4H-SiC devices simulation with DEVSIM

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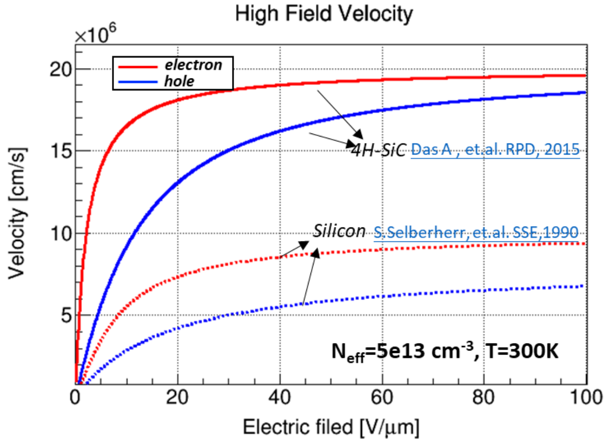
Why 4H-SiC？

Silicon & 4H-SiC

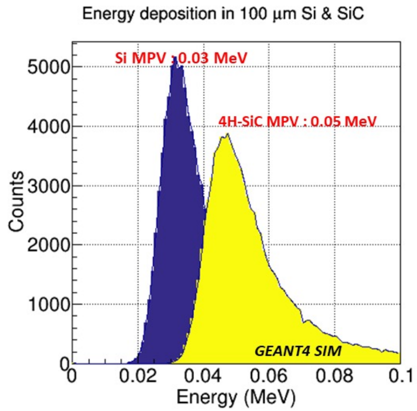
Characteristic	Si	4H-SiC
Eg (eV)	1.12	3.26
Thermal conductivity	1.5	4.9
$E_{breakdown}$ (V/cm)	0.5	3
Saturated electron velocity (cm/s)	1×10^7	2×10^7
ionization energy for e-h pair (eV)	3.64	7.8
displacement energy	13	21.8

- ✓ High radiation hardness
- ✓ Low dark current
- ✓ high temperature resistance
- ✓ High saturated carrier velocity -> fast response

Potential application for fast MIPs detection



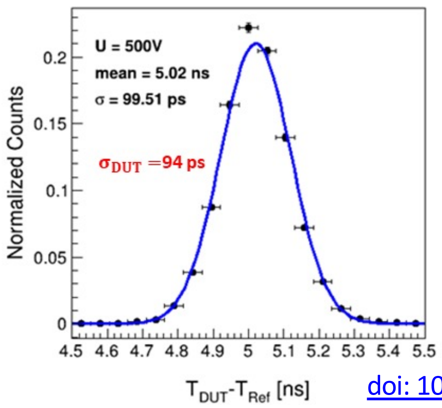
Saturated Carrier Velocity: 4H-SiC > Silicon



~ 55 e-h pairs/ um for MIPs in SiC

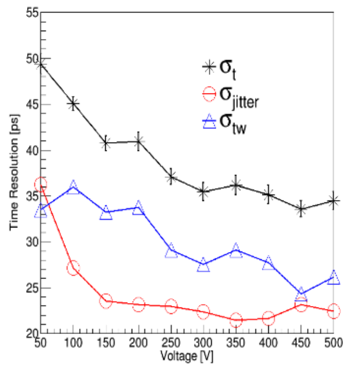
Good time resolution of 4H-SiC detector

100 µm 4H-SiC PIN for MIPs (measurement)



doi: 10.3389/fphy.2022.718071

3D 4H-SiC Detector for MIPs (simulation)



doi: 10.3390/mi13010046

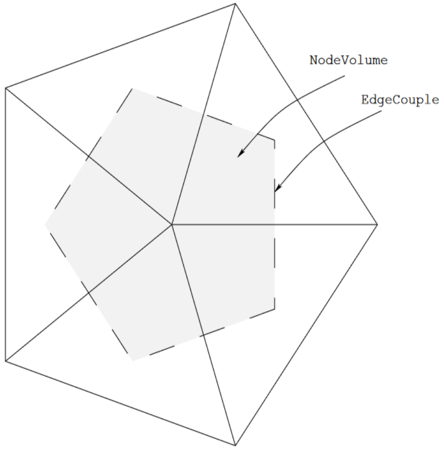
Introduction of DEVSIM

- **DEVSIM is a TCAD device simulation package written in C++, with a Python front end. It is capable for simulating 1D, 2D, 3D structures with models describing advanced physical effects https://devsim.org/**

- **DEVSIM uses the control volume approach for assembling partial-differential equations (PDE's)**

Node model

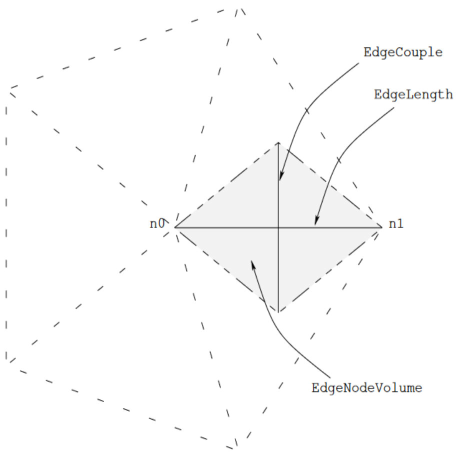
- **The simplest model**
- **Represents the solution variables being solved for**



$\boldsymbol{n}, \boldsymbol{p}, \boldsymbol{\varphi}$ …

Edge model

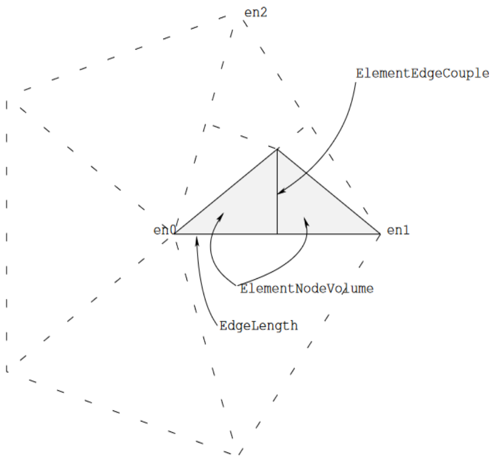
- **Reference node models defined on the ends of the edge**
- **The two nodes on the edge, n0 and n1**



$\boldsymbol{E}(\boldsymbol{\varphi})$ …

Element Edge model

- **Cannot be specified on both nodes of the edge,**
- **The three nodes on each triangle edge and are denoted as en0, en1, and en2**



$\boldsymbol{\mu_n}(\boldsymbol{E}), \boldsymbol{\mu_p}(\boldsymbol{E})$ …

Advantages:

◆ Open Source;

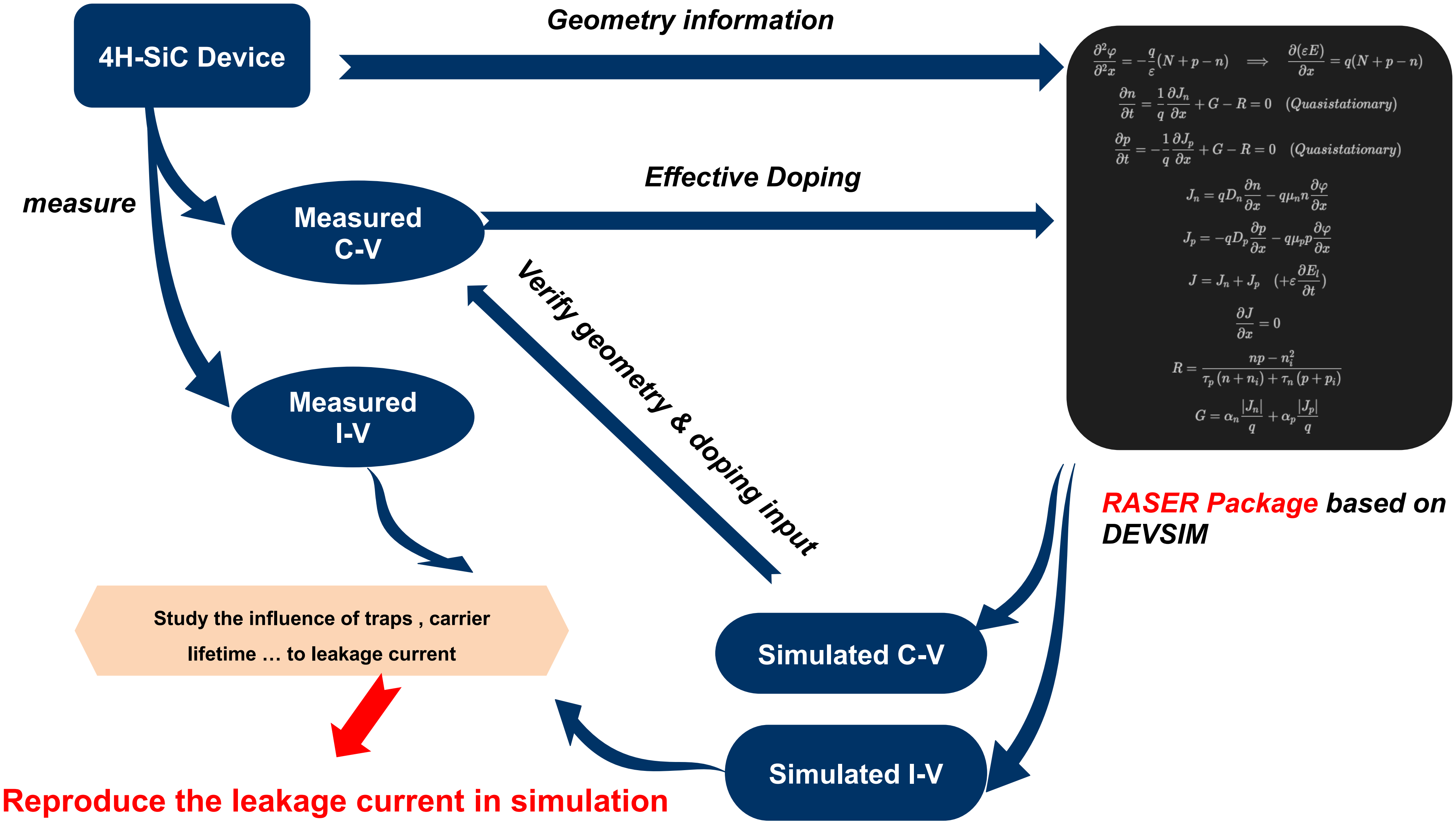
◆ Strong expandability;

