Study of Irradiation-Induced Defects in PINs and LGADs by DLTS

4th DRD3, CERN

Yunyun Fan, IHEP

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Outline

- Motivation
- DLTS Measurements☆
  - Experimental Details
  - Results I: Proton-Irradiated PINs at Different Fluences
  - Results II: Proton-Irradiated LGADs at Different Fluences
- Summaries

• Motivation

- **Low Gain Avalanche Detectors (LGADs)**：

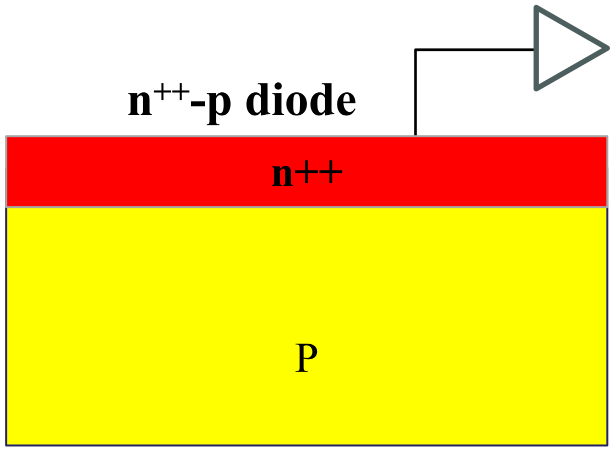
  Introducing a gain layer into the traditional PIN.

  Ultrafast time resolution.

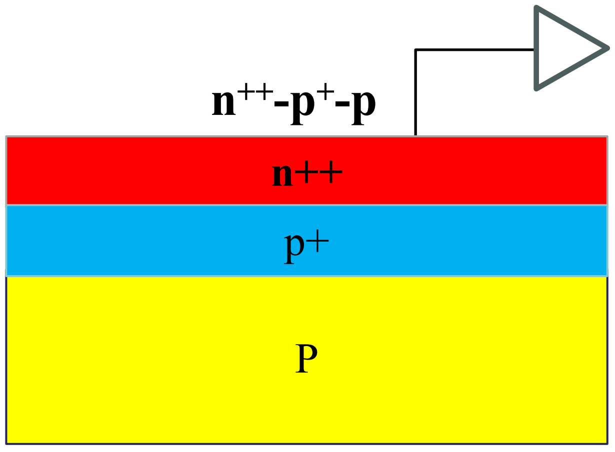
  Gain layer degradation under irradiation.

- LGADs with carbon implantation exhibit excellent radiation resistance.

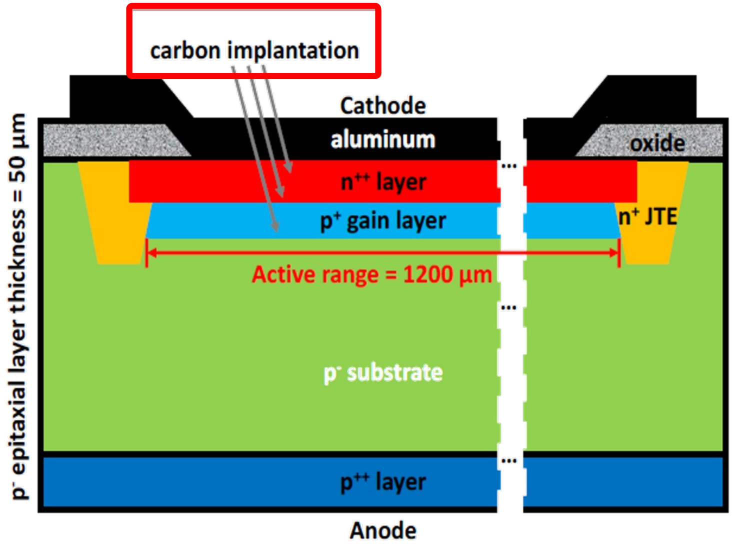
- This work aims to identify **the species and concentrations of irradiation-induced defects in LGADs**, and to evaluate **their contribution to gain degradation.**



Traditional PIN



LGAD: PIN + Gain Layer



LGAD with carbon implantation

DLTS samples

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- **PINs with 50um epi layer, 1K Ω cm：**

(1) NO Irradiation;

(2) Proton Fluence: 1E11 cm^{-2};

(3) Proton Fluence: 1E12 cm^{-2};

(4) Proton Fluence: 1E13 cm^{-2};

- **LGADs with/without carbon with 50um epi layer：**

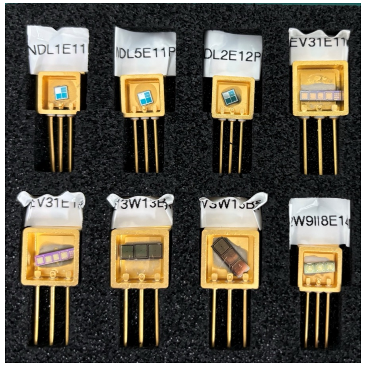
(1) NO Irradiation (With Carbon Doping, 1K Ω cm);

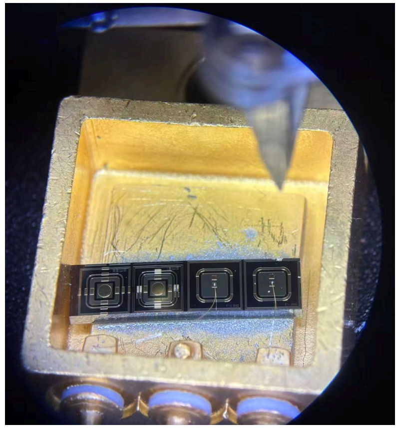
(2) Proton Fluence: 1E11 cm^{-2} (Without Carbon Doping, 350 Ω cm);

(3) Proton Fluence: 5E11 cm^{-2} (Without Carbon Doping, 350 Ω cm);

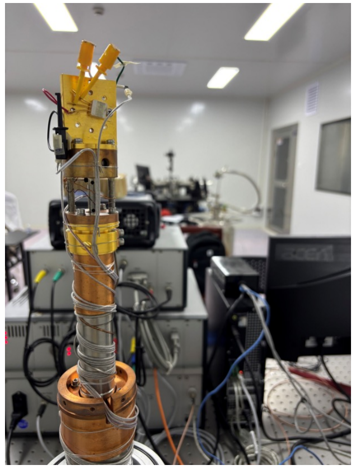
(4) Proton Fluence: 2E12 cm^{-2} (Without Carbon Doping, 350 Ω cm);

(5) Proton Fluence: 8E14 cm^{-2} (With Carbon Doping: ①0.5 a.u. C dose; ② 1 a.u. C dose, 1K Ω cm);





