Time resolution simulation of 2D and 3D SiC detectors

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Outline

- Motivation
- Simulation and measurement of 2D-SiC
- 3D-SiC simulation
- 3D-SiC manufacturing

Motivation

- SiC detectors advantages:
  - High displacement energy – good radiation resistance
  - Low dark current and high saturated carrier velocity – good time resolution
  - Normal operation at high or normal temperature – no need cooling
- 3D-SiC advantages:
  - Narrow electrode spacing – good time resolution and charge collection
  - Thick thickness – larger charge collection and signal
  - More radiation resistant

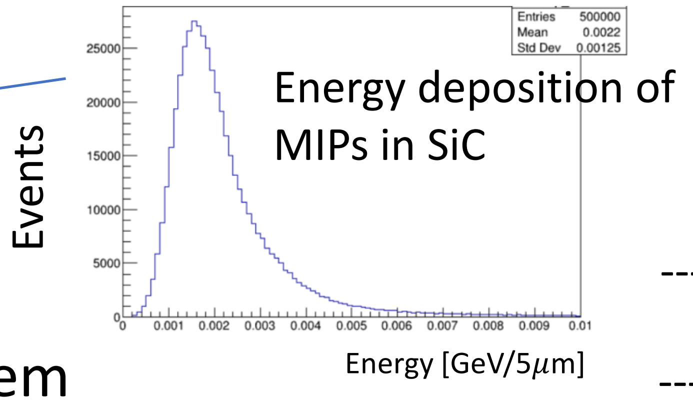
Simulation software RASER for time resolution of SiC detectors

- RAdiation SEmiconductoR – RASER
  - https://github.com/dt-np/raser
- Purpose of RASER:
  - Predict time resolution of SiC with different structures, voltages, temperatures…
  - Predict effect of irradiation fluence on time resolution of SiC
- Characteristic of RASER:
  - FEniCS: electric field and weighting potential of 2D,3D SiC detectors
  - ROOT framework with python language

Composition of RASER

- **FEniCS:** Electric field and weighting potential ---(Inspired by TRACS)
- **MIPs:** ---(Inspired by Weightfield2)

GEANT4
  - Non-uniform charge deposition
  - Amplitude variability



- **Induced current:** Shockley-Ramo’s theorem ---(Reference KDetSim)
  - Drift step of e-h: 1 μm
  - Thermal diffusion
- Read-out **electronics:** simplified charge sensitive amplifier ---(Reference Weightfield2)
- **Mobility model** and permittivity of 4H-SiC

Mobility model of 4H-SiC[1]

- Low electric field

$$\mu_e = \frac{947 \times \left(\frac{T}{300}\right)^{-2}}{1 + \left(\frac{N_i}{1.94 \times 10^{19}}\right)^{0.61}} \qquad \mu_h = 15.9 + \frac{124 \times \left(\frac{T}{300}\right)^{-2}}{1 + \left(\frac{N_i}{1.76 \times 10^{19}}\right)^{0.34}}$$

- High electric field

$$\mu_{HF,sat} = \frac{\mu_{low}}{\left(1 + \left(\frac{\mu_{low} E}{v_{sat}}\right)^{\beta 1}\right)^{\frac{1}{\beta 1}}}$$

  - Saturation drift velocity of electrons and holes

$$v_{sat\ e} = 2 \times 10^7 \left(\frac{T}{300}\right)^{0.87} \qquad v_{sat\ h} = 2 \times 10^7 \left(\frac{T}{300}\right)^{0.52}$$

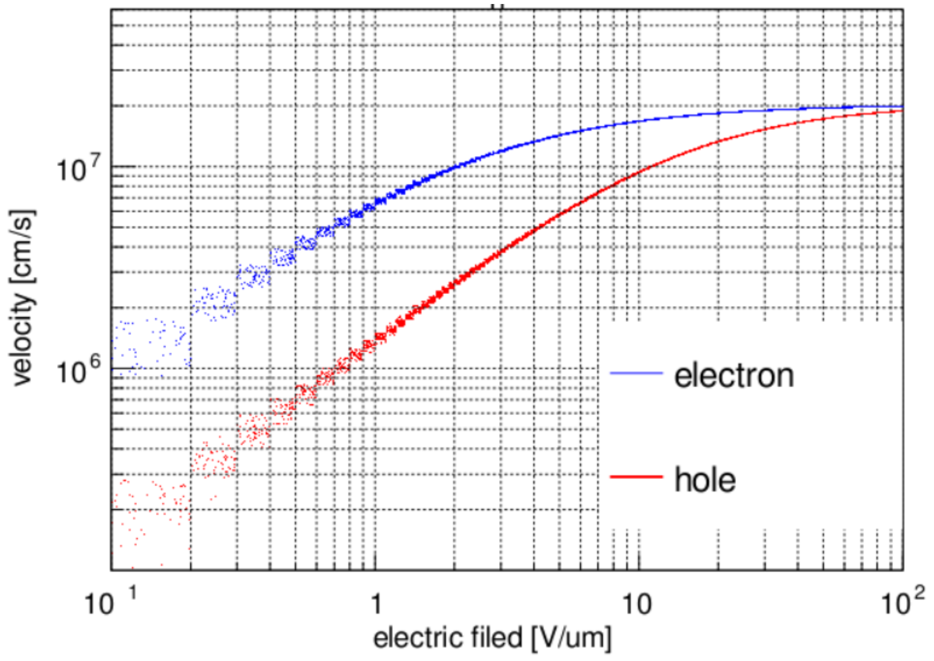
  - β_1 vs temperature

$$\beta 1_{\ e} = 1 \times \left(\frac{T}{300}\right)^{0.66} \qquad \beta 1_{\ h} = 1.213 \times \left(\frac{T}{300}\right)^{0.17}$$