◆ Easily interact with Gennt4 for detector simulation;

Drawbacks:

◆ Finite element physical equations written by users

Simulation roadmap



4H-SiC Device

Geometry information

measure

Measured C-V

Effective Doping

Measured I-V

Verify geometry & doping input

$$\frac{\partial^2\varphi}{\partial^2 x} = -\frac{q}{\varepsilon}(N+p-n) \quad \Longrightarrow \quad \frac{\partial(\varepsilon E)}{\partial x} = q(N+p-n)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + G - R = 0 \quad (Quasistationary)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G - R = 0 \quad (Quasistationary)$$

$$J_n = qD_n\frac{\partial n}{\partial x} - q\mu_n n\frac{\partial\varphi}{\partial x}$$

$$J_p = -qD_p\frac{\partial p}{\partial x} - q\mu_p p\frac{\partial\varphi}{\partial x}$$

$$J = J_n + J_p \quad (+\varepsilon\frac{\partial E_l}{\partial t})$$

$$\frac{\partial J}{\partial x} = 0$$

$$R = \frac{np - n_i^2}{\tau_p(n+n_i) + \tau_n(p+p_i)}$$

$$G = \alpha_n\frac{|J_n|}{q} + \alpha_p\frac{|J_p|}{q}$$

***RASER Package* based on DEVSIM**

Study the influence of traps , carrier lifetime … to leakage current

Simulated C-V

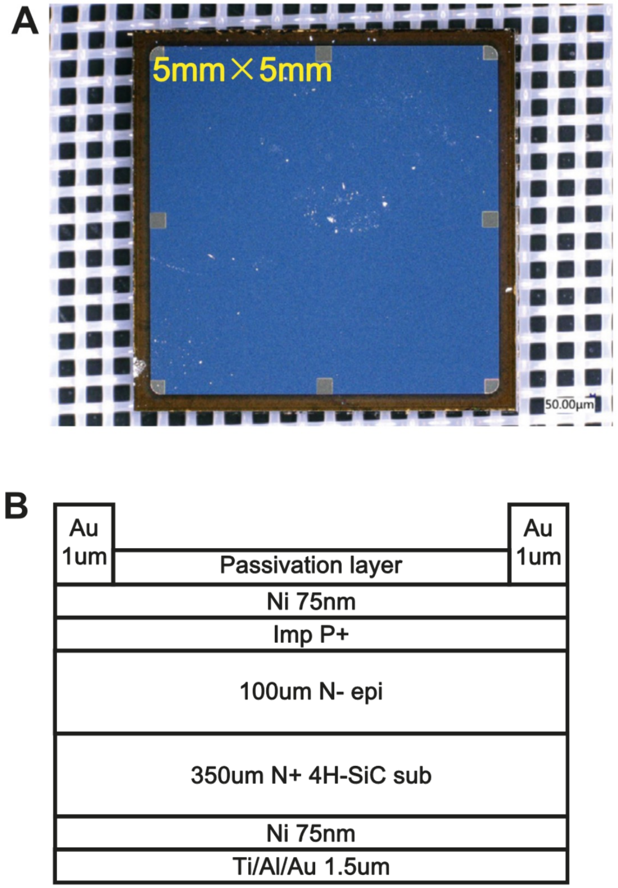
Simulated I-V

Reproduce the leakage current in simulation

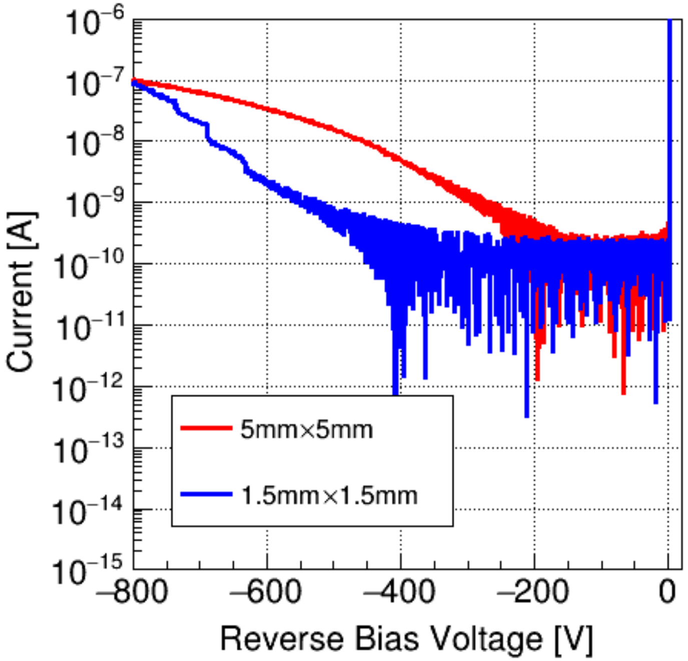
4H-SiC PIN under study

A time resolution σ_T=**94ps** indicates 4H-SiC sensor has potential application of fast MIPs detection.

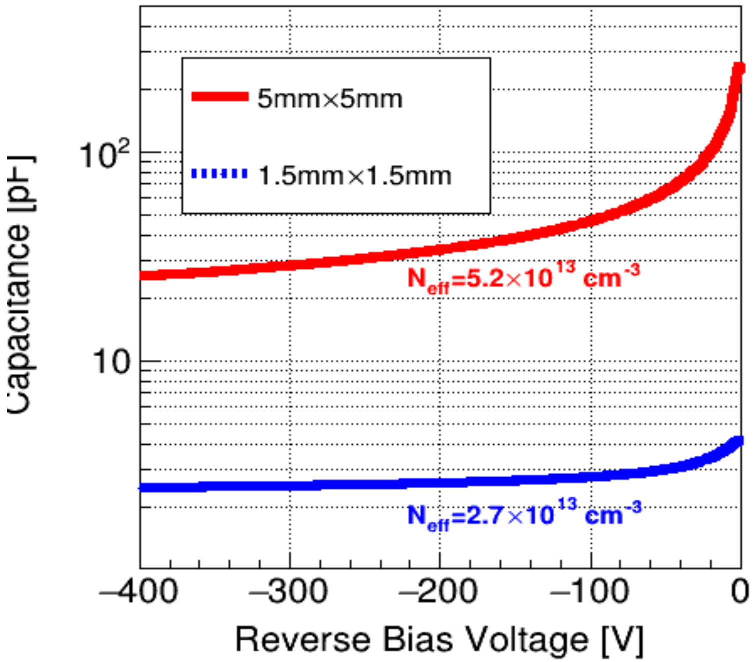
Geometry



***I-V* performance**



***C-V* performance**

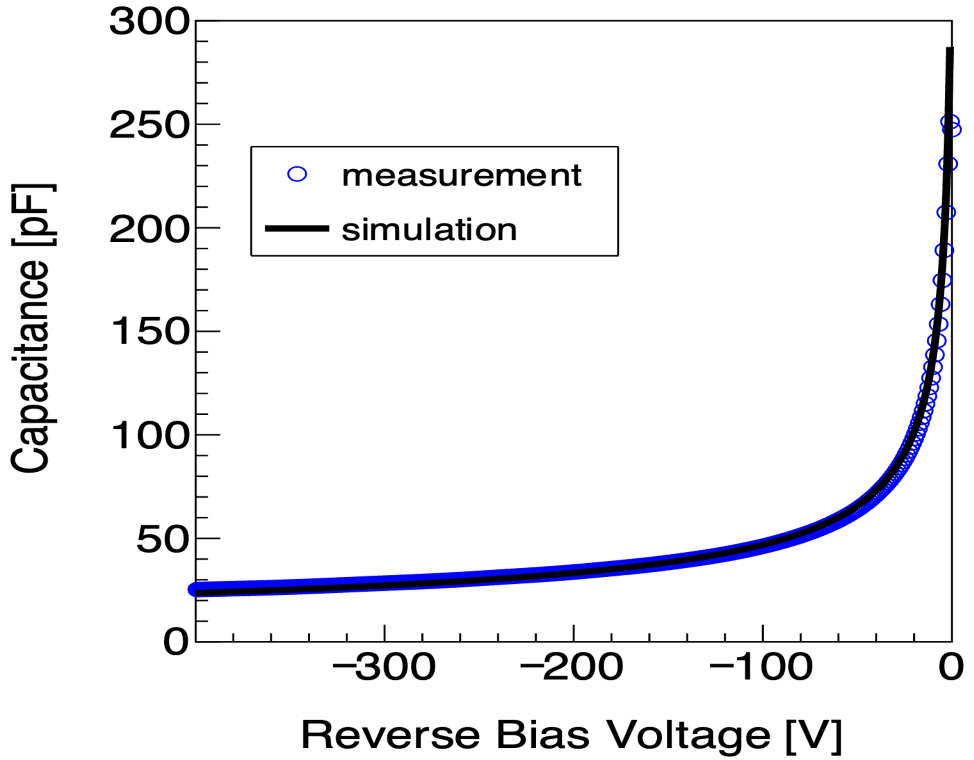


The NJU 100 µm PIN with 5mm*5mm size as device to study.