DLTS -- Deep Level Transient Spectroscopy



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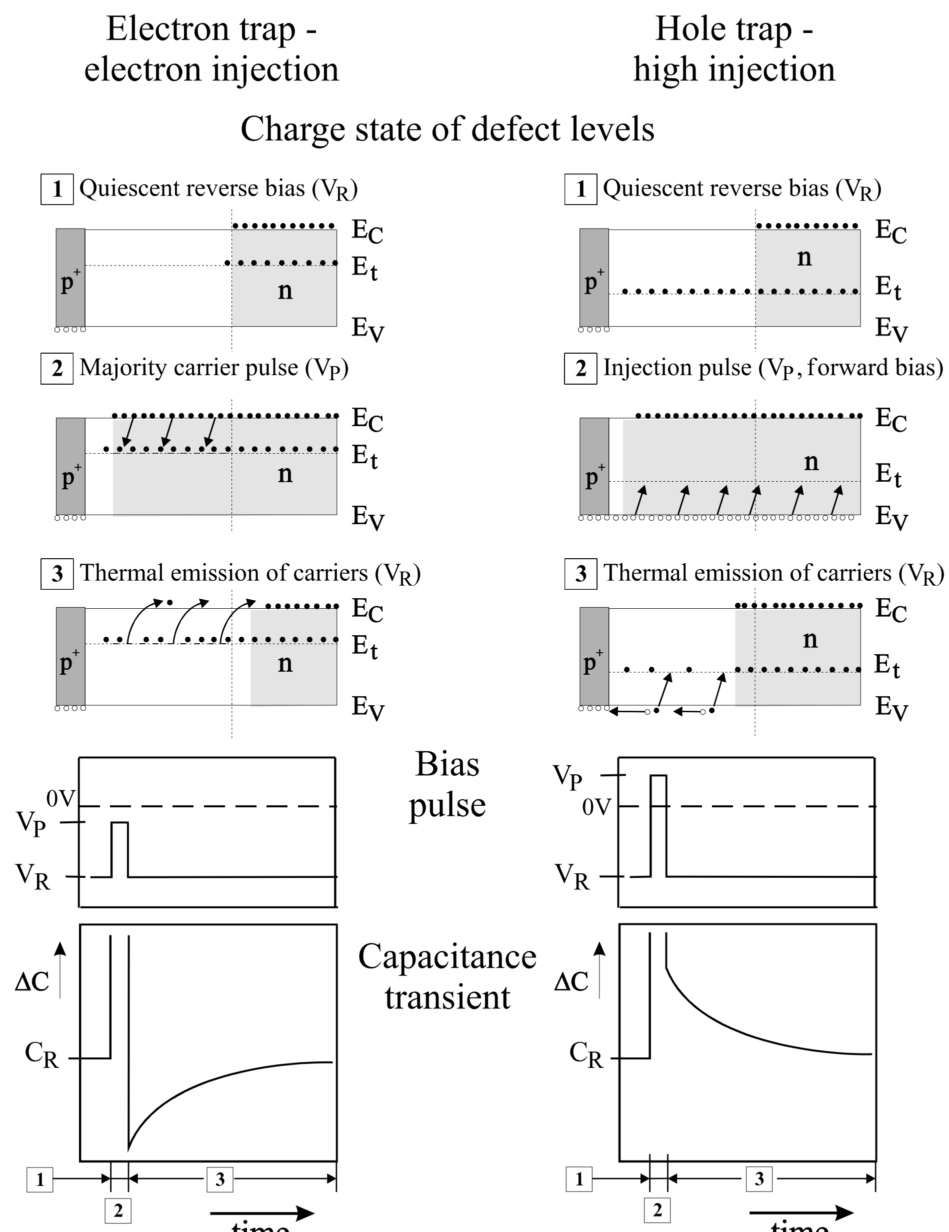
DLTS -- Deep Level Transient Spectroscopy



(1) Step 1 (Empty): Apply reverse bias (U_R) to create a depletion region with empty traps.

(2) Step 2 (Fill): A short pulse (U_P) fills the traps with carriers.

(3) Step 3 (Emit): Traps emit carriers exponentially after the pulse; the capacitance transient C(t)is recorded.

We obtain:

(1) **Defect Energy Level (E_t):** The position of the defect level within the bandgap, relative to either the conduction or valence band.

(2) **Defect Concentration (N_t):** The volume density of the specific defect in the material.

(3) **Capture Cross-Section (σ):** A measure of the probability or efficiency for a defect to capture a charge carrier.

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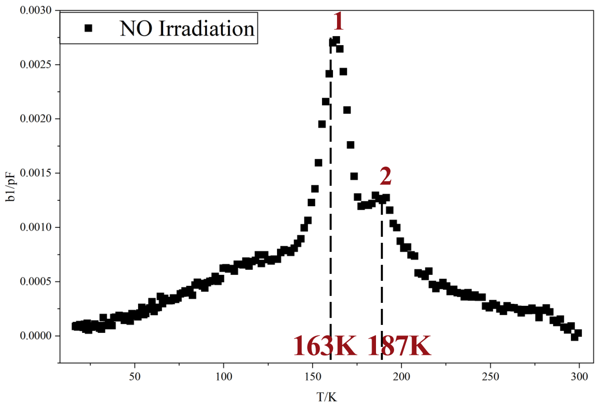
C-DLTS Measurements: PINs 50um epi layer, 1K Ω cm

V3 PIN: (1) un -irradiation

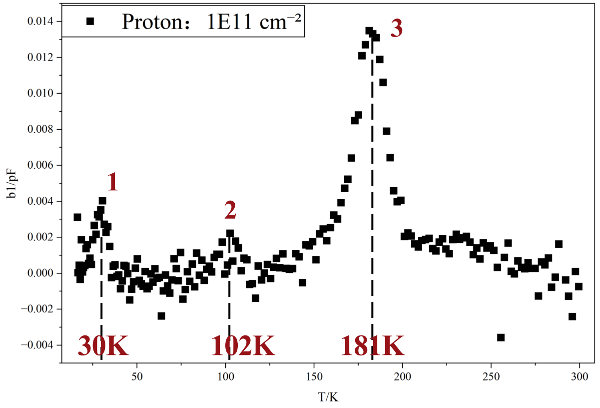
U_R=-10V, U_P=0.6V, T_W=192ms, t_p=100us



	E_t/eV	N_t/cm²
1	E_V+0.327	3.20E+11
2	E_V+0.365	1.36E+11

(2) Proton: 1E11 cm²

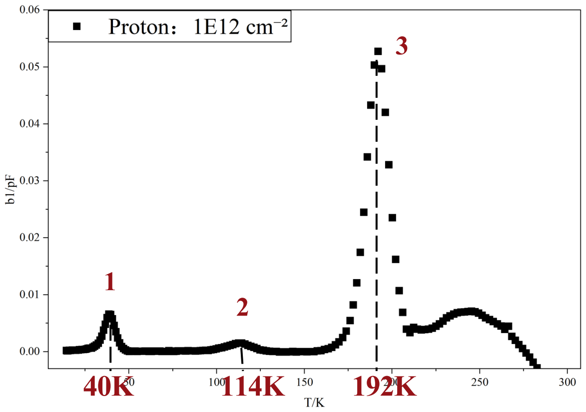
U_R=-10V, U_P=1V, T_W=192ms, t_p=100us



	E_t/eV	N_t/cm²
1	E_V+0.020	5.83E+11
2	E_V+0.162	3.45E+11
3	E_V+0.357	1.64E+12

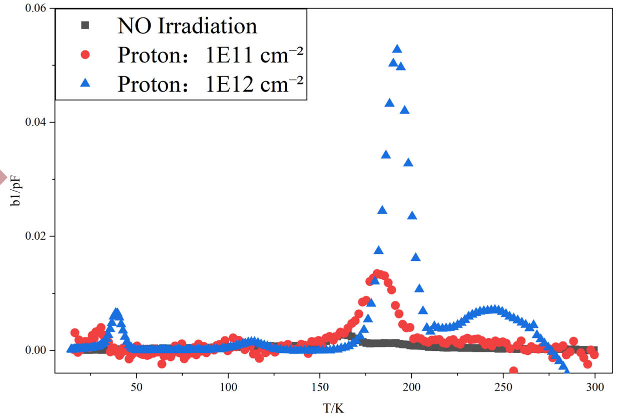
(3) Proton: 1E12 cm²

U_R=-10V, U_P=0.6V, T_W=192ms, t_p=100us



	E_t/eV	N_t/cm²
1	E_V+0.052	1.85E+12
2	E_V+0.181	1.86E+11
3	E_V+0.416	7.39E+12

(1)+(2)+(3)



The same type with same level

The same type with higher level？ /different defect type?

