ShanghaiTech GaNology Lab
氮化镓电子器件实验室

Deep Level Transient Spectroscopy and its Application in Wide Bandgap Semiconductor & Devices

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Outline:

- Deep level basics
- Introduction of capacitance-DLTS
- Various DLTS modes
- Applications

Part I: Deep level basics

Introduction of defect

A defect is any perturbation of the semiconductor lattice, this can be:

- a vacancy
- an impurity atom
- cluster of atoms
- a self-interstitial
- an extended defect (dislocation)
- an atom on the wrong site

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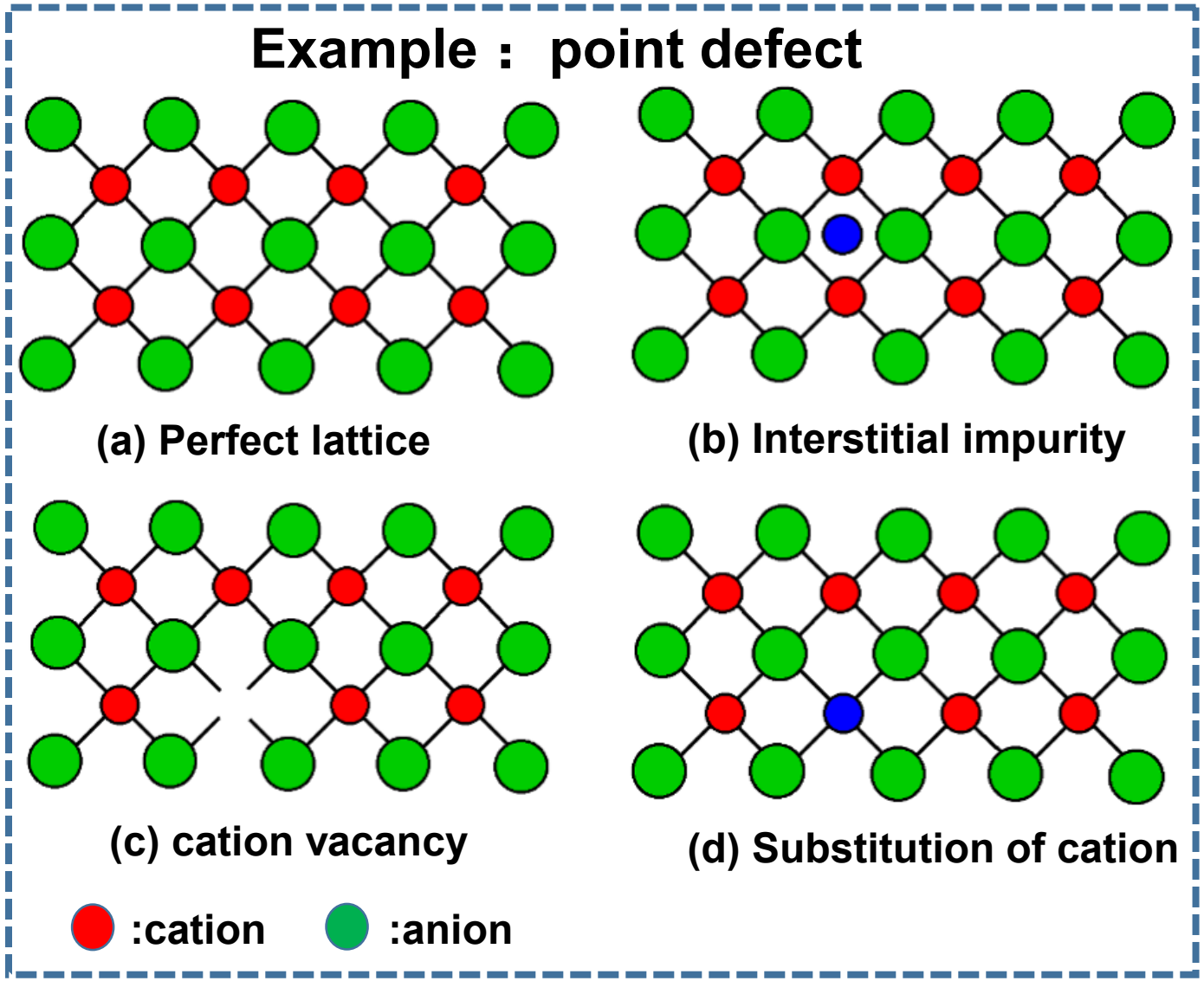

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Shockley-Read-Hall (SRH)

- SRH processes result in carrier generation and recombination
- The recombination rate of excess carriers:

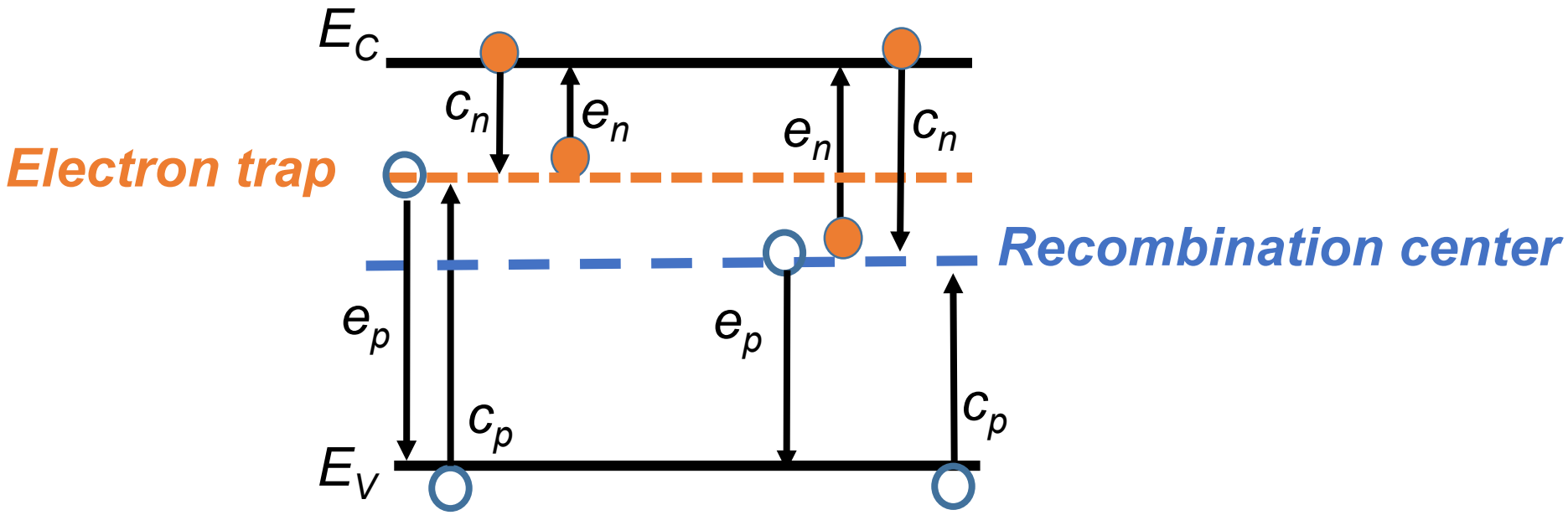
$$R^{\mathrm{SRH}} = \frac{c_{\mathrm{n}} c_{\mathrm{p}} N_{\mathrm{t}} \left(n \cdot p - n_i^2\right)}{c_{\mathrm{n}} \cdot \left(n + n^{'}\right) + c_{\mathrm{p}} \cdot \left(p + p^{'}\right)}$$

$$n^{'} = N_c \exp\left[\frac{-\left(E_c - E_t\right)}{kT}\right] \qquad p^{'} = N_v \exp\left[\frac{-\left(E_t - E_v\right)}{kT}\right]$$

n_i is intrinsic carrier concentration;
N_t is total concentration of trapping center;
n is concentration of electron; p is concentration of holes;
c_n and c_p are the capture rate of electron and hole;

D. Neamen, "*Semiconductor Physics and Devices*". Fourth edition, 2017.

Capture and emission processes of deep level



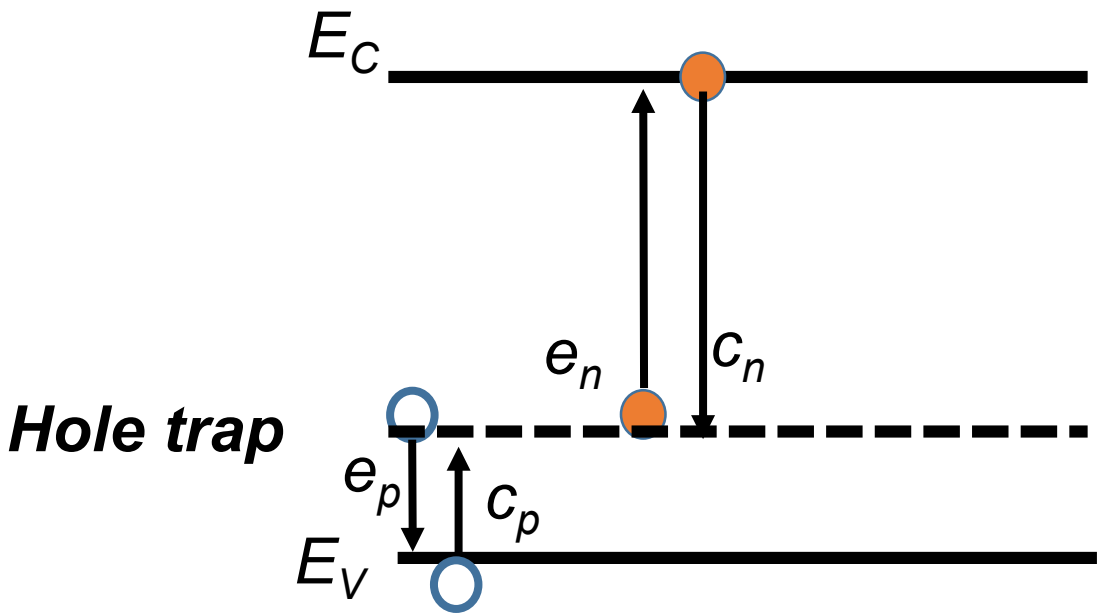
Deep levels in the band gap act as

- **Recombination centers**: can interact with both edges of bandgap c_n=c_p.
- **Electron traps**: If they mostly interact with the conduction band c_n>>c_p.

Notes:

- The capture rate of electrons (c_n) and holes (c_p)
- The generation rate of electrons (e_n) and holes (e_p)

Capture and emission processes of deep level

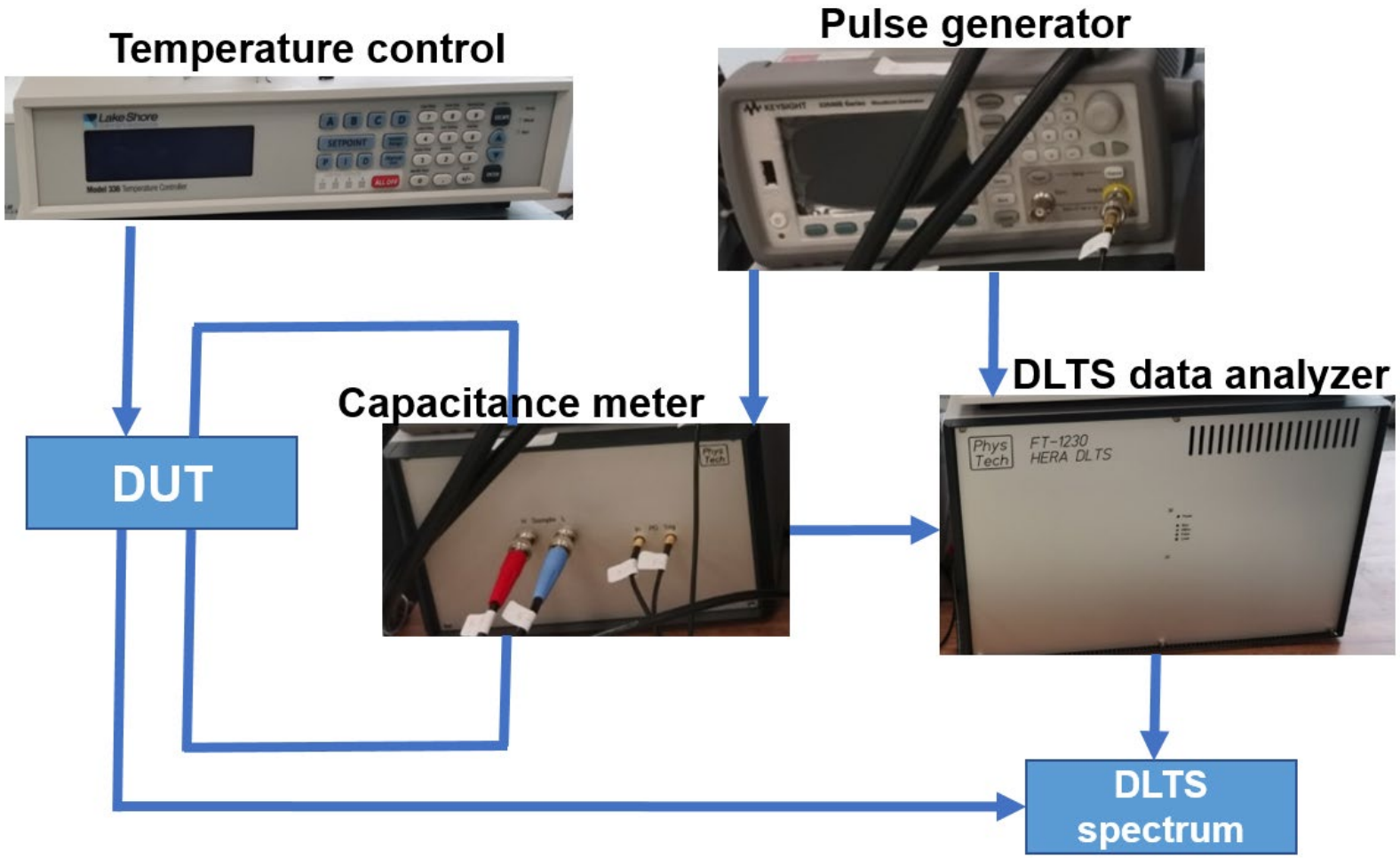


Deep levels in the band gap act as

- **Hole traps**: If they mostly interact with the conduction band $c_p >> c_n$.

