Neutron Transmutation Doping for SiC Wide Band Gap Material in Research Reactor

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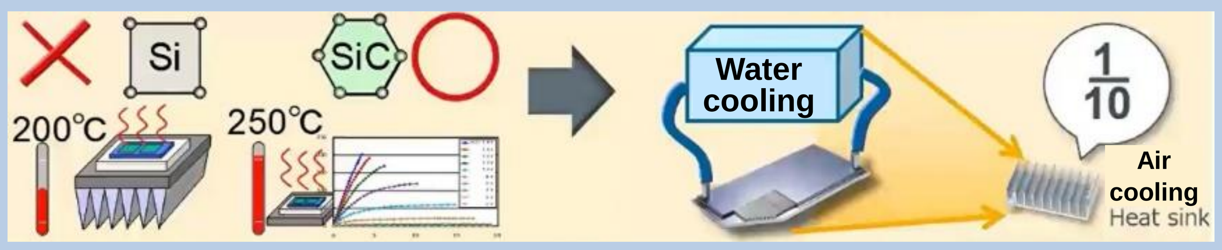
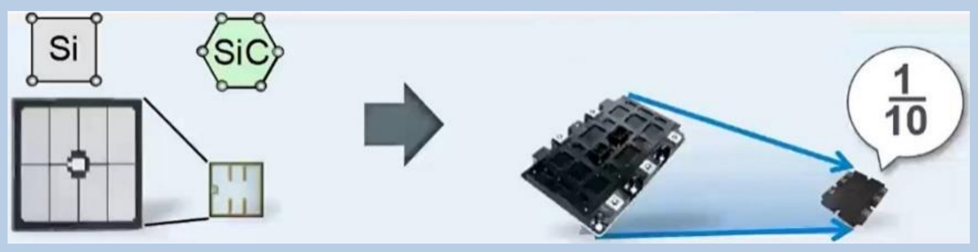
Introduction

- **Next-generation semiconductor material: Silicon Carbide (SiC) and NTD for SiC Semiconductor**
  - SiC is a compound material composed of elements from group IV of the periodic table, and it possesses distinctive physical and chemical properties
  - Superior power semiconductor properties of SiC



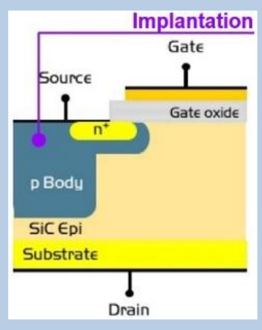
Wide bandgap & High thermal conductivity
→ Stable operation at high temperature, minimization of cooling system



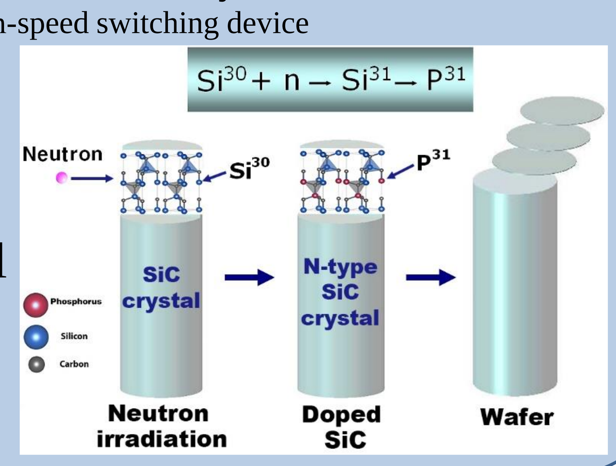
High electric breakdown field
→ High current density, small size device can be manufactured

High saturation drift velocity
→ Low power loss, high-speed switching device

- Key issues in SiC power semiconductors: **implantation**
  : Doping profile and ion concentration
  : Activation ratio
  : Implantation damage
  : Surface roughness

