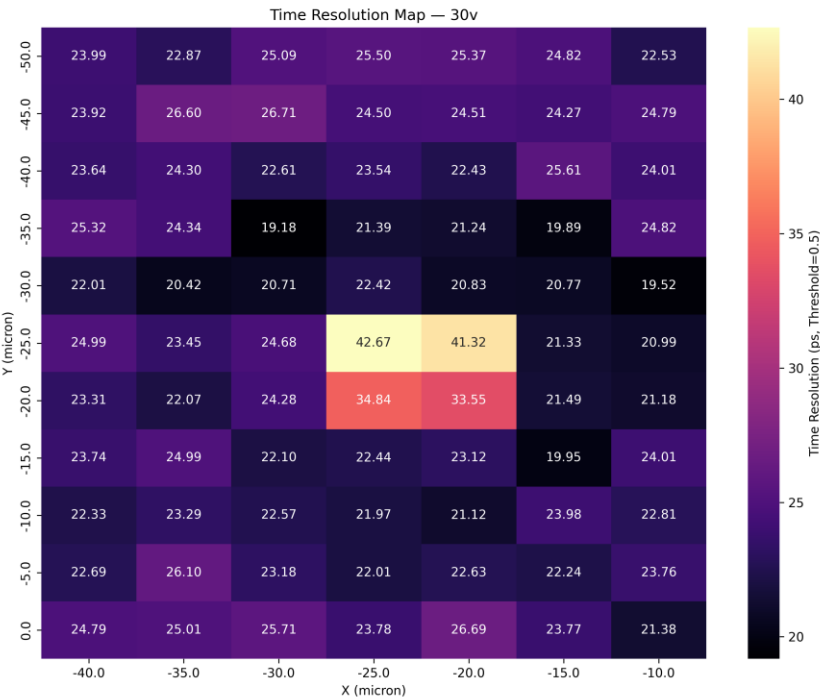
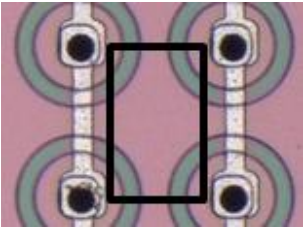
Results for position depends timing resolution

1064 nm IR laser results:

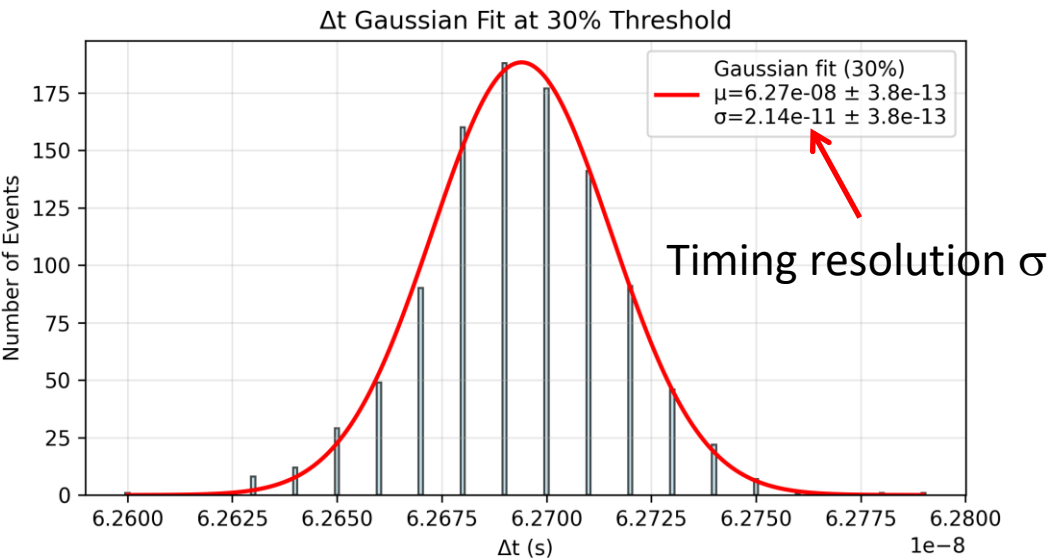
Marked position



Position Scan:

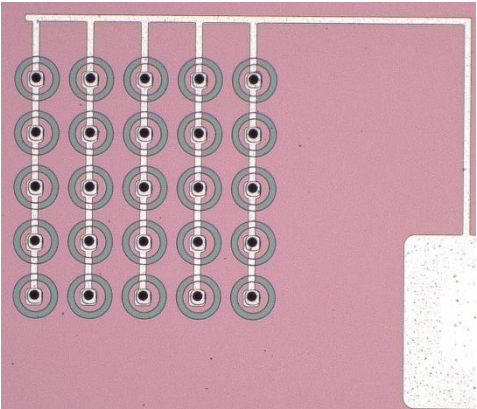


Vbias = -50V

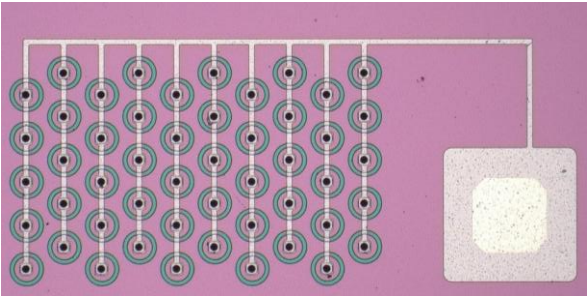


Results for the uniformity

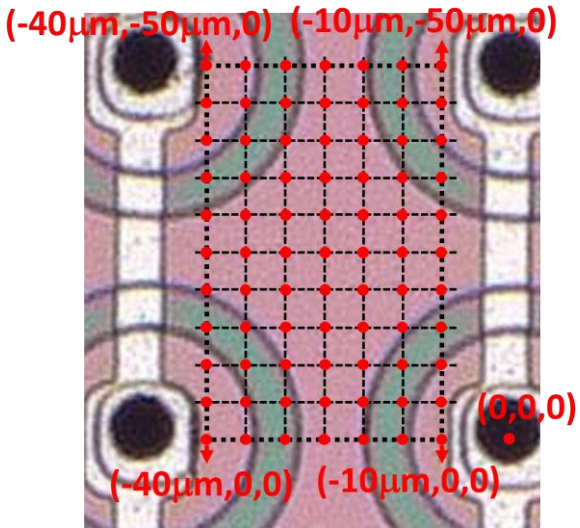
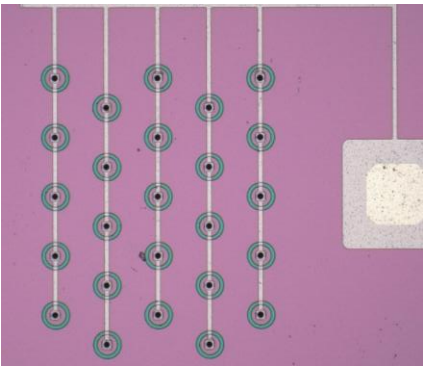
Square 30μm