Part II: Introduction of Capacitance-DLTS

Schematic of the C-DLTS measurement setup



Standard DLTS system

- Pulse voltage range: ±100V
- pulse generator for pulses: (1μs-1000s)
- Test frequency : 1MHz

DLTS modes

- C-DLTS (Capacitance - DLTS)
- O-DLTS (Optically stimulated DLTS)
- I-DLTS (Current - DLTS)

……

Capacitance DLTS (C-DLTS)

- **Structures for C-DLTS test**
- p-n junction
- Schottky junction
- MIS



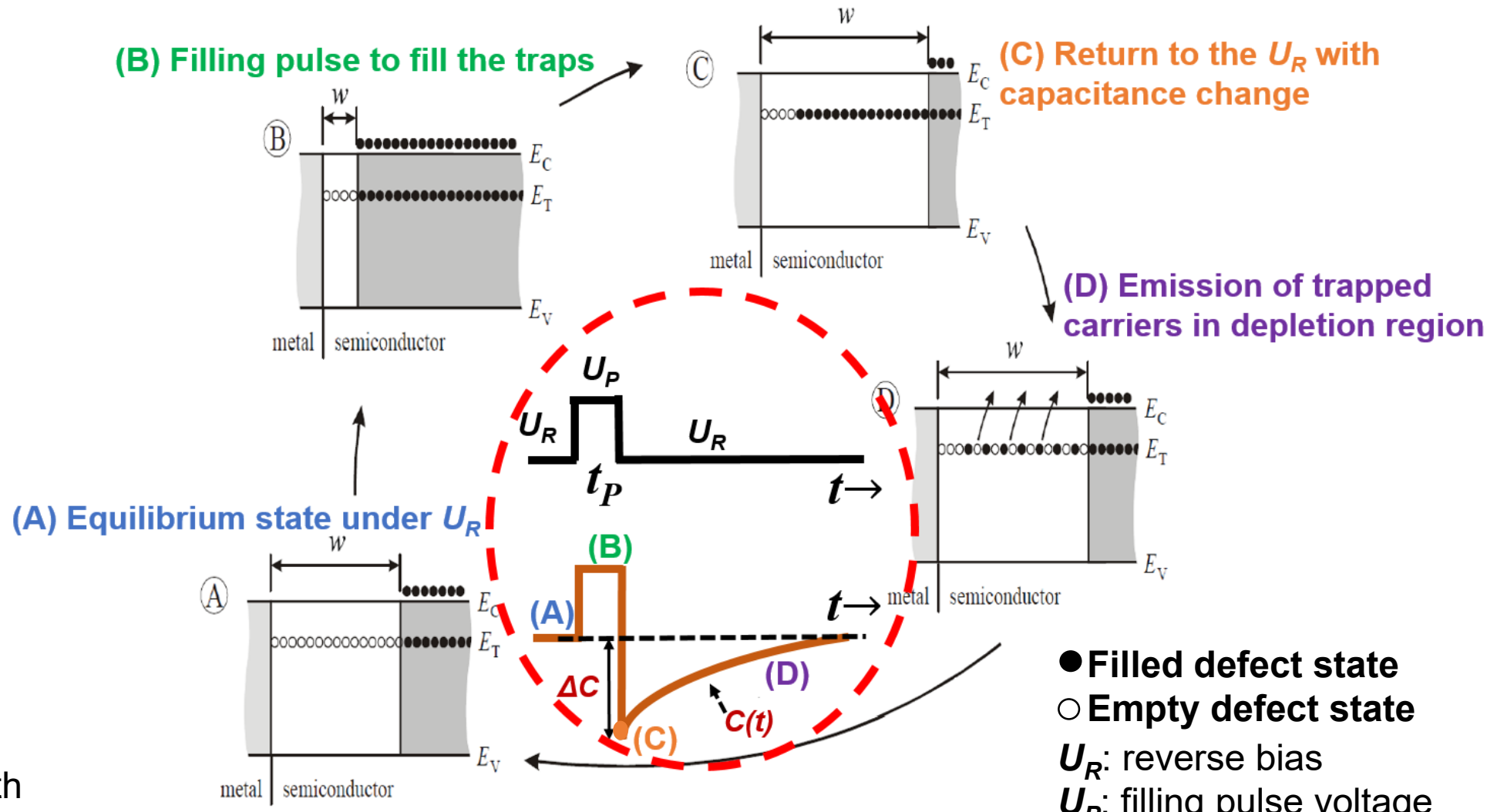
Test “**capacitance transient change**” in depletion region to detect the deep levels

Capacitance change in SCR (example: Schottky diode)

The capacitance (C) of Schottky contact:

$$\begin{cases} C = \dfrac{\varepsilon\varepsilon_0 A}{W} \\ W = \sqrt{\dfrac{2\varepsilon(U+U_D)}{qN_D}} \end{cases}$$

Where:
A: Schottky contact area
ε : the relative permittivity
ε_0 : the vacuum permittivity
W: the depletion region width
U: an external voltage
U_D: the diffusion voltage
N_D: shallow doping concentration



● **Filled defect state**
○ **Empty defect state**
U_R: reverse bias
U_P: filling pulse voltage
t_p: pulse width

Majority and minority carrier trap emission transient

For majority carrier traps, the capacitance transient:

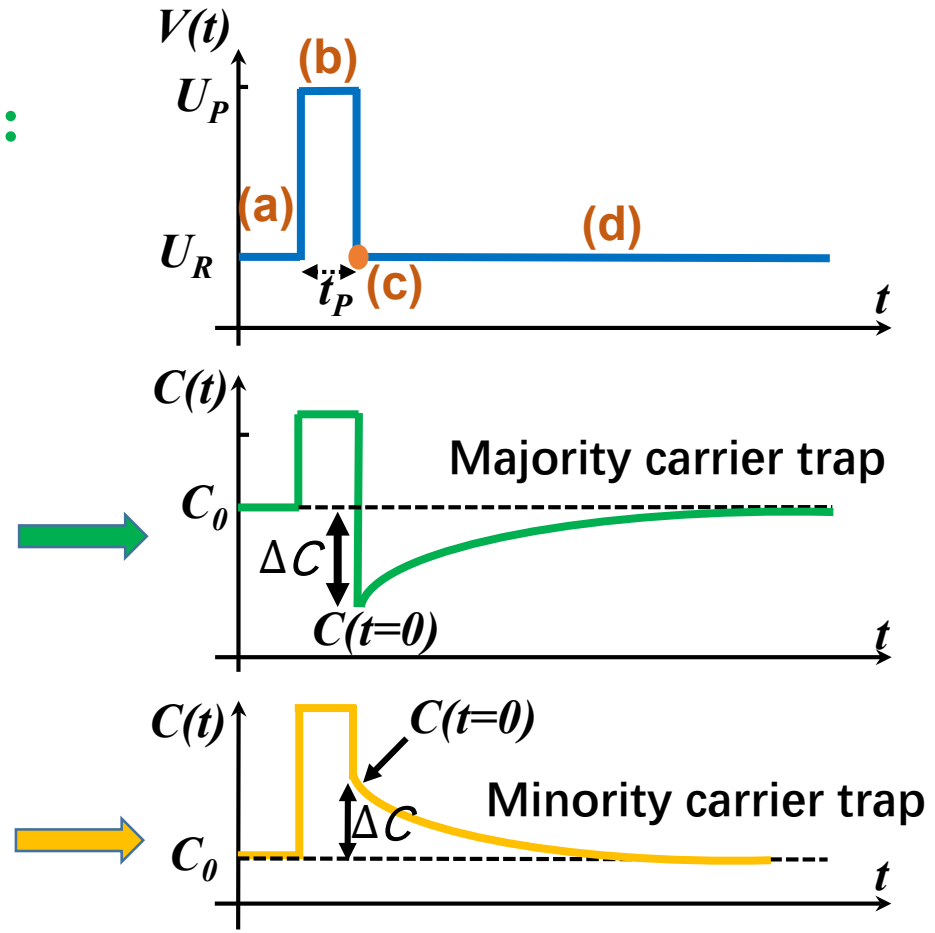
$$C(t) - C_0 = \Delta C_0 \exp(-e_n t) = -\frac{N_T C_0}{2N_D} \exp(-e_n t)$$

The capacitance change of trap impact:

$$\Delta C = A\sqrt{\frac{\varepsilon\varepsilon_0 q(N_D - N_T)}{2(U_R + U_D)}} - A\sqrt{\frac{\varepsilon\varepsilon_0 q N_D}{2(U_R + U_D)}} \approx -C_0 \frac{N_T}{2N_D}$$

For minority carrier traps, the capacitance change:

$$\Delta C = A\sqrt{\frac{\varepsilon\varepsilon_0 q(N_D + N_T)}{2(U_R + U_D)}} - A\sqrt{\frac{\varepsilon\varepsilon_0 q N_D}{2(U_R + U_D)}} \approx C_0 \frac{N_T}{2N_D}$$



Where the C(t) is time dependent capacitance transient;
C_0 is equilibrium state capacitance under U_R;
N_D is shallow doping concentration;
N_T is trap concentration;

e_n is emission rate of trap center;
q is quantity of electric charge;
U_D is the diffusion voltage;

Temperature scan DLTS

The emission process of trapped carrier and the capacitance transient by boxcar method:

$$\Delta C(t) = C(t_1) - C(t_2) = \frac{C_0 N_T}{2N_D}\left(e^{-e_n t_2} - e^{-e_n t_1}\right) \quad \text{(a)}$$