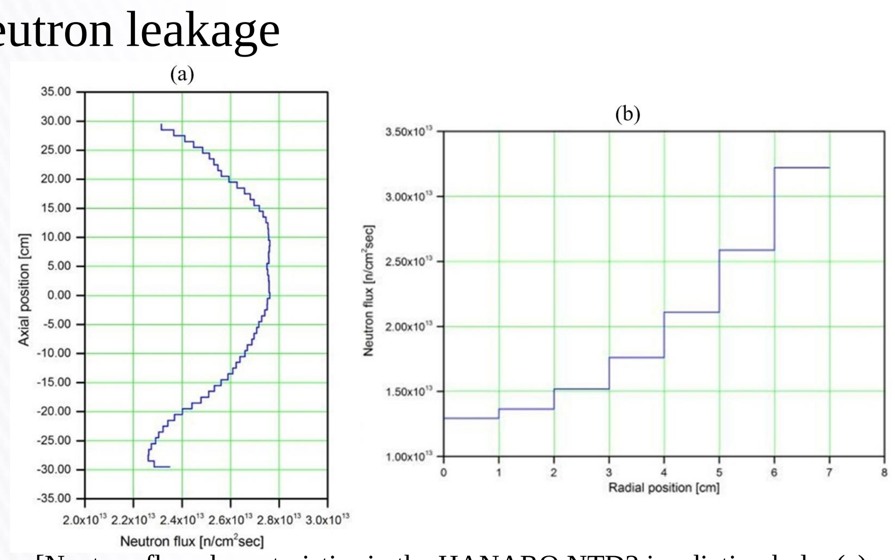


- Neutron Transmutation Doping (NTD) for SiC
  : Commercial application field of a research reactor
  : Realization of uniform doping concentration in a SiC single crystal
  : Development of a high-quality SiC power device
  : $^{30}Si + n \rightarrow {}^{31}Si \rightarrow {}^{31}P + \beta^-$



Methods

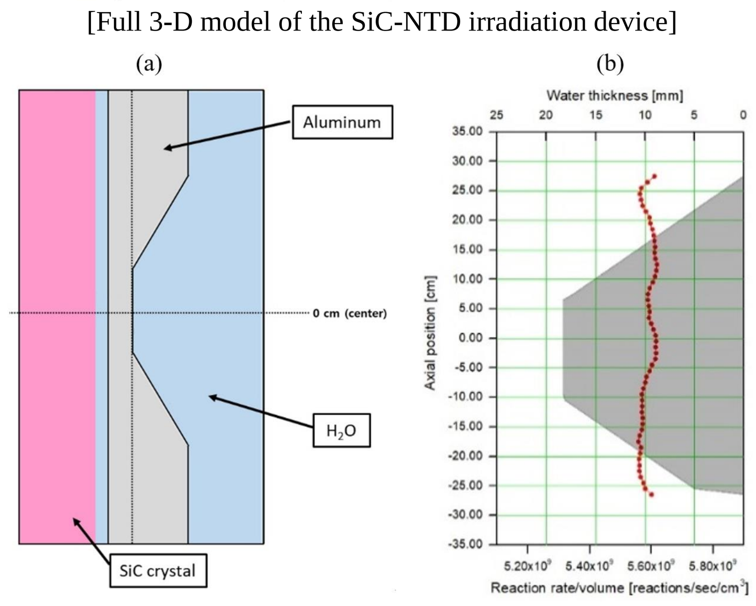
- **Development of SiC-NTD device at HANARO**
  - Design concept of the SiC-NTD device
    1) Resistivity of the SiC single crystal is within 10% of the target resistivity
    2) Reaction rate of $^{30}Si(n,\gamma)^{31}Si$ in the axial direction of SiC is within ±5%
    3) Reaction rate of $^{30}Si(n,\gamma)^{31}Si$ in the radial direction of SiC is within ±7%
  - Components
    - Screen (Al-6061 + water channels) for axial flux flattening
    - Graphite reflectors at top/bottom to minimize neutron leakage



[Neutron flux characteristics in the HANARO NTD2 irradiation hole: (a) axial neutron flux distribution, (b) radial neutron flux distribution]

