Fundamental Study for Precise Control of Threshold Voltage in SiC MOSFETs

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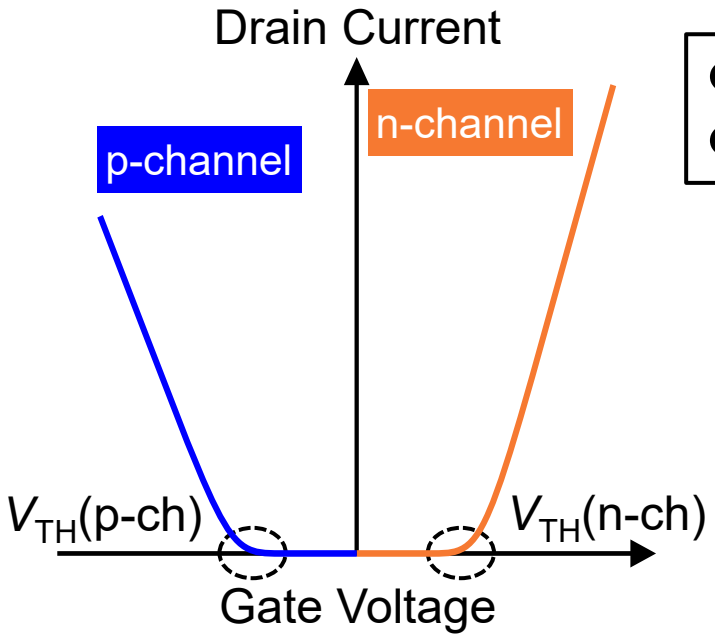
Outline

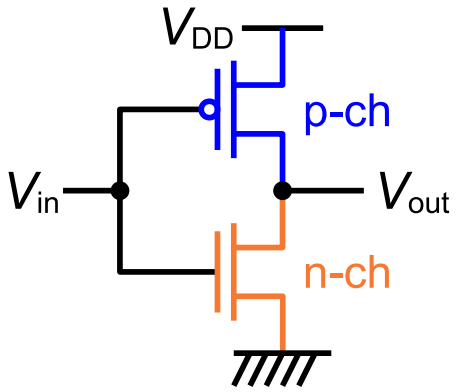
Importance of Threshold Voltage

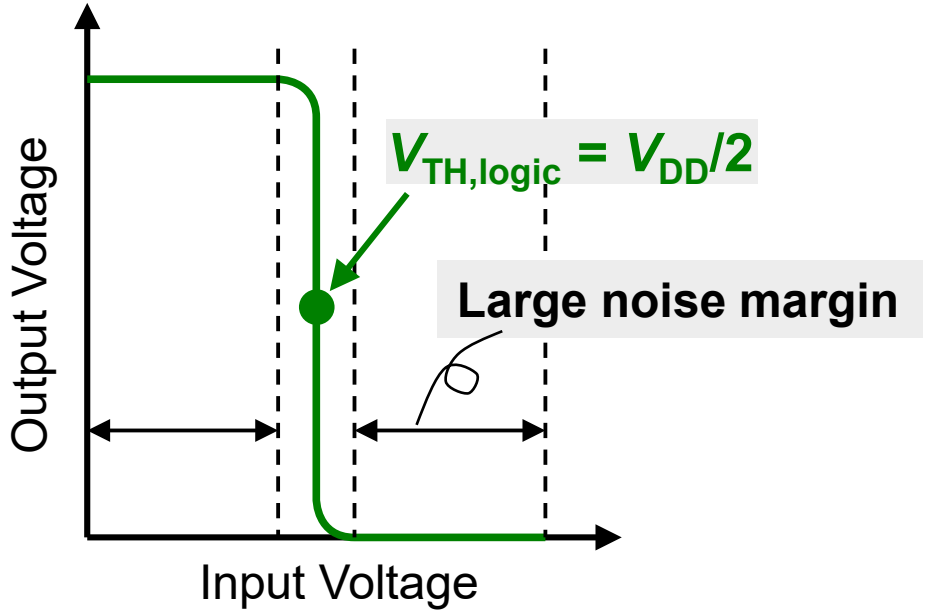
Required device characteristics

- Power MOSFETs: normally off
- CMOS devices: normally off & V_{TH} balancing between **NMOS** and **PMOS**



- V_{TH}(p-ch) = V_{TH}(n-ch)
- I_D(p-ch) = I_D(n-ch)





Threshold voltage control is essential for both applications

Threshold Voltage Control in MOSFETs

$$V_{\mathrm{TH}} = \boldsymbol{\phi_{\mathrm{Gate}}} - \phi_{\mathrm{S}} + 2\psi_{\mathrm{B}} + \frac{\sqrt{4\varepsilon_{\mathrm{S}} q \boldsymbol{N_{\mathrm{Body}}} \psi_{\mathrm{B}}}}{\boldsymbol{C_{\mathrm{ox}}}}$$