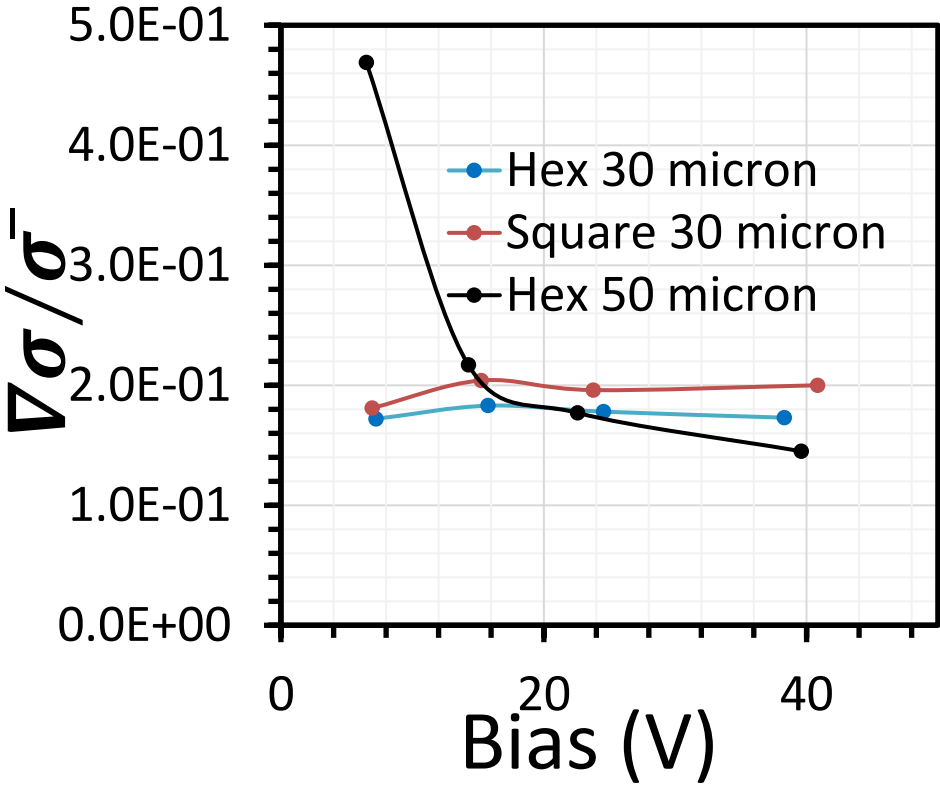
hexagonal 30μm



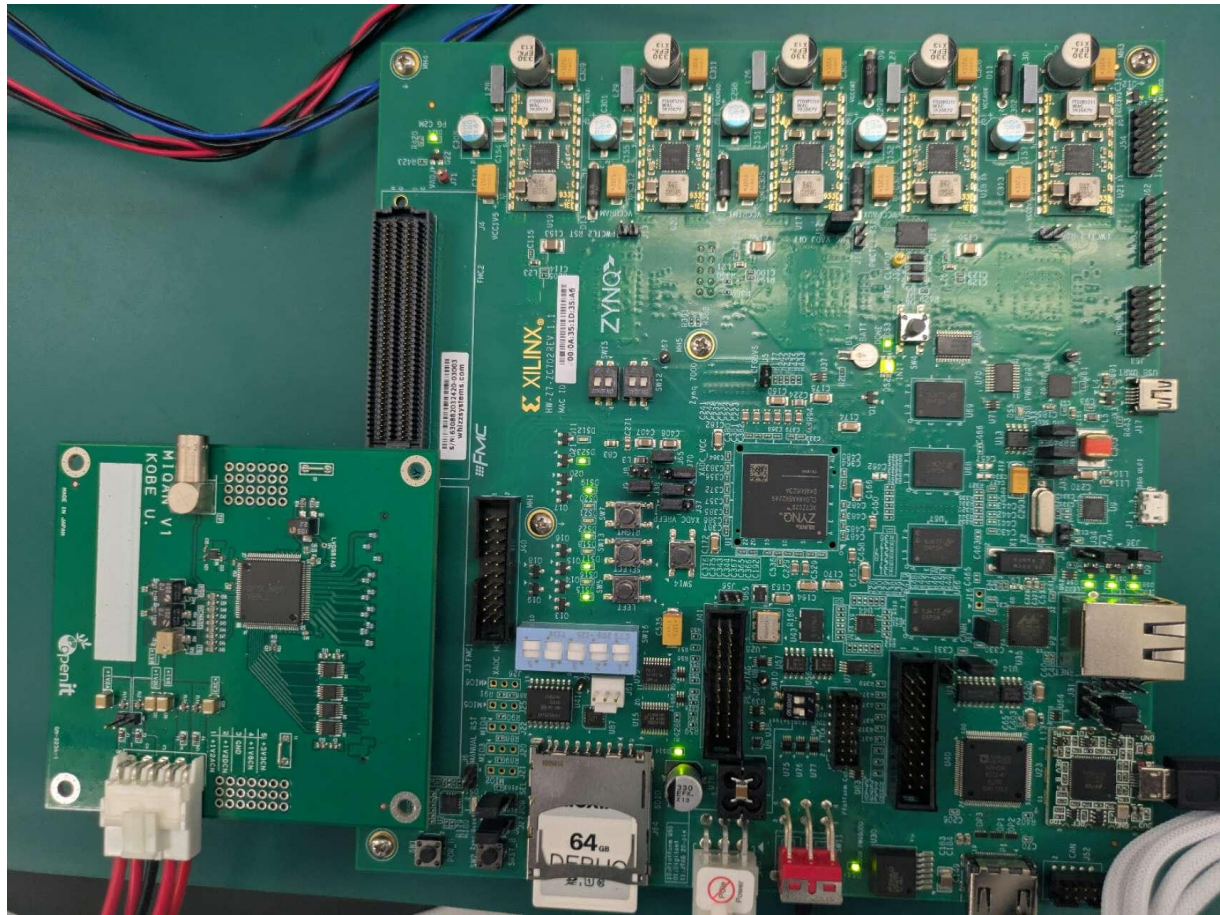
