Simulation of Neutron-Induced Degradation of Lateral PNP Bipolar Transistor Using a Defect-Based TCAD Model

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Outline

1. Introduction
2. Modeling Methods
3. Experimental and DLTS Results
4. Simulation results
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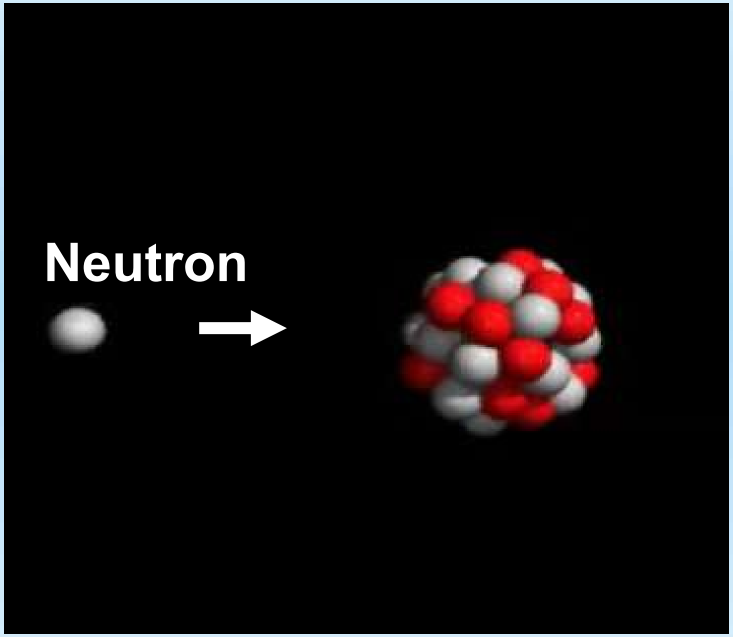
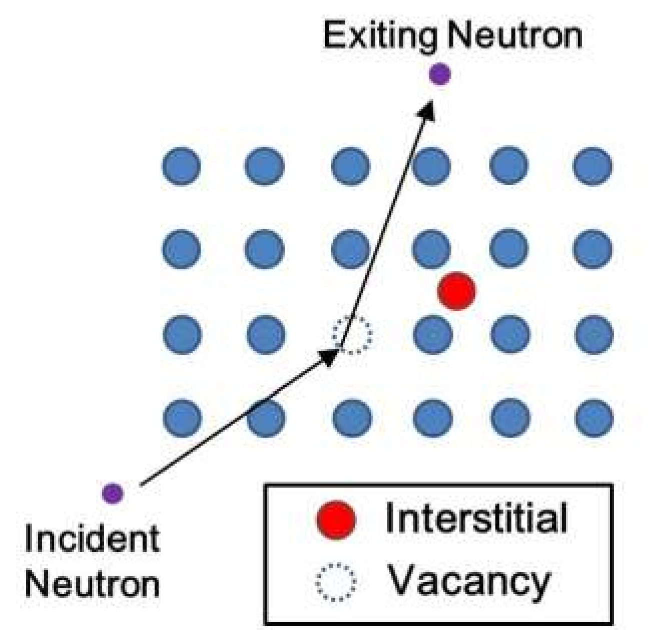
1. Introduction