- as the proton irradiation fluence increases, the variety and concentration of defects in PINs also increase. The PIN irradiated with proton fluence of 1E12 cm² clearly contains a greater number and more complex types of defects.
- Are those defects the same type at different irradiation dose?
  - Merge of defects with similar defect energy level
  - Higher irradiation， higher defect energy level

LGADs without carbon doping, 350 Ω cm

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(1) NO Irradiation (C-DLTS) (Without Carbon Doping)

U_R=-25V, U_P=-2.5V, T_W=192ms, t_p=1ms

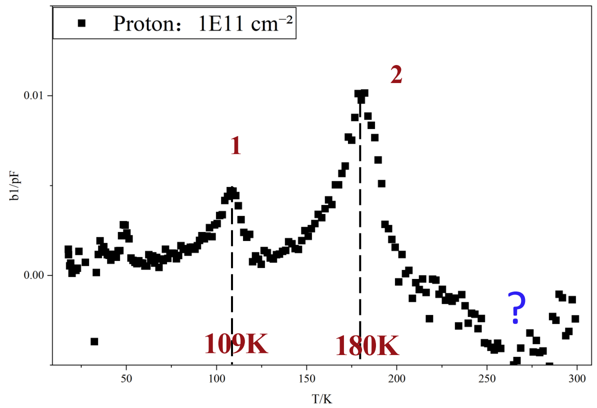
U_R=-10V, U_P=-1V, T_W=192ms, t_p=10ms

No C-DLTS curve （Arrhenius） To be tested with i-DLTS

Several DLTS setup parameters tried and failed

(2) Proton: 1E11 cm² (Without Carbon Doping)

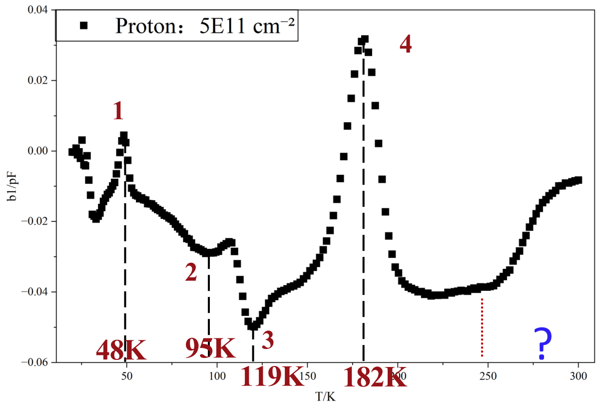
U_R=-10V, U_P=-1V, T_W=192ms, t_p=10ms



	E_t/eV	N_t/cm²
1	E_V+0.133	7. 93E+09
2	E_V+0.287 (large error)	1.03E+10

(3) Proton: 5E11 cm² (Without Carbon Doping)

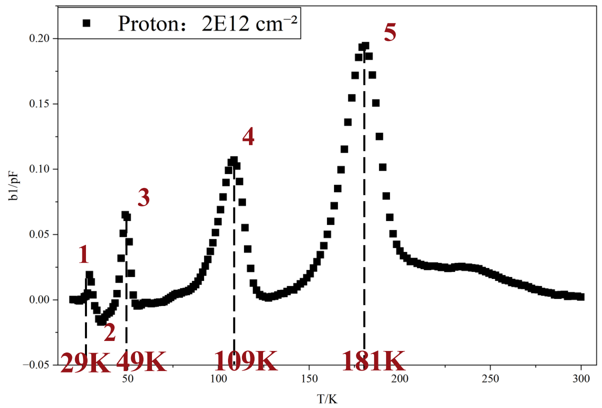
U_R=-10V, U_P=0.4V, T_W=192ms, t_p=10ms



	E_t/eV	N_t/cm²
1	E_V+0.068	5.39E+09
2	E_C-0.190	1.54E+10
3	E_C-0.184	3.42E+10
4	E_V+0.345	2.68E+10
5	new negative peak ?	

(4) Proton: 2E12 cm² (Without Carbon Doping)

U_R=-10V, U_P=0.4V, T_W=192ms, t_p=10ms

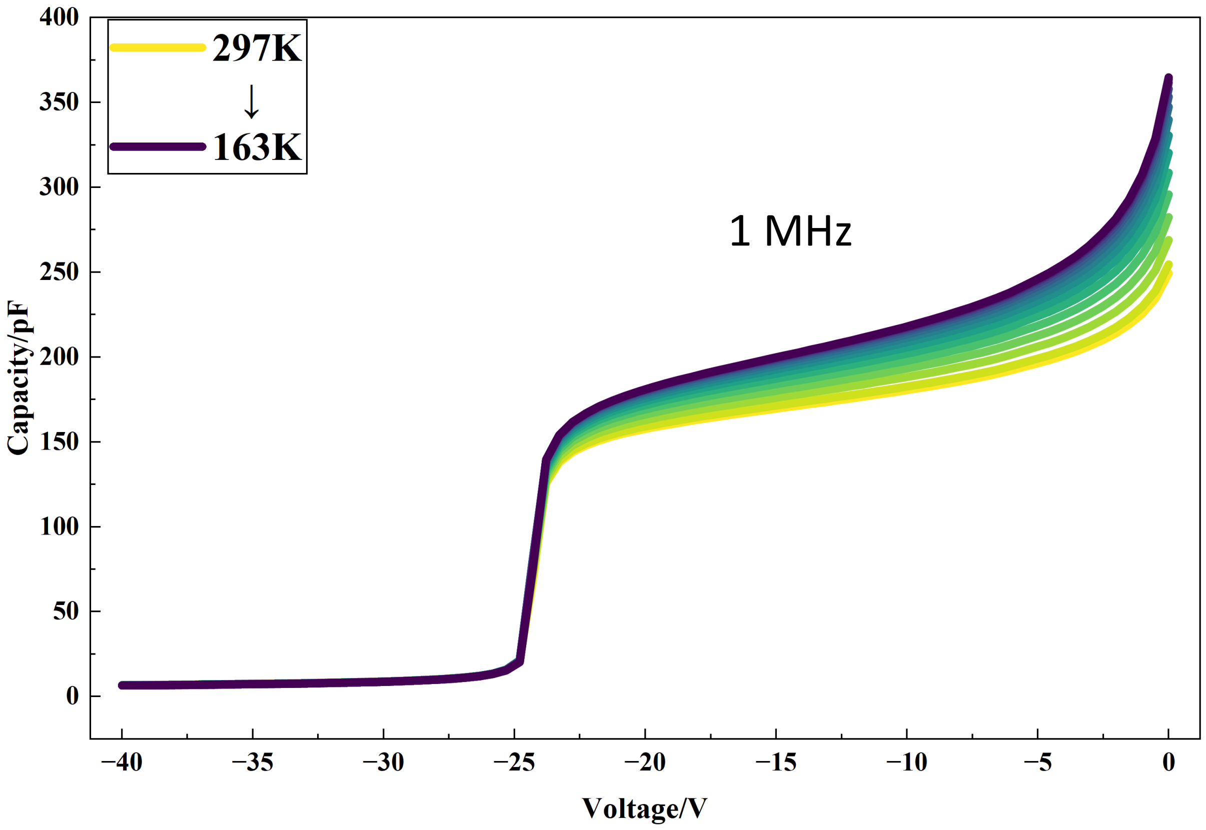


	E_t/eV	N_t/cm²
1	E_V+0.070	4.87E+10
3	E_V+0.094	3.95E+10
4	E_V+0.181	5.53E+10
5	E_V+0.354	9.93E+10

