西安交通大學
XI'AN JIAOTONG UNIVERSITY
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

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

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Presenter: Wei LI

Outline

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

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

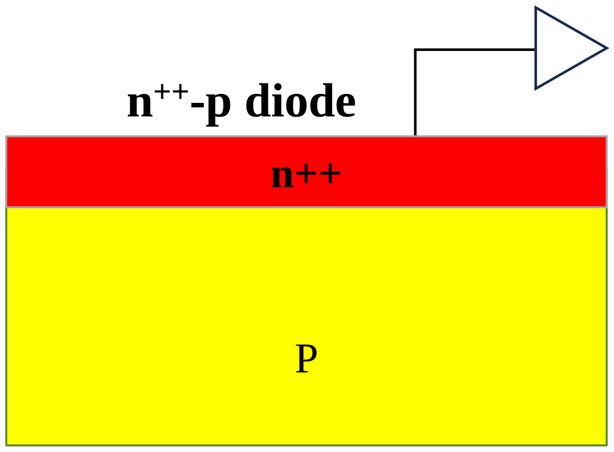
  Introducing a gain layer into the traditional PIN.

  Ultrafast time resolution.

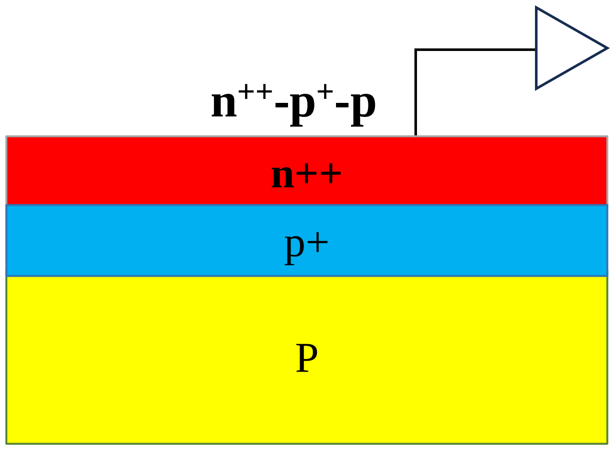
  Gain layer degradation under irradiation.

- LGADs with carbon implantation exhibit excellent radiation resistance.

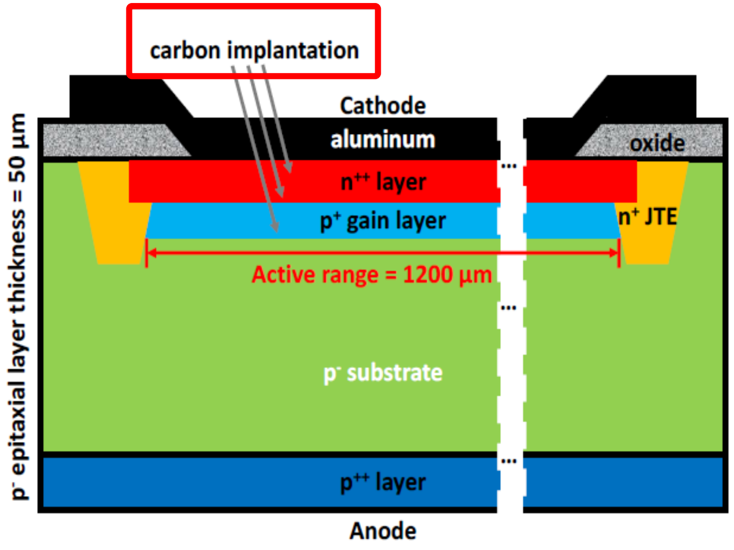
- This work aims to identify **the species and concentrations of irradiation-induced defects in LGADs**, and to evaluate **their contribution to gain degradation.**



Traditional PIN



LGAD: PIN + Gain Layer



LGAD with carbon implantation

1. Samples

- **PINs:**

(1) NO Irradiation;