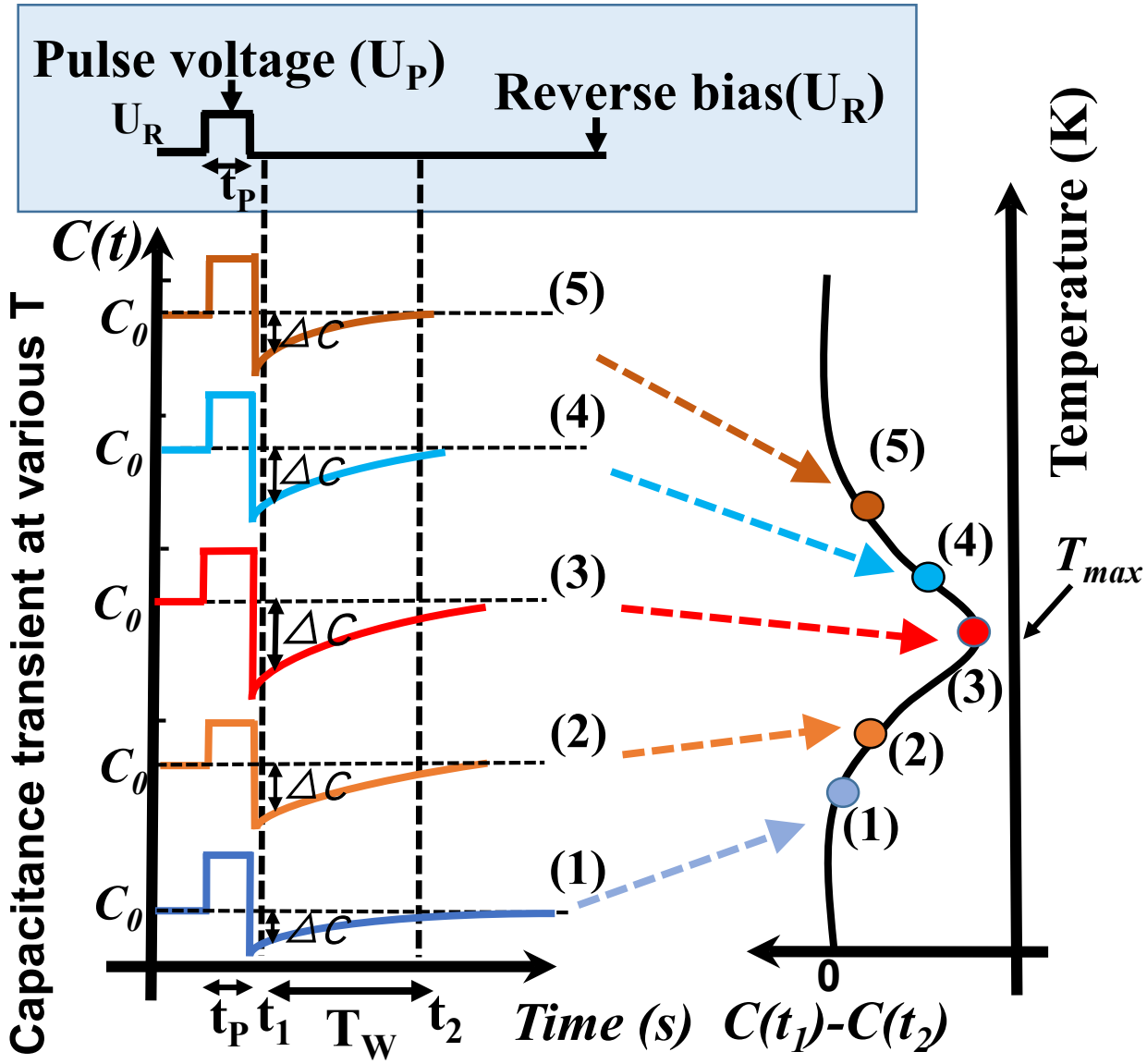
Where the N_T is trap concentration; N_D is doping concentration; measured trap emission rate (e_n) ;C_0 *is capacitance under* U_R.

- In experiment, the e_n^{max} corresponding with T_{max} .
- When e_n matches a "standard" time window, the maximum of e_n *is :*

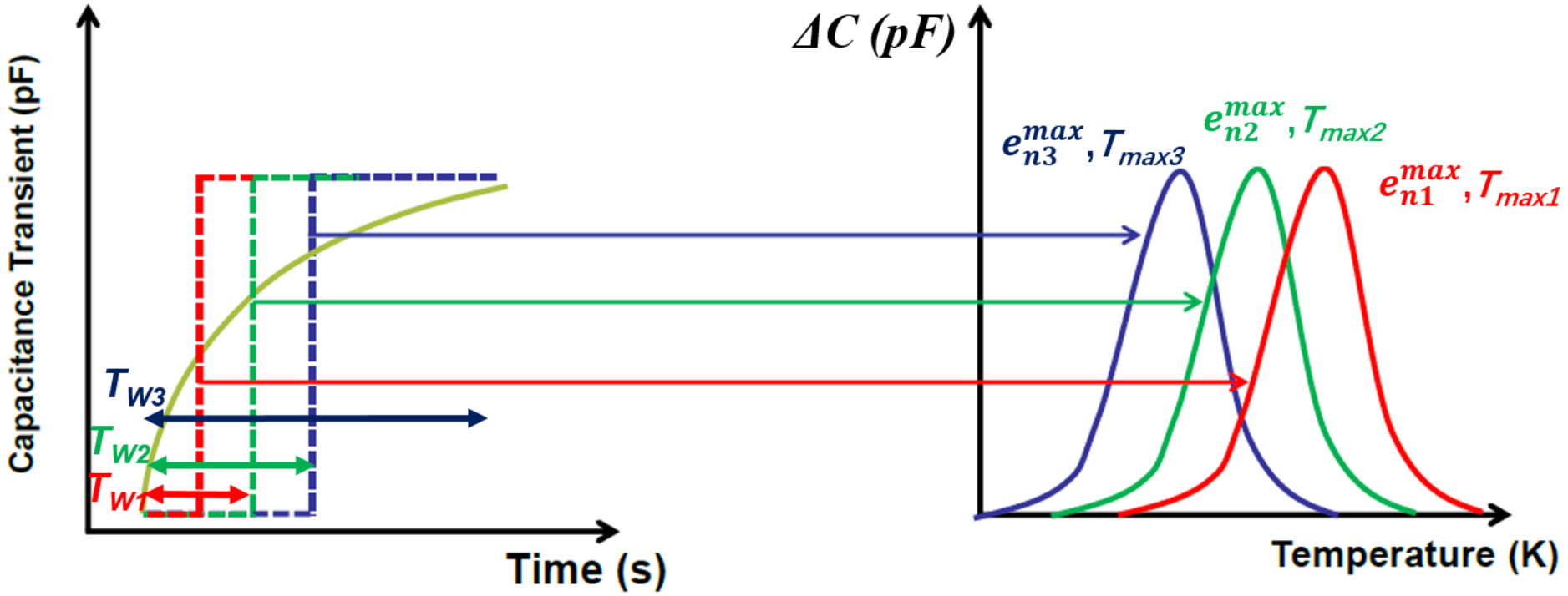
$$e_n^{\max} = \frac{1}{\tau_e} = \frac{\ln(t_2 / t_1)}{t_2 - t_1} \quad \text{(b)}$$

Repeated transient test at fixed T_W through a temperature scan:

- **DLTS spectrum**



Thermal emission rate (e_n) of trap by Boxcar method



- Varying time-window T_W (t_2-t_1), the DLTS peak will shift in temperatures
- *Numerically calculate the* $\boldsymbol{e_n^{max}}$ of each T_W corresponding peak temperature $\boldsymbol{T_{max}}$

$$e_{n1}^{max}, T_{max1}\ ;\ e_{n2}^{max}, T_{max2}\ ;\ e_{n3}^{max}, T_{max3}\ ;\ \ldots\ldots$$

Arrhenius plot to extract trap properties

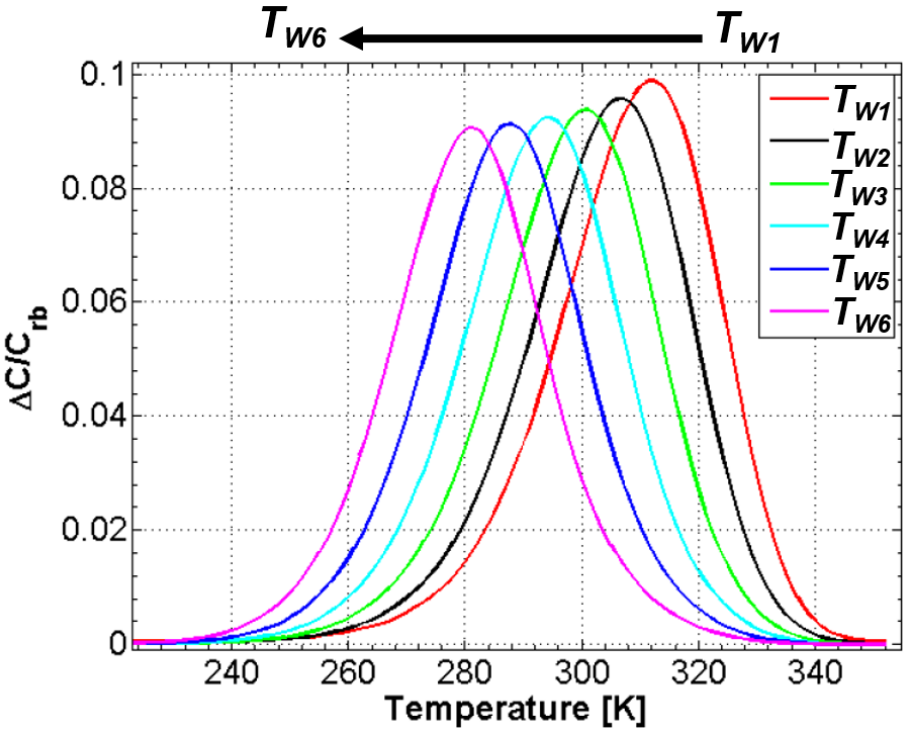
Trap emission rate:

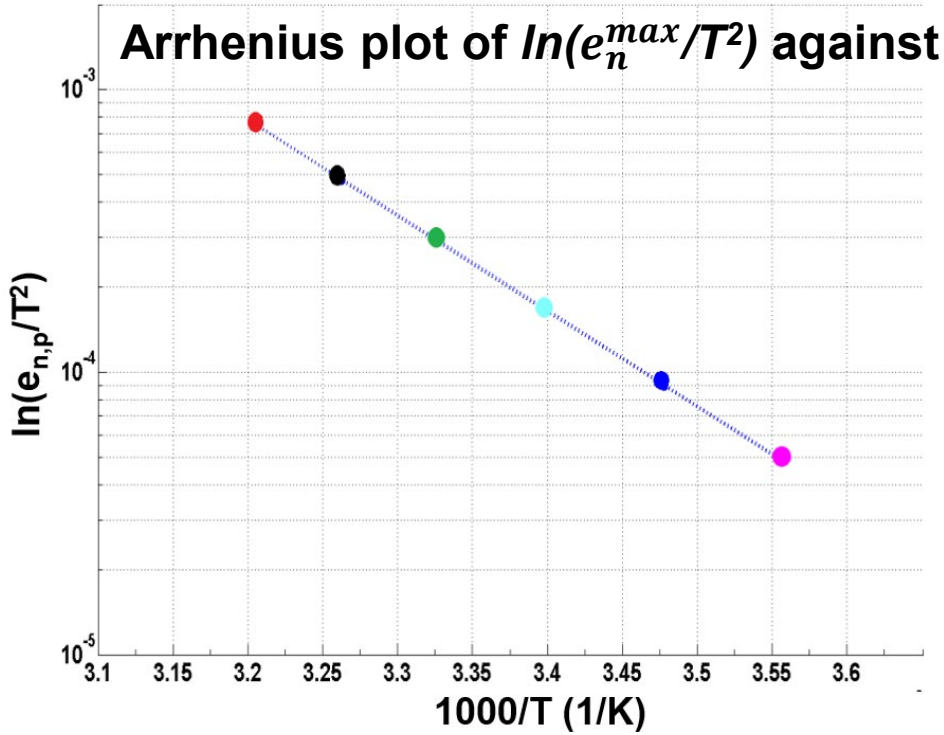
$$e_{n;p}^{max} = \sigma_n \gamma T^2 exp\left(-\frac{E}{kT}\right)$$

$$ln\left(\frac{e_{n;p}^{max}(T)}{T^2}\right) = -\frac{E}{kT} + ln\left(\gamma \sigma_n\right)$$

Linear regression

- Slope gives: **activation energy** ($E_C - E_T$ *or* $E_V + E_T$)
- *Intersection gives:* ***capture cross section*** (σ_n)
- γ *is the constant*





Trap parameters could be extracted from C-DLTS

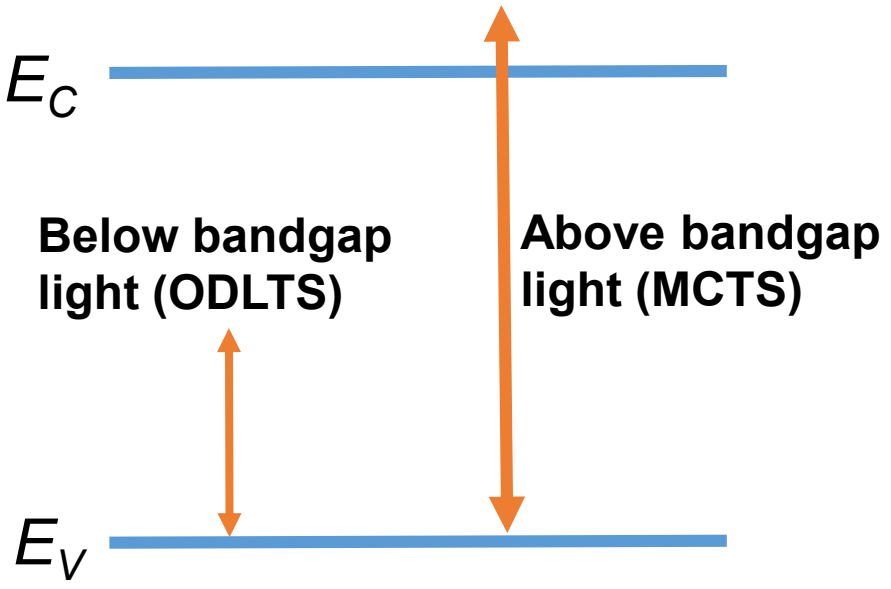
(1) **Trap activation energy** (E_C-E_T *or* E_V+E_T)
(2) **Capture cross section** (σ)
(3) **Trap concentration** (N_T)
(4) **Distinguish the trap type** (majority or minority)