- as c-DLTS was not feasible
- Higher irradiation dose， higher defect concentration, more defects types

CV test for the LGAD with carbon

- Capacitance vs bias voltage for v3 LGAD with carbon



LGADs with carbon doping

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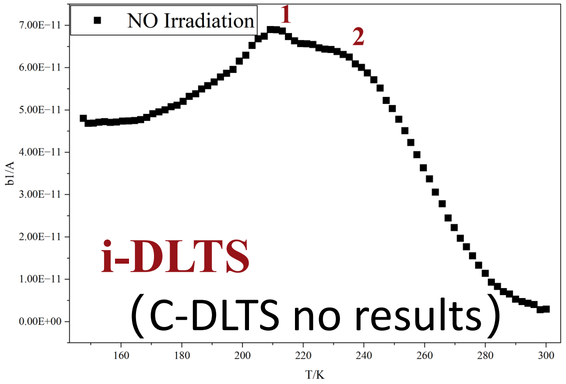
(1) NO Irradiation (i-DLTS) (With Carbon Doping)

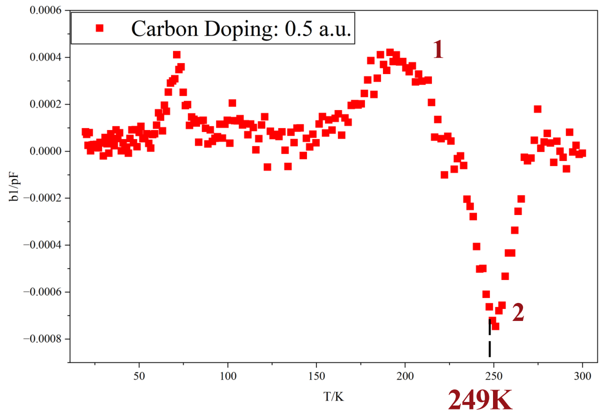
U_R=-25V, U_P=-2.5V, T_W=192ms, t_p=1ms



	E_t/eV	N_t/cm^2
1	E_V+0.355	1.88E+12
2	E_V+0.441	1.56E+12

(5) Proton: 8E14 cm² (With Carbon Doping: 0.5 a.u. , annealing at 60 Celsius 80 min)

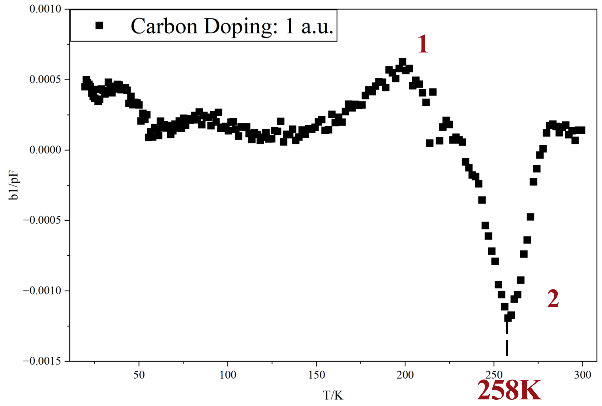
UR=-20V, UP=-2V, Tw=192ms, tp=10ms



	E_t/eV	N_t/cm^2
1	Ev+0.418	6.02E+10
2	E_C-0.488	1.99E+11

(6) Proton: 8E14 cm² (With Carbon Doping: 1 a.u. , annealing at 60 Celsius 80 min))

UR=-20V, UP=-2V, Tw=192ms, tp=10ms



	E_t/eV	N_t/cm^2
1	-	-
2	E_C-0.443	3.47E+11

~ 2 times

- For highly irradiated LGAD samples（8e14）， the defects was measured after annealing at 60 Celsius 80 min.
- The samples irradiated up to 1e15 and 2.5e15, were not be able to get results with c-DLTS.
- Compared with the defect types, there's new defect Ec-0.488 appear which maybe carbon related.
  - ✓ The LGAD with higher carbon doping has higher defects concentration after 8e14 proton irradiation.

Summary

Defects in PINs:

- **Higher proton irradiation**
  - ✓ **More defect types**
  - ✓ **Higher defects concentration**

Defects in LGADs without Carbon:

- **Higher proton irradiation**
  - ✓ **More defect types**
  - ✓ **Higher defects concentration**

Defects in LGADs without Carbon

- **Higher proton irradiation**
  - ✓ **More defect types**
  - ✓ **Higher defects concentration**
  - ✓ **New defect Ec-0.488 eV appear which maybe carbon related**

Plan：
Irradiated more carbonated LGAD up to 8e14 to compare the behavior with the LGAD without carbon doping

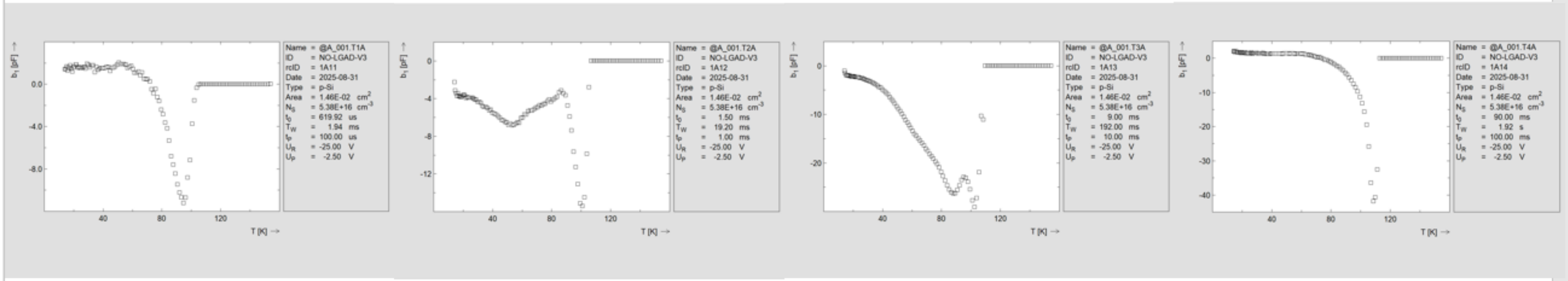
CV attached

Thanks for Your Attention!