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

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

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

- **LGADs:**

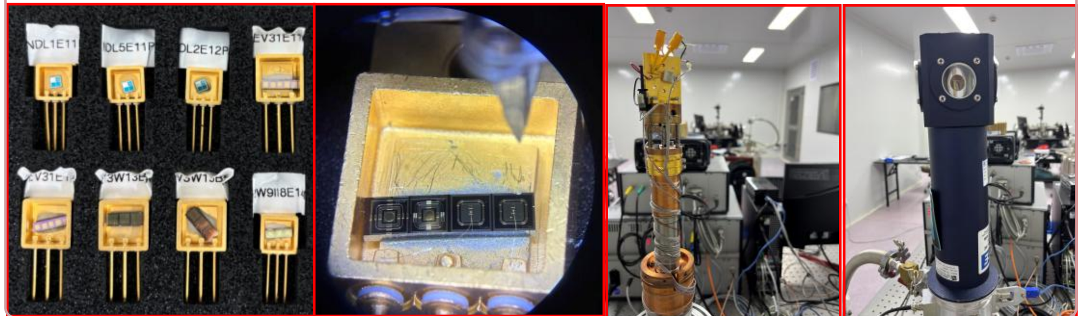
(1) NO Irradiation (With Carbon Doping);

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

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

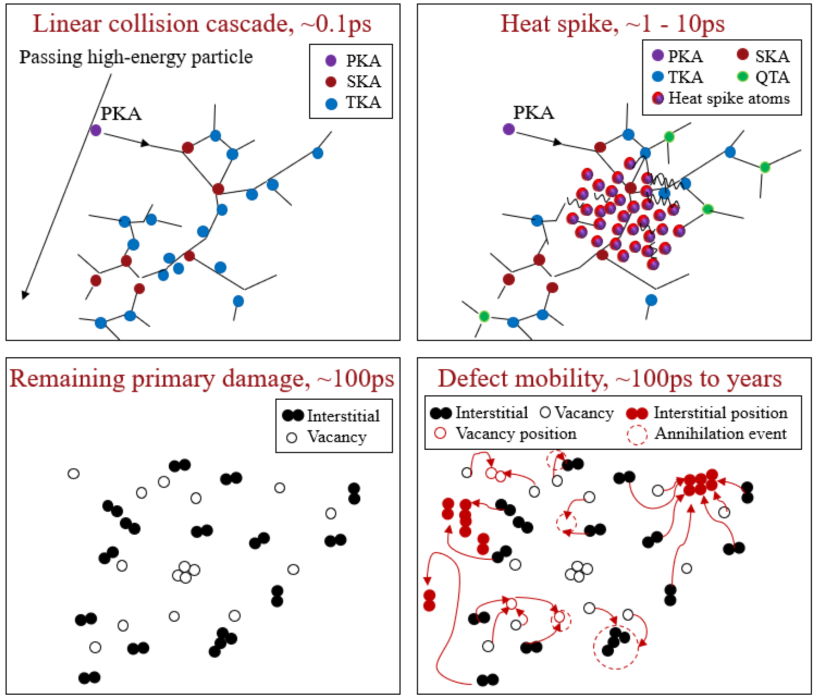
(4) Proton Fluence: 2E12 cm^{-2} (Without Carbon Doping);

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



2. Mechanism of Gain Degradation: Acceptor Removal Effect

Boron typically acts as a substitutional dopant (B_s) in silicon. However, it may lose its electrical activity after irradiation:

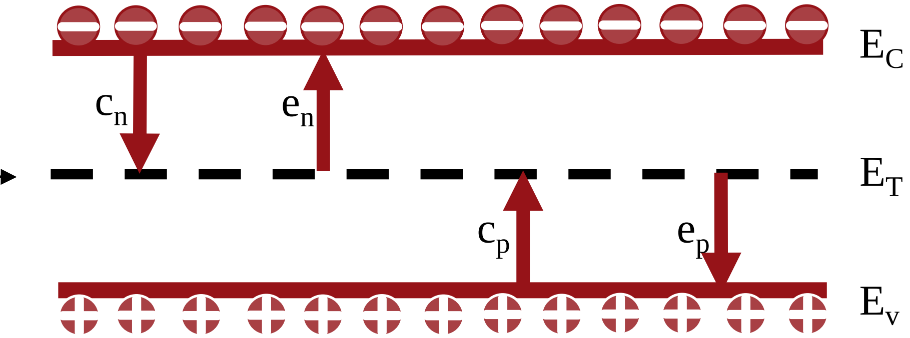


$$Si \rightarrow I + V$$

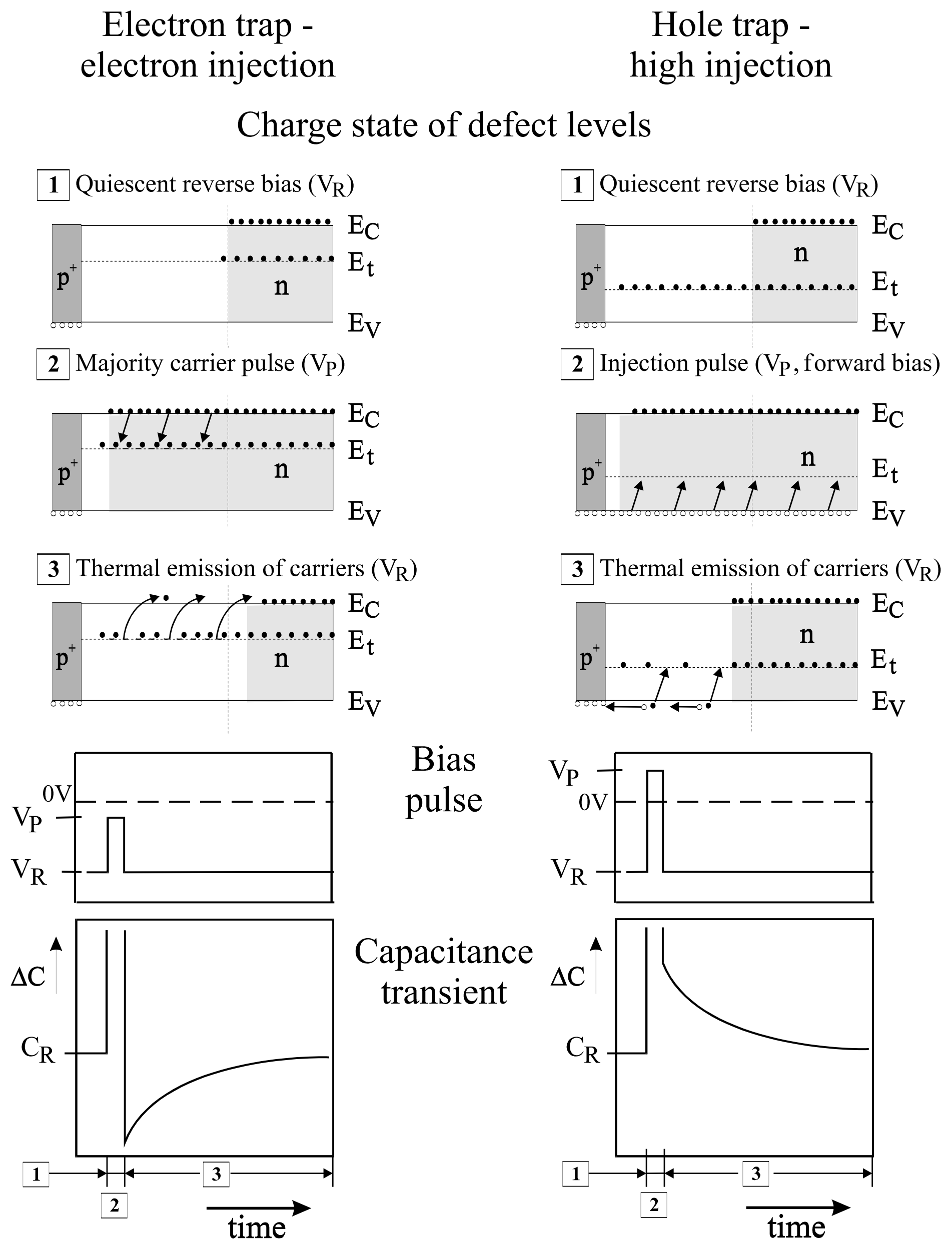
$$B_s \rightarrow B_i + V$$

$$I + B_s \rightarrow B_i$$

$$B_i + O_i \rightarrow B_iO_i$$



3. 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.