- Anisotropy of 4H-SiC ignored

Mobility model in RASER

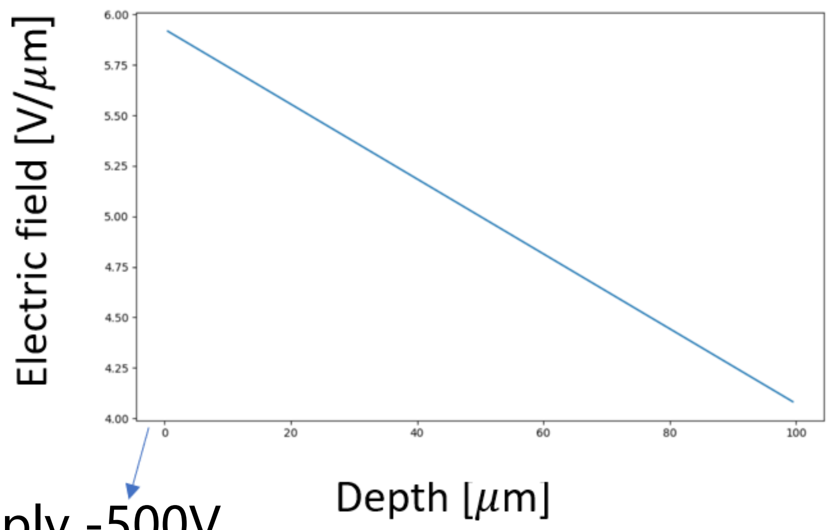
velocity $\begin{cases} v_e = \mu_e \times E \\ v_h = \mu_h \times E \end{cases}$



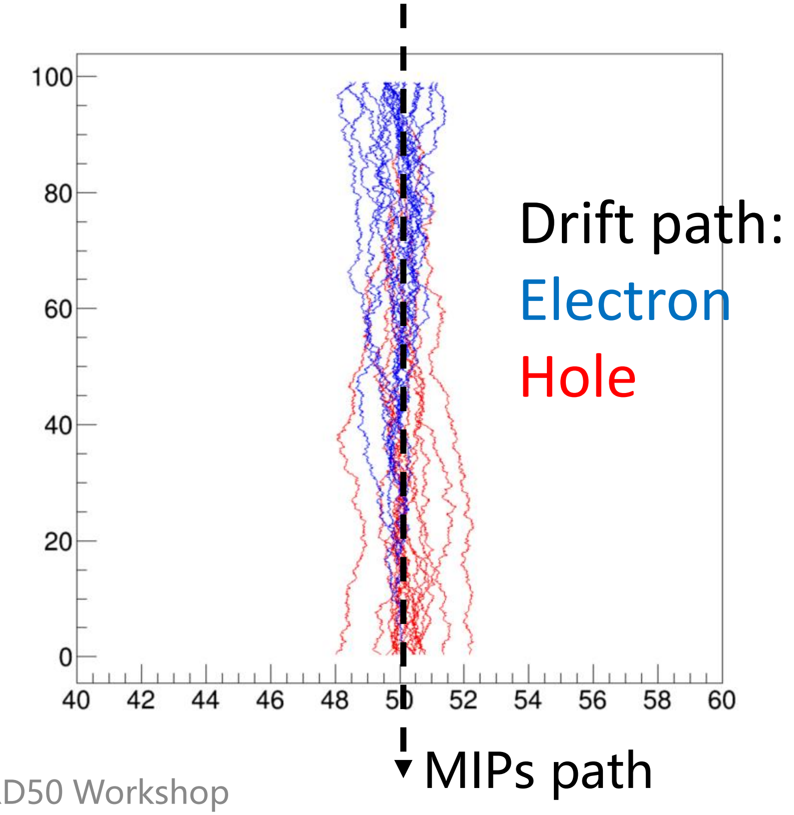
Ref [1]. DOI: 10.1093/rpd/ncu369

2D-SiC Simulation – basic information

- ➢ Purpose: Compare with measurement to verify reliability of simulation
- ➢ Simulation structure:
  - Size: 100μmX100μm, thickness:100μm, doping concentration: 1e13 cm^{-3}
- ➢ Electric field and drift path