Neutron-Induced Displacement Damage



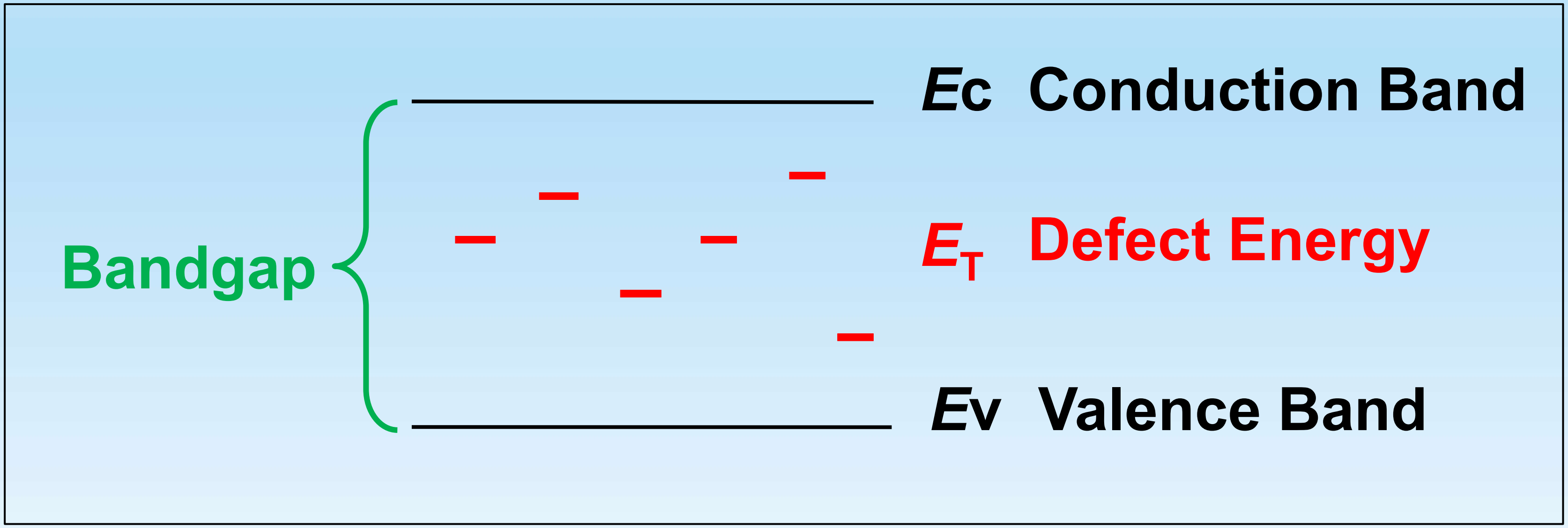


Incident neutron collides with nucleus in the semiconductor material. The target nucleus is given enough energy to leave its lattice position, generating displacement damage defects.

1. Introduction

- Defect energy inside the bandgap

Neutron-induced displacement damage defects produce the defect energy inside the bandgap in the semiconductor (such as silicon) which forms the electronic devices.