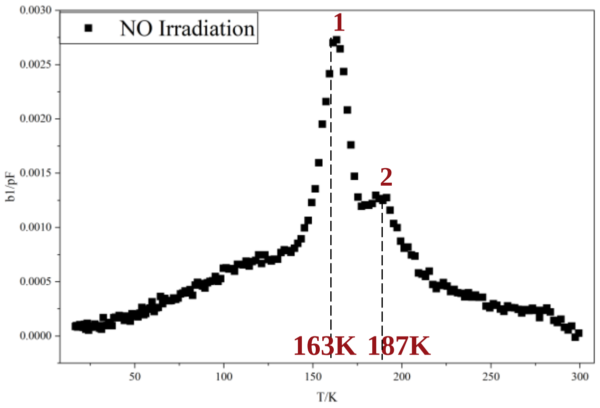
(3) **Capture Cross-Section (σ):** A measure of the probability or efficiency for a defect to capture a charge carrier.

DLTS Measurements: Result I - PINs

V3：

(1) NO Irradiation

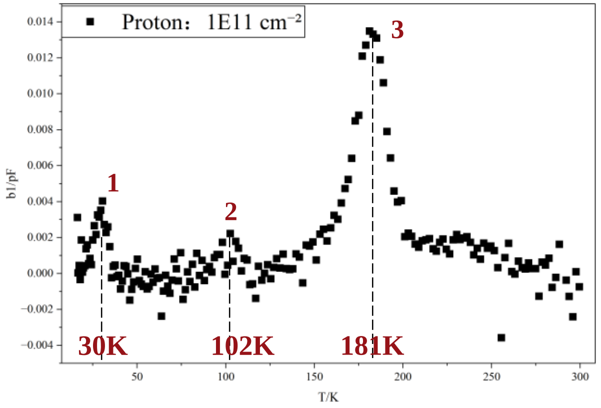
U_R=-10V, U_P=0.6V, T_W=192ms, t_p=100us



	E_t/eV	N_t/cm^2
1	E_V+0.317	3.20E+11
2	E_V+0.380	1.89E+11

(2) Proton: 1E11 cm²

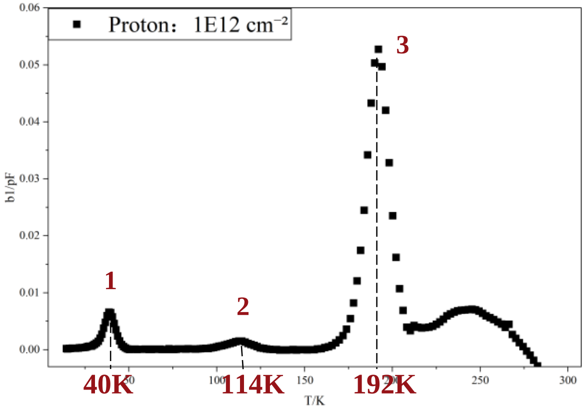
U_R=-10V, U_P=1V, T_W=192ms, t_p=100us



	E_t/eV	N_t/cm^2
1	E_V+0.016	6.57E+12
2	E_V+0.153	2.84E+12
3	E_V+0.369	3.97E+12

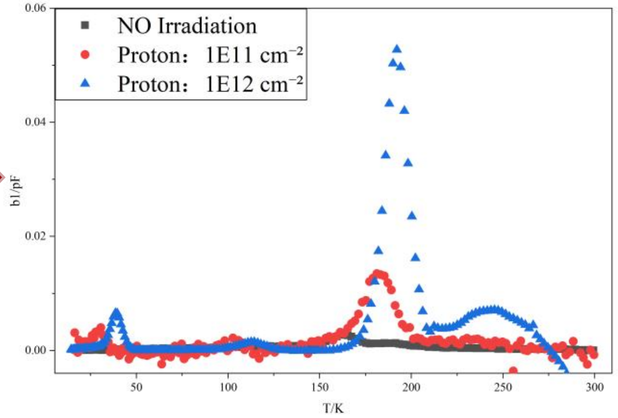
(3) Proton: 1E12 cm²

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



	E_t/eV	N_t/cm^2
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)