Part III: Various DLTS modes

DLTS with optical pulse

Light can be used:

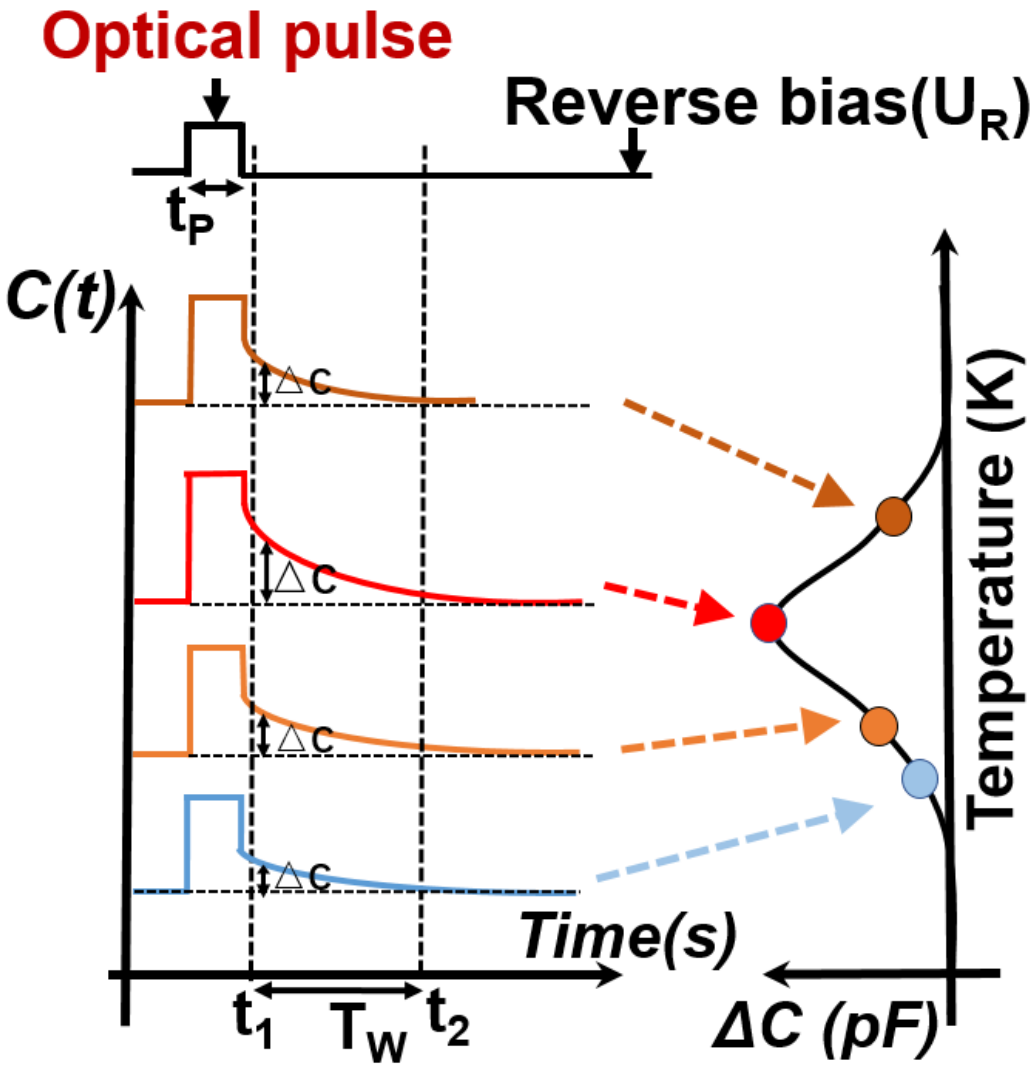
- (1) to determine optical properties of traps, such as optical capture cross-sections
- (2) to create electron-hole pairs (ephs) for **minority carrier injection**
- (3) to create ehps in semi-insulating materials, where electrical injection is difficult



Some DLTS modes with light pulse:

- **MCTS**: using above-bandgap light pulse
- **ODLTS**: using below-bandgap light pulse

DLTS with optical pulse (O-DLTS)



Temperature-dependent O-DLTS signal was obtained by plotting capacitance difference for a fixed time window (t_2-t_1).

1. during the optical pulse period:

- carriers would be generated by light and captured by traps

2. after optical pulse:

- carriers be re-emitted, forming capacitance transients

3. repeated through a temperature scan:

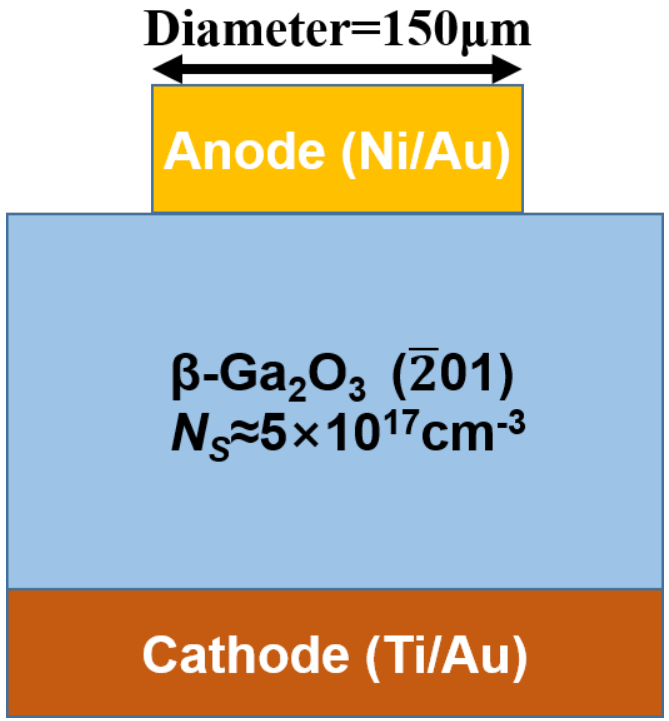
- Obtain the optical DLTS spectra

Part IV: Applications

Outline:

- **1. β-Ga_2O_3 Schottky barrier diodes**
- **2. Neutron-irradiated GaN SBDs on sapphire substrates**
- **3. Quasi-Vertical GaN p-i-n Diodes on Si Substrates**
- **4. InGaN/GaN LEDs grown Si substrates**

1. β-Ga_2O_3 Schottky barrier diodes



- A ($\bar{2}$01) β-Ga_2O_3 wafer was prepared by EFG method with a thickness of 600 μm [1]
- a top Sn:Ga_2O_3 layer electron concentration of around 2.3 × 10^{17} cm^{-3}.
- Ni/Au for the Schottky contact and Ti/Au for the ohmic contact.

[1] Jiaxiang Chen, Xing Lu, and Xinbo Zou, Semiconductor Science and Technology **36** (5) (2021).

1. Tempscan DLTS for β-Ga_2O_3 SBD

During the emission process, the concentration of electron filled traps:

$$n_{Te}(t) = N_T \exp\left(-\frac{t}{\tau_e}\right)$$

The trap emission time is :

$$\tau_e = \left(\sigma_n v_{th,n} X_n N_C \exp\left(-\frac{E_C - E_T}{kT}\right)\right)^{-1}$$

the X_n is coefficient, $v_{th,n}$ is thermal velocity

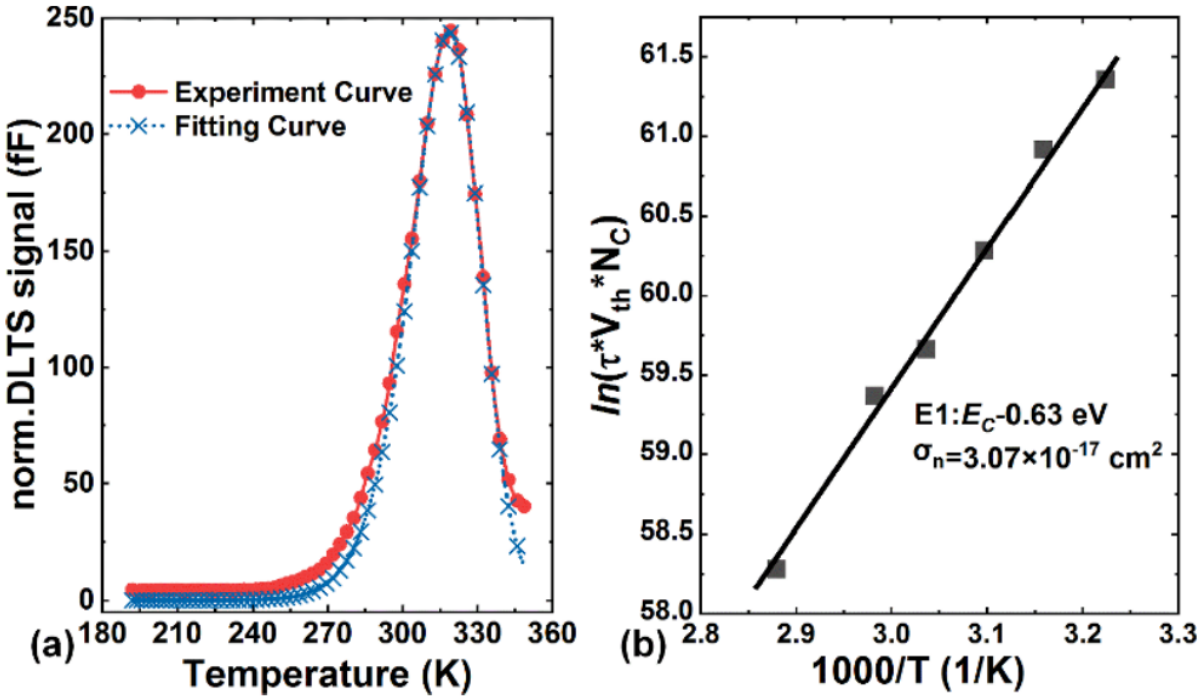
$$\tau_e = 1/e_n^{\max} \qquad v_{th,n} = \sqrt{\frac{3kT}{m_n^*}}$$

Thus,

$$ln\left(\frac{e_n^{max}(T)}{T^2}\right) = ln\left(\frac{1}{\tau_e T^2}\right) = -\frac{E}{kT} + ln(\gamma\sigma_n)$$

$$ln(\tau_e T^2 (v_{th} N_C / T^2)) = ln(\tau_e v_{th} N_C)$$

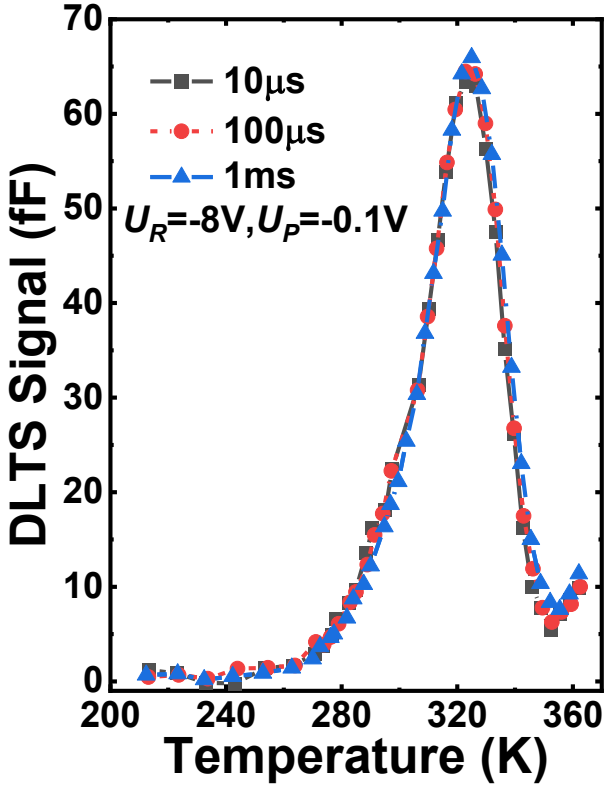
$$\ln\left(\tau_e v_{th,n} N_C\right) = \frac{E_C - E_T}{k}\frac{1}{T} - \ln\left(X_n \sigma_n\right)$$