Gate work function ($\boldsymbol{\phi_{\mathrm{Gate}}}$)

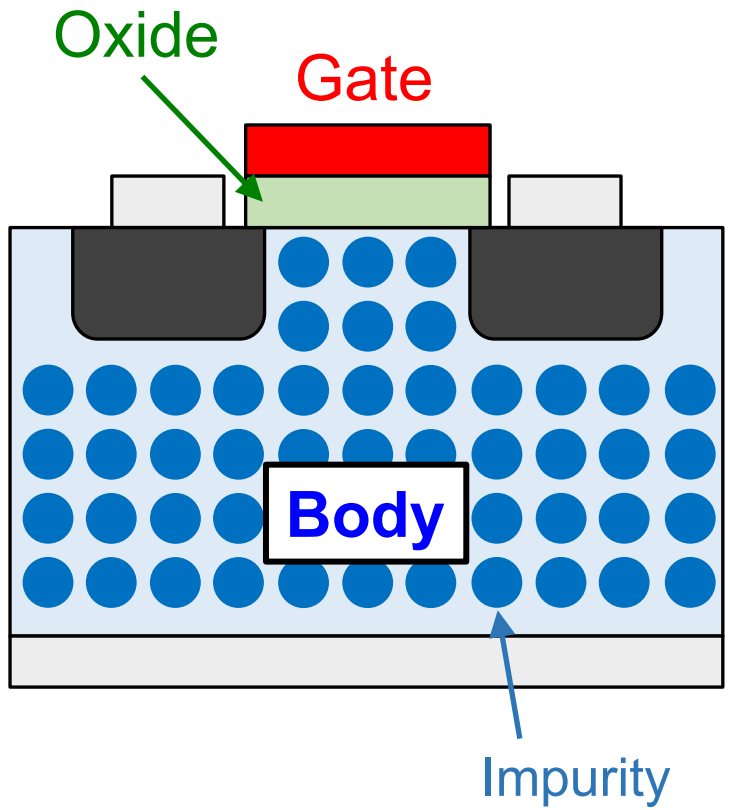
Typical ϕ_{Gate} : 4.1 eV (n^+ poly-Si) ~ 5.2 eV (p^+ poly-Si)
→ Controllable V_{TH} range: **narrow**

Oxide capacitance ($\boldsymbol{C_{\mathrm{ox}}}$)

Gate oxide of NMOS and PMOS is formed at the same time
→ Individual V_{TH} control: **difficult**

Body doping concentration ($\boldsymbol{N_{\mathrm{Body}}}$)

- **Individual control**
- **Wide-range control**
- **Precise control** by ion implantation



V_{TH} vs. N_{Body} in SiC MOSFETs

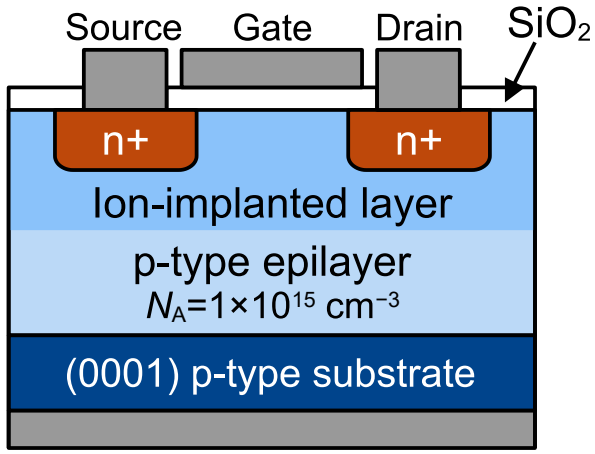
Outline

Device Fabrication

Process flow of MOSFET fabrication

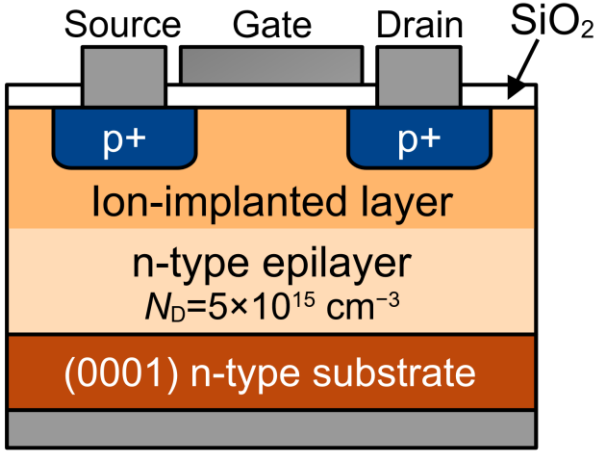
- Ion implantation to change N_{Body}
  - n-channel: Al, 1×10^{15}–4×10^{17} cm^{-3}
  - p-channel: N, 5×10^{15}–2×10^{18} cm^{-3}
- Ion implantation for source/drain
- Post-implantation annealing
- Oxidation to form SiO_2 (1300℃)
  → 30 nm-thick oxide
- Post-oxidation annealing
  (NO annealing, 1250℃)
- Electrode formation (Gate: Al)