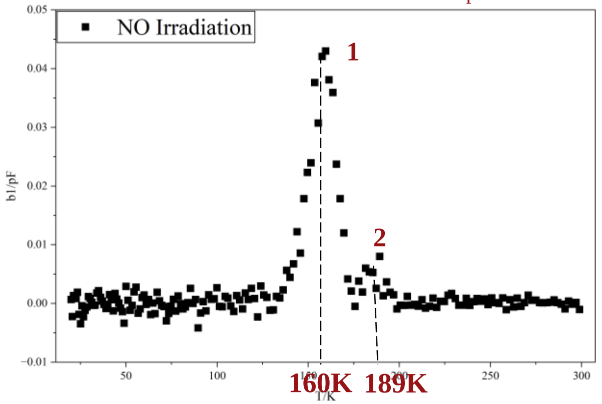


- **Qualitative Conclusions:** as the proton irradiation fluence increases, the variety and concentration of defects in PINs also increase. The PIN irradiated with proton fluence of 1E12 cm² clearly contains a greater number and more complex types of defects.
- **Quantitative Conclusions:** the dominant defects in the different samples are not all the same type. For different fitting methods, our fitting error is σ = 0.003. For the dominant defects in the three samples, the difference in their energy levels is approximately 0.028, which is about 9σ. According to the 1σ criterion, we can conclude that these correspond to different energy levels.

V2:

(4) NO Irradiation

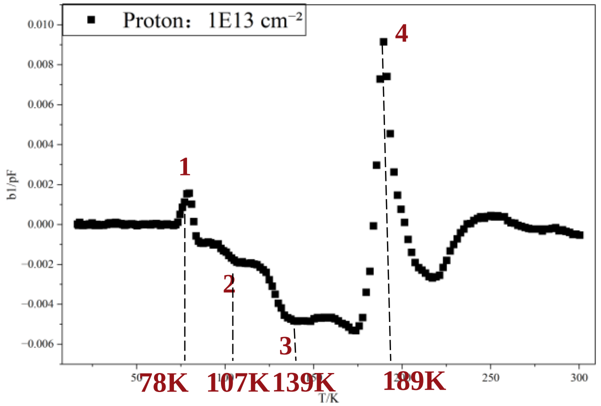
U_R=-10V, U_P=1V, T_W=192ms, t_p=100us



	E_t/eV	N_t/cm²
1	E_V+0.380	2.32E+12
2	--	--

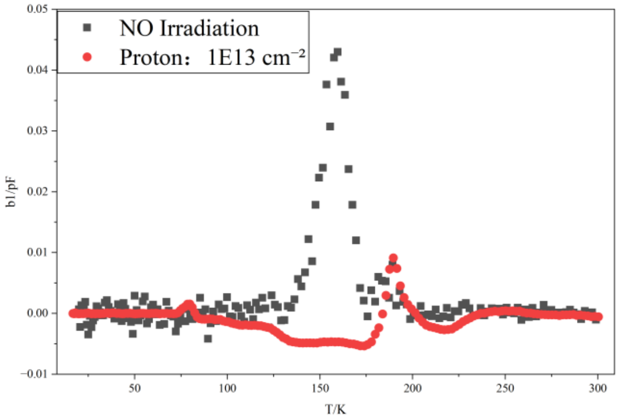
(5) Proton: 1E13 cm²

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



	E_t/eV	N_t/cm²
1	E_V+0.123	7.32E+11
2	E_C-0.260	4.28E+12
3	E_C-0.232	2.83E+12
4	E_V+0.350	5.19E+12

(4)+(5)



- **Qualitative Conclusions:** a higher irradiation fluence leads to a greater variety of defects. Notably, we even observed two negative peaks in the sample(5), indicating that the corresponding energy level is closer to the conduction band, which means, this defect primarily captures electron carriers .
- **Quantitative Conclusions:** the dominant defect in the unirradiated PIN is not the same as that in the sample(5). Interestingly, we observed that the energy level position of the dominant defect in the sample(5) overlaps with that of Peak 2 in the unirradiated sample. However, unfortunately, due to systemic noise, a reliable fit for Peak 2 in the unirradiated sample could not be achieved.

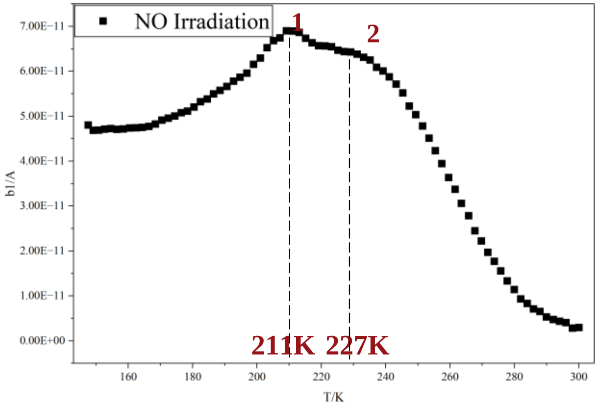
Defects in PINs:

- Qualitatively, it is concluded that a higher proton irradiation fluence leads to a greater variety of defects.
- Quantitative data support that the dominant defects in PINs are not all same in different proton fluences.