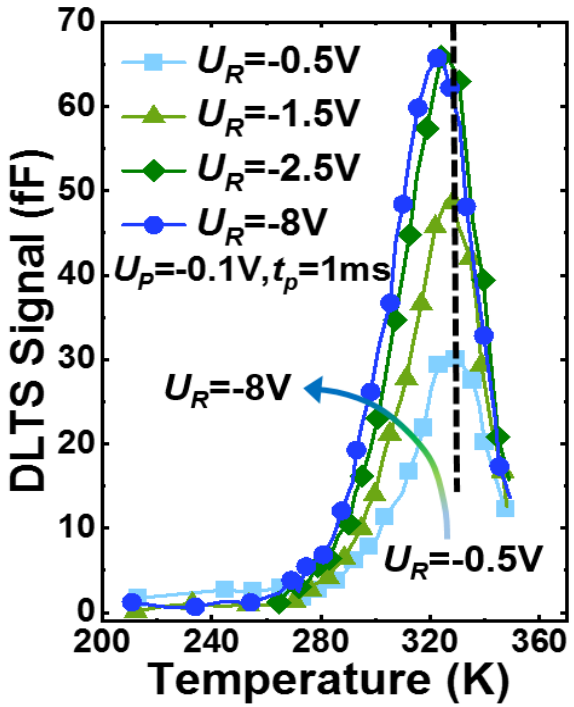
- Activation energy: *E1* (E_C−0.63 eV)
- Capture cross-section: 3.07×10^{-17} cm^2
- Trap concentration (N_T) was 9.5 $\times10^{15}$ cm^{-3}

[1] Jiaxiang Chen et al 2021 *Semicond. Sci. Technol.* 36 055015

Varying different DLTS parameters

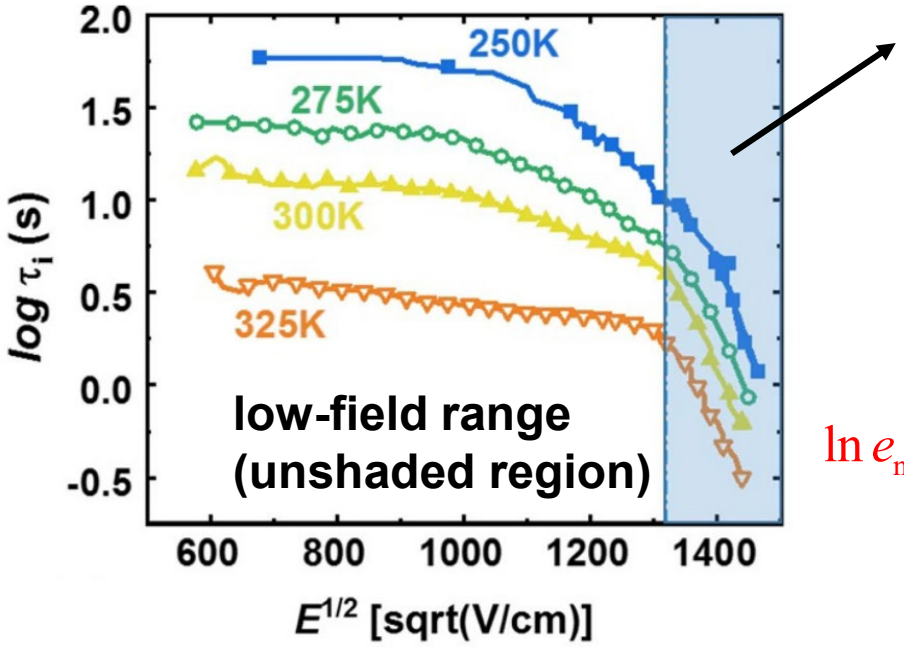


- The time fully fill the traps was less than 10 μs.
- Further increasing the filling time would not help to amplify the signal.



The traps are thought to be mainly located in the bulk Ga_2O_3 layer rather than interface-related.

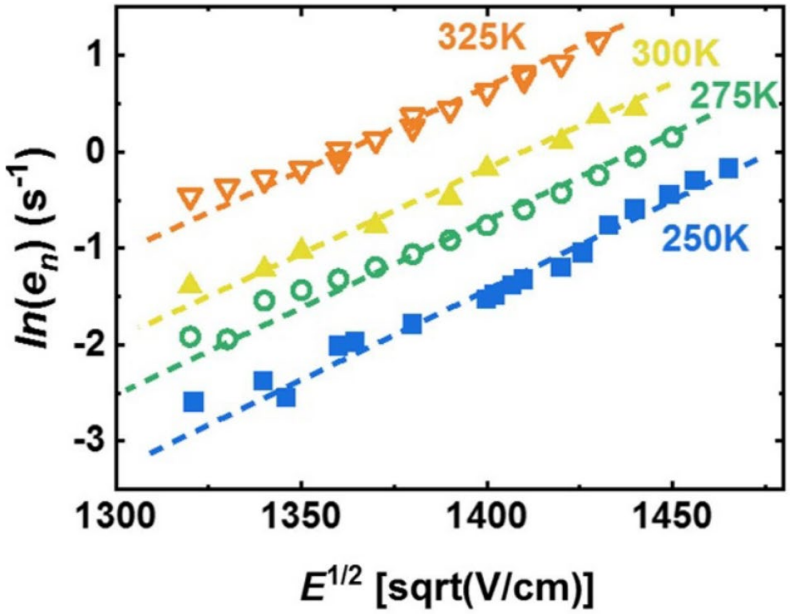
E-field dependent emission time (τ_i) for Ga_2O_3 SBD



high-field range (shaded region)

Poole–Frenkel effect fitting for high *E-field*

$$\ln e_n(E,T) = \ln\left(\tau(0,T)^{-1}\right) + \left(\frac{\beta_{PF}}{kT}\right) E^{1/2}$$

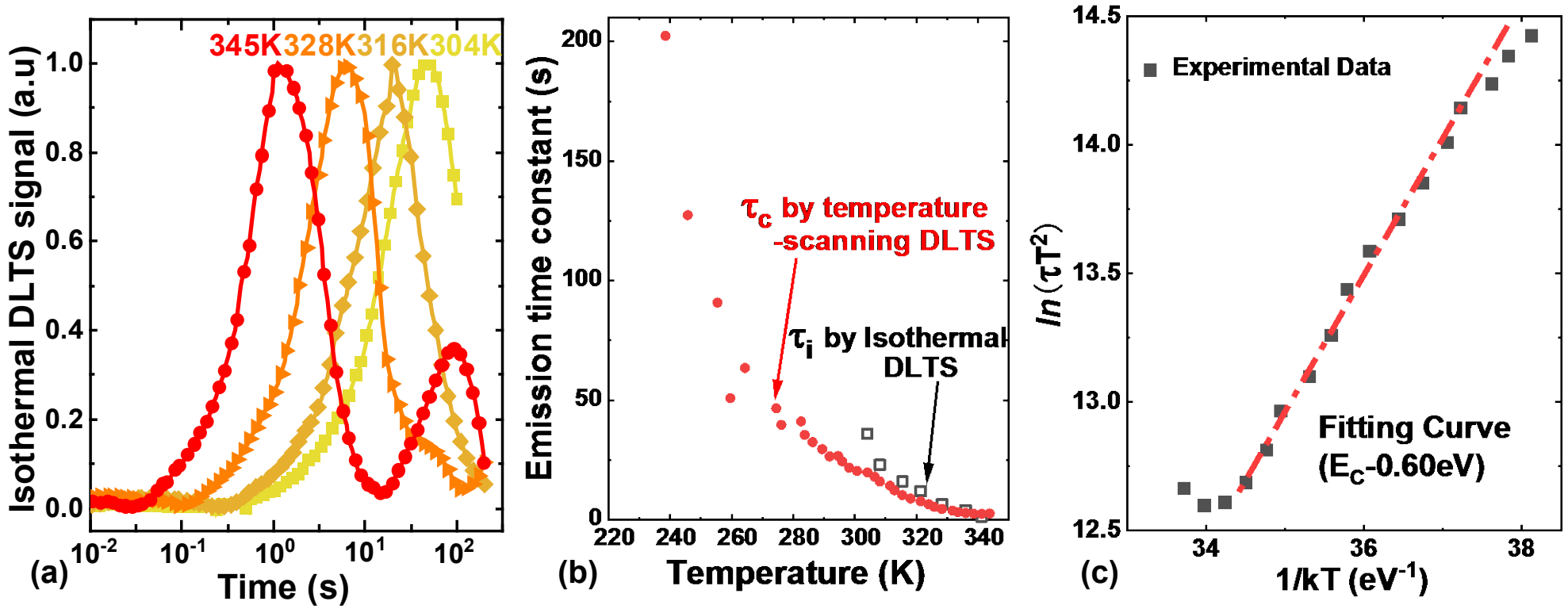


- **In the low-field range (**when $E^{1/2}$ <1325 (V cm^{-1})$^{1/2}$**):**[1]
- the τ only slightly decreased when the *E-field* increased.
- **In the relatively high field range (**when $E^{1/2}$ is higher than 1325 (V cm^{-1})$^{1/2}$**):**

The emission mechanism is Poole–Frenkel effect model.

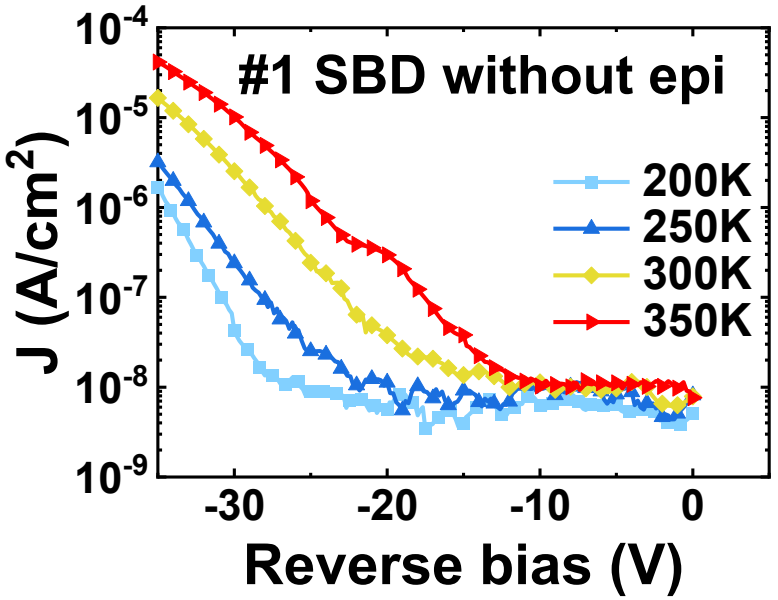
[1] Jiaxiang Chen, Xing Lu, and Xinbo Zou, Semiconductor Science and Technology **36** (5) (2021).

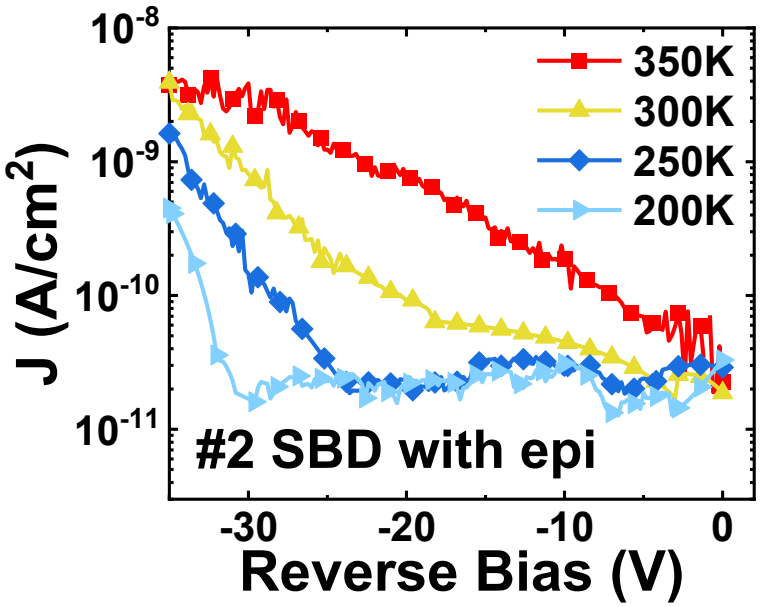
Thermal emission mechanism by isothermal DLTS



- The time constant extracted from the main peaks of the isothermal DLTS signal (τ_i) decreased from 36.8 s to 1.4 s when the temperature increased from 304 K to 345 K.
- The time constants extracted by the two methods are a good match for each other.