n-channel MOSFET



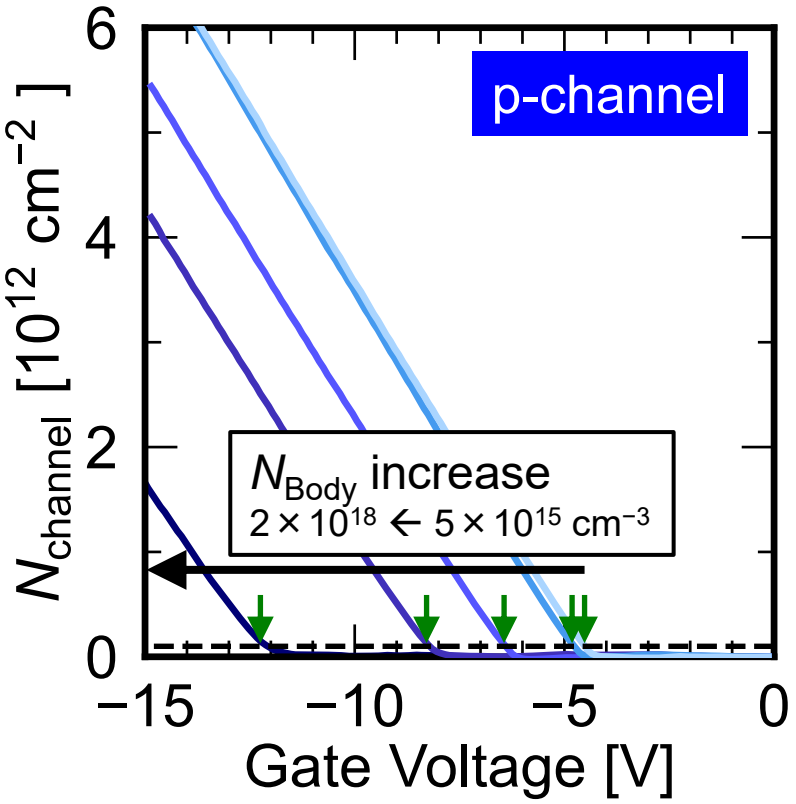
L = 100 μm
W = 50−170 μm

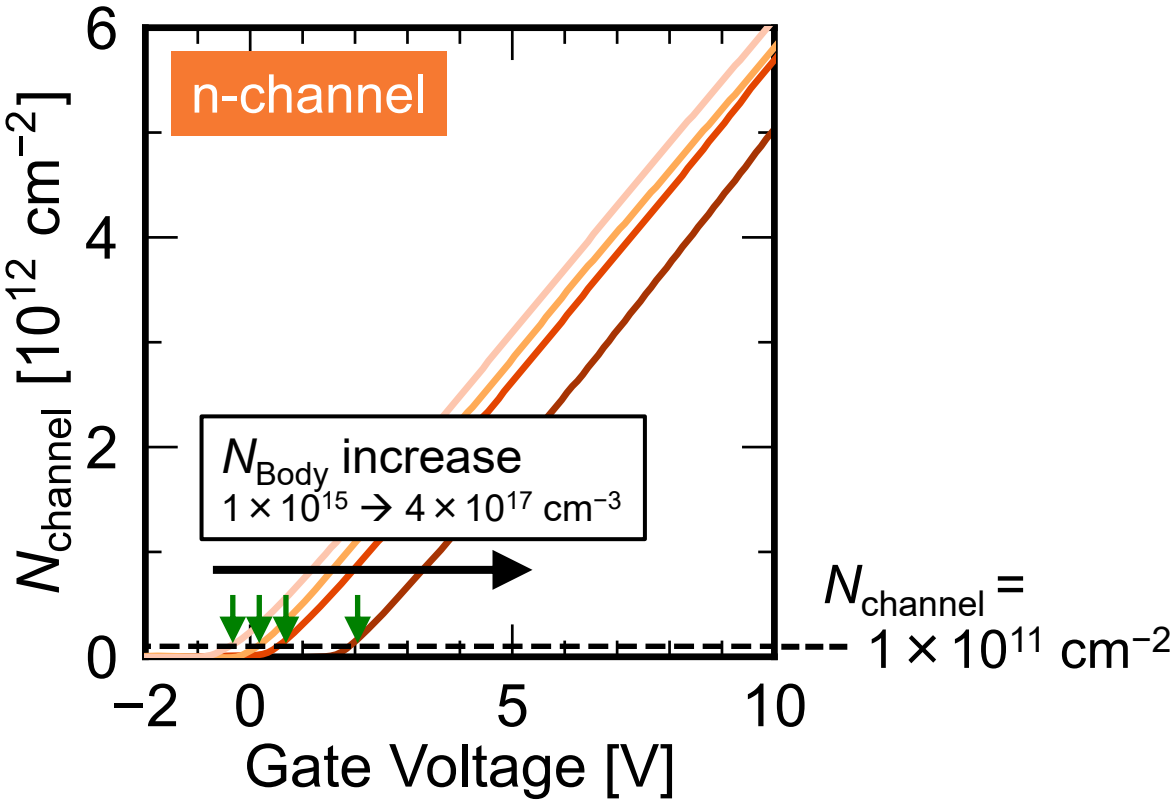
p-channel MOSFET



Extraction of Threshold Voltage (V_{TH})