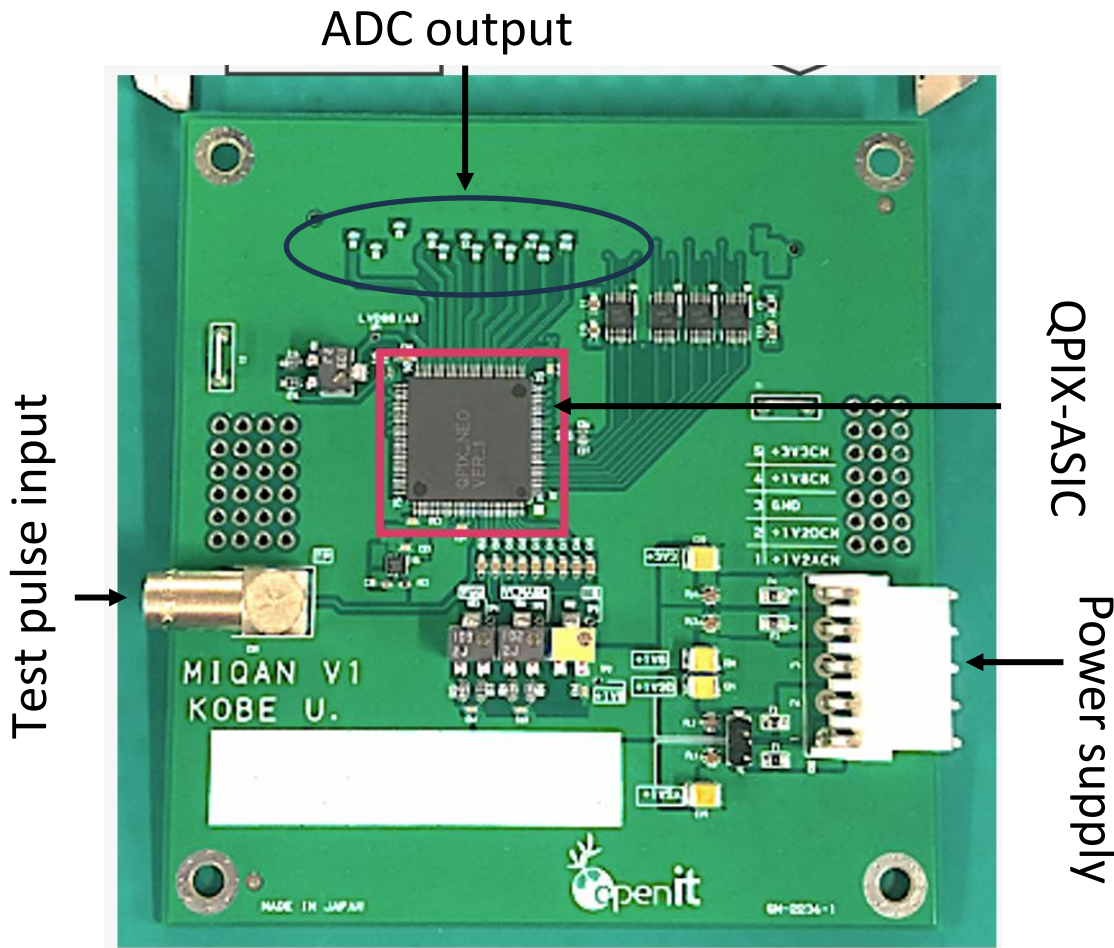
hexagonal 50μm