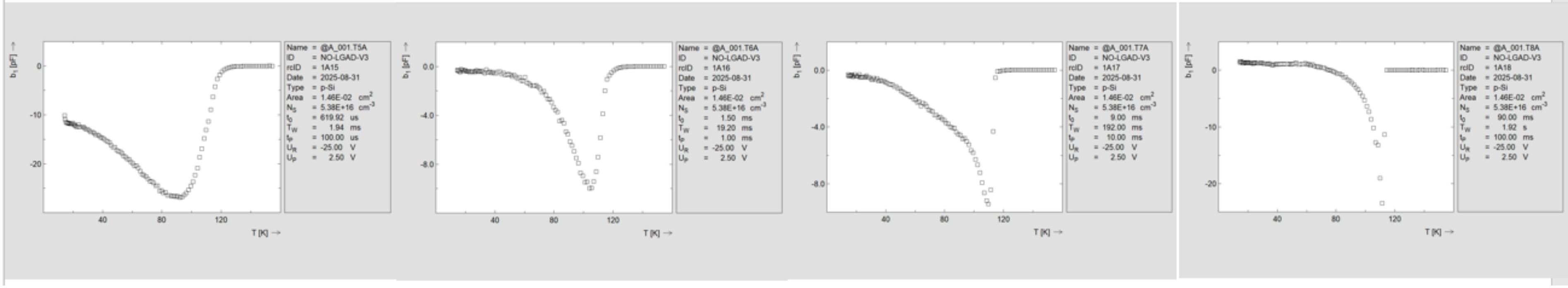
Email: nuclear@stu.xjtu.edu.cn
fanyy@ihep.ac.cn

Backup

A_001的8组谱(UR=-25V，UP=-2.5V，1.92ms(100us)，19.2ms(1ms)，192ms(10ms)，1.92s(100ms))



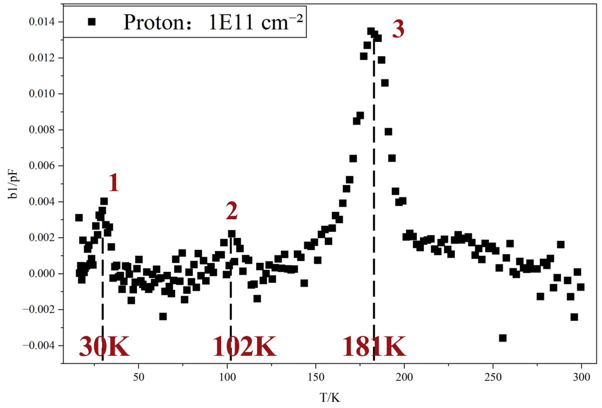
UP=2.5V，其他不变



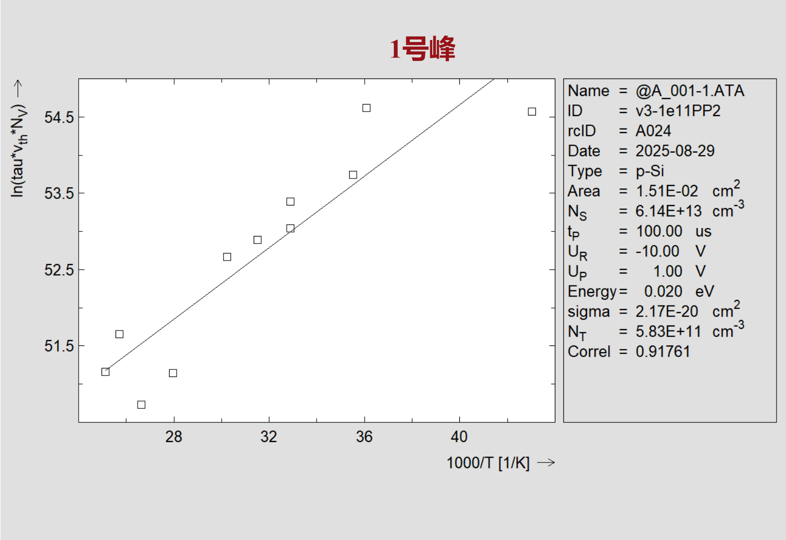
V3：(2) Proton: 1E11 cm²-PIN

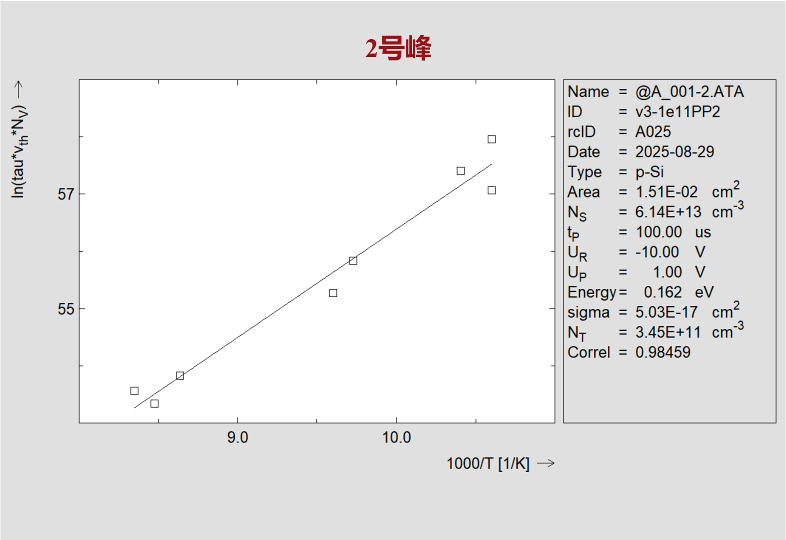
U_R=-10V, U_P=1V, T_W=192ms, t_p=100us

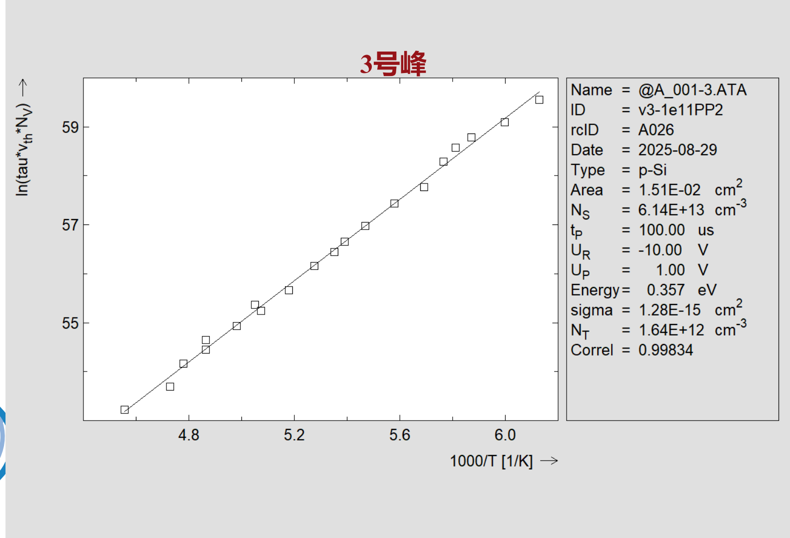
Arrhenius拟合：(默认拟合方法为main)