***E*c Conduction Band**

E_T Defect Energy

Bandgap

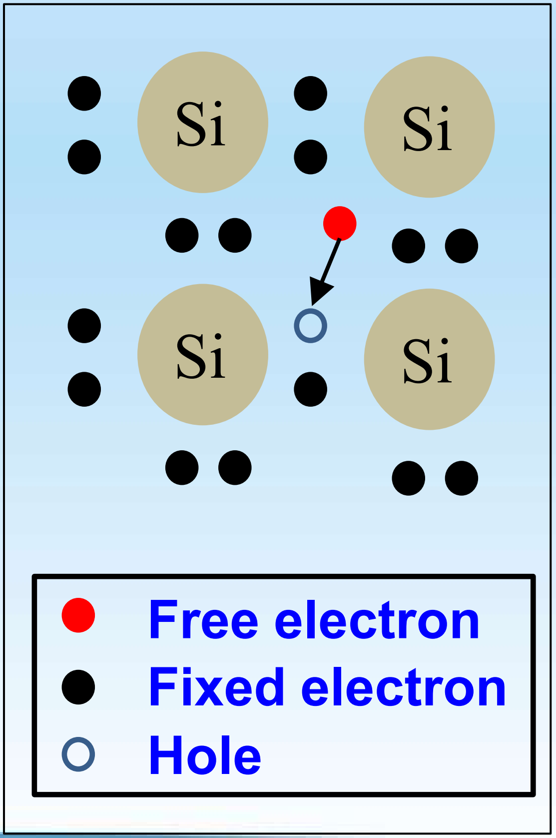
***E*v Valence Band**

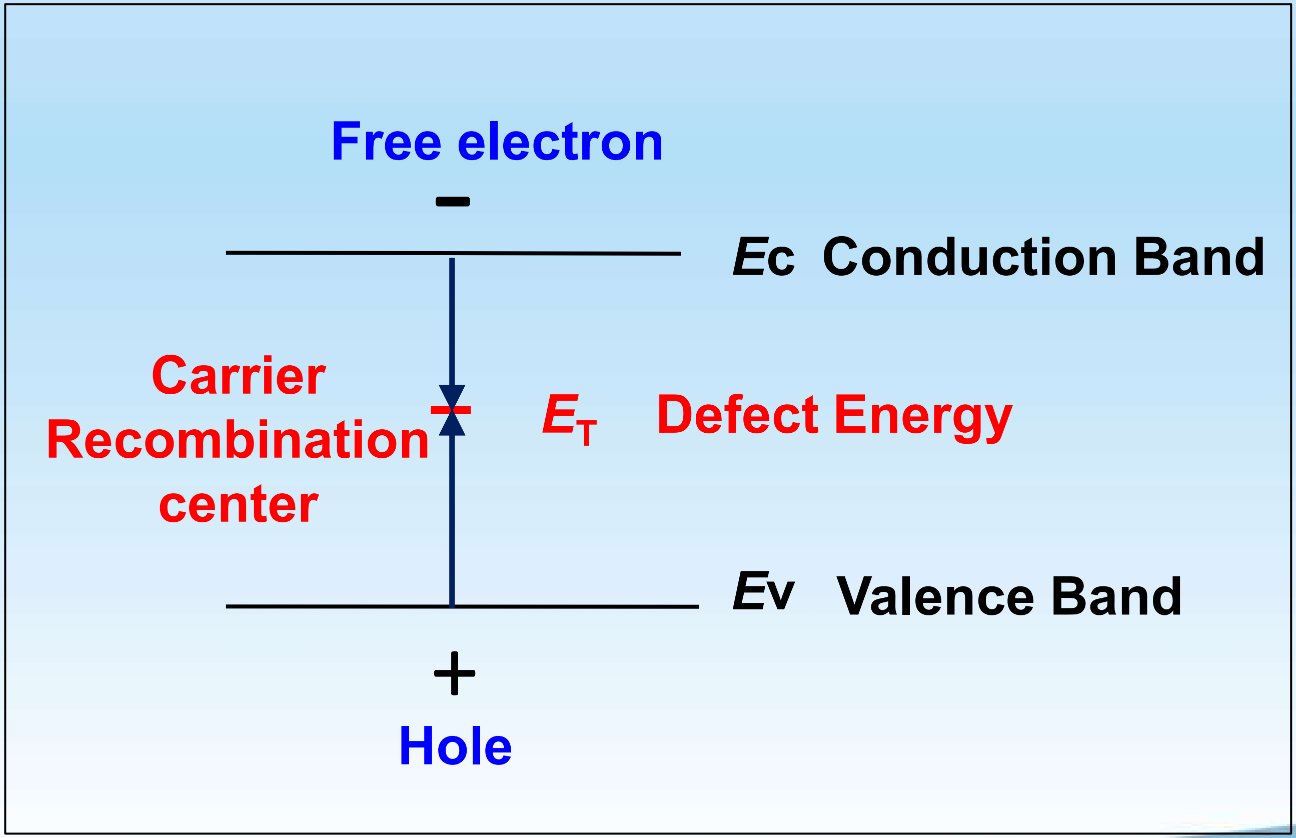
Energy band diagram of silicon

1. Introduction

- Carrier recombination

Defect energy inside the bandgap can act as the carrier recombination center to reduce the amount of free electrons and holes in the semiconductor.

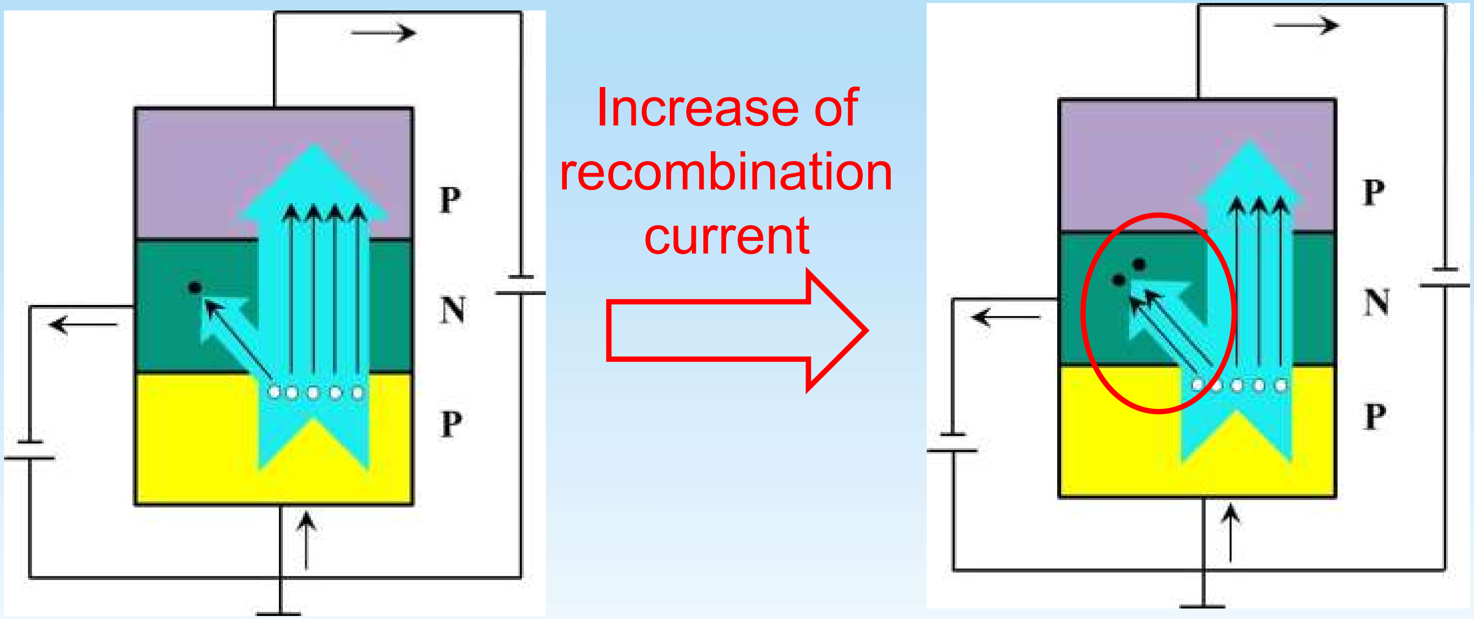




1. Introduction

- Degradation of lateral PNP bipolar transistor

Carrier recombination in the neutron-induced displacement damage defects leads to the increase of recombination current in the base region of lateral PNP bipolar transistor, degrading the current gain of the transistor.



Increase of recombination current

Current in the lateral PNP bipolar transistor

2. Modeling Methods

Defect-based carrier recombination model

Neutron-induced increase of recombination current in the base region of bipolar transistor:

$$I_{rB} = q\int_V R dV$$

I_{rB} is the main reason for current gain degradation, q the electron charge, R carrier recombination rate, V the volume of the region where the carrier recombination occurs.