Uniformity : $\nabla\sigma/\bar{\sigma}$, $\nabla\sigma = \sum_{i=0}^N \sqrt{\frac{(\sigma_i - \bar{\sigma})^2}{N}}$



Multi-channel readout



FPGA digital analysis

Multi-channel readout

All the code used can be found in the **project manager**

Time Constraints, Logic Generation....

Pin arrangements

Bistream file for run FPGA

Connect and control FPGA

The screenshot displays the Vivado 2025.1 IDE interface for a project named 'miqan_20230302'. The interface is divided into several panes:

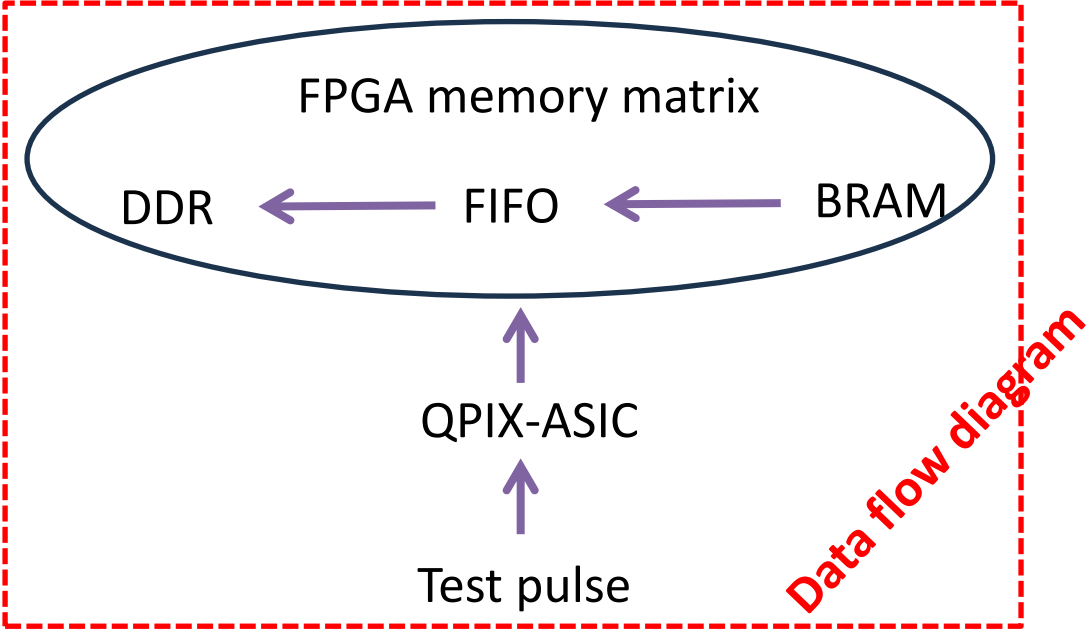
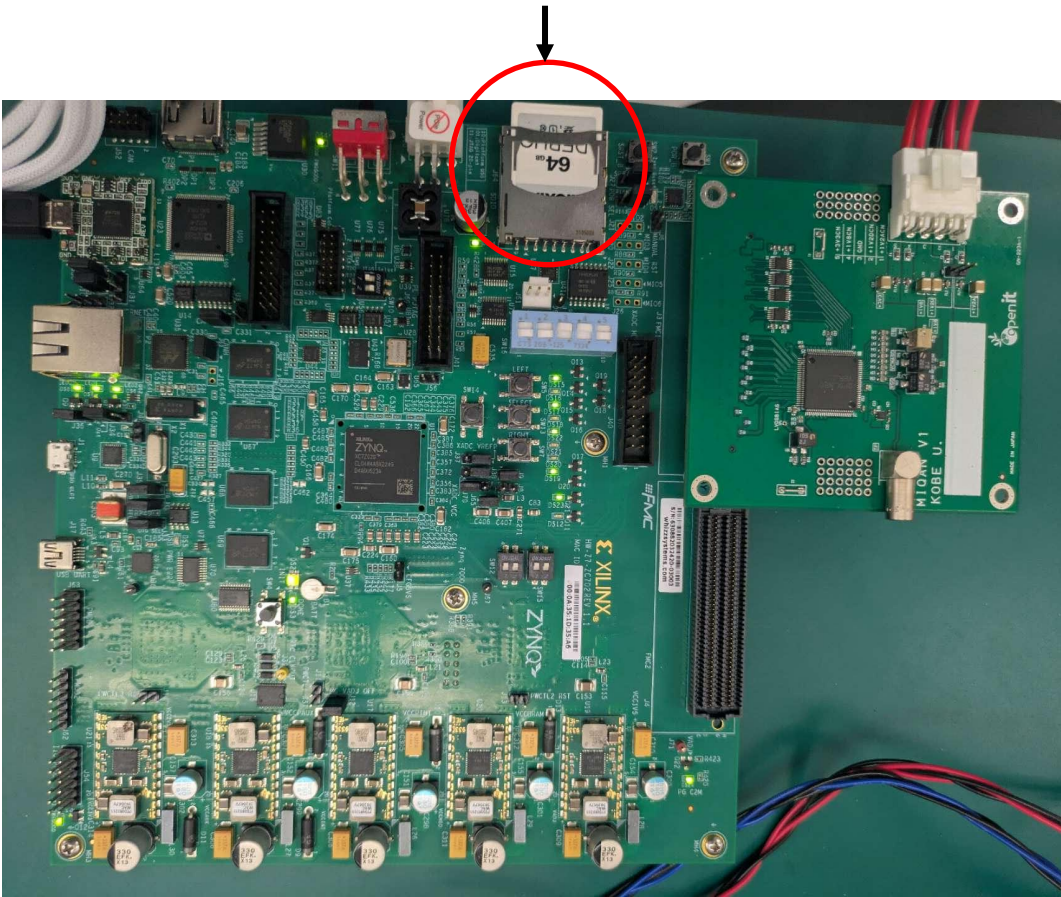
- Flow Navigator:** Located on the left, it shows the project's workflow steps: PROJECT MANAGER, IP INTEGRATOR, SIMULATION, RTL ANALYSIS, SYNTHESIS, IMPLEMENTATION, and PROGRAM AND DEBUG. Arrows point from external text labels to specific steps: 'All the code used can be found in the project manager' points to PROJECT MANAGER; 'Time Constraints, Logic Generation....' points to Run Synthesis; 'Pin arrangements' points to Run Implementation; 'Bistream file for run FPGA' points to Generate Bitstream; and 'Connect and control FPGA' points to Open Hardware Manager.
- PROJECT MANAGER:** The central pane shows the project's file structure. It includes a 'Sources' list with 'zynq7000_preset_wrapper' and 'MIQAN_DAQ'. A 'Hierarchy' tab is selected, showing the project's structure. A 'Source File Properties' pane is open for 'clk_wiz_0.xci', showing the 'IP' tab with 'IP name: Clocking Wizard'.
- Code text:** The right pane shows the 'MIQAN_DAQ.v' source file. It contains Verilog code defining a module 'MIQAN_DAQ' with parameters for ADC_DEPTH, ADC_BUS, ADC_SERIAL, ADC_CHANNEL, and ADC_WORD_SIZE.
- Design Runs:** The bottom pane shows the 'Design Runs' table, which tracks the progress of various design runs. The table has columns for Name, Constraints, Status, and various timing metrics (WNS, TNS, WHS, THS, WBSS, TPWS, Total Power, Methodology, Failed Routes).