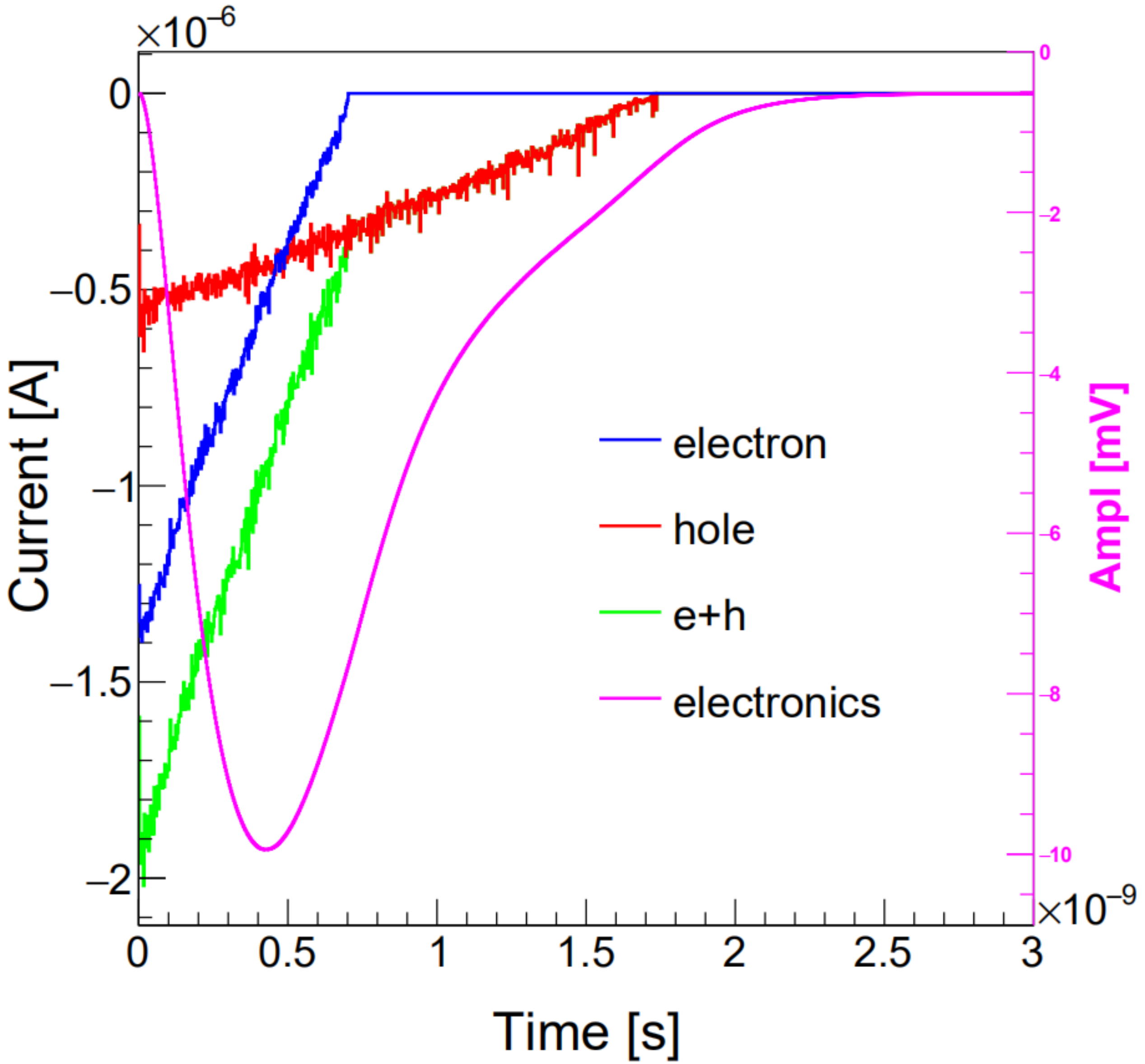


Apply -500V



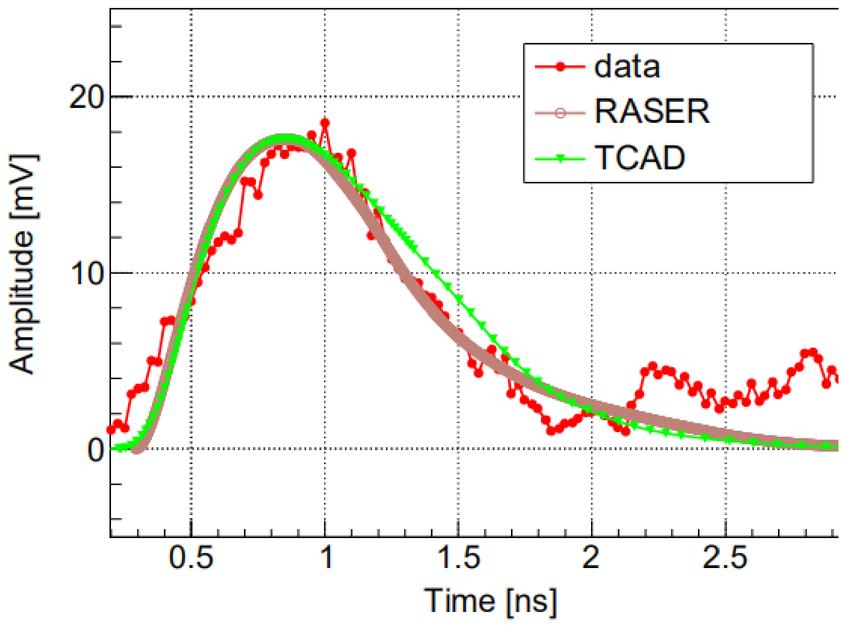
2D-SiC Simulation – current

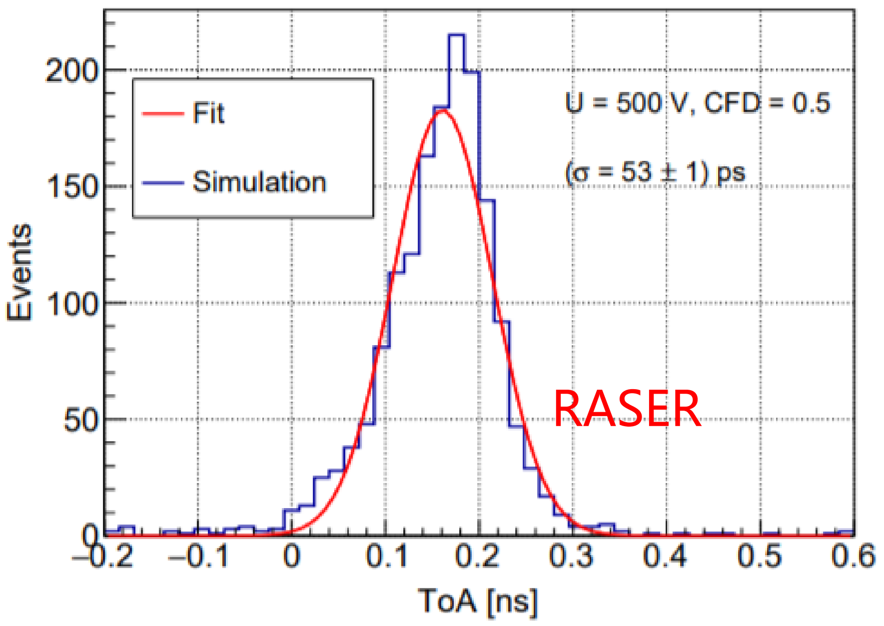
- Induced current
  - Electron
  - Hole
  - Electron+hole
- $v_e > v_h$
- Amplitude after electronics [mV]
- $t_{rise} < 1$ ns
- Time resolution:
  - Simulate 10000 events
  - Incident parallel to thickness



Comparison for simulation and measurement of 2D-SiC