According to the SRH carrier recombination theory, carrier recombination rate R_{T} in the neutron-induced defect energy E_{T} is:

$$R_{\mathrm{T}} = \frac{np - n_i^2}{\tau_p(n+n_l)+\tau_n(p+p_l)}$$

2. Modeling Methods

Defect-based carrier recombination model

If $\tau_{\mathrm{n}} = \tau_{\mathrm{p}} = \tau_{\mathrm{r}}$, namely $\sigma_{\mathrm{n}}=\sigma_{\mathrm{p}}=\sigma$, after derivation, the form turns to：

$$\boxed{R_{\mathrm{T}} = \frac{v_{th}\sigma N_T(np-n_i^2)}{n+p+2n_i\cosh(\frac{E_T-E_i}{kT})}}$$

n is the equilibrium electron concentration, p the equilibrium hole concentration, v_{th} carrier thermal velocity, n_{i} intrinsic carrier concentration, E_{i} intrinsic energy level in the bandgap.

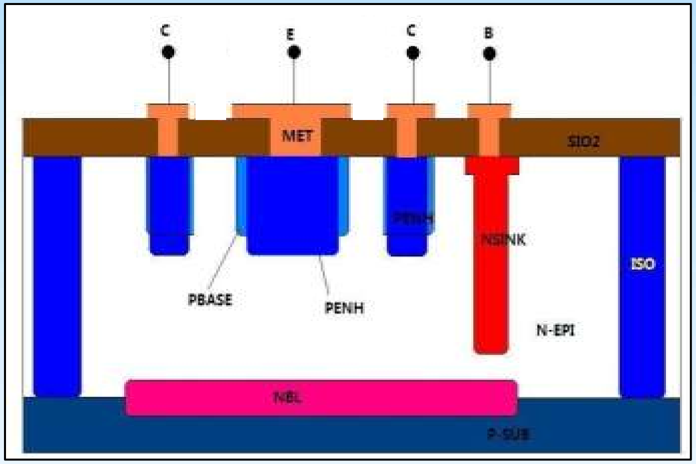
The degradation of transistor can be simulated if acquiring the neutron-induced defect parameters including **Defect density N_{T}, Energy level E_{T}, Carrier capture cross-section σ.**

3. Experimental and DLTS Results

Lateral PNP bipolar transistor → **Irradiation with different neutron fluence** → **Electrical characteristic testing** → **DLTS testing**

Lateral PNP bipolar transistors with different base widths and doping concentrations were selected to accomplish neutron displacement effects experiments.

Type	Base Width W_B/μm	Base Doping Concentration N_B/cm^{-3}
LPNP1	10	6×10^{15}
LPNP2	10	3×10^{15}
LPNP3	10	1×10^{15}
LPNP4	15	6×10^{15}
LPNP5	15	3×10^{15}
LPNP6	15	1×10^{15}



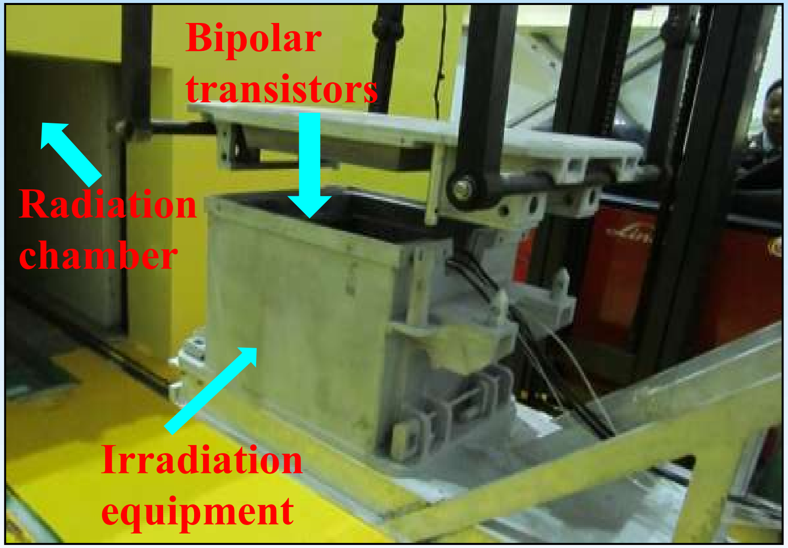
Lateral PNP bipolar transistor

3. Experimental and DLTS Results

Lateral PNP bipolar transistor → **Irradiation with different neutron fluence** → **Electrical characteristic testing** → **DLTS testing**

Irradiation Facility: Xi’an Pulsed Reactor (XAPR), an important facility for the research of neutron radiation effects. It has a specific irradiation platform for electronic devices and components.