Name	Constraints	Status	WNS	TNS	WHS	THS	WBSS	TPWS	Total Power	Methodology	Failed Routes
synth_1 (active)	constrs_1	synth_design Complete!									
impl_1	constrs_1	Running Design Initialization...									
synth_1_copy_1	constrs_1	Not started									
Out-of-Context Module Runs											
zynq7000_preset		Submodule Runs Complete									
fifo_generator_0_synth_1	fifo_generator_0	synth_design Complete!									

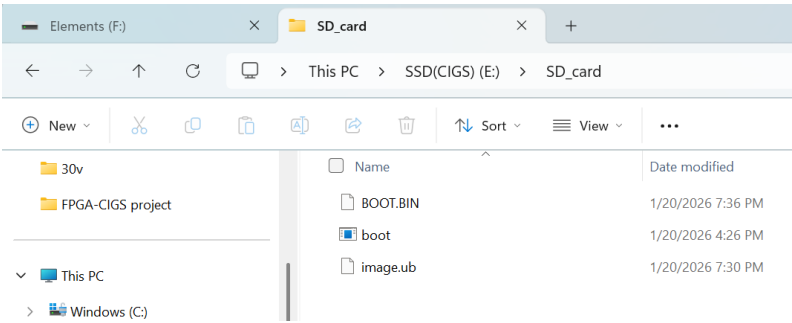
DAQ Frame: Select data, calculate data, transfer data, store data

Multi-channel readout

To solve the "insufficient memory" issue shown in Vivado, add an SD card to communicate with the FPGA board