	E_t/eV	N_t/cm²
1	E_V+0.020	5.83E+11
2	E_V+0.162	3.45E+11
3	E_V+0.357	1.64E+12





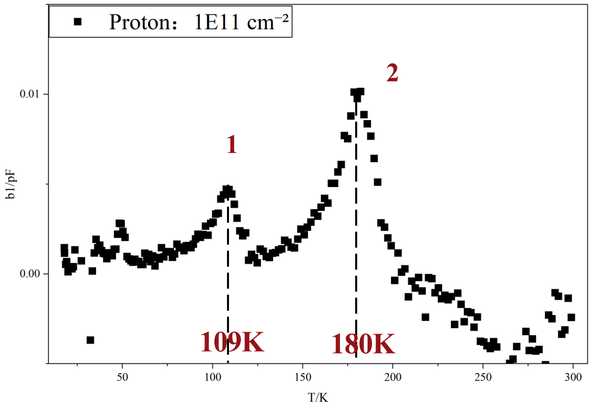


EXPERIMENT

NDL-LGAD：

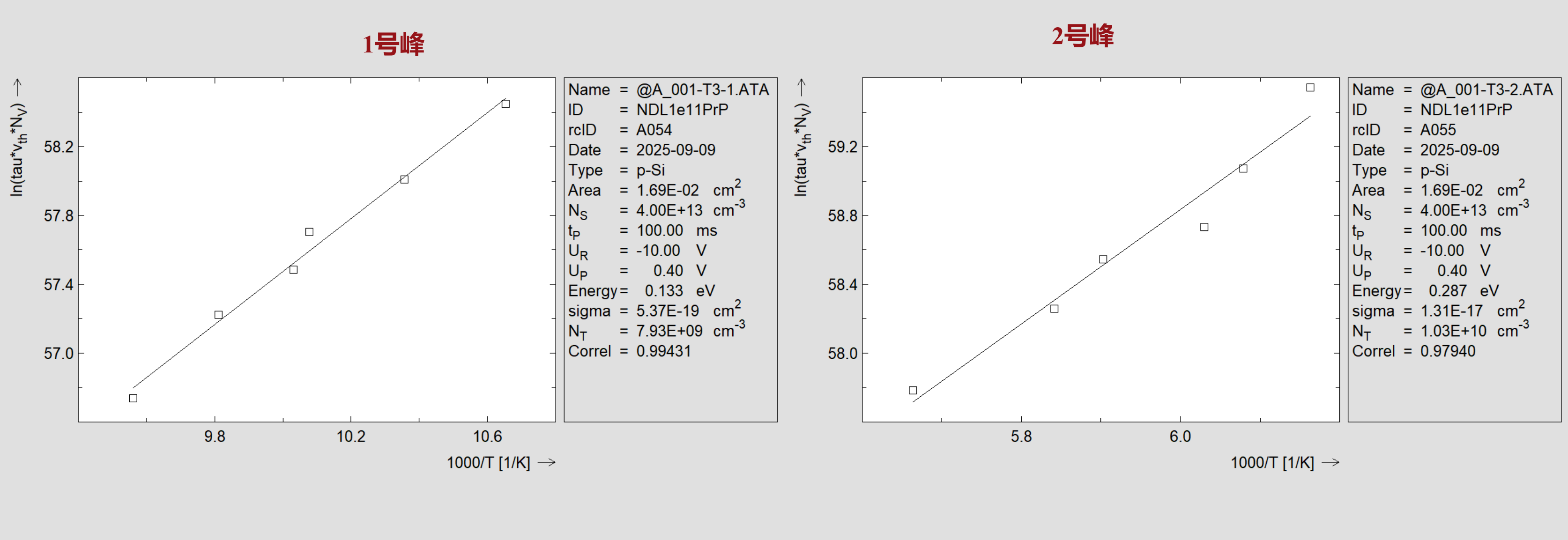
(2) Proton: 1E11 cm²
(Without Carbon Doping)

U_R=-10V, U_P=-1V, T_W=192ms, t_p=10ms



	E_t/eV	N_t/cm²
1	E_V+0.133	7.93E+09
2	E_V+0.287	1.03E+10

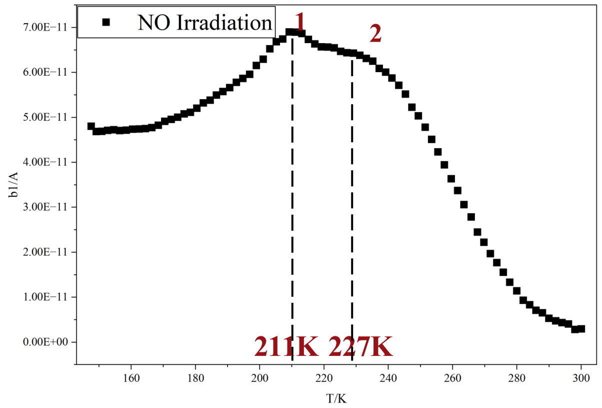
Arrhenius拟合：(默认拟合方法为main)



V3-LGAD：

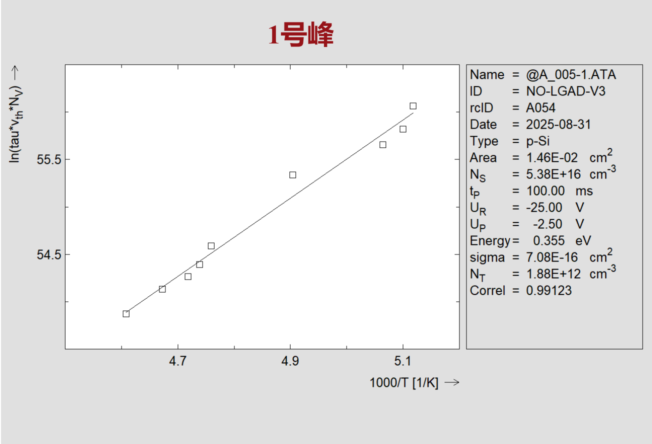
(1) NO Irradiation (i-DLTS)
(With Carbon Doping)

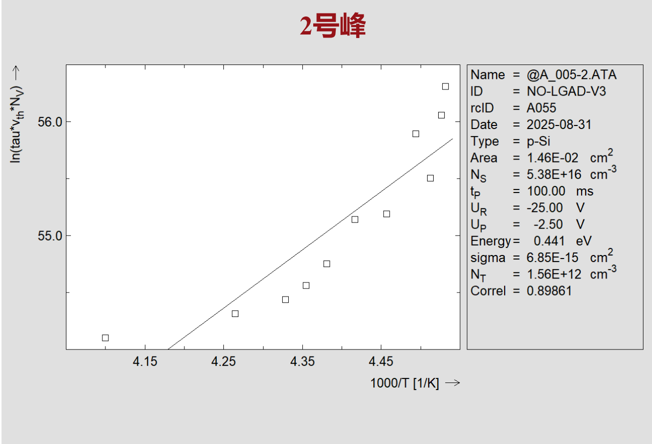
U_R=-25V, U_P=-2.5V, T_W=192ms, t_p=1ms



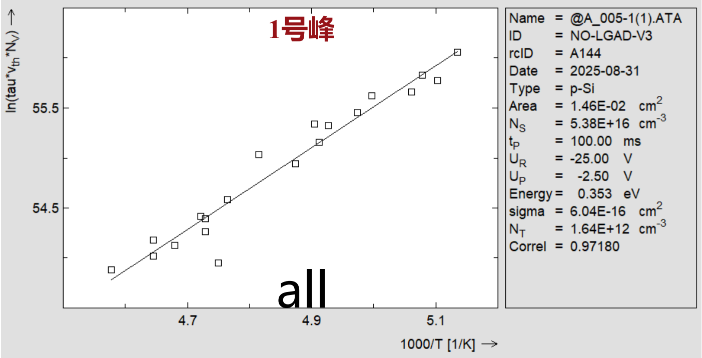
	E_t/eV	N_t/cm²
1	E_V+0.355	1.88E+12
2	E_V+0.441	1.56E+12

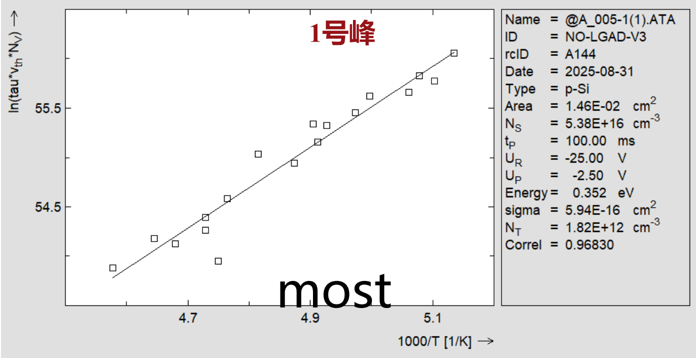
Arrhenius拟合：(默认拟合方法为main)