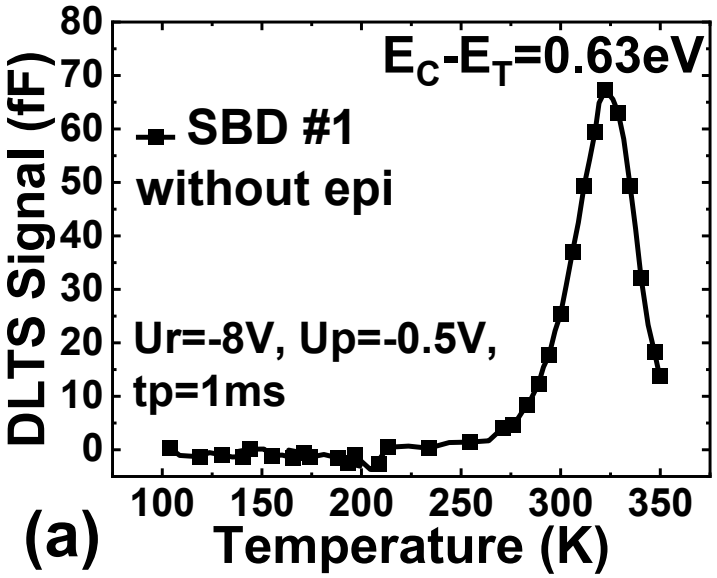
Comparison of leakage current in Ga_2O_3 SBDs w/o epi-layer

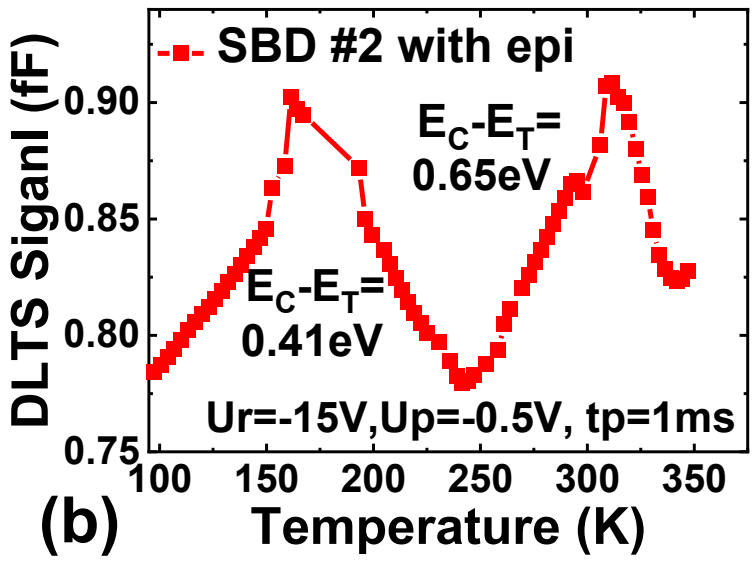


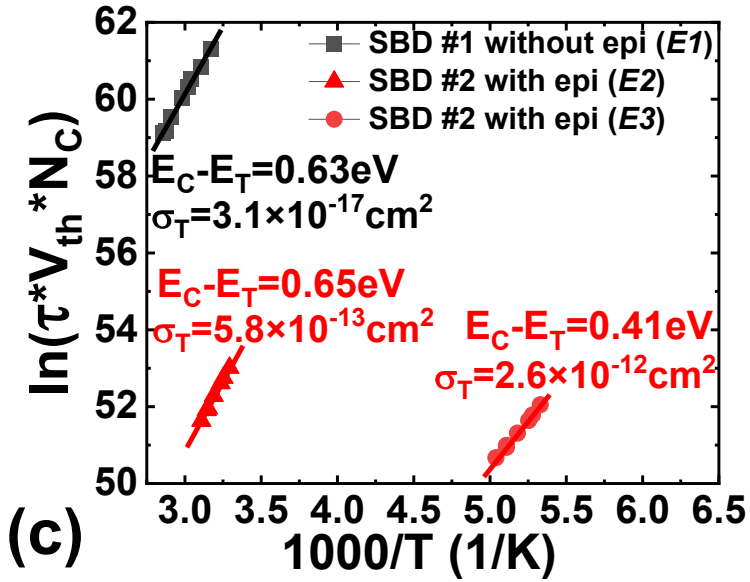


- Sample #1 was fabricated directly on a 600μm-thick β-Ga_2O_3 wafer prepared by EFG.
- Sample #2 was fabricated on a wafer with 11μm-thick homoepitaxial layer on top.
- At 300K, the reverse current density of SBD #1 is 1.7×10^{-5} A/cm^2 at -35V, much higher than 3.9×10^{-9} A/cm^2 in the SBD #2 with epi-layer.
- The leakage current could be suppressed by growing a high-quality epi-layer.

Trap information of β-Ga_2O_3 SBDs w/o epi-layer



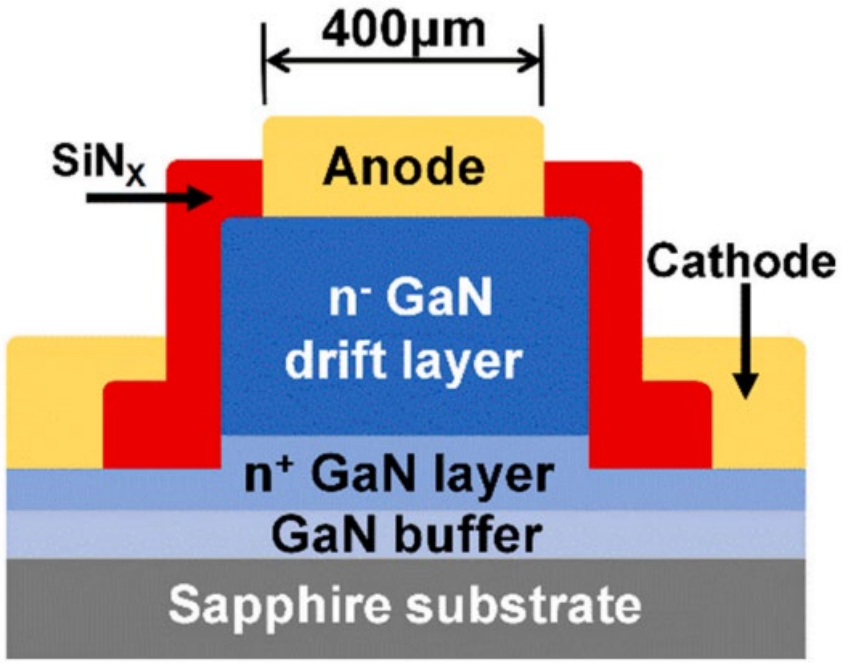




	Trap No.	Activation energy(eV)	Capture cross section (cm^2)	N_T ×10^{13} (/cm^3)
SBD#1 (without epi)	E1	E_C-0.63	3.1×10^{-17}	9.5×10^{15}
SBD#2 (with epi)	E2	E_C-0.65	5.8×10^{-13}	5.5×10^{13}
	E3	E_c-0.41	2.6×10^{-12}	7.1×10^{13}

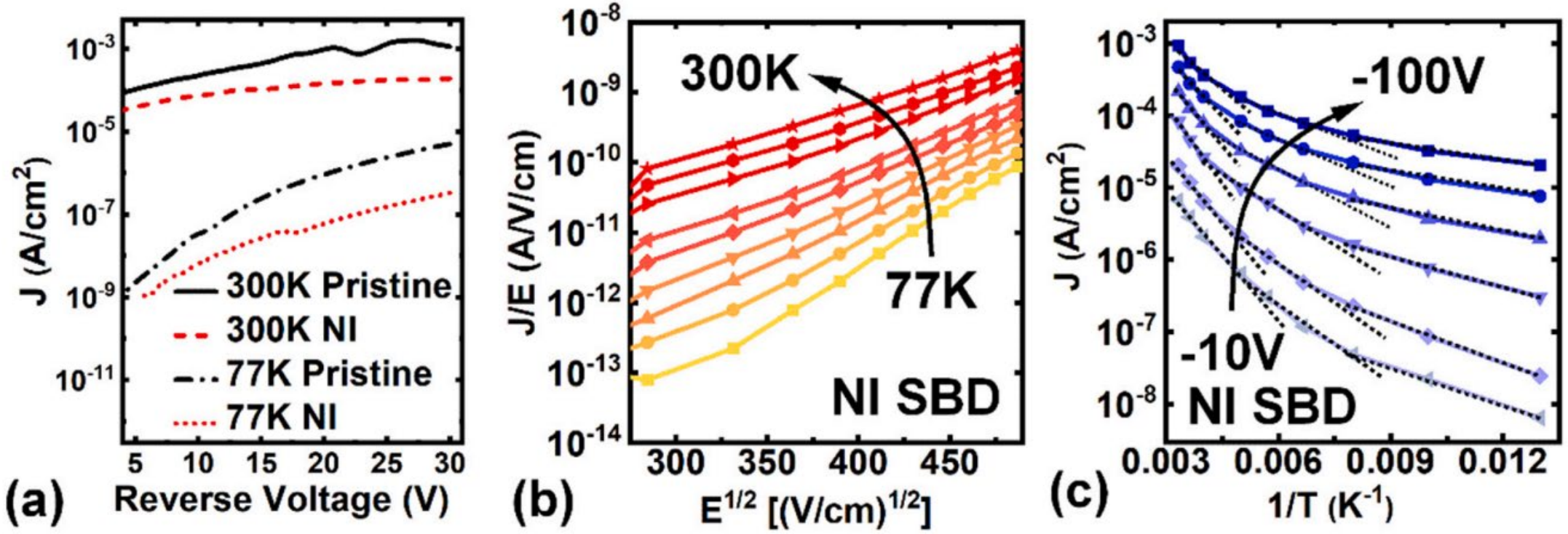
- The N_T of E2 and E3 in SBD #2 is 2-3 orders lower in magnitude than trap E1 in SBD #1, which results in mitigated recombination-generation processes and leads to a lower leakage current of SBD #2.

2. Neutron-irradiated GaN SBDs on sapphire substrates



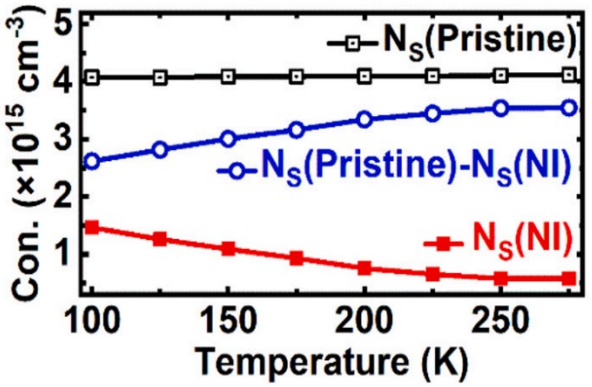
- The GaN SBDs were grown on a 2-in. sapphire substrate by metal organic chemical vapor deposition (MOCVD).
- The epitaxial structure started from a 1-μm thick GaN buffer layer
- A 1.8-μm thick n+-GaN layer (electron concentration of 5×10^{18} cm^{-3}
- A 5.8-μm thick unintentionally-doped n− -GaN layer (with nominal carrier concentration of 5.3×10^{15} cm^{-3}) was grown.

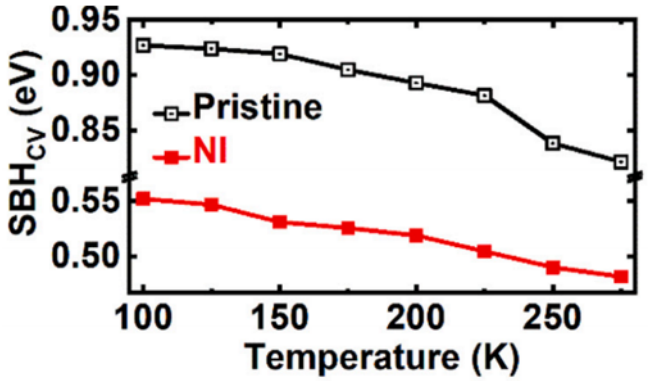
Comparison of reverse current between pristine and NI SBDs



- The average I_{leak} of the NI SBD was slightly lower than that of the pristine samples.
- For NI SBDs, the leakage mechanism is Poole-Frenkel emission model.