- ➢ Compare waveform of RASER, TCAD and data, good agreement is obtained
- ➢ $\sigma_{fit+TDC}^{sim}$ = 68 ps , and $\sigma_{data} - \sigma_{fit+TDC}^{sim}$ = 26 ps (fairly good of simulation)
  - Optimization direction: anisotropy, electronics and incidence angle



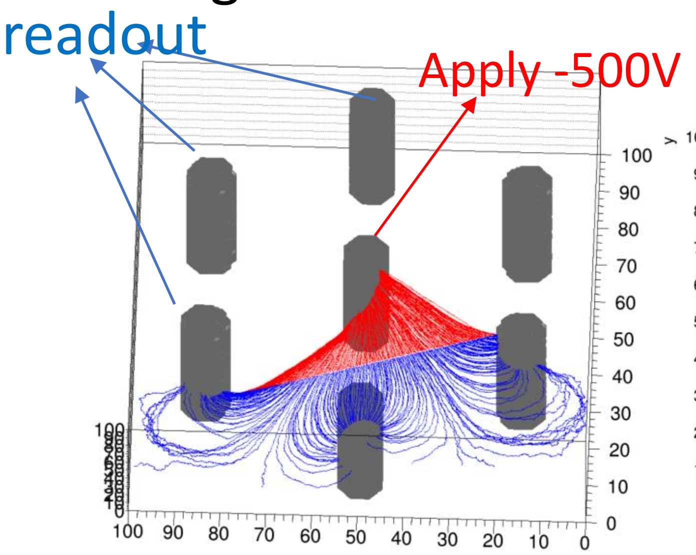


Sampling rate 20Gsa/s

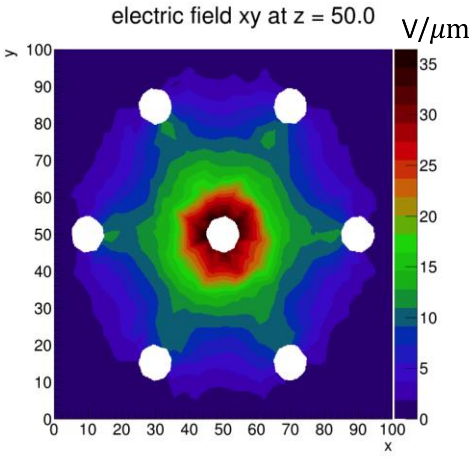
	Time Resolution [ps]
Data	94±1
Simulation	68±1