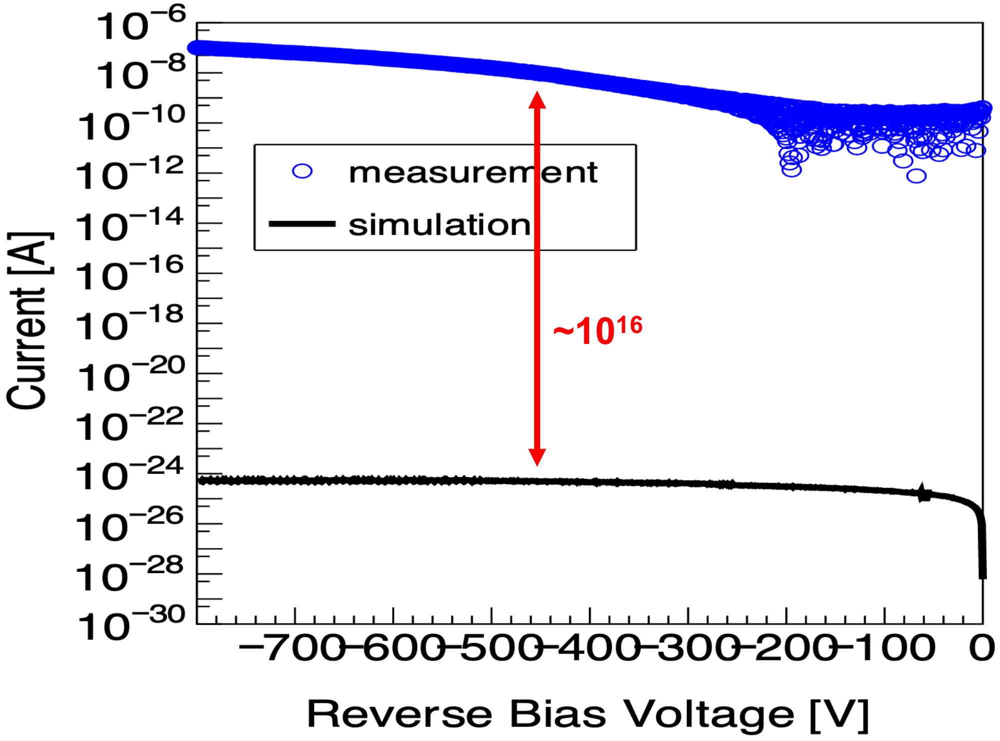
10.3389/fphy.2022.718071

DEVSIM Simulation of 4H-SiC PIN detector

C-V performance & simulation



I-V performance & simulation



- **Good agreement** between measurement and simulation !
- Verify the geometry & doping input to SICAR is correct.

- **Large discrepancy** between measurement and simulation !
- The influence of **Carrier Recombination & Generation** to leakage current should be considered.

Shockley-Read-Hall G&R to Leakage Current

Recombination

$$R = \boxed{R_{SRH}} + R_{Trap} + \cdots$$

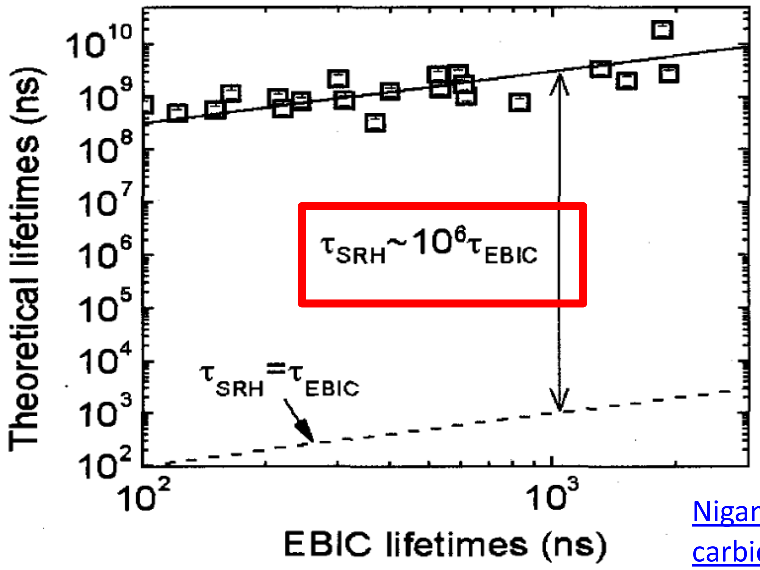
$$R_{\text{net}}^{\text{SRH}} = \frac{np - n_{\text{i,eff}}^2}{\boxed{\tau_p}(n + n_1) + \boxed{\tau_n}(p + p_1)}$$

$$n_1 = n_{\text{i,eff}} \exp\left(\frac{E_{\text{trap}}}{kT}\right)$$

$$p_1 = n_{\text{i,eff}} \exp\left(\frac{-E_{\text{trap}}}{kT}\right)$$

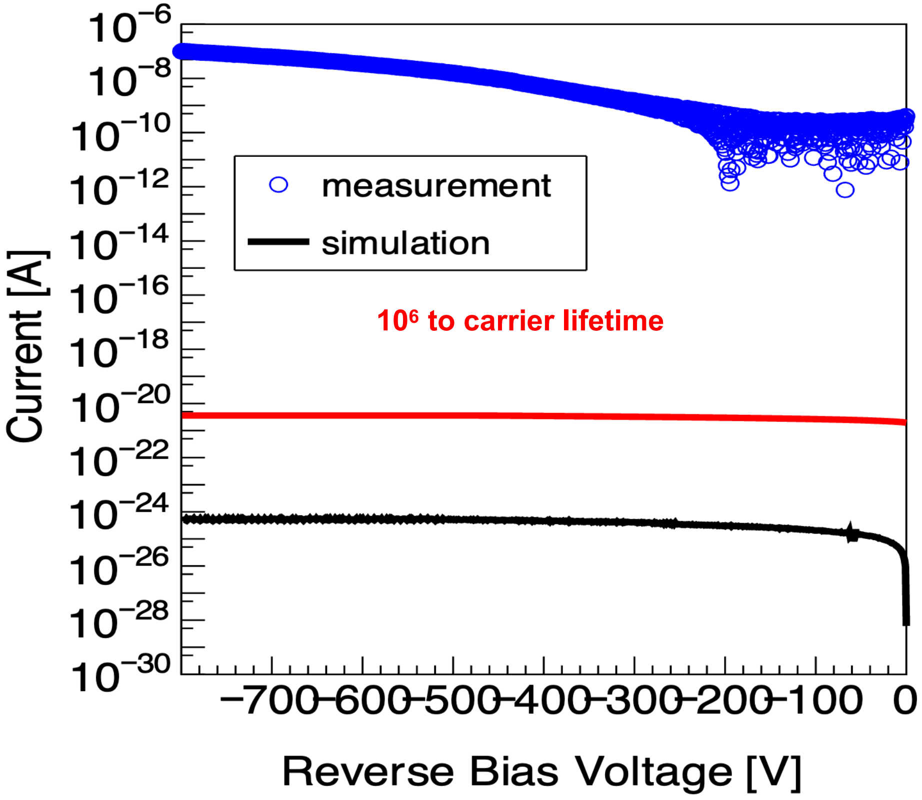
Default carrier lifetime:

$$\tau_n = 2.5 \times 10^{-6}\ s$$
$$\tau_p = 0.5 \times 10^{-6}\ s$$



[Nigam, Saurav, Carrier lifetimes in silicon carbide, PhD Thesis, 2008]

I-V performance & simulation



◆ **The calibration of carrier lifetime could increase the leakage current.**

◆ **The SRH is not dominated term of leakage current.**

Bulk Defects G&R to Leakage Current

Recombination

$$R = R_{SRH} + \boxed{R_{Trap}} + \cdots$$

$$R_{\text{net}} = \frac{N_t v_{\text{th}}^n v_{\text{th}}^p \sigma_n \sigma_p (np - n_{\text{i,eff}}^2)}{v_{\text{th}}^n \sigma_n (n + n_1/g_n) + v_{\text{th}}^p \sigma_p (p + p_1/g_p)}$$

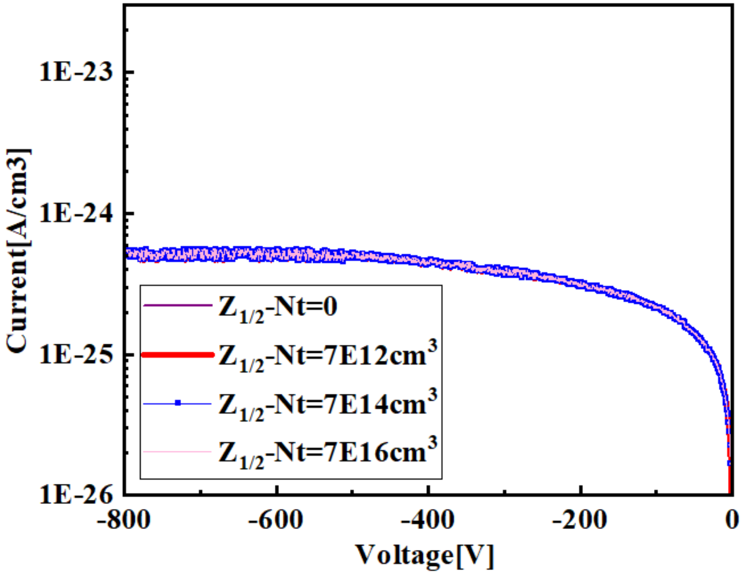
$Z_{1/2}$ electron defects observed by Deep Level Transient Spectroscopy (DLTS)

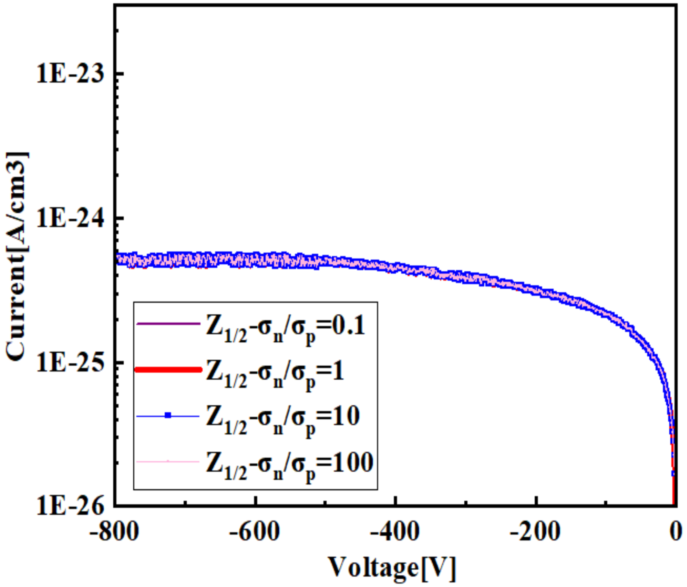
Trap level	Type	Et (eV)	Nt (cm-3)	σinter(cm2)
$Z_{1/2}$	Electron	0.62-0.68	1e15~1e13	1e-12~1e-16

http://aip.scitation.org/doi/10.1063/1.114800

http://aip.scitation.org/doi/10.1063/1.364397

http://aip.scitation.org/doi/10.1063/1.1334907





- Nt and σ of $Z_{1/2}$ have no effect on the leakage current
- σ of $Z_{1/2}$ have no effect on the leakage current