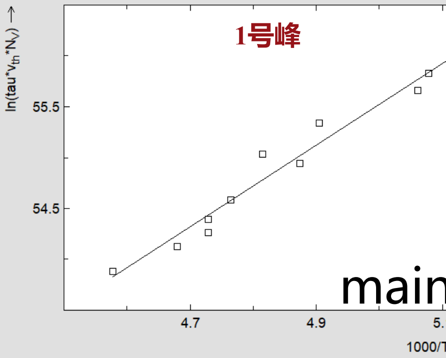


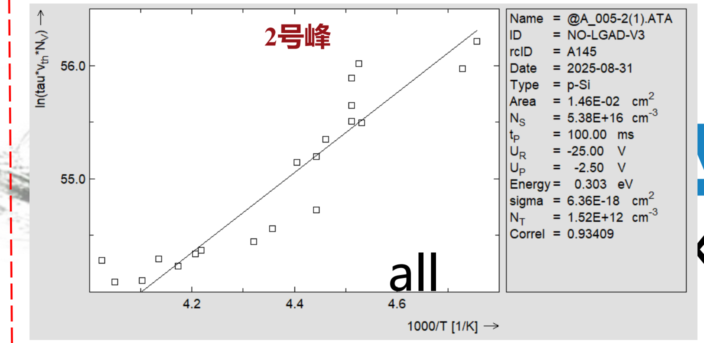


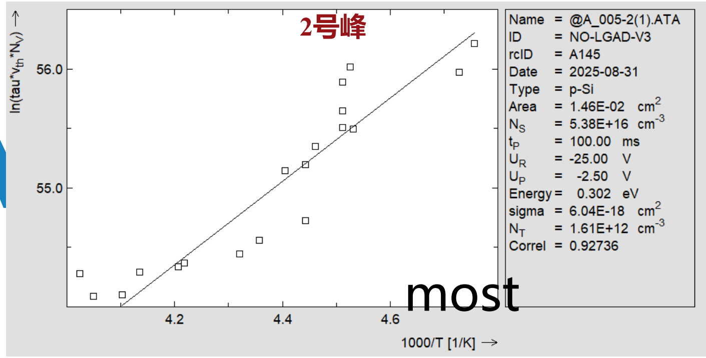
第二次拟合：

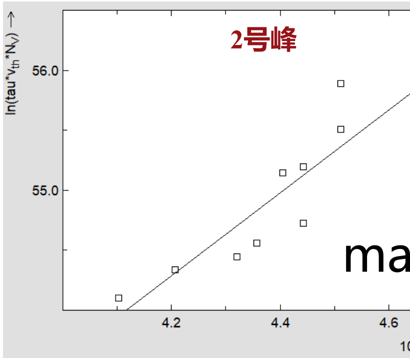








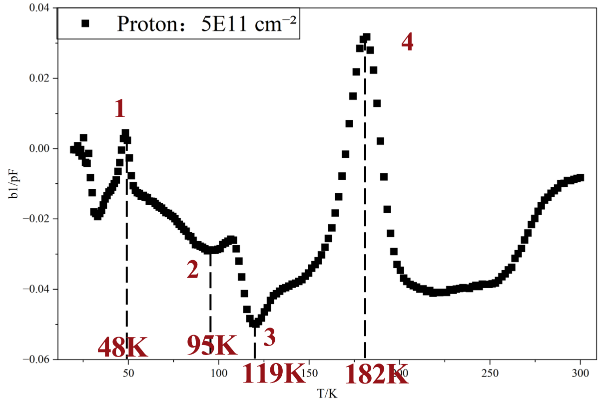




NDL-LGAD：

(3) Proton: 5E11 cm²
(Without Carbon Doping)

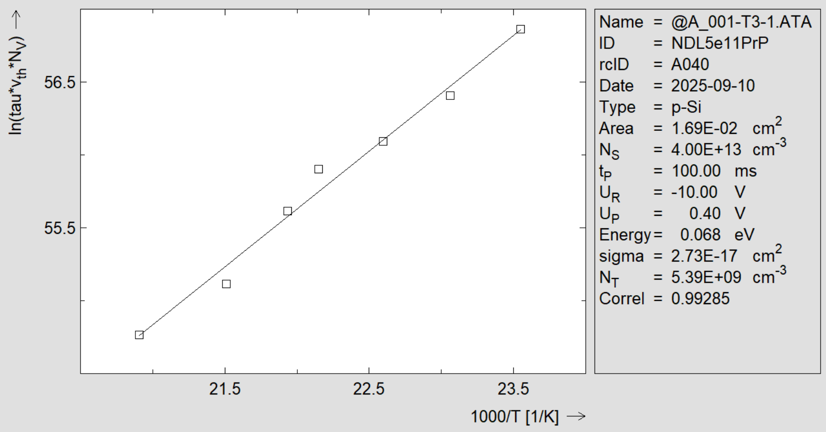
U_R=-10V, U_P=0.4V, T_W=192ms, t_p=10ms



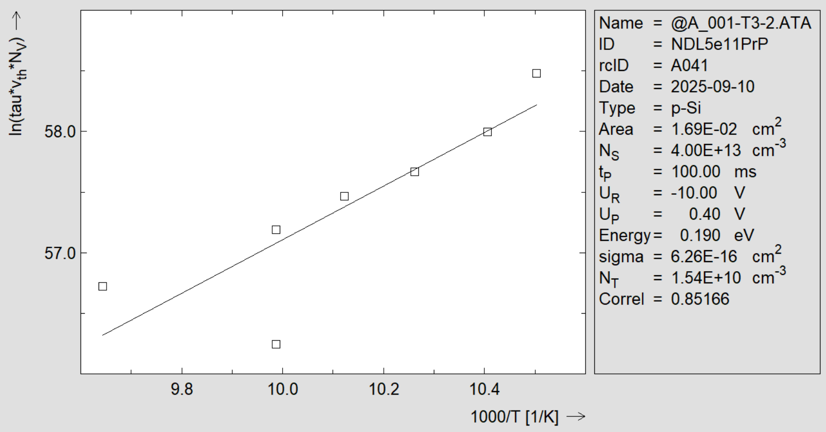
	E_t/eV	N_t/cm²
1	E_V+0.068	5.39E+09
2	E_C-0.190	1.54E+10
3	E_C-0.184	3.42E+10
4	E_V+0.345	2.68E+10

Arrhenius拟合：(默认拟合方法为main)