DLTS Measurements: Result II - LGADs

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

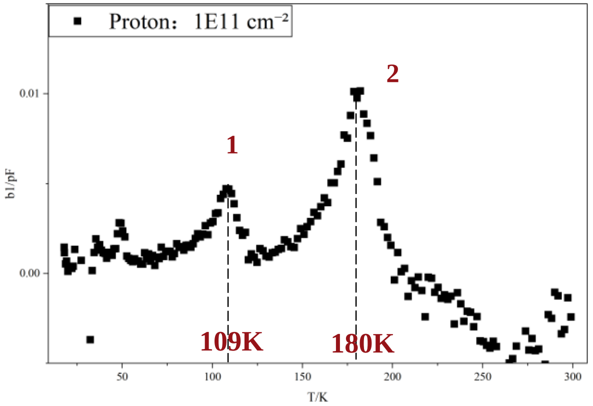
U_R=-25V, U_P=-2.5V, T_W=192ms, t_p=1ms



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

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

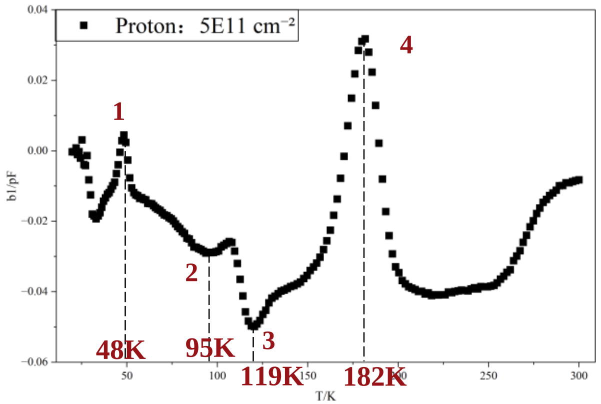
U_R=-10V, U_P=-1V, T_W=192ms, t_p=10ms



	E_t/eV	N_t/cm²
1	E_V+0.133	7.89E+09
2	E_V+0.287	1.03E+10

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

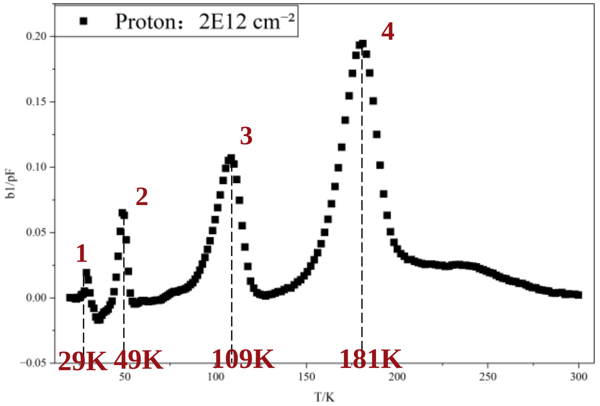
U_R=-10V, U_P=0.4V, T_W=192ms, t_p=10ms



	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

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

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

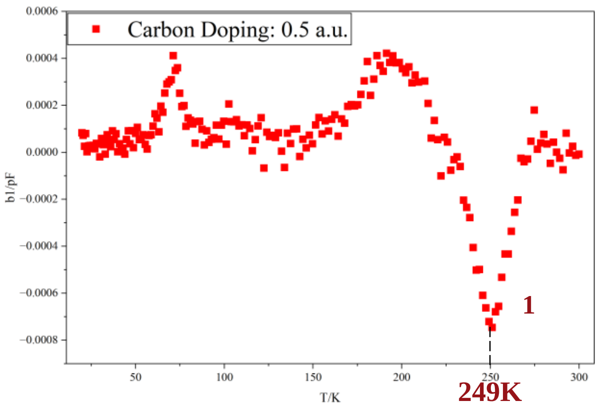


	E_t/eV	N_t/cm²
1	E_V+0.070	4.87E+10
2	E_V+0.094	3.95E+10
3	E_V+0.181	5.53E+10
4	E_V+0.354	9.93E+10