3D-SiC simulation – basic information

- Fig.a: SiC structure. Electrode radius 5μm, electrode spacing 40μm and 100μm thick
- Drift path: blue electrons and red holes in Fig.a
- Fig.b and Fig.c: Electric field xy plane at z=50μm
  - Fig.c: Explain curvature in the drift path of Fig.a
- Fig.d : Current distribution



a



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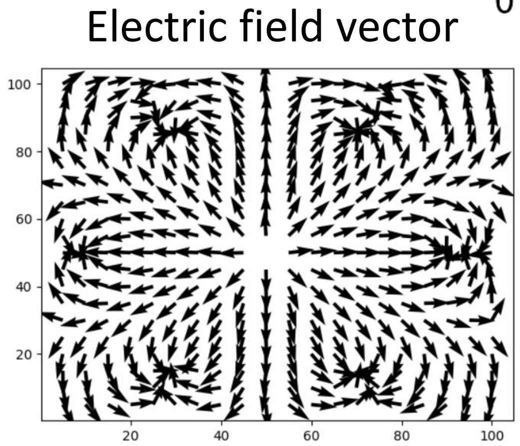

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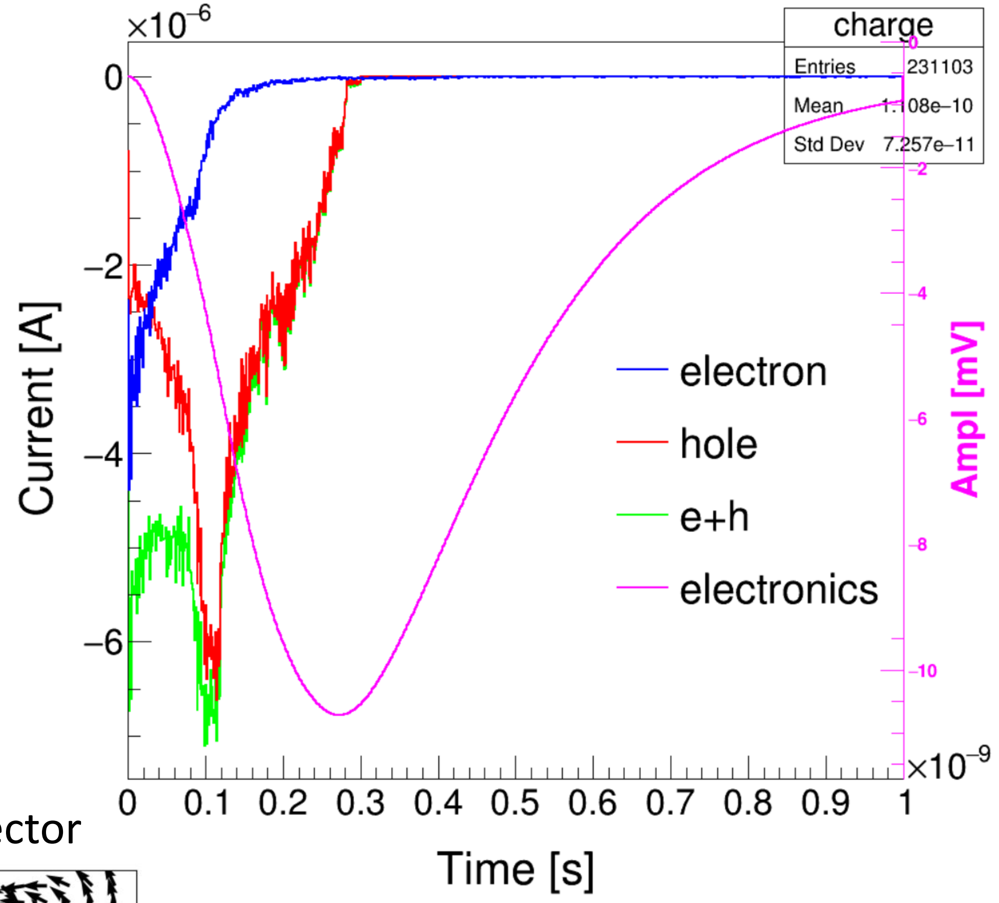