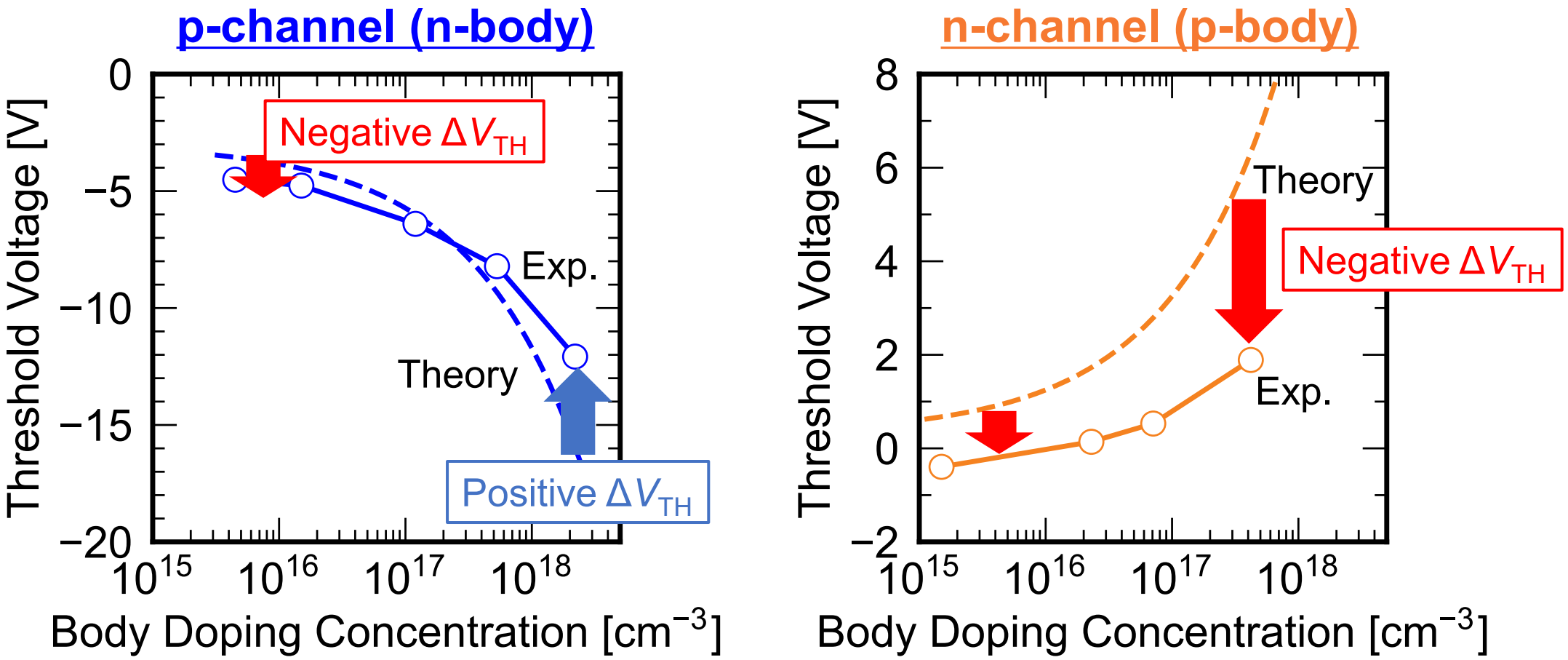
- Split C–V measurement → Hole/Electron density in the channel region ($N_{channel}$)
- V_{TH} is defined as the gate voltage at $N_{channel}$=1 × 10^{11} cm^{-2} (↓)