Xi’an Pulsed Reactor (XAPR)

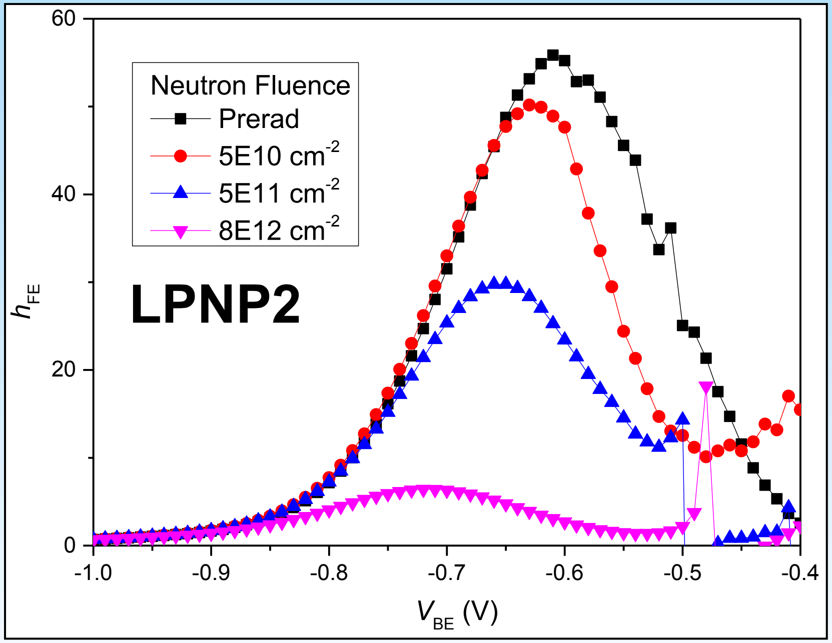


Irradiation platform of XAPR

3. Experimental and DLTS Results

Lateral PNP bipolar transistor → **Irradiation with different neutron fluence** → **Electrical characteristic testing** → **DLTS testing**

Electrical characteristic degradations of LPNPs were measured after neutron irradiation with different neutron fluence.



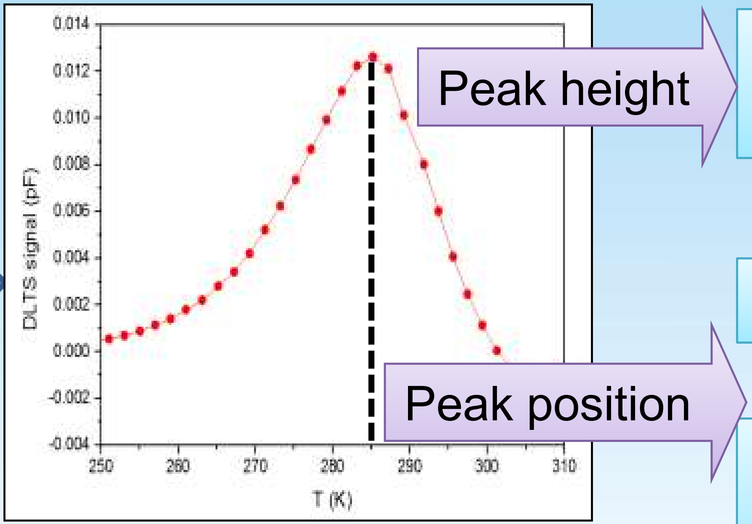
Current gain degrades obviously with the increasing neutron fluence.

3. Experimental and DLTS Results

Lateral PNP bipolar transistor → **Irradiation with different neutron fluence** → **Electrical characteristic testing** → **DLTS testing**

Deep Level Transient Spectroscopy (DLTS) was tested to acquire the defect parameters of neutron-induced displacement damage in LPNPs.

DLTS Testing System



Peak height → Defect density N_T

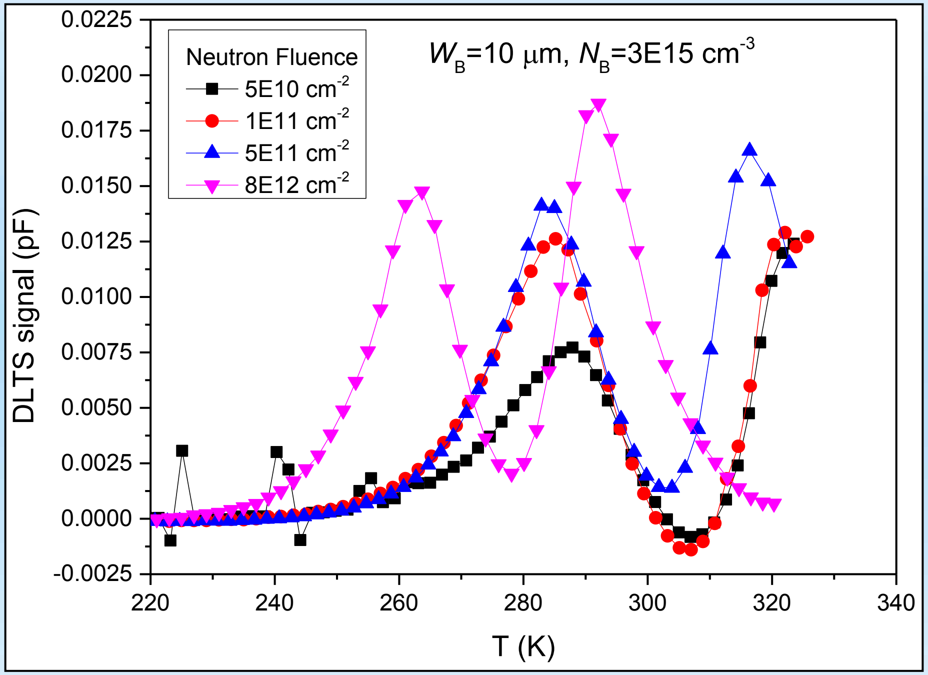
Peak position → Energy level E_T; Carrier capture cross-section σ