Bulk Defects G&R to Leakage Current

Recombination

$$R = R_{SRH} + \boxed{R_{Trap}} + \cdots$$

$$R_{\mathrm{net}} = \frac{N_t v_{\mathrm{th}}^n v_{\mathrm{th}}^p \sigma_n \sigma_p (np - n_{\mathrm{i,eff}}^2)}{v_{\mathrm{th}}^n \sigma_n (n + n_1/g_n) + v_{\mathrm{th}}^p \sigma_p (p + p_1/g_p)}$$

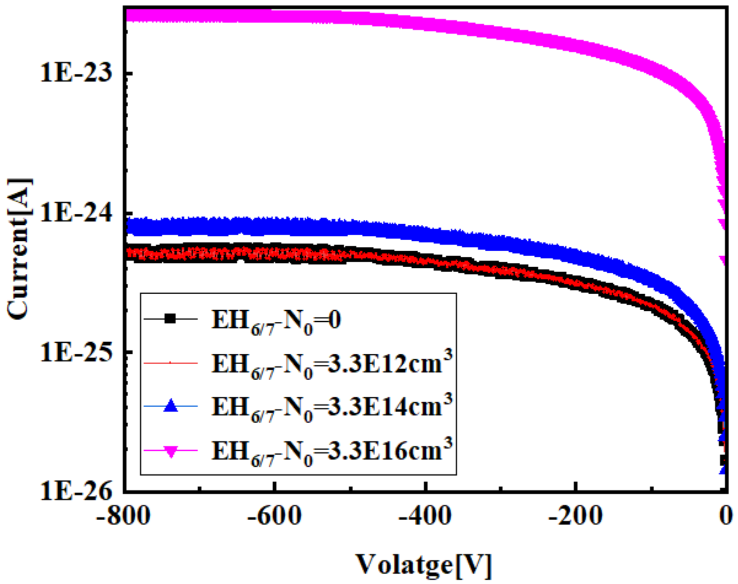
$EH_{6/7}$ electron defects observed by Deep Level Transient Spectroscopy (DLTS)

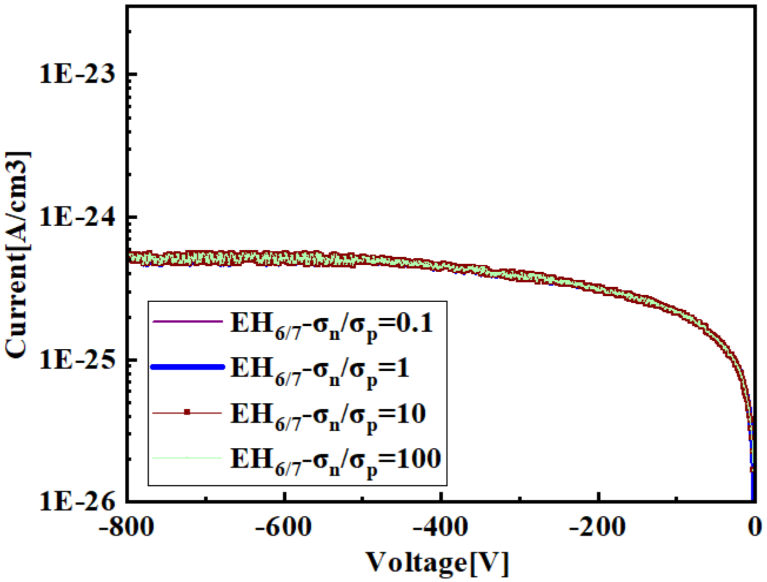
Trap level	Type	Et (eV)	Nt (cm-3)	σinter(cm2)
$EH_{6/7}$	Electron	1.25-1.73	1e15~1e17	1e-12~1e-15

https://linkinghub.elsevier.com/retrieve/pii/S0921452699006018

http://aip.scitation.org/doi/10.1063/1.1543240

http://aip.scitation.org/doi/10.1063/1.2170144





- σ of $EH_{6/7}$ have no effect on the leakage current
- N_t of $EH_{6/7}$ has little effect on the leakage current
- Deep level defects not the main factor affecting leakage current!

Calibration the leakage current

Macroscopic defects may have a greater impact on leakage current.

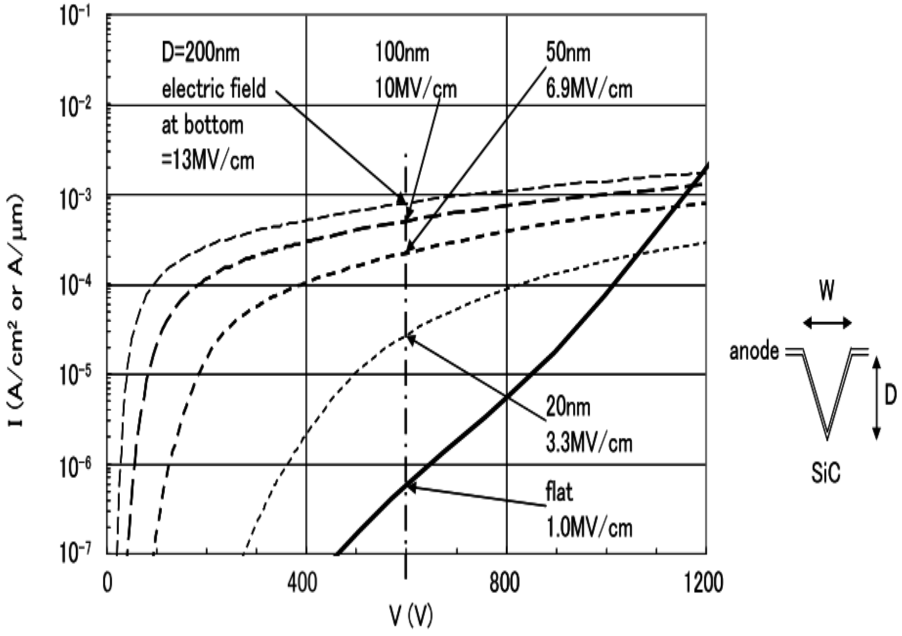
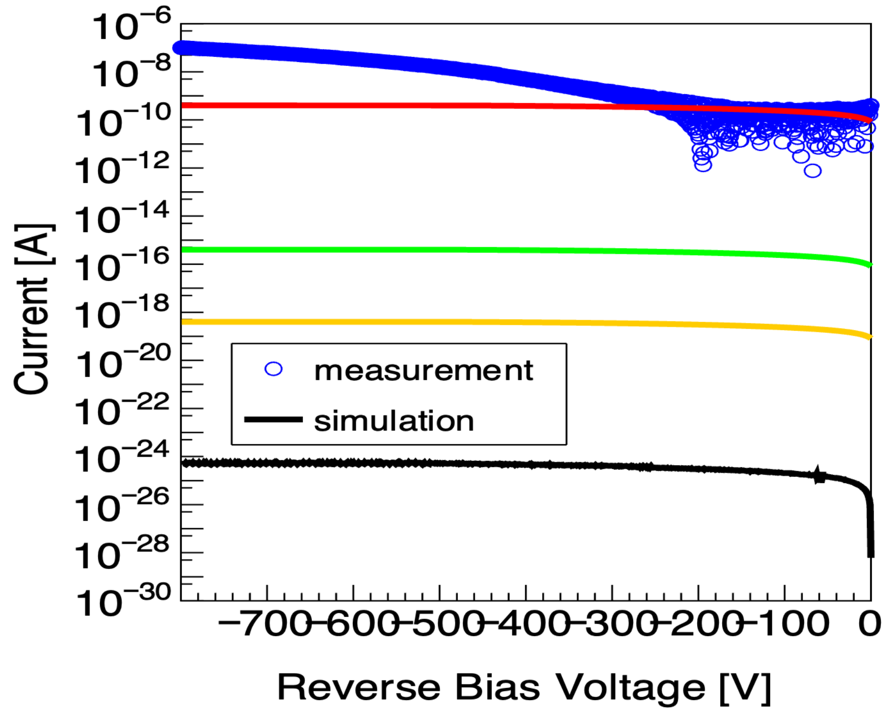


Fig. 3. Calculated current only in portion around macroscopic defects, grooves of W=20nm. The value of electric field is taken at 600V.

https://doi.org/10.4028/www.scientific.net/MSF.725.53

Use constant G&R rate to replace the complex traps effects.

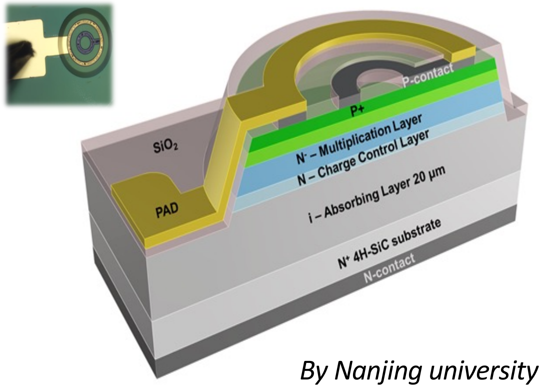
$$R_{\text{net}} = \frac{N_0 v_{\text{th}}^n v_{\text{th}}^p \sigma_n \sigma_p (np - n_{\text{i,eff}}^2)}{v_{\text{th}}^n \sigma_n (n + n_1/g_n) + v_{\text{th}}^p \sigma_p (p + p_1/g_p)} \sim \text{Constant}$$



Constant G&R rate 10^{12} cm^{-3} —— Same leakage current level

NJU 4H-SiC LGAD under study

Prototype Structure of NJU 4H-SiC LGAD



By Nanjing university (NJU)