Increase in body doping concentration (N_{Body})
→ p-channel: negative V_{TH} shift, n-channel: positive V_{TH} shift

Threshold Voltage vs. Body Doping Concentration

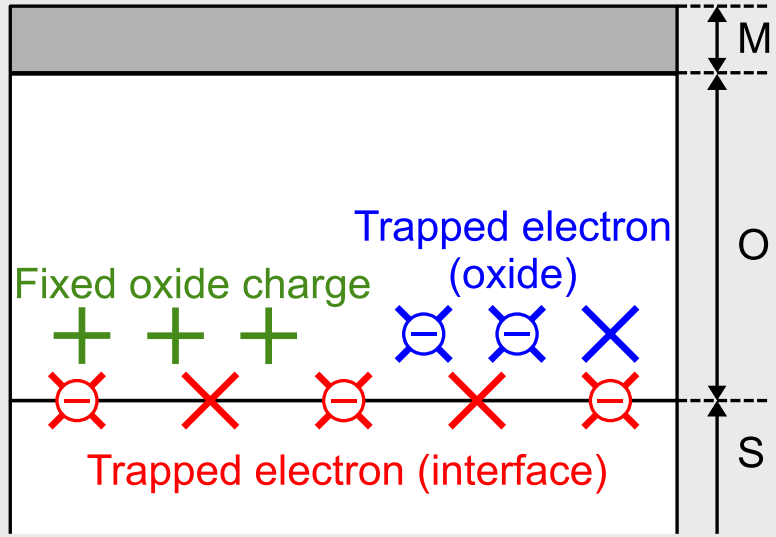


- Low N_{Body} region : Small negative ΔV_{TH} in both p-channel and n-channel
- High N_{Body} region: Positive ΔV_{TH} in p-channel & Negative ΔV_{TH} in n-channel

Cause for V_{TH} Difference (Experimental vs. Theory)

Non-ideal charges in MOS structure

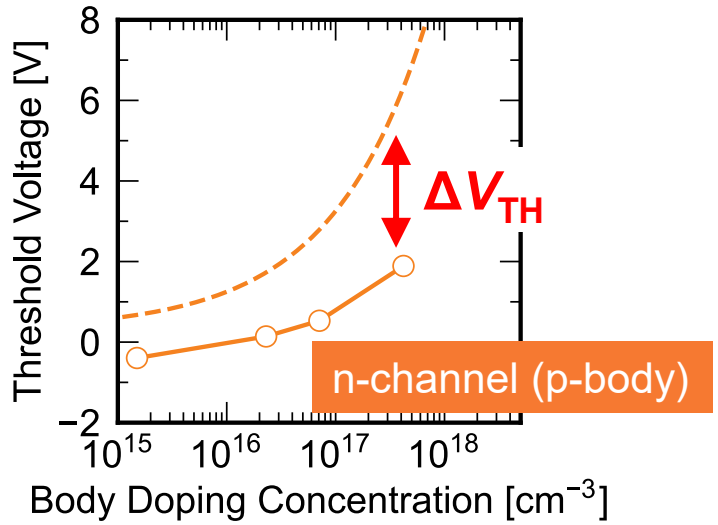
- **Fixed charges** (known in Si MOS) [1,2]
  Independent of gate voltage & temperature
- **Trapped electrons/holes**
  Depending on gate voltage & temperature



"Trapped" + "Fixed" = Effective fixed charges (Q_{eff})
…Extracted by threshold voltage shift (ΔV_{TH})