Typical DLTS: C~T

3. Experimental and DLTS Results

DLTS results:

LPNP with base width W_B=10 μm， base doping concentration $N_B=3\times10^{15}$ cm^{-3} as an example



At low neutron fluence

- DLTS peak temperature position almost stays the same.
- DLTS peak height turns larger.

At high neutron fluence

- DLTS peak height changes slightly.
- DLTS peak temperature position shifts to the lower obviously.

3. Experimental and DLTS Results

DLTS results:

LPNP with base width W_B=10 μm， base doping concentration $N_B=3\times10^{15}$ cm^{-3} as an example

Defect parameters of neutron-induced displacement damage in LPNP

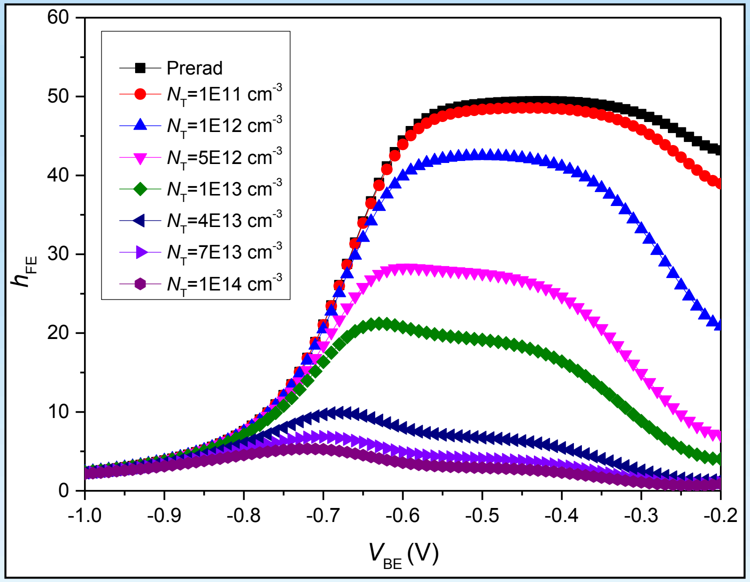
Neutron Fluence/cm^{-2}	Energy level E_T-E_V/eV	Defect density N_T/cm^{-3}	Carrier capture cross-section σ /cm^{-2}
5E10	0.641	6.06×10^{11}	1.25×10^{-16}
5E11	0.695	1.19×10^{12}	1.19×10^{-15}
	0.756	1.88×10^{12}	4.95×10^{-16}
8E12	0.645	1.22×10^{12}	1.94×10^{-15}
	0.796	1.72×10^{12}	3.69×10^{-14}

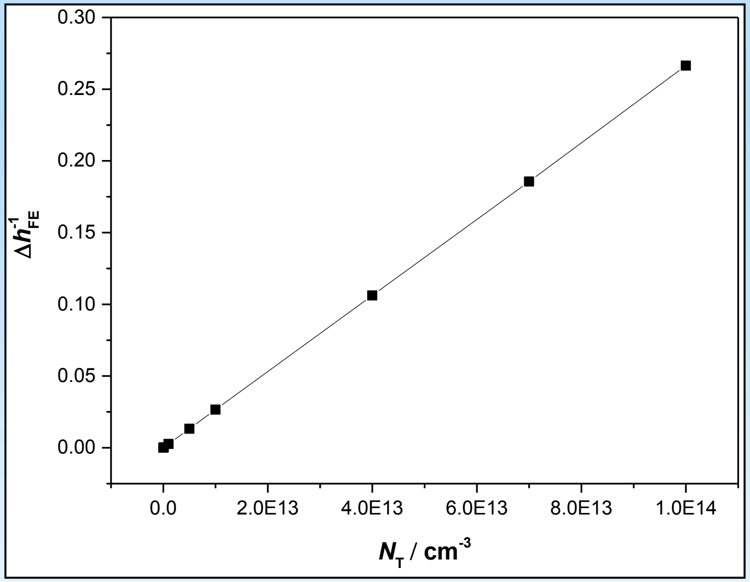
4. Simulation Results

Defect-based model

$$R_T = \frac{v_{th}\sigma N_T (np - n_i^2)}{n + p + 2n_i \cosh(\frac{E_T - E_i}{kT})}$$

Influence of defect density N_T on gain degradation:
(Fixing $E_T = E_i$, $\sigma = 10^{-15}$ cm^2)