- Defect characterization in unirradiated LGADs required i-DLTS (current-DLTS) method, as conventional DLTS was not feasible
- Qualitatively, for the non-carbon-doped samples (2), (3), and (4), both the concentration and variety of defects increase with higher proton irradiation fluence. In contrast, for the carbon-doped sample (1), the introduction of carbon leads to a significantly higher initial defect concentration compared to other samples.
- Quantitatively, the dominant defects in LGADs differ in different proton fluences. This observation is consistent with the results obtained from PINs.

(5) Proton: 8E14 cm²
(With Carbon Doping: 0.5 a.u.)

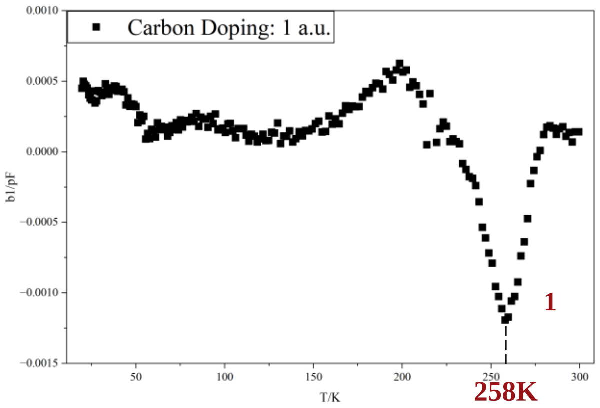
UR=-20V, UP=-2V, Tw=192ms, tp=10ms



	E_t/eV	N_t/cm^2
1	E_C-0.488	1.99E+11

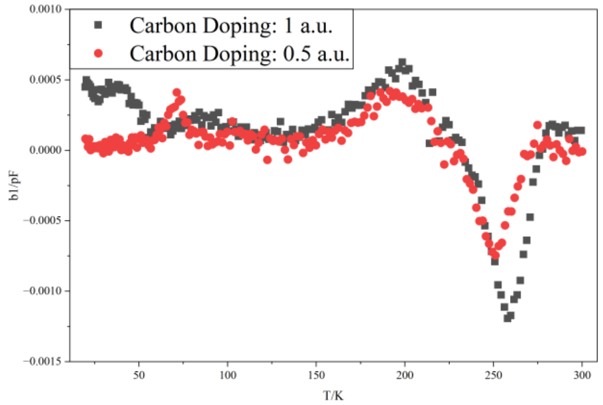
(6) Proton: 8E14 cm²
(With Carbon Doping: 1 a.u.)

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



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

(5)+(6)



- A high-concentration negative peak was detected in both samples, indicating that the energy level of this defect is close to the conduction band, acting as a minority carrier trap that primarily captures electron carriers.
- Since an error analysis has not yet been performed on these two samples, we currently lack evidence to confirm that peak1 in both samples is the same defect species. However, given the higher defect concentration observed in the high-carbon-dose sample, we propose that this defect is likely carbon-related.

Defects in LGADs:

- Qualitatively, it is concluded that a higher proton irradiation fluence results in a greater variety of defects. While Quantitative data support that the dominant defects in LGADs differ in different proton fluences. These characteristics are consistent with the observations in the PINs.
- Furthermore, in the carbon-doped LGADs, carbon-related defects were identified as the dominant one in the samples irradiated with proton fluence of 8E14 cm^2. This experimentally confirms that carbon doping introduces specific defects, which in turn enhances the radiation resistance of the gain layer.

Summaries:

- For both PINs and LGADs, a higher proton irradiation fluence leads to a greater variety of defects. Under different fluence levels, the energy levels of the dominant defects in both PINs and LGADs are not identical. This indicates that the gain layer of the LGAD and the bulk region of the PIN exhibit similar qualitative characteristics.
- We are currently investigating more detailed defect information, such as the specific identity of these energy levels.
- Furthermore, in carbon-doped LGADs, carbon-related defects are the dominant type. This experimentally confirms that carbon doping introduces specific defects, which enhance the radiation resistance of the gain layer.

Thanks for Your Attention!

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