Fluctuations of process

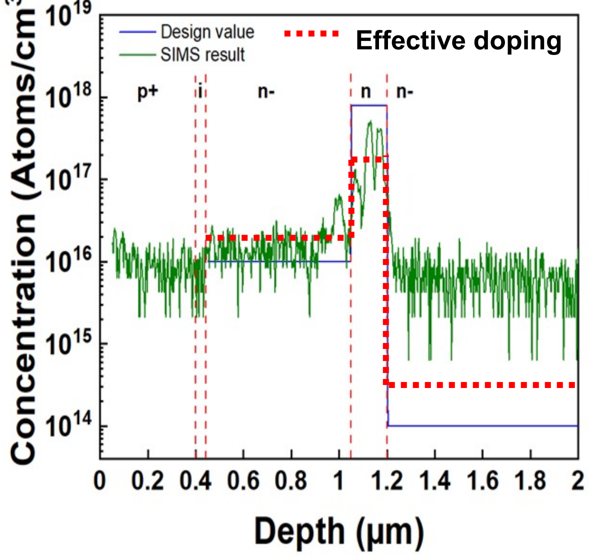
Designed doping

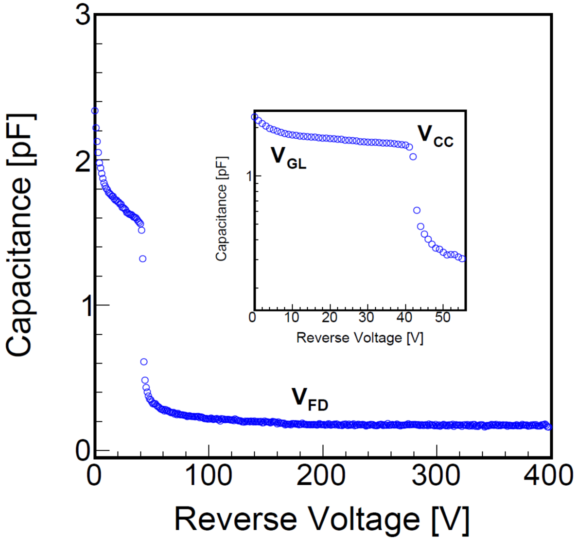
P+ 3e18 0.4μm
50nm I-SIC
N- **1e16** 0.6μm
N **8e17** 0.15μm
N- **1e14** 20μm
N+ Substrate

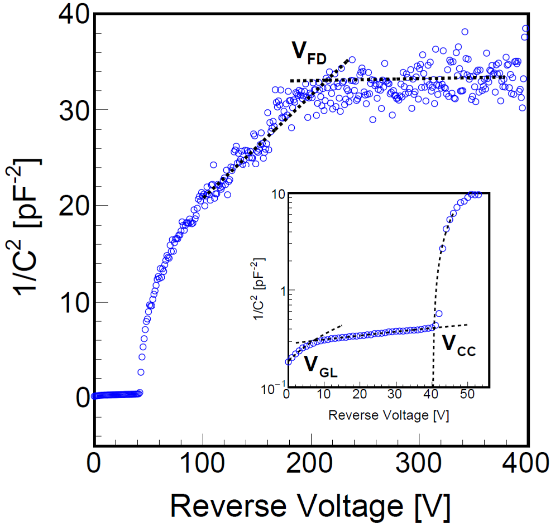
Effective doping

P+ 3e18 0.4μm
50nm I-SIC
N- **2e16** 0.6μm
N **1.7e17** 0.15μm
N- **3.2e14** 20μm
N+ Substrate

SIMS of NJU 4H-SiC LGAD







- **The NJU 4H-SiC LGAD could be fully depleted when U > 200 V.**

V_{GL}: Gain Layer depletion voltage

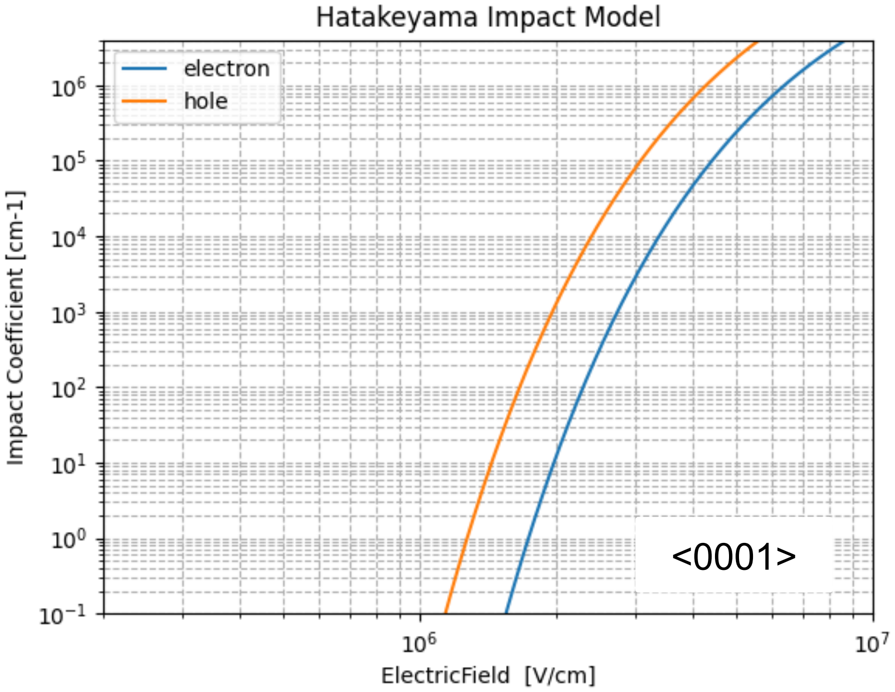
V_{CC}: Charge Control Layer depletion voltage

V_{FD}: Full Depletion voltage

The 40th RD50 Workshop (CERN) Development of 4H-SiC Low Gain Avalanche Diode · Indico

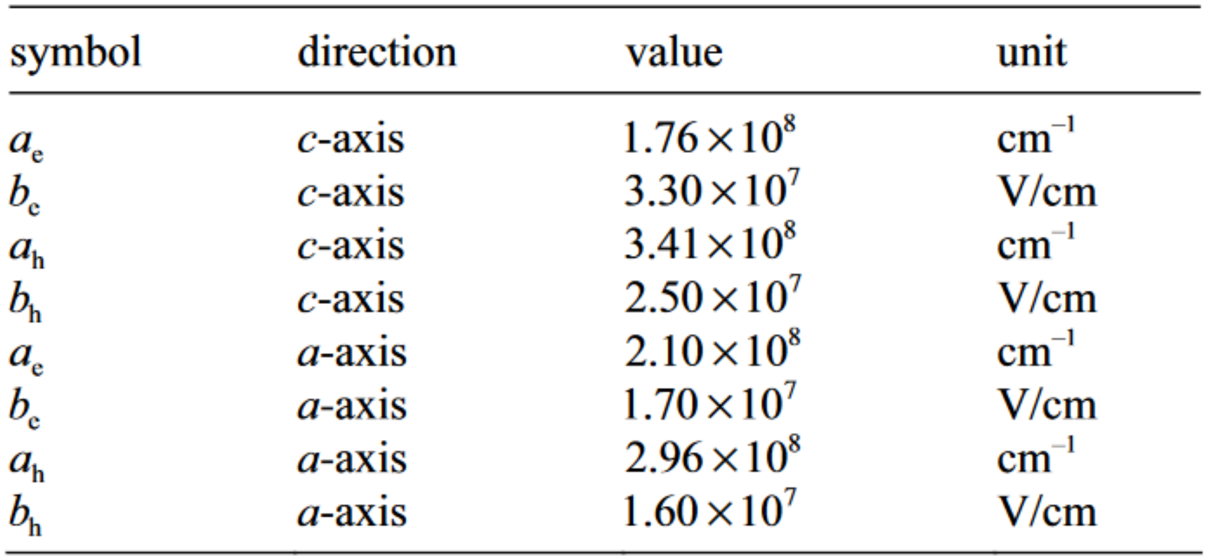
Simulation of NJU 4H-SiC LGAD

◆ **To simulate the impact ionization of 4H-SiC LGAD, the Hatakeyama avalanche model was selected due to the anisotropic behavior in 4H-SiC devices.**



Impact ionization coefficient $\alpha = \gamma a e^{-\frac{\gamma b}{F}}$

The driving force F is defined as the straight electric field E



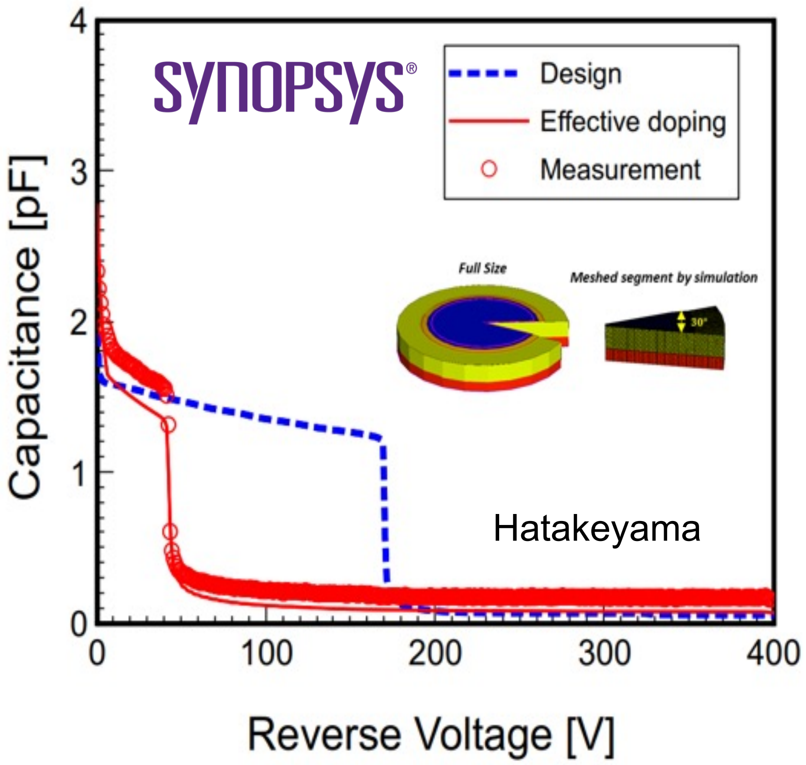
symbol	direction	value	unit
a_e	*c*-axis	1.76×10^{8}	cm^{-1}
b_e	*c*-axis	3.30×10^{7}	V/cm
a_h	*c*-axis	3.41×10^{8}	cm^{-1}
b_h	*c*-axis	2.50×10^{7}	V/cm
a_e	*a*-axis	2.10×10^{8}	cm^{-1}
b_e	*a*-axis	1.70×10^{7}	V/cm
a_h	*a*-axis	2.96×10^{8}	cm^{-1}
b_h	*a*-axis	1.60×10^{7}	V/cm