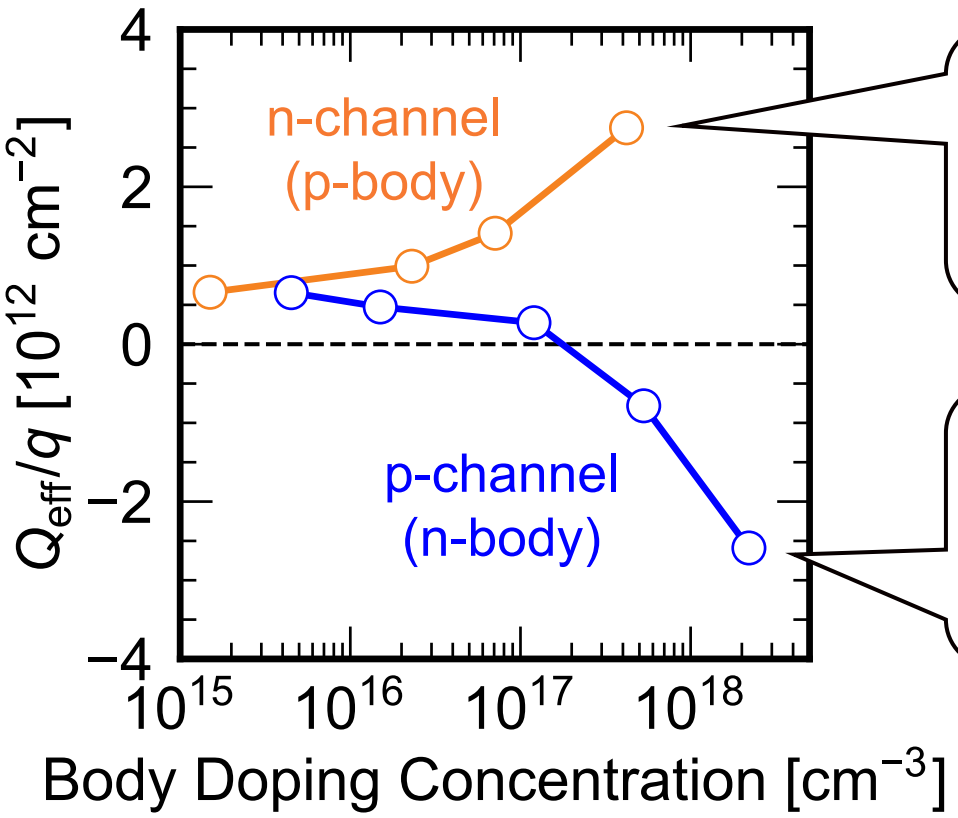
$$Q_{eff} = C_{ox}\Delta V_{TH} = C_{ox}(V_{TH,theory} - V_{TH,exp})$$

C_{ox} : Oxide capacitance
$V_{TH,theory}$: Theoretical threshold voltage
$V_{TH,exp}$: Experimental threshold voltage



[1] B. E. Deal *et al., J. Electrochem. Soc.* **114**, 266 (1967). [2] A. S. Grove *et al., Solid-State Electron.* **8**, 145 (1965).

Effective Fixed Charges vs. Body Doping Concentration



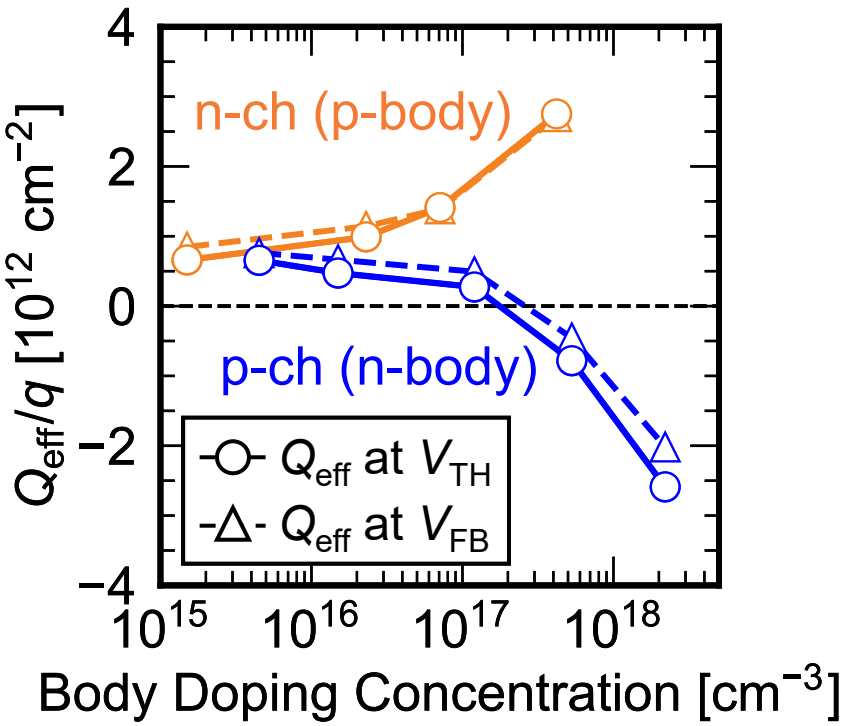
n-channel (p-body)
Increase in acceptor density
→ **Positive Q_{eff}** increases

p-channel (n-body)
Increase in donor density
→ **Negative Q_{eff}** increases

Q_{eff} = Trapped electrons/holes + Fixed charges
…Which is dominant?