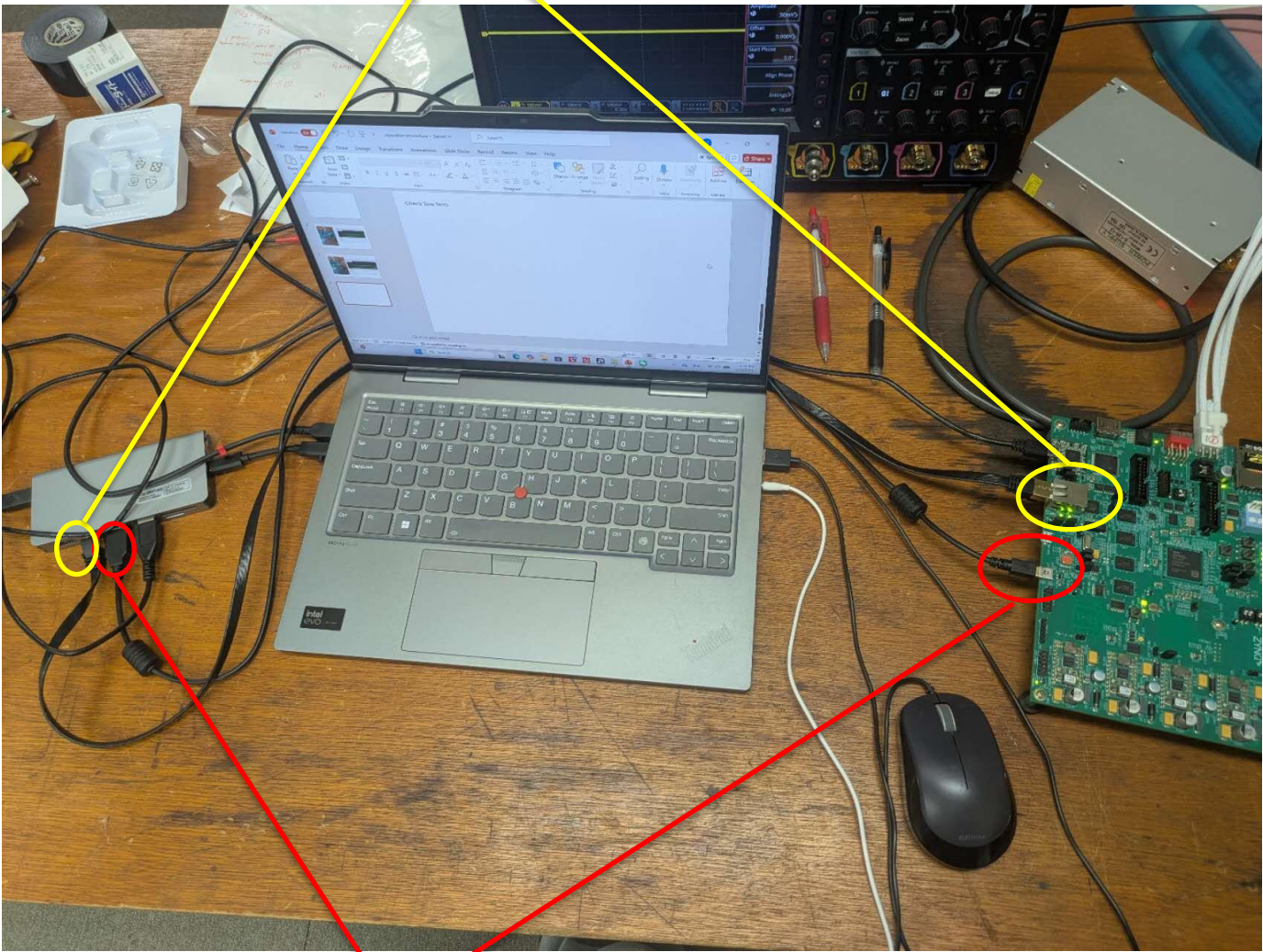


Install Linux OS onto an SD card for Zynq-FPGA communication



Multi-channel readout

Ethernet cable for communication with the FPGA



Ultra USB controls the SD card under Linux

SD Linux (Tera Term)

```
COM3 - Tera Term VT
File Edit Setup Control Window Help
[ OK ] Created slice system-getty.slice.
[ OK ] Started Getty on tty1.
[ OK ] Reached target Login Prompts.
[ OK ] Started System Logging Service.
[ OK ] Started Login Service.
[ OK ] Started OpenBSD Secure Shell server.
[ OK ] Started Dispatcher daemon for systemd-networkd.
[ OK ] Reached target Multi-User System.
[ OK ] Reached target Graphical Interface.
[ OK ] Starting Update UTMP about System Runlevel Changes...
[ OK ] Finished Update UTMP about System Runlevel Changes.

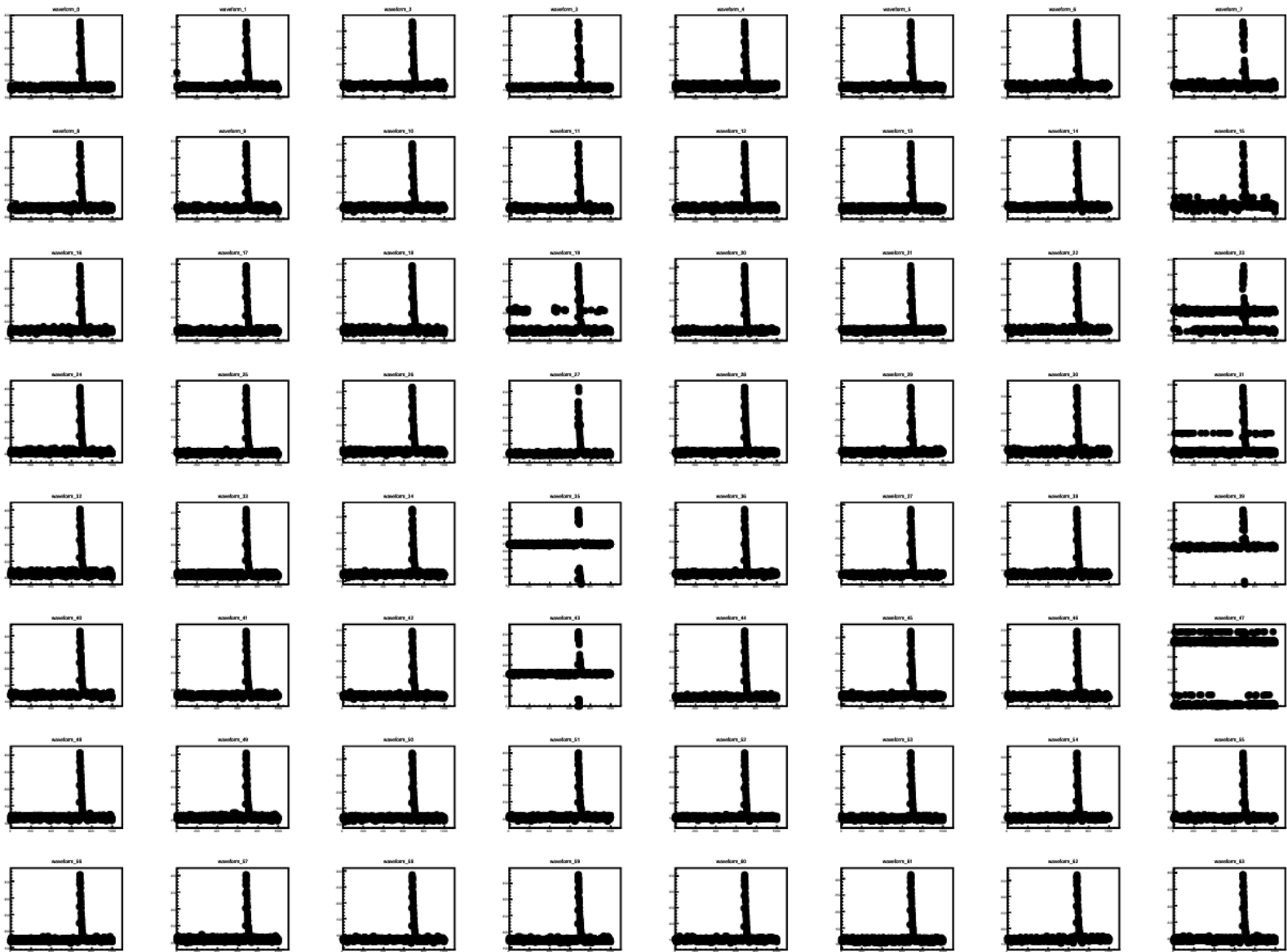
Ubuntu 20.04 LTS liaochuan-Precision-3660 ttyPS0

liaochuan-Precision-3660 login: root
Password:
Welcome to Ubuntu 20.04 LTS (GNU/Linux 5.15.36-xilinx-v2022.2 armv7l)

* Documentation: https://help.ubuntu.com
* Management: https://landscape.canonical.com
* Support: https://ubuntu.com/advantage

Last login: Sun Dec 28 09:48:41 UTC 2025 on ttyPS0
root@liaochuan-Precision-3660:~# busybox devmem 0x40400034 32
```