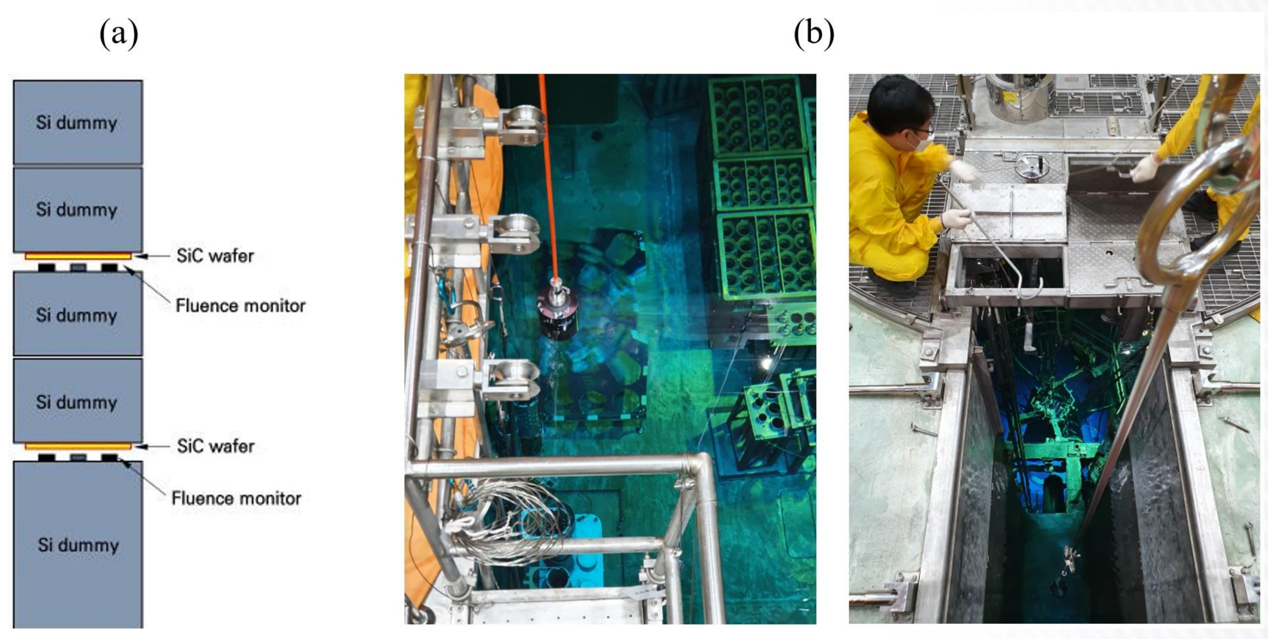
- **Fabrication & Installation**
  - 3D-optimized design fabricated for in-core use
  - Cooling holes, adjusted reflector geometry, and aluminum structural housing
  - Accommodates: 4-inch, 50 cm SiC single crystal

[Full 3-D model of the SiC-NTD irradiation device]



[MCNP model for optimized neutron screen of SiC-NTD device (a), and the calculated axial reaction rate distribution with the SiC-NTD device (b)]

- **SiC NTD Test Irradiation**
  - 4-inch HPSI 4H-SiC wafers (Synlight Crystal, China)
  - Dummy Si ingots used to hold wafers; Zr foil for neutron flux monitoring
  - Irradiation at HANARO
    - Power: 25 MW
    - Time: 15.8 hr (57,070 s)
    - Control rod position: 453–458 mm



[Layout of the SiC-NTD irradiation device with the installed SiC wafer (a), and a photograph of the SiC NTD test irradiation (b)]

Results and Discussions

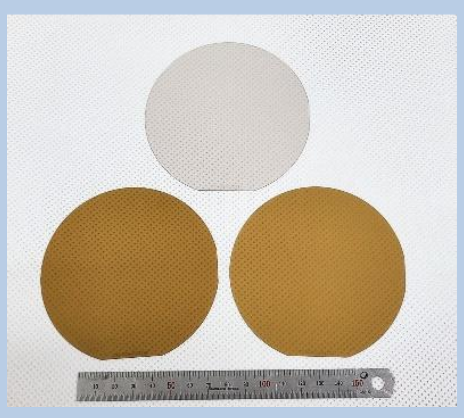
- **Safety evaluation of experiments using HANARO**

Item	Design requirement	Item	Design requirement
Reactivity	Minimize impact on core and irradiation holes of the reactor	Installation place	Select a location that does not affect the core
Heating and cooling	Minimize heat generation, cooling when overheating, and remove of residual heat	Vibration	Must withstand fluid-induced vibration (FIV) and not cause its own vibration
Activation	Using materials with short half-life	Interference	Eliminate interference with other installations, cables, tubes, etc.
Buoyancy	Prohibit self-buoyant structures, Multiple anti-flotation measures	Air release	Limitation of air release
Lifespan	Provide an expiration date	Remote dealing	Gain the ability to remotely install and uninstall
Testability	Designed for periodic testing to ensure durability	Welding inspection	Weld integrity testing (leakage, non-destructive testing)
Defense in depth	Secure a second layer of protection	Explosion	Use non-explosive structures and materials
Corrosion	Use corrosion-resistant materials	Spare	Securing spares of devices (parts) essential for reactor operation and experiments
Water quality	Use materials that don't affect water quality	Documents	Documents and specifications for design, fabrication, procurement, installation, and performance testing
Quality class	Safety-related components must be at least T-class		