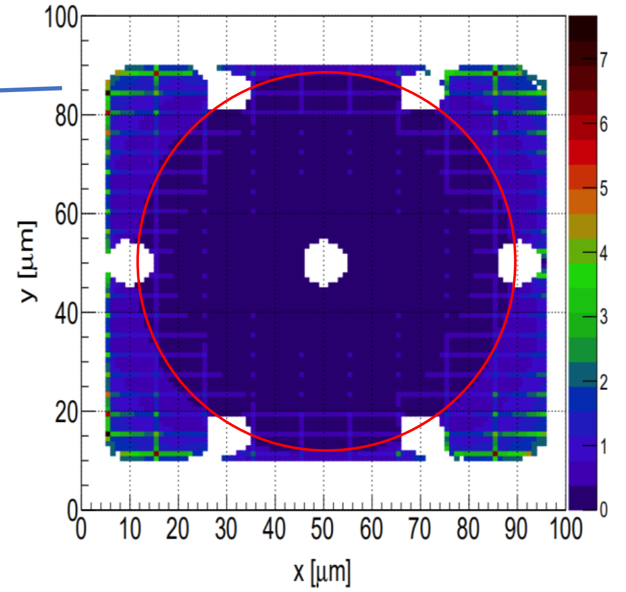
d

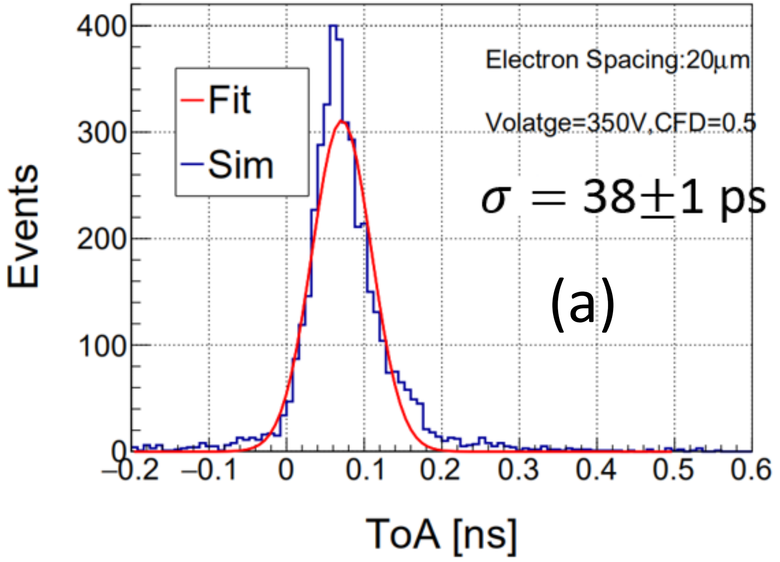
3D-SiC simulation – time resolution

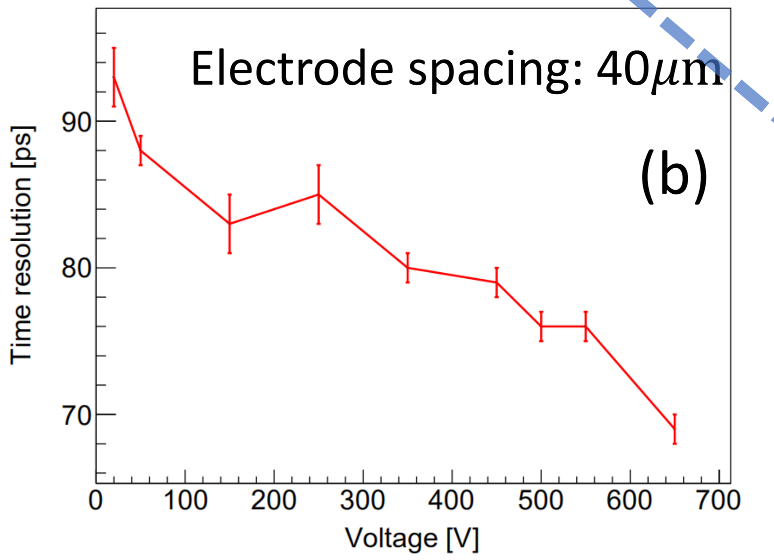
- Detector scan: 10000 events. Step: $1\mu m X 1\mu m$
- Fig.a: Time resolution is 38 ps

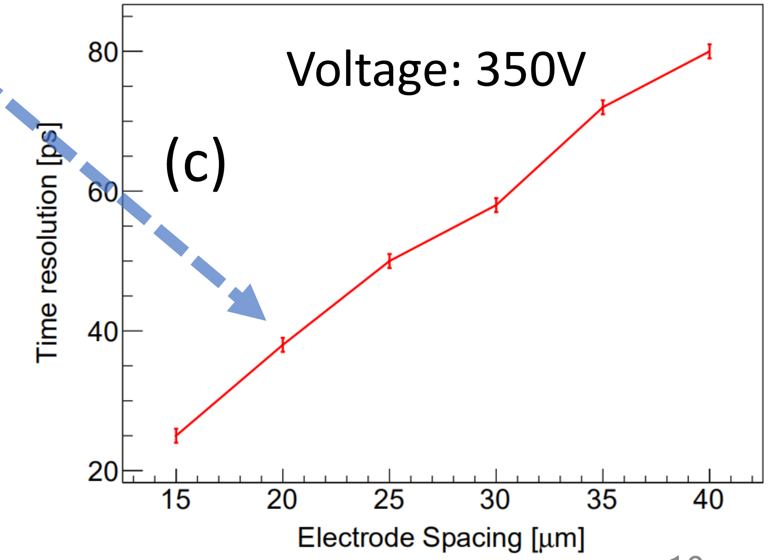
  at 350V with electrode spacing $20\mu m$
- Fig.b: Time resolution vs voltage
- Fig.c: Time resolution vs electrode spacing