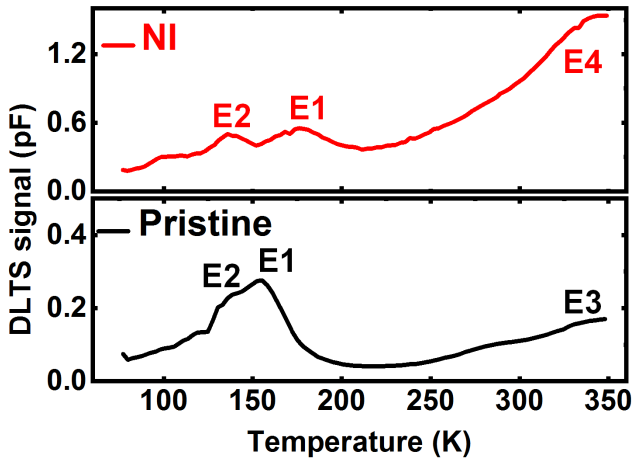
C-DLTS for neutron-irradiated (NI) GaN SBD





- Increase of carrier concentration after **neutron-irradiation**
- SBH of NI SBD lower than pristine SBD

- A new deep-level trap (E4) was revealed for the NI-diode by C-DLTS.
- Increase of σ and N_T of traps [2]



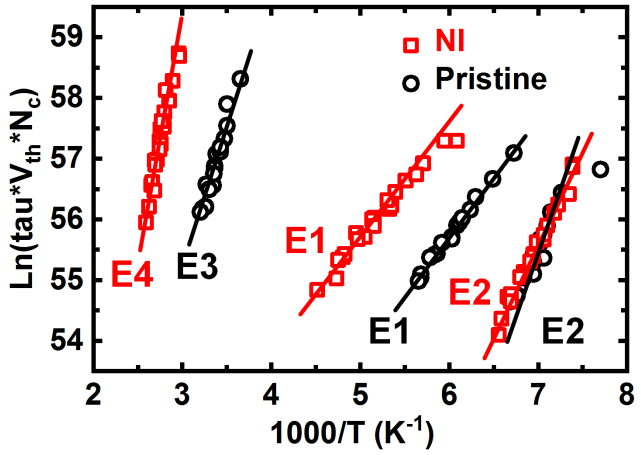
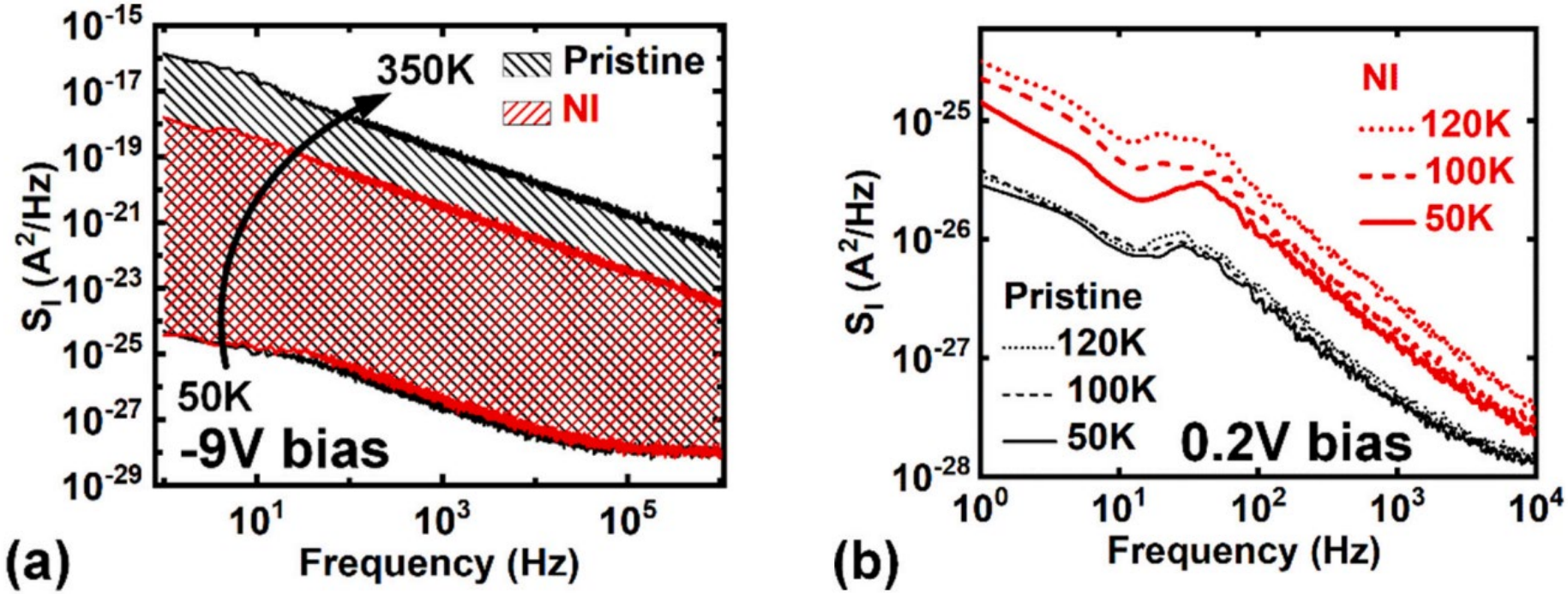


Table 1
Detailed *DLTS* results including activation energy, capture cross section and trap concentration.

		E_C-E_T (eV)	σ (cm^2)	N_T ($\times 10^{14}$ cm^{-3})
Pristine	E1	0.144	1.06×10^{-21}	1.16
	E2	0.266	2.87×10^{-15}	0.61
	E3	0.468	1.78×10^{-17}	0.58
NI	E1	0.149	3.50×10^{-21}	1.60
	E2	0.254	6.44×10^{-16}	1.40
	E4	0.640	9.77×10^{-17}	5.06

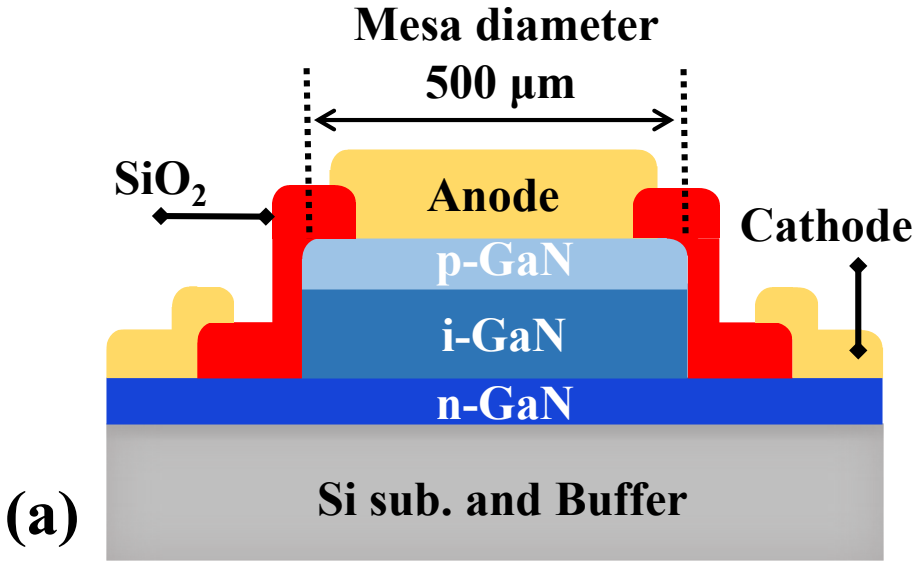
[2] Min Zhu, Yuan Ren, Leidang Zhou, Jiaxiang Chen, Haowen Guo, Liqi Zhu, Baile Chen, Liang Chen, Xing Lu, and Xinbo Zou, Microelectronics Reliability **125**, 114345 (2021).

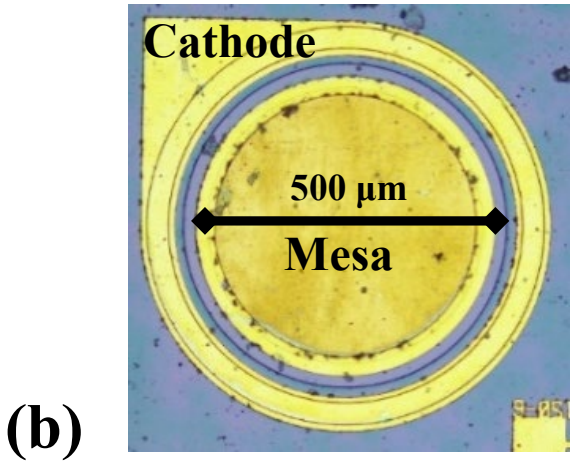
Low frequency noise spectroscopy (LFNS)



- As increasing the temperature, the noise level of NI SBD was still kept low, about two orders of magnitude lower than the pristine sample at 350 K.
- The active generation-recombination process was believed to be linked with high trap concentration of deep-level trap E4 as well as of E1 &E2.

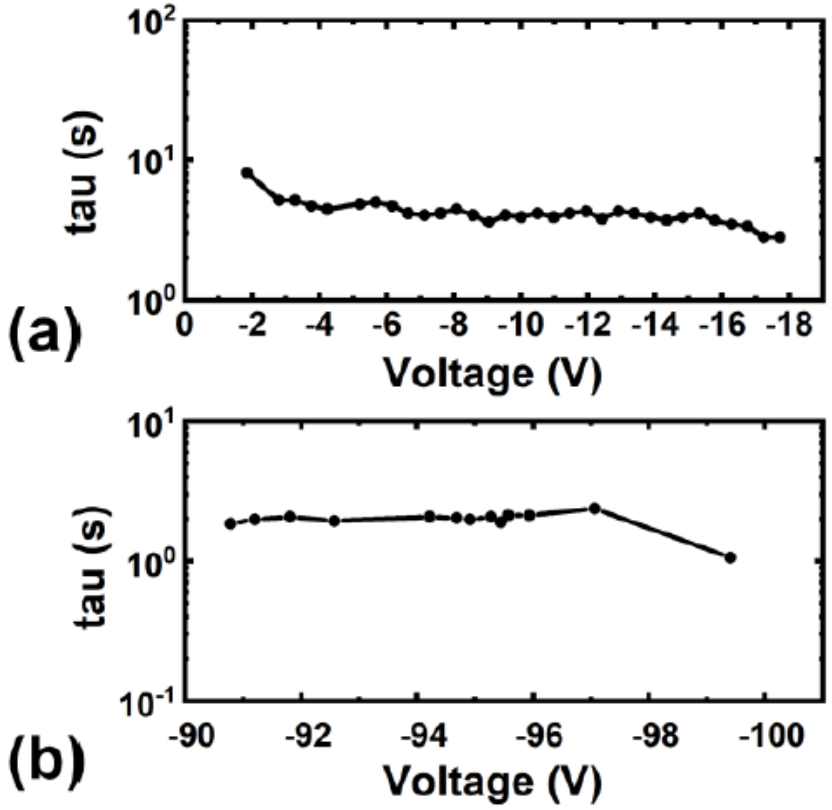
3. Quasi-Vertical GaN p-i-n Diodes on Si Substrates

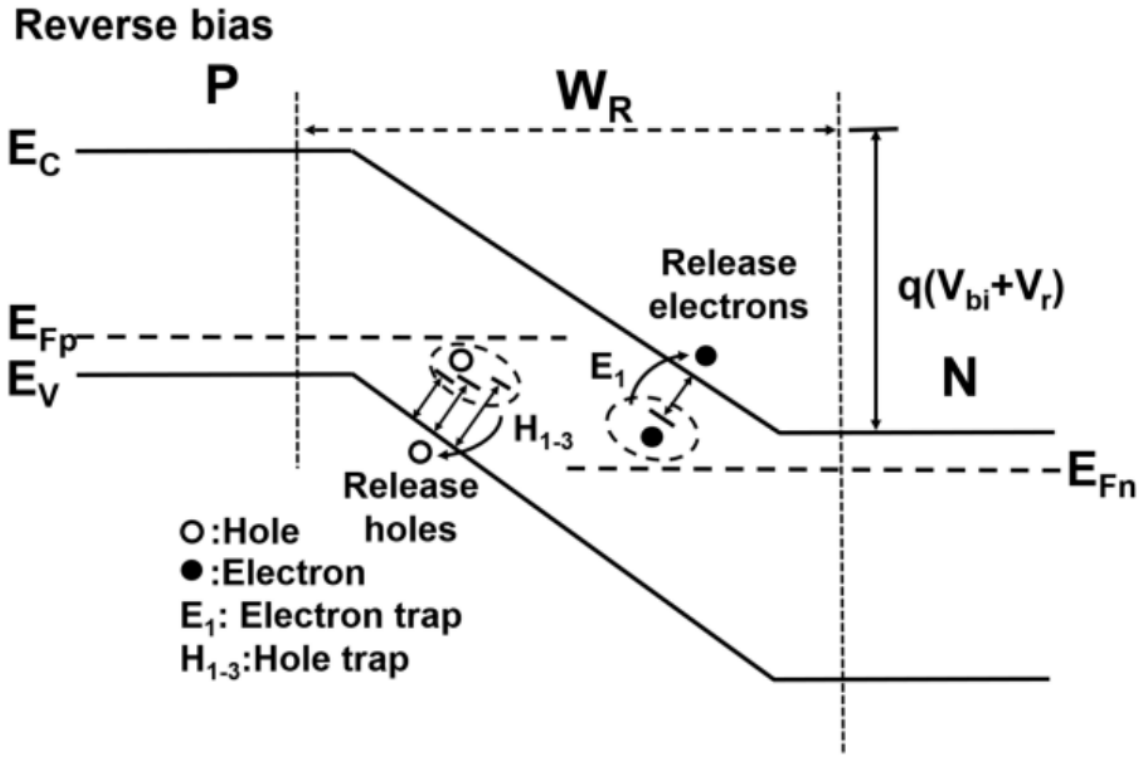




- 1.6-µm-thick graded AlGaN and GaN buffer
- A 500-nm-thick Si-doped n-GaN layer (electron concentration n = 1 × 10^{19} cm^{-3})
- 2-µm-thick undoped i-GaN layer (carrier concentration on the order of 10^{16} cm^{-3})
- A 500-nm-thick Mg-doped p-GaN layer (hole concentration p = 2×10^{17} cm^{-3} at 300 K)