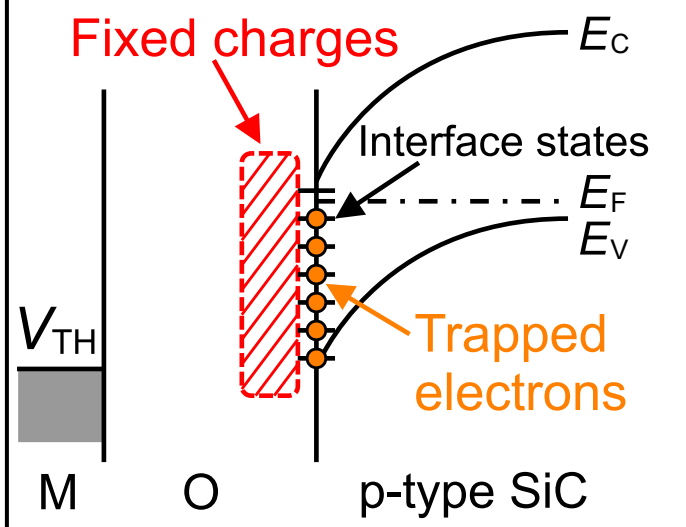
Gate Voltage Dependence of Q_{eff}

Q_{eff} at V_{TH} and V_{FB}



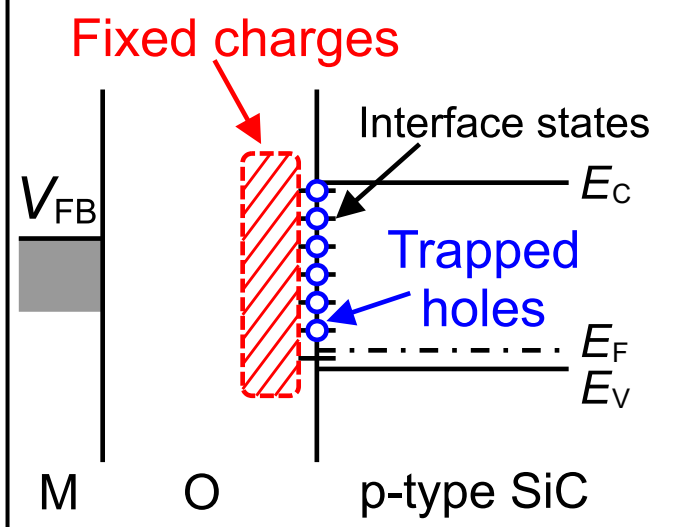
Band diagram of MOS structure

Threshold voltage (V_{TH})



$Q_{eff}(V_{TH}) = Q_{fix} + Q_{trap}(-)$

Flatband voltage (V_{FB})



$Q_{eff}(V_{FB}) \simeq Q_{fix} + Q_{trap}(+)$

1. $Q_{eff}(V_{TH}) \simeq Q_{eff}(V_{FB})$ → **Q_{fix} is dominant**
2. n-channel (p-body): Positive Q_{fix} increases
   p-channel (n-body): Negative Q_{fix} increases

} in high N_{Body}

cf) Si MOSFET: Q_{fix} is constant

Outline

1. Background

2. Body doping dependence of threshold voltage

3. Insight into doping-dependent fixed charges

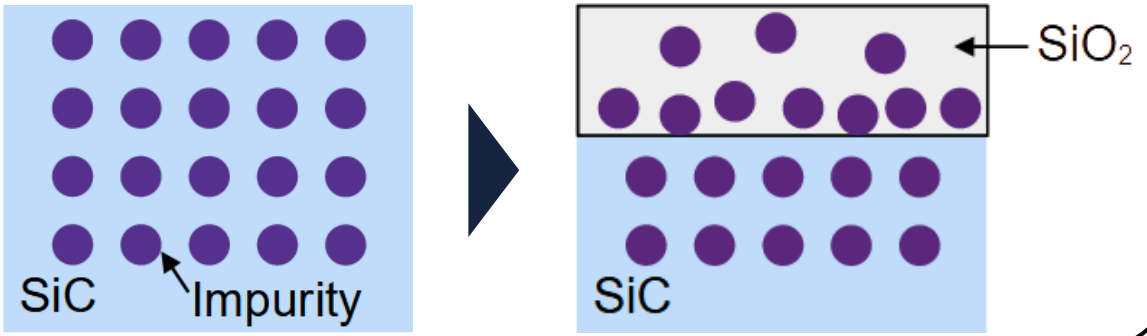
5. Summary

Possible Origin of N_{Body}-dependent Fixed Charges

Process flow of MOSFET fabrication

- Ion implantation to change N_{Body}
  …n-channel: Al, p-channel: N
- Ion implantation for source/drain
- Post-implantation annealing
- Oxidation to form SiO_2
  → 30 nm-thick oxide
- Post-oxidation annealing
  (NO annealing, 1250℃)
- Electrode formation

SiC is replaced by SiO_2 via oxidation
→Impurities incorporated inside SiO_2 create Q_{fix}?