Vertical incidence









Dalian University of Technology brief introduction:

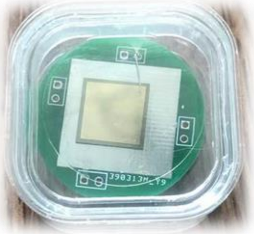
➢ GaN based radiation detector:

- Developed: Self powered GaN alpha particle detector
- Designed: GaN 3D neutron detector with position resolution
  - ✓ Theoretical breakdown voltage increases significantly
  - ✓ Leakage current density decreases significantly

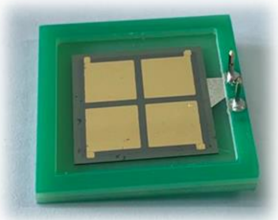
➢ SiC based radiation detector:

- Developed: Irradiation resistant SiC neutron detector
- Developed: X-ray detector based on SiC single crystal

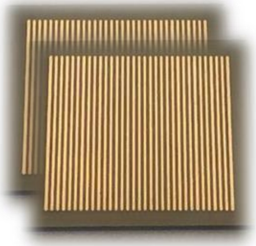
Sample device



20mm*20mm



10mm*10mm
four pixels



10mm*0.15mm
32 way micro strip

Lithography

Electron beam evaporation

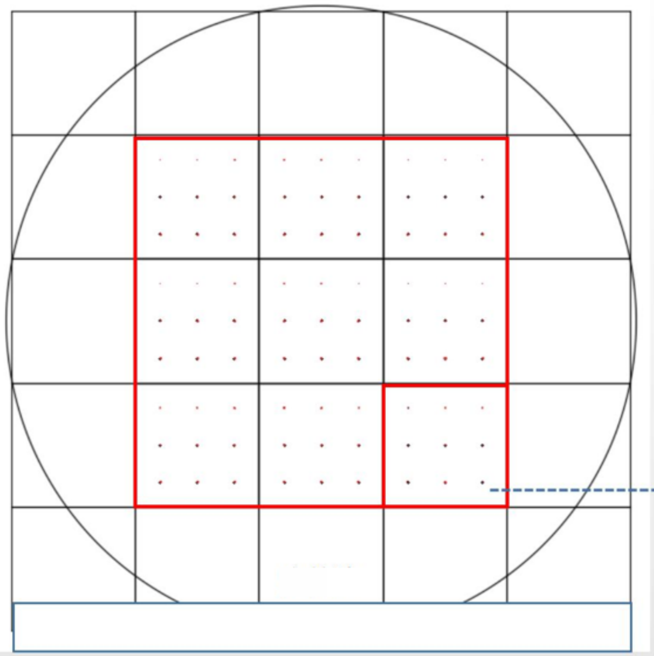
MOCVD growth equipment for nitrides and oxides

3D-SiC manufacturing – 3D drilling

- 6H-SiC Single crystal drilling experiment

Experiment design

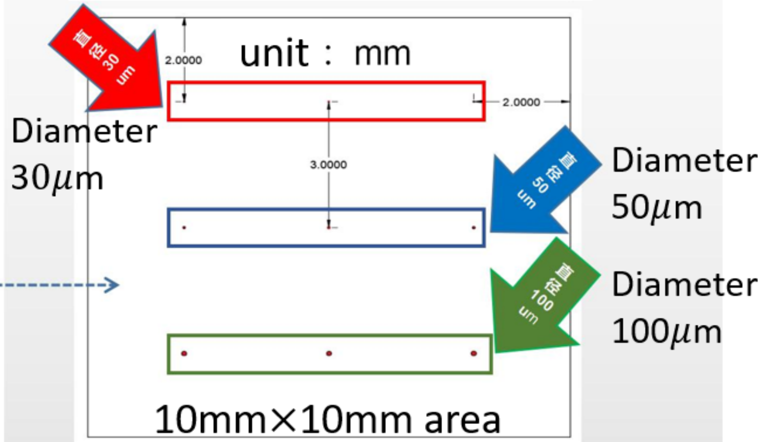
Hole drilling distribution



There are 81 holes in three sizes:

- $30\mu m$
- $50\mu m$
- $100\mu m$

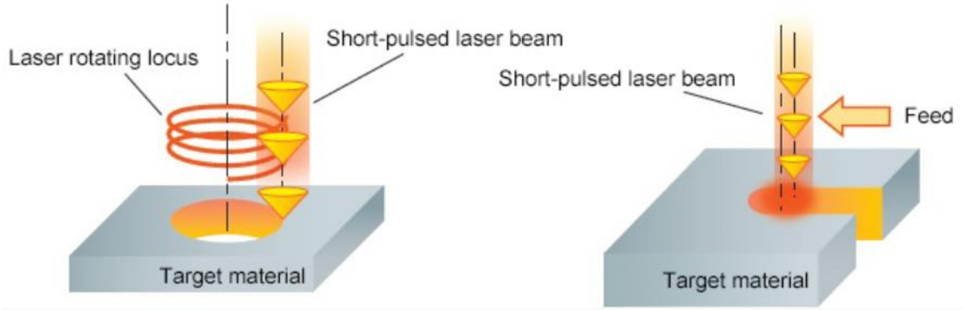
} Diameter



- 2-inch 6H-SiC single crystal
- Thickness 300-360 μm

Processing conditions - nanosecond laser

Diameter	Width	Drilling	Power
30 μm	20 ns	Pulse	4.5W
50 μm	20 ns	Auger	3W
100 μm	20 ns	Auger	3W