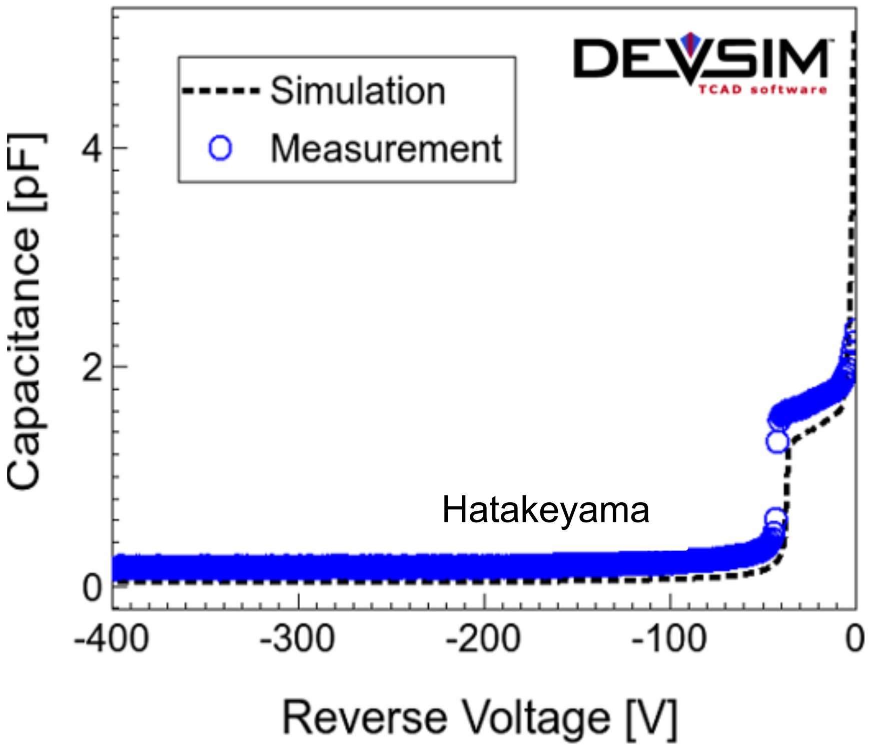
From database

◆ **holes share a greater multiplication rate than electrons**

◆ **The impact ionization of initial holes dominates the carrier multiplication**

Simulation of NJU 4H-SiC LGAD

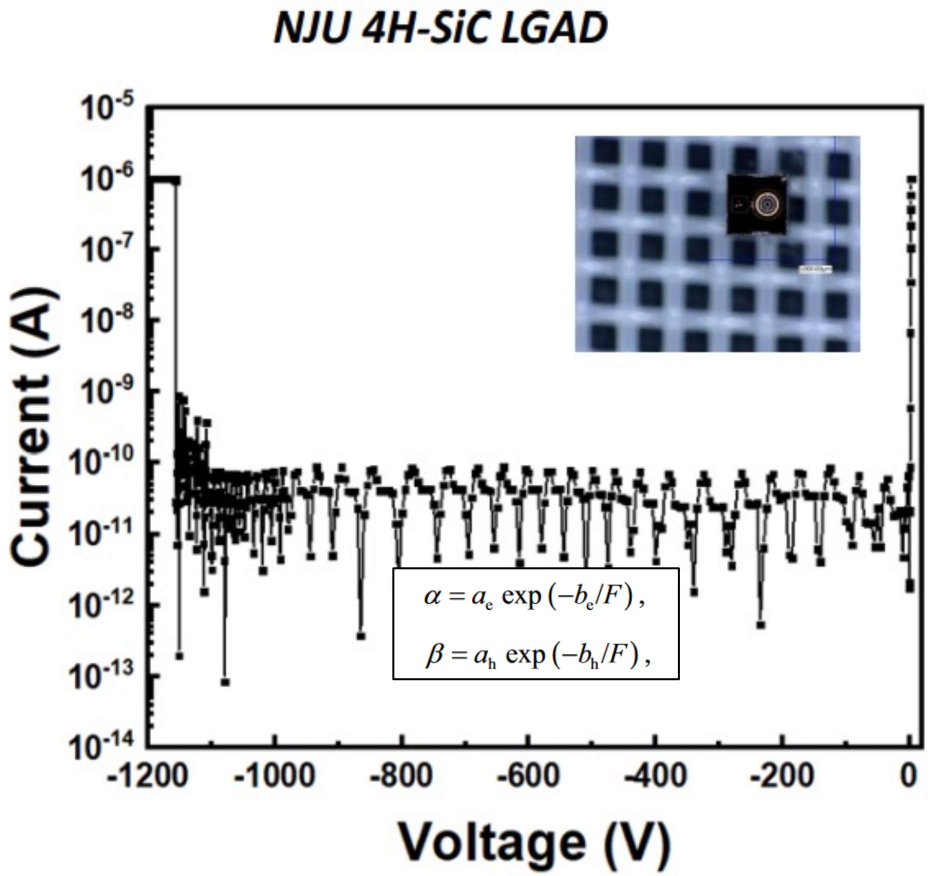




- ◆ **A certain gap between the designed doping and the effective doping concentration.**
- ◆ **The calibrated effective doping concentration selected in simulation (Synopsys/ DEVSIM).**
- ◆ **Good agreement between measurement and DEVSIM simulation of C-V for 4H-SiC LGAD.**

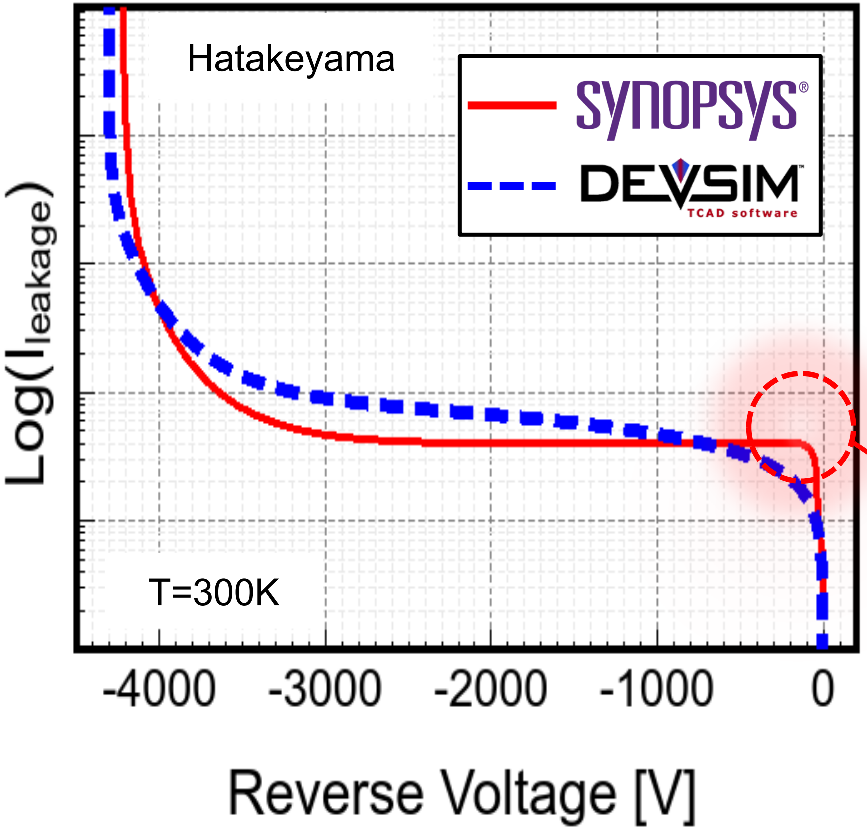
Simulation of NJU 4H-SiC LGAD

Measurement of leakage current



$$\alpha = a_e \exp\left(-b_e/F\right),$$
$$\beta = a_h \exp\left(-b_h/F\right),$$

DEVSIM simulation of leakage current



- ◆ **Leakage current at low voltage not tuned**

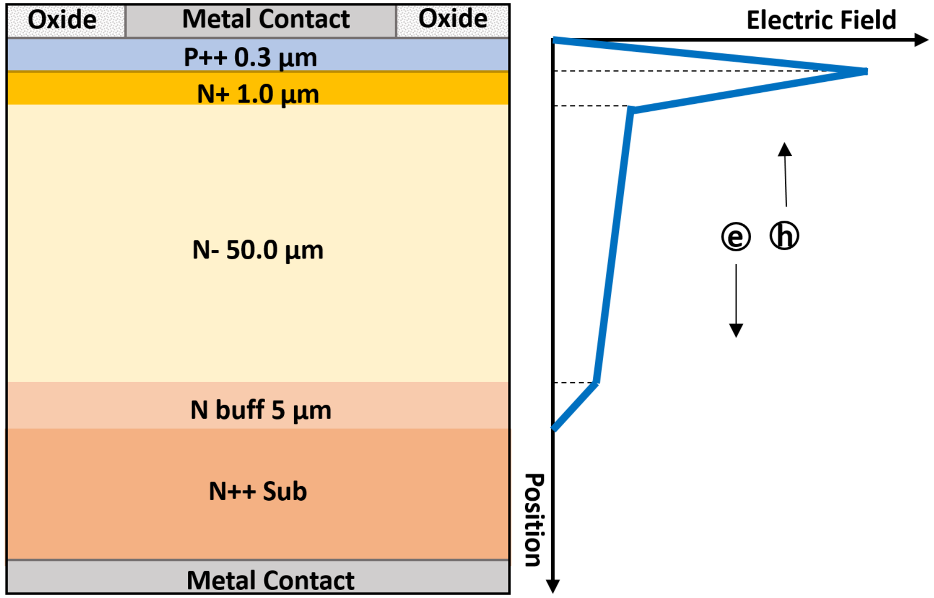
- ◆ **A large discrepancy for V$_{BD}$.**