Voltage dependence of carrier emission time at 300K



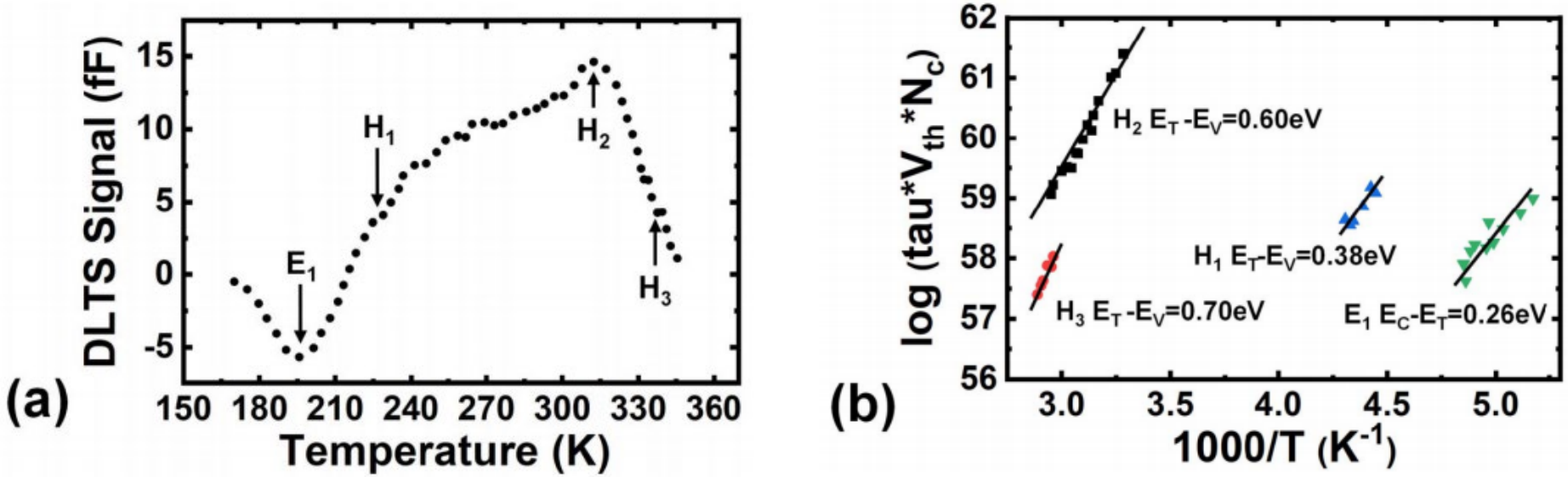


Conclusion:

- Extracted electron traps and hole trap information of p-i-n sample
- Detrapping time constants could be extracted under low and high bias

[3] Yuliang Zhang, Xu Zhang, Min Zhu, Jiaxiang Chen, and Xinbo Zou, IEEE Transactions on Electron Devices **67** (10), 3992 (2020).

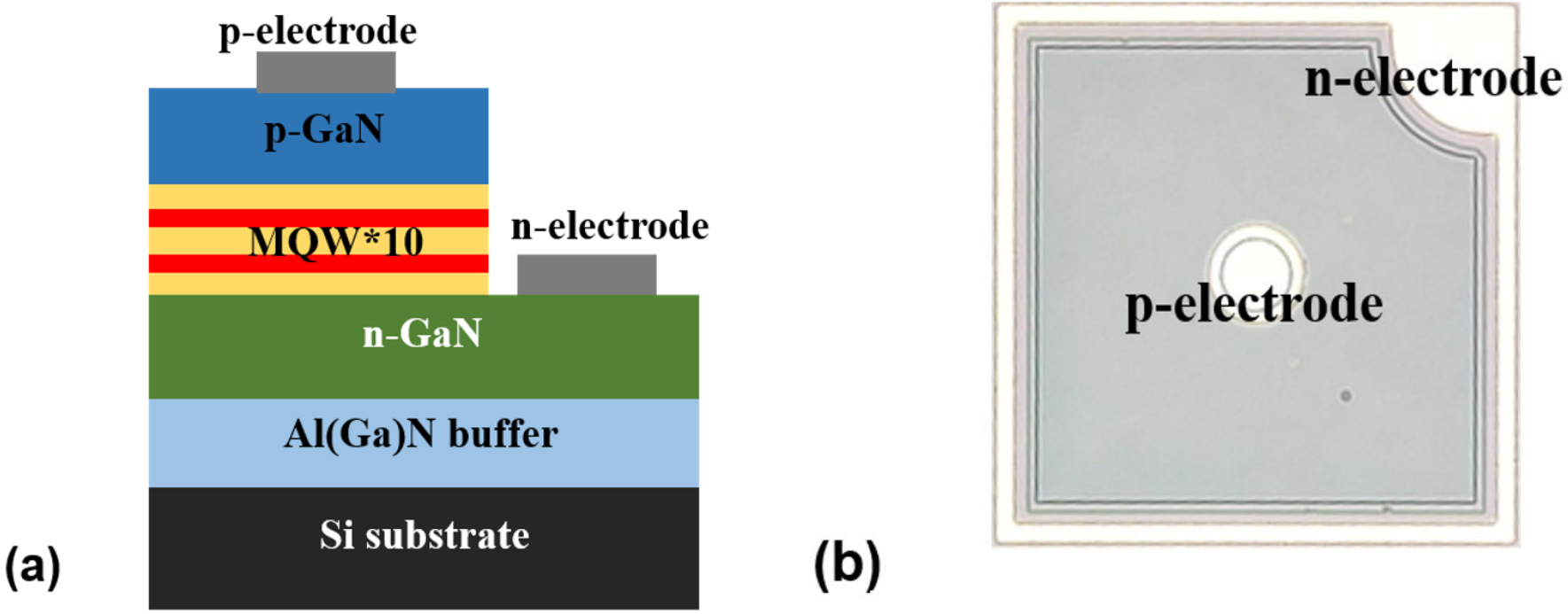
DLTS siganl and energy band related detrapping process



Trap No.	Energy Level (eV)	Capture Cross section (cm^2)	Trap Concentration N_T (cm^{-3})
E_1	E_c-0.26	2.59×10^{-19}	9.37×10^{14}
H_1	E_v+0.38	7.16×10^{-18}	7.68×10^{15}
H_2	E_v+0.60	2.18×10^{-17}	1.94×10^{15}
H_3	E_v+0.70	1.60×10^{-15}	3.72×10^{15}

[3] Yuliang Zhang, Xu Zhang, Min Zhu, Jiaxiang Chen, and Xinbo Zou, IEEE Transactions on Electron Devices **67** (10), 3992 (2020).

4. InGaN/GaN LEDs grown Si substrates



Multiple quantum well (MQW) blue LED structures were grown on silicon (111) substrates by metal–organic chemical vapor deposition.

From the Si substrate to the top surface:

- the LED structure consisted of a thin nucleation layer
- a AlGaN buffer layer, a 2-μm-thick Si-doped n-GaN layer
- ten periods of InGaN/GaN QWs
- a 200-nm-thick Mg-doped p-GaN layer.

Trap Characterization of InGaN/GaN Blue LED

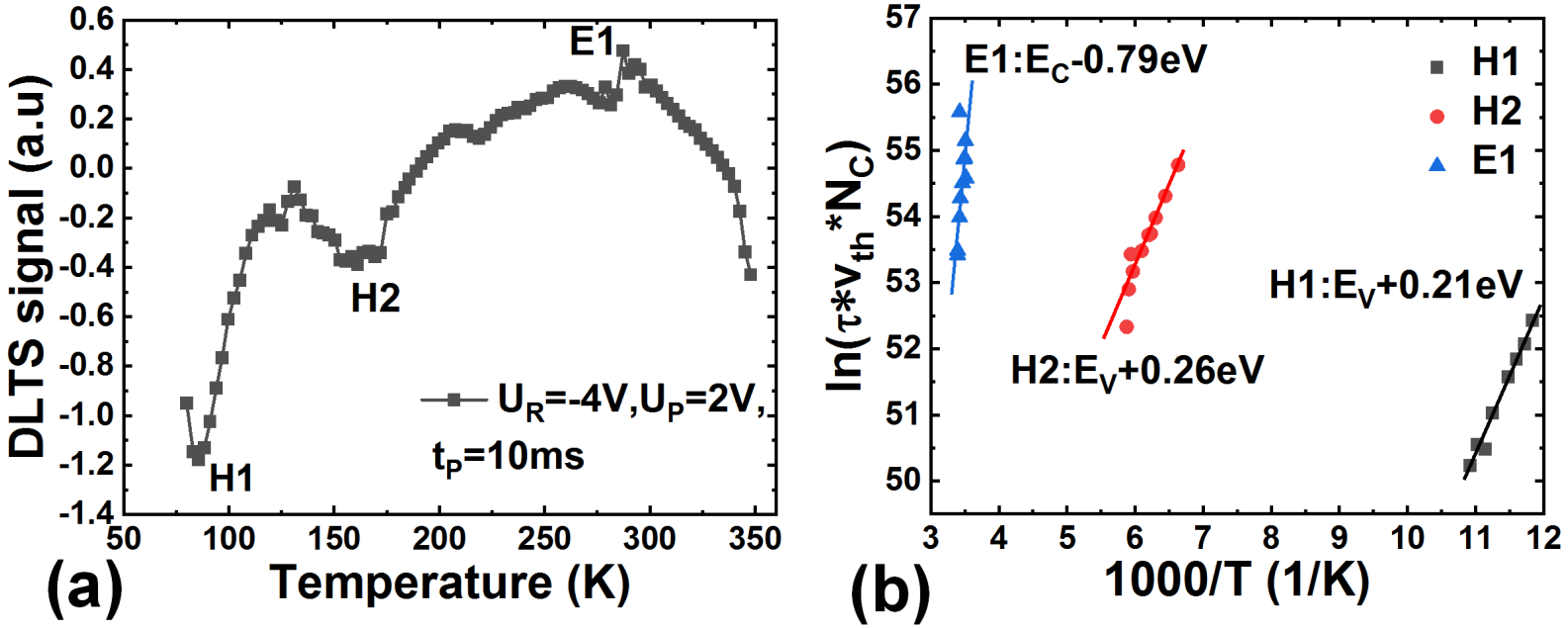


Table . Properties of traps extracted from DLTS.

Trap No.	Activation energy(eV)	Capture cross section (cm^2)	N_T $\times 10^{13}$($/cm^3$)
E1	E_C-0.79	1.38×10^{-10}	3.22
H1	E_V+0.21	5.28×10^{-11}	15.4
H2	E_V+0.26	8.29×10^{-16}	2.04

Publication list

Journal:

- Jiaxiang Chen, Haoxun Luo, HaoLan Qu, Min Zhu, Haowen Guo, Baile Chen, Yuanjie Lv, Xing Lu, and **Xinbo Zou*,** " Single-trap emission kinetics of vertical β-Ga_2O_3 Schottky diodes by deep-level transient spectroscopy ", *Semiconductor Science and Technology,* 36 (5) (2021).
- Min Zhu, Yuan Ren, Leidang Zhou, Jiaxiang Chen, Haowen Guo, Liqi Zhu, Baile Chen, Liang Chen, Xing Lu, and **Xinbo Zou*,** " Temperature-dependent electrical characteristics of neutron-irradiated GaN Schottky barrier diodes", *Microelectronics Reliability,* 125, 114345 (2021).
- Yuliang Zhang, Xu Zhang, Min Zhu, Jiaxiang Chen, Chak Wah Tang, Kei May Lau, and **Xinbo Zou*,** "Forward Conduction Instability of Quasi-Vertical GaN p-i-n Diodes on Si Substrates," *IEEE Transactions on Electron Devices,* 67 (10), 3992 (2020).
- Jiaxiang Chen, Min Zhu, Xing Lu, and **Xinbo Zou*,** " Electrical characterization of GaN Schottky barrier diode at cryogenic temperatures" , *Applied Physics Letters,* 116 (6) (2020).

Conference:

- Jiaxiang Chen, Haolan Qu, Longheng Qi, Yaying Liu, Xu Zhang, **Xinbo Zou*;** Trap Characterization of InGaN/GaN Blue Light Emitting Diode on Si Substrate, *Asia Communications and Photonics Conference (ACP 2021),* Oct 24-27; Shanghai, China.
- Jiaxiang Chen, Haolan Qu, Xing Lu, **Xinbo Zou*;** Electrical Characterization of Vertical β-Ga_2O_3 SBD w/o epi-layer; *National Wide bandgap semiconductor Conference (WBGS 2021),* Oct. 12-15, Fujian, China

END

Thank you for watching !