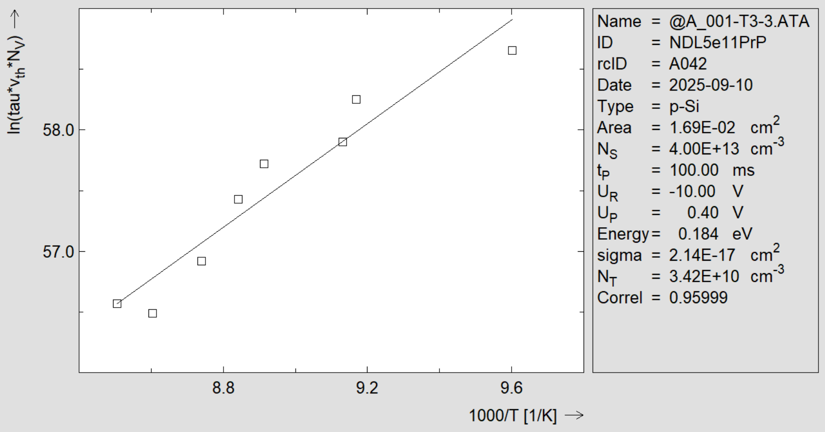
1号峰



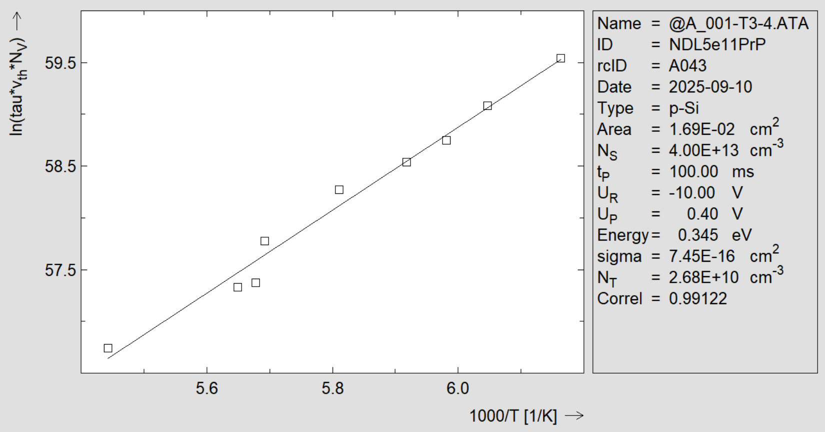
2号峰



3号峰



4号峰



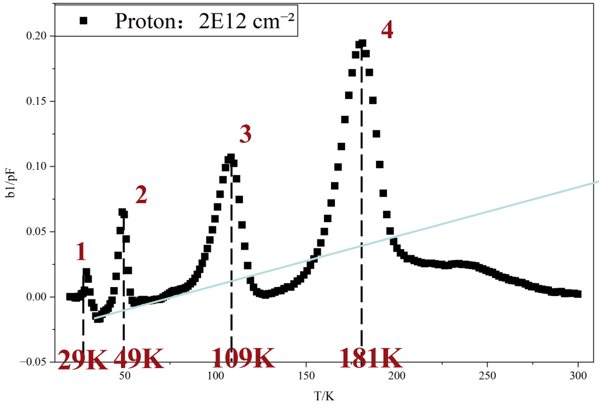
NDL-LGAD：

Arrhenius拟合：(默认拟合方法为main)

CEPC报告上没标注这个负峰

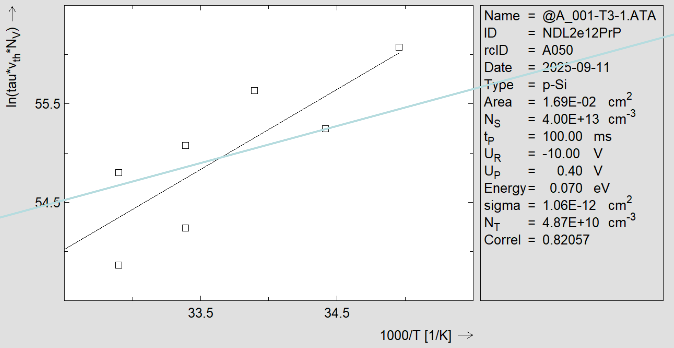
(4) Proton: 2E12 cm²
(Without Carbon Doping)

U_R=-10V, U_P=0.4V, T_W=192ms, t_p=10ms

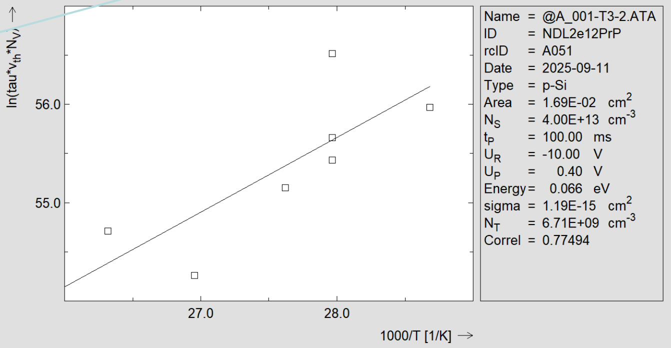


	E_t/eV	N_t/cm²
1	E_V+0.070	4.87E+10
2	E_V+0.094	3.95E+10
3	E_V+0.181	5.53E+10
4	E_V+0.354	9.93E+10

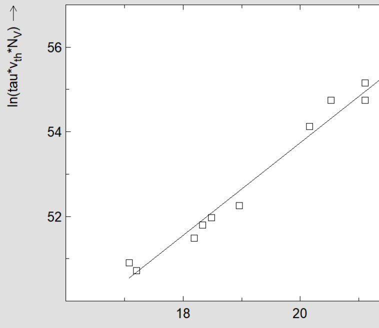
1号峰



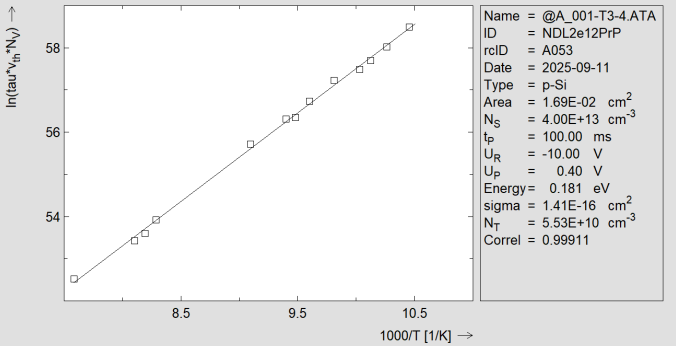
负峰



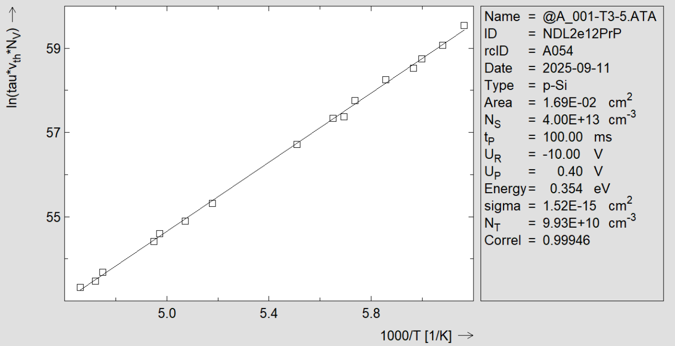
3号峰



4号峰



5号峰

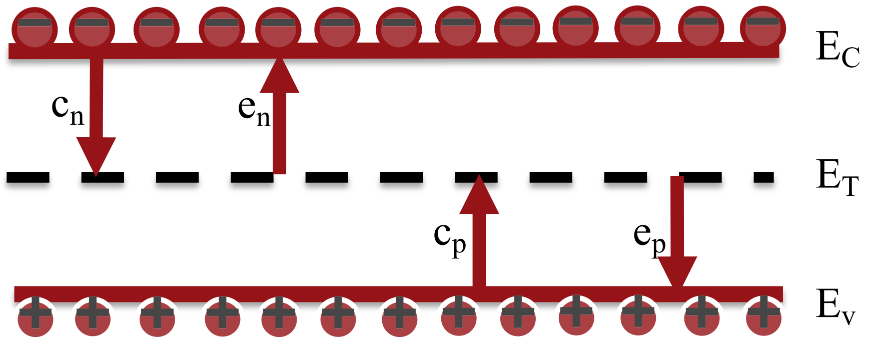


$Si \rightarrow I + V$

$B_s \rightarrow B_i + V$

$I + B_s \rightarrow B_i$

$B_i + O_i \rightarrow B_iO_i$



Thank you for your attention！

- **Back up**