- ◆ **DEVSIM and SYNOPSYS simulation results at breakdown voltage are consistent**

Introduction of SICAR— 4H-SiC LGAD for MIP

◆ SICAR (SIlicon CARbide): 4H-SiC device for MIPs

- Improve low gain issue of NJU
- Independent designed by RASER team [1]
- Fabricate the 4H-SiC LGAD
- Prototype of SICAR1

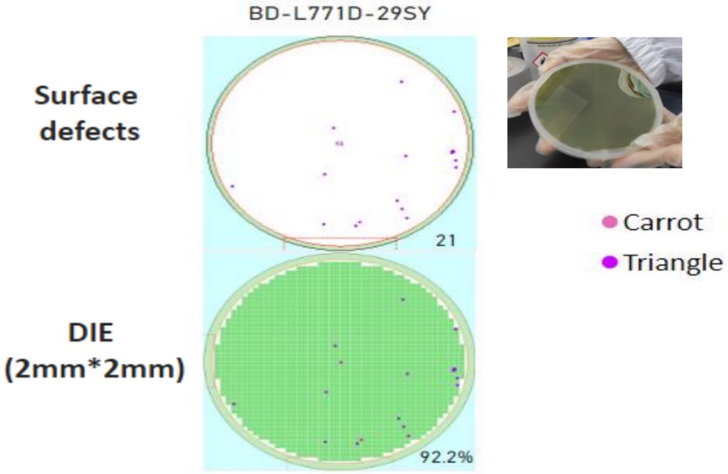


Structure of SICAR1

Design of SICAR1

Epi structure	Thickness [um] (Design)	Doping [cm^{-3}] (Design)
P++	0.3	2e19
N+ (gain layer)	1.0	1e17
N- (active layer)	50.0	1e14
N buff	5.0	1e18

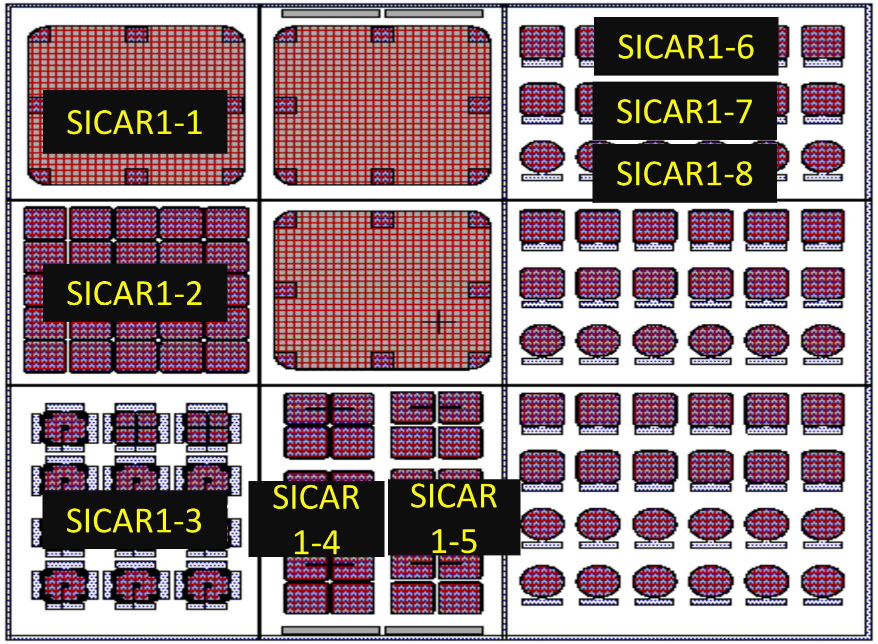
Distribution of defects



[1] RASER -

Processing technology of SICAR1

Lithography mask



Name	Type	Size (μm x μm)	Corner Radius(μm)
SICAR1-1	Single	5000 x 5000	500
SICAR1-2	5x5	1000 x 1000	100
SICAR1-3	Single	1000 x 1000	100
SICAR1-4	2x2	1000 x 1000	100
SICAR1-5	2x2	1000 x 1000	100
SICAR1-6	Single	1000 x 1000	100
SICAR1-7	Single	1000 x 1000	200
SICAR1-8	Single	1000 x 1000	500

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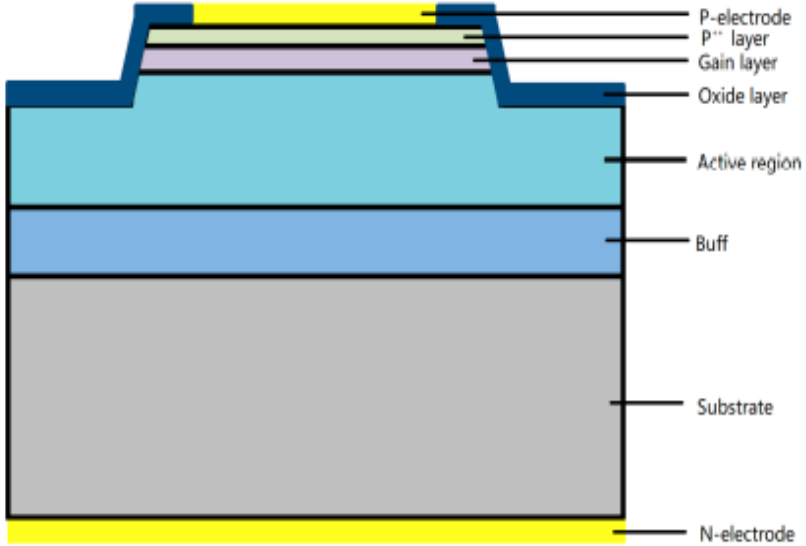
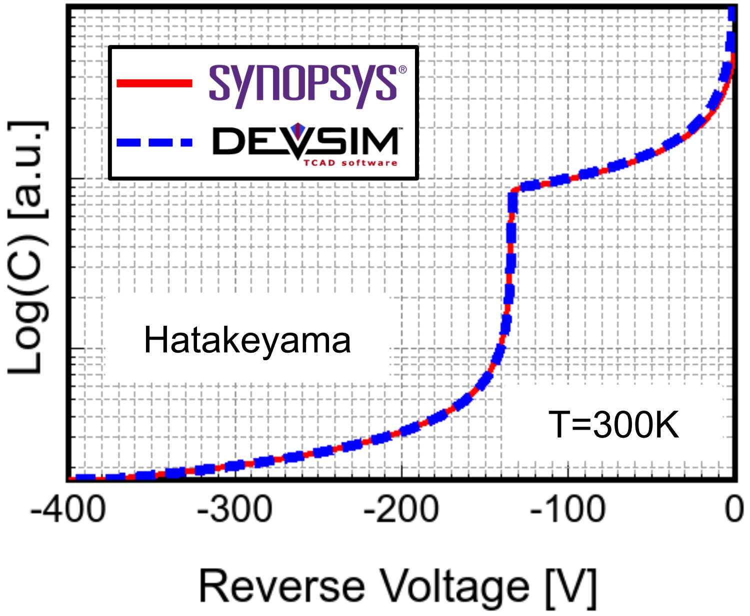
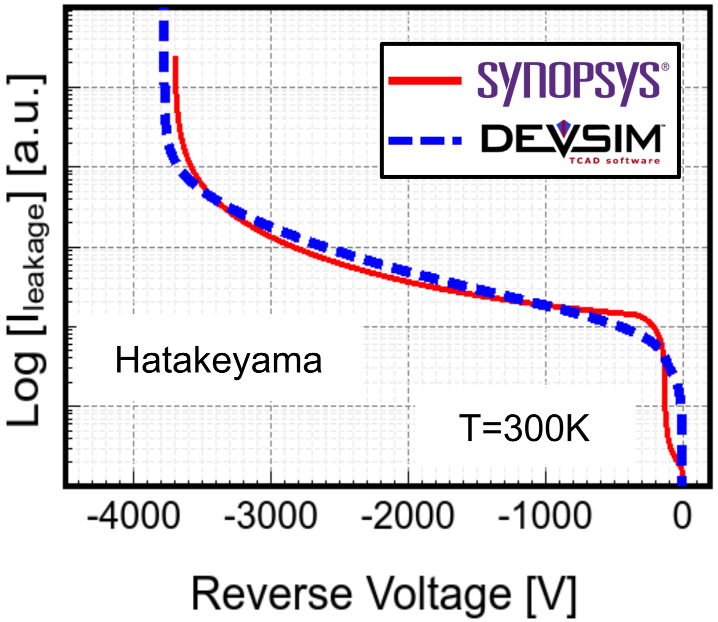


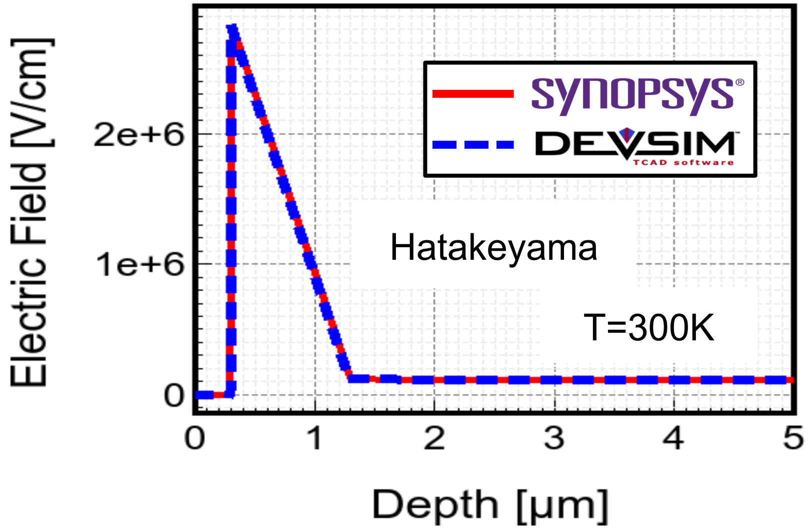
Final structure

- **Different device size correspond to different requirement**
- **Processing is in progress…**

Simulation of SICAR1







- **Good agreement between the DEVSIM and SYNOPSYS simulation**

Summary & Plan

DEVSIM Simulation:

1. Good agreement between measurement and DEVSIM simulation for 4H-SiC PIN.
2. Deep level defects aren’t the main factor affecting the leakage current.
3. Good agreement between the DEVISM simulation and SYNOPSYS simulation of the 4H-SiC LGAD.