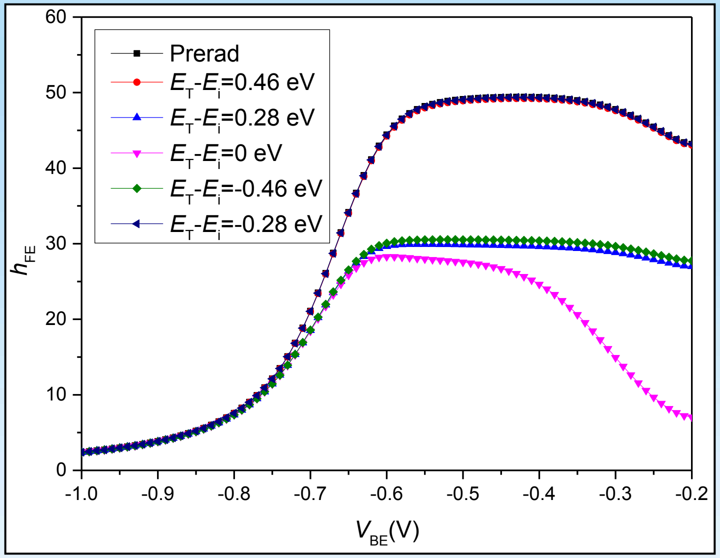
The change of the reciprocal of current gain $\Delta h_{FE}^{-1}(N_T)$ varies linearly with defect density N_T.

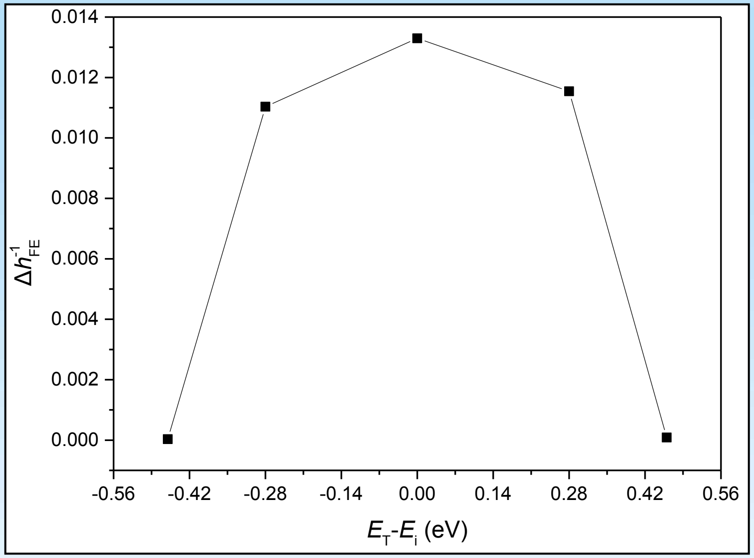
4. Simulation Results

Defect-based model

$$R_\mathrm{T} = \frac{v_{th}\sigma N_T(np-n_i^2)}{n+p+2n_i\cosh(\frac{\boxed{E_T}-E_i}{kT})}$$

Influence of energy level of defect E_T on gain degradation:
(Fixing $N_\mathrm{T}=5\times10^{12}$ cm^{-3}, $\sigma=10^{-15}$ cm^2)





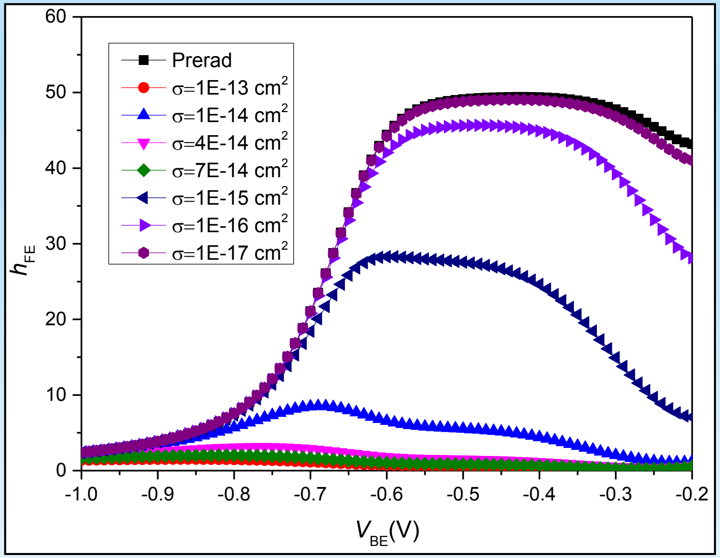
The change of the reciprocal of current gain $\Delta h_\mathrm{FE}^{-1}(E_\mathrm{T}-E_\mathrm{i})$ maximizes when $E_\mathrm{T}=E_\mathrm{i}$ and drops symmetrically as E_T gets close to E_c or E_v of the silicon.