Dopant Redistribution during Oxidation

Sample preparation

N-doped or Al-doped (0001) samples

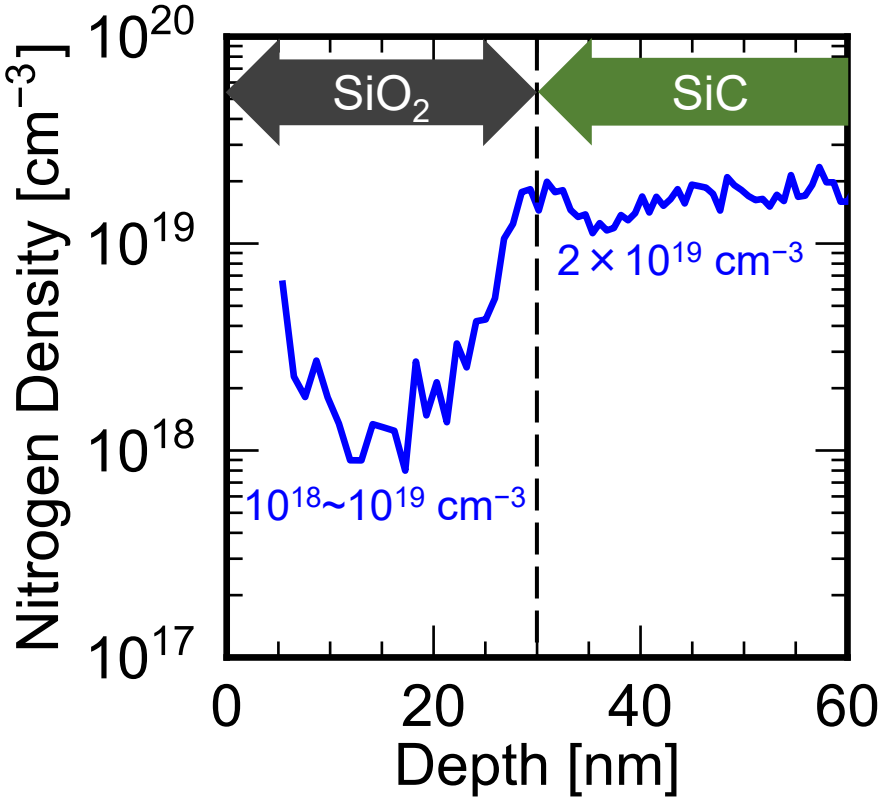
↓

Oxidation 1300℃, 20 min

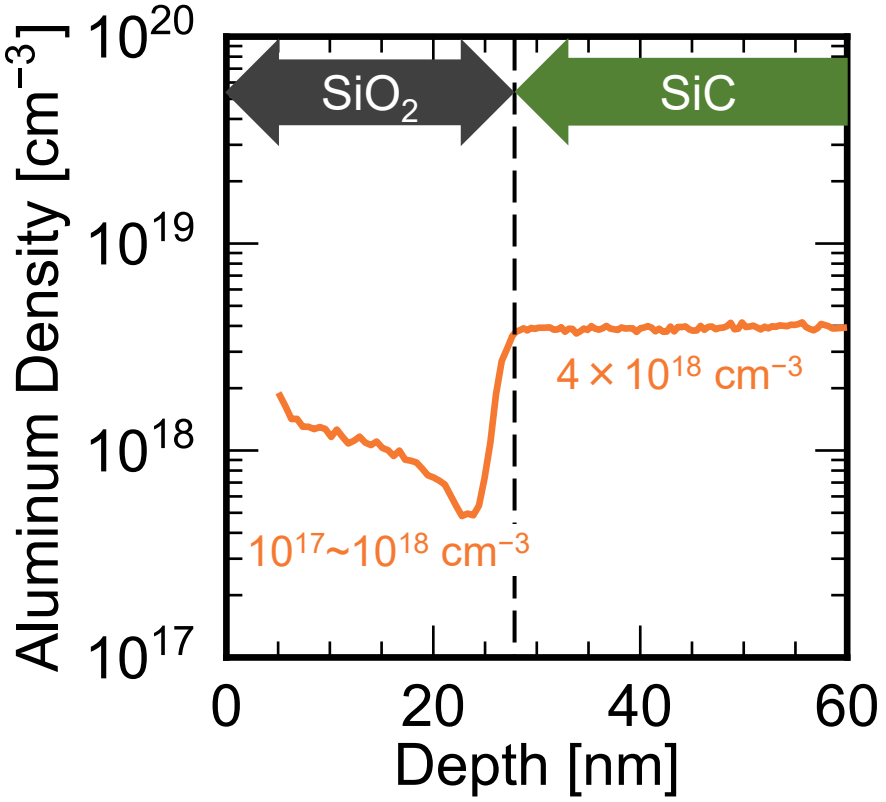