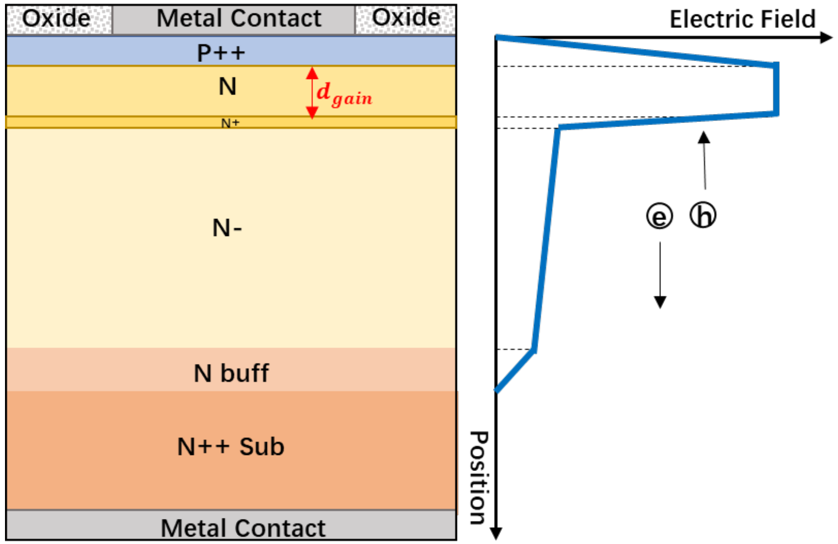
NEXT:

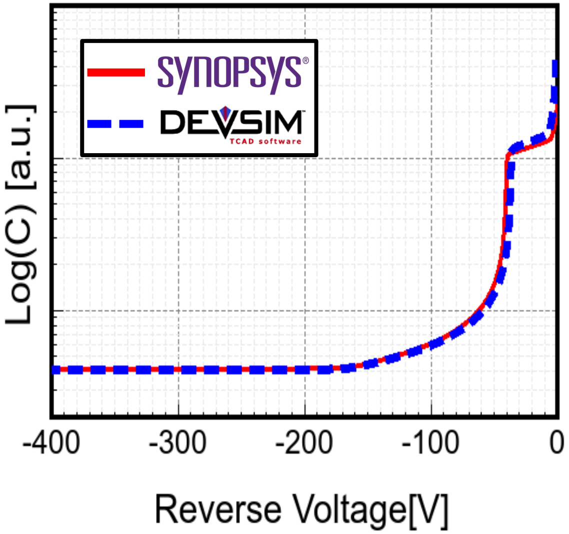
1. Independently develop the 4H-SiC LGAD (SICAR)
2. Combine the macroscopic defects in DEVSIM to calibrate the leakage current.
3. Calibrate the breakdown voltage of the 4H-SiC LGAD.

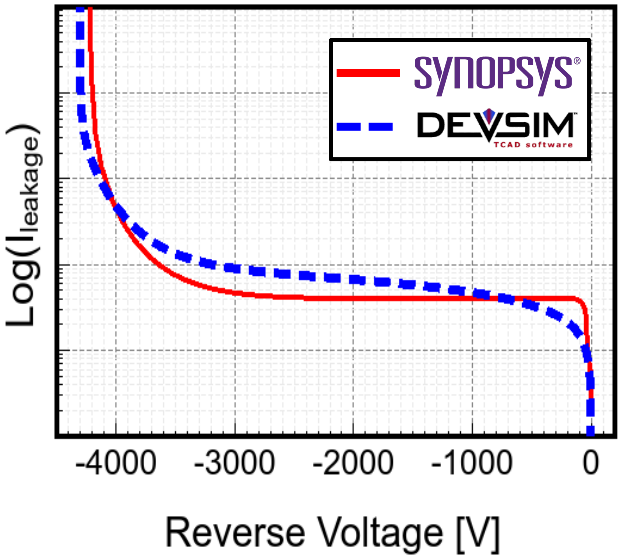
Thanks for your attention!

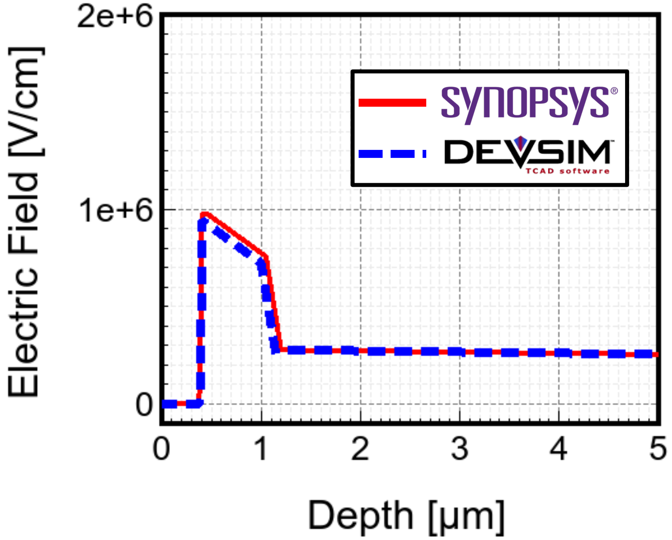
Backup

DEVSIM and SYNOPSYS simulation of NJU 4H-SiC LGAD

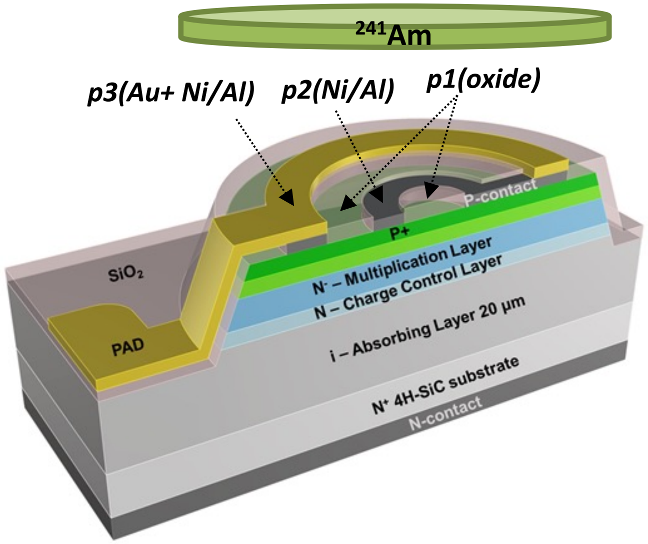




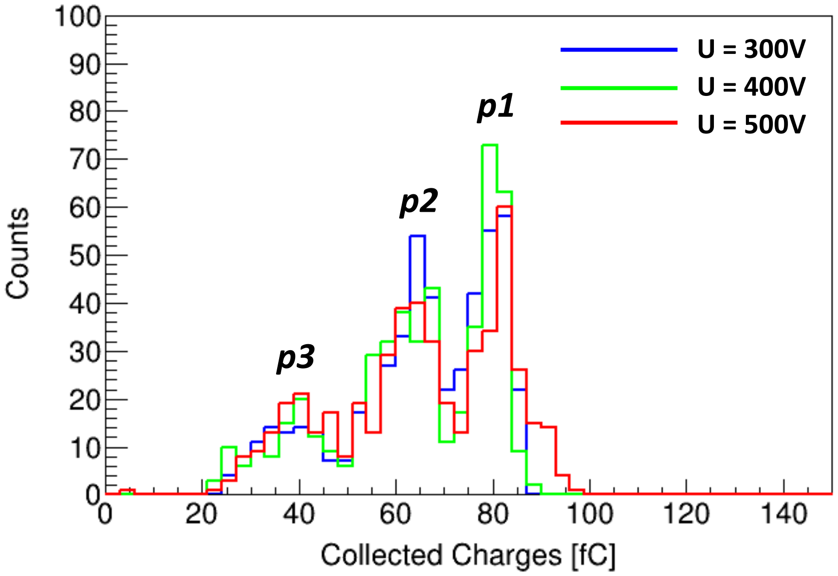




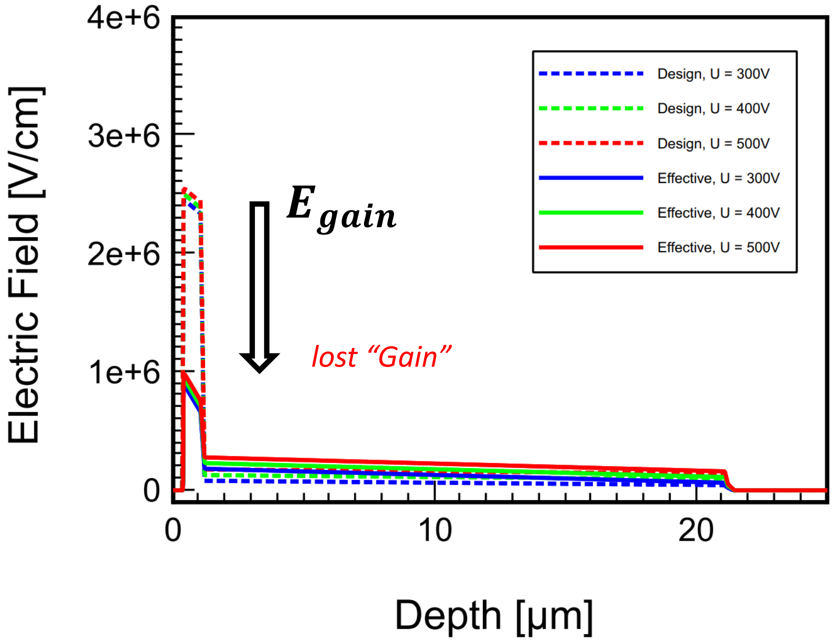
α particles detection of NJU 4H-SiC LGAD of NJU 4H-SiC LGAD



Collected charges spectrum for v2



Simulated electric field for v2



- No collected charges increasing by increase of voltage. -> No gain observed that agrees with the simulation by effective doping.