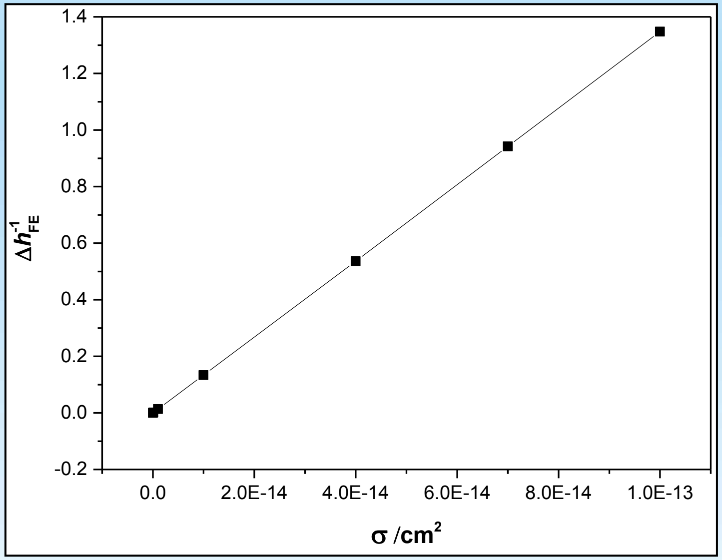
4. Simulation Results

Defect-based model

$$R_T = \frac{v_{th}\sigma N_T (np - n_i^2)}{n + p + 2n_i \cosh(\frac{E_T - E_i}{kT})}$$

Influence of carrier capture cross-section σ on gain degradation:
(Fixing E_T=E_i, N_T=5×10^{12} cm^{-3})





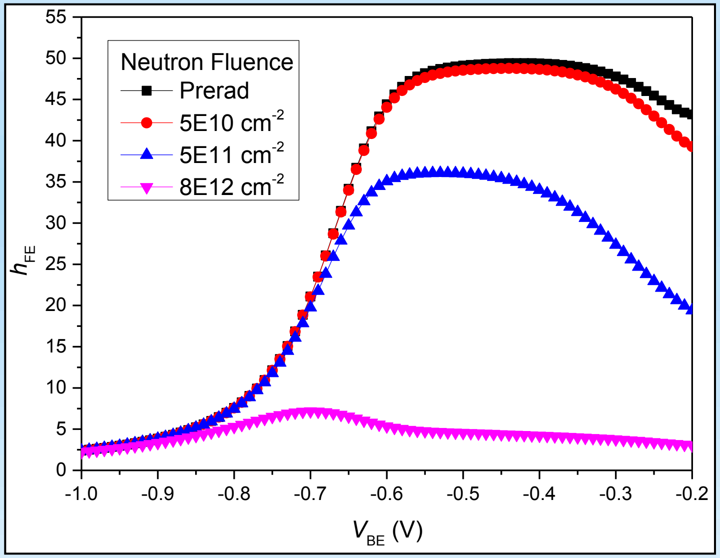
The change of the reciprocal of current gain $\Delta h_{FE}^{-1}(\sigma)$ varies linearly with carrier capture cross-section σ.

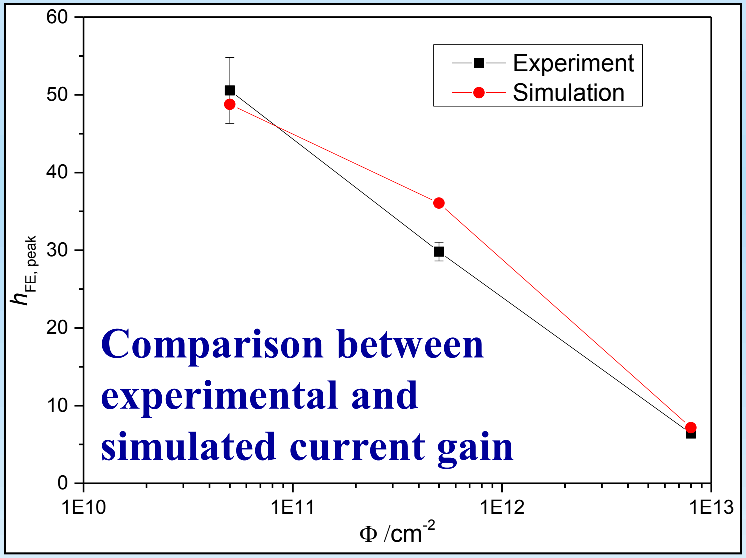
4. Simulation Results

DLTS analysis:
N_T , E_T , σ

Defect-based model

$$R_T = \frac{v_{th}\sigma N_T(np - n_i^2)}{n + p + 2n_i \cosh\left(\frac{E_T - E_i}{kT}\right)}$$





Comparison between experimental and simulated current gain

The simulation results of current gain degradation under different neutron fluence have a good consistency with the experimental results, verifying the correctness of the defect-based model.

5. Conclusion

- A defect-based TCAD model was developed to simulate the nuclear reactor neutron-induced degradation of the lateral PNP bipolar transistor.
- The critical parameters needed for the model are defect density N_T, energy level E_T and carrier capture cross-section σ.
- Deep Level Transient Spectroscopy (DLTS) of the transistor after neutron irradiation was tested to acquire the defect parameters and the current gain degradation was simulated by the model.