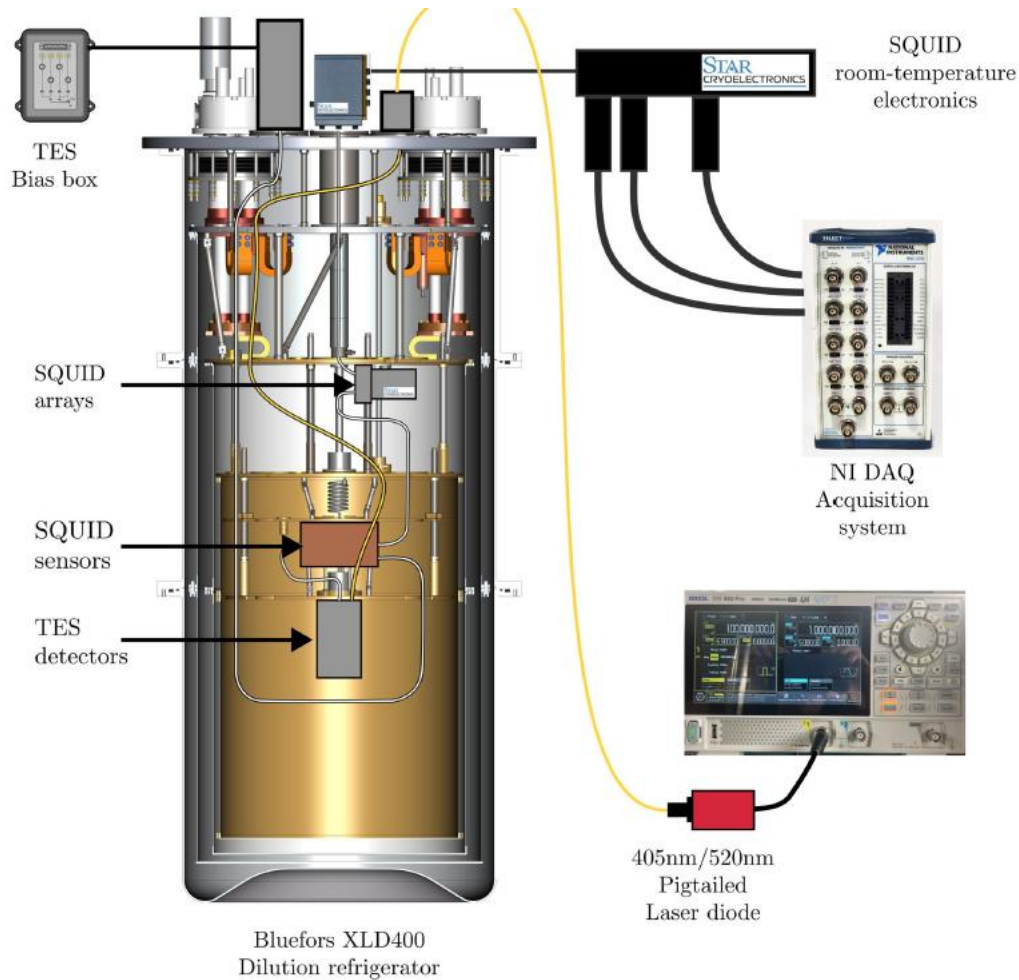
Multi-channel readout



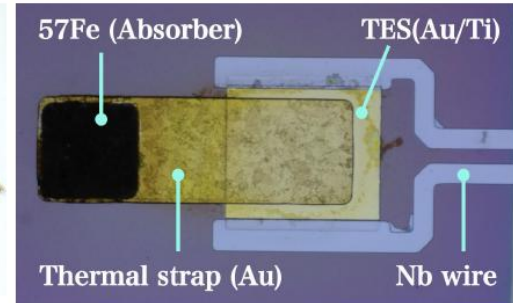
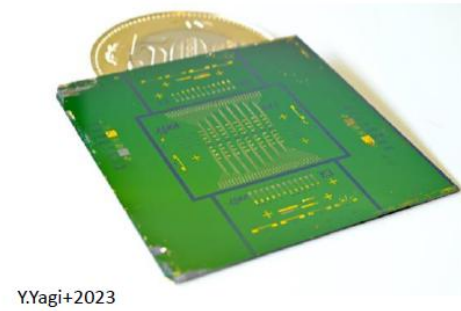
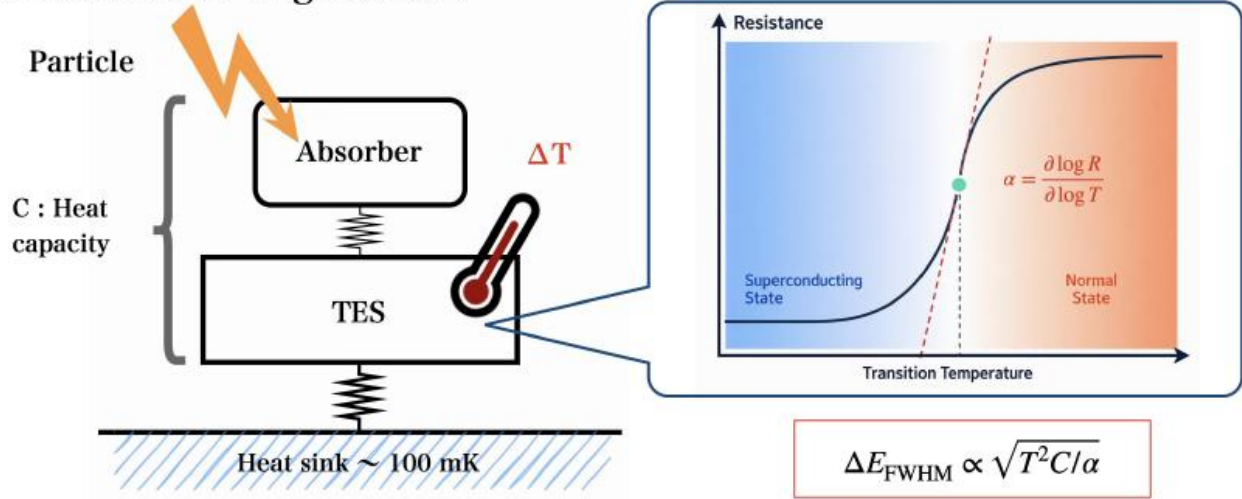
100 Hz pulse signal input, readout results from 64 channels

Perspectives on Future Detector Technologies

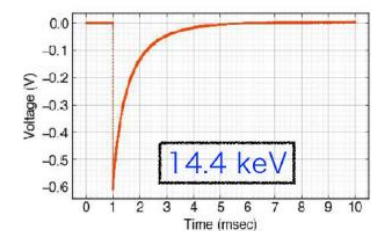
Low temperature detector (“quantum sensors”, **I don’t like this name!**)



TES: Transition Edge Sensor



- ✓ 64 pixels TES were fabricated at ISAS/JAXA and Riken (Y.Yagi+2023)
- ✓ The TES and Fe absorber are separated
- ✓ Successfully demonstrated operation with a single pixel



谢谢！ 欢迎提问

廖川 | KEK / QUP