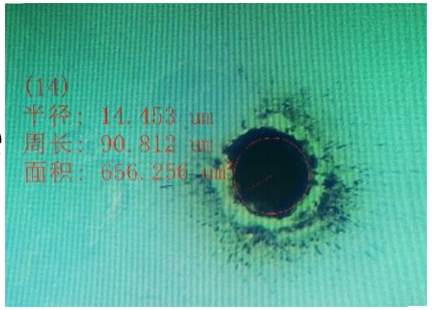
Auger drilling　　Pulse drilling

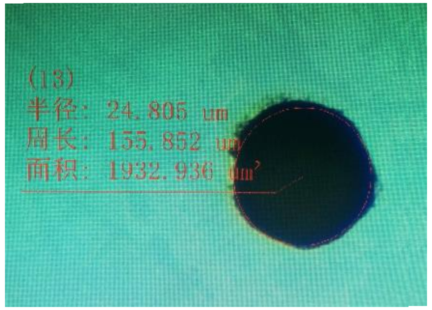
www.mhi-machinetool.com/en

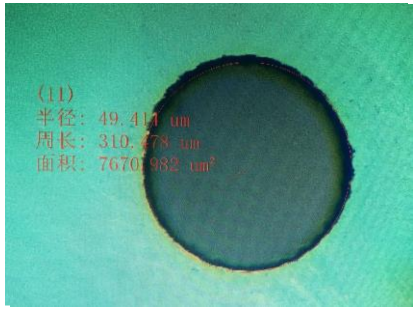
3D-SiC manufacturing – micrograph and holes distribution

Design diameter   30 μm 50 μm 100 μm

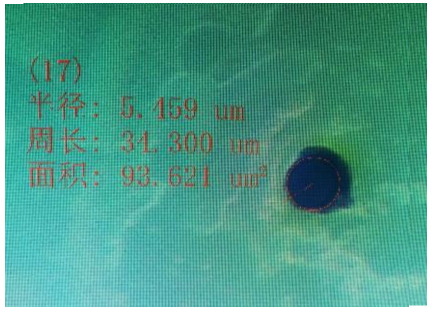
Incident surface

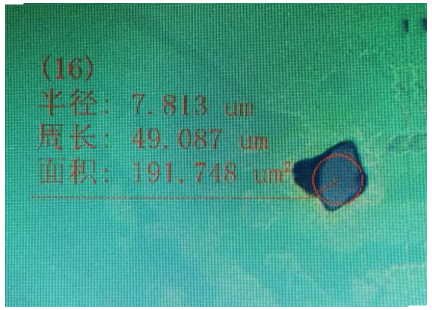


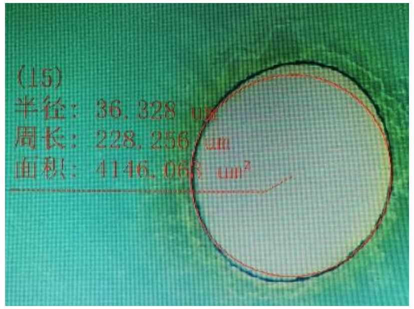




Exit surface







- Nonuniform holes
- Optimization：
  - Picosecond laser
  - Femtosecond laser

Design	30 μm	50 μm	100 μm
Incident Diameter	29 μm	50 μm	99 μm
Exit Diameter	11 μm	16 μm	73 μm

3D-SiC manufacturing – 3D drilling plan

- Samples processed by nanosecond laser
  - Understand current situation
  - Cross section characterization
  - Chemical treatment
  - Cross section characterization
- Picosecond and femtosecond laser plan
  - Select processing conditions
  - Processing in near future

Summary and plan

- Developed a new simulation software for time resolution of SiC – RASER
- 2D-SiC: Compare simulation and data for waveform and time resolution
  - Good agreement of waveform is obtained
  - $\sigma_{time}^{\mathrm{data}} - \sigma_{time}^{\mathrm{sim}}$ = 26 ps, and initial simulation is fairly good
  - Simulation still needs to be optimized
- 3D-SiC simulation:
  - Scan detector and obtained $\sigma_{time}^{3D\_SiC}$
  - Obtained trends: $\sigma_{time}^{3D\_SiC}$ vs voltage and $\sigma_{time}^{3D\_SiC}$ vs electrode spacing
  - Plan: simulate $\sigma_{time}^{3D\_SiC}$ according to actual sample size and electrode shape
- 3D-SiC manufacturing:
  - Tried nanosecond laser drilling
  - Try picosecond and femtosecond laser drilling in near future