- **Reactivity of SiC-NTD device**
  - Calculation of the effective multiplication factor (K_{eff}) and reactivity of the core when a SiC-NTD rig containing a SiC single crystal ingot is loaded into the NTD2 vertical hole

Before loading the rig	Loaded SiC-NTD rig		
$K_{eff} \pm \sigma$	$K_{eff} \pm \sigma$	$\Delta k \pm \sigma$ (pcm)	$\Delta k \pm \sigma$ (mk)
1.01604±0.00002	1.01591±0.00002	-13 ± 3	-0.13 ± 0.03

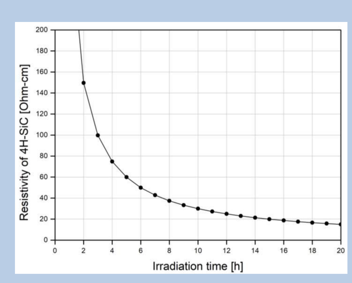
- **Post-Irradiation Analysis**
  - Visual Inspection
    - Color change (light gray → yellow-brown) indicates successful P doping
    - Dose rate dropped to background after 1 week cooling
  - Neutron Flux Measurement
    - Zr foil activation and gamma-ray spectroscopy
    - Flux at wafer locations:
      - Bottom: 2.525E13 n/cm²·s
      - Top: 2.623E13 n/cm²·s



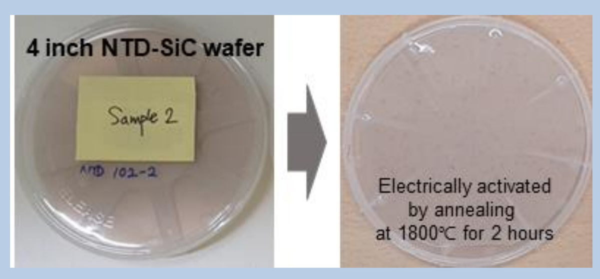
[4-inch HPSI SiC wafers before and after NTD at HANARO]

[Measurement of gamma-ray spectrum from irradiated Zr foil]

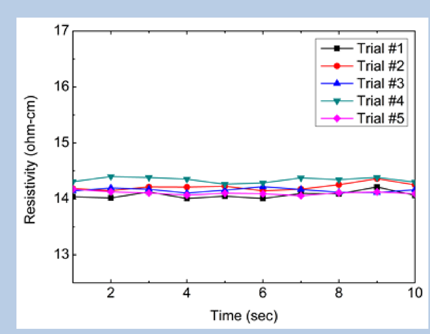
- **Electrical Property Evaluation**
  - Post-annealing: 1800 ℃ for 2 h
  - Eddy current resistivity measurement:
    - Mean resistivity: 14.2 Ω·cm
    - Target: 15.1 Ω·cm
    - Radial variation: ±5.86%
  - Indicates compliance with doping uniformity targets



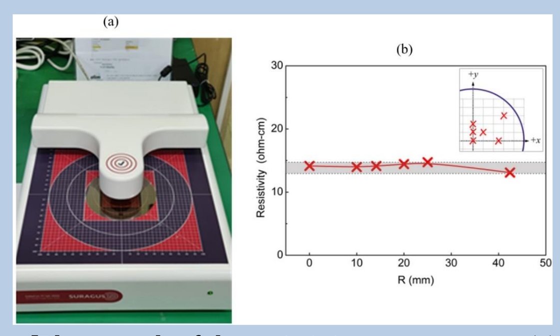
[Resistivity of the 4H-SiC as a function of the neutron irradiation time]



[SiC wafers before and after thermal annealing process]



[Repeated resistivity measurements at the center of the NTD SiC wafer]



[Photograph of the resistivity measurement (a), and the measured radial resistivity distribution (b)]

Conclusions

The SiC-NTD device was designed for SiC single crystal irradiation in the NTD2 hole of HANARO, which is optimum in achieving a flat axial and radial distribution of resistivity in the irradiated SiC. Although this experiment was limited in scale, the results clearly demonstrate the feasibility of using a research reactor for uniform and controllable n-type doping of SiC via NTD. Ongoing and future work will focus on expanding the sample set, refining the process parameters, and evaluating reproducibility and scalability for commercial high-voltage power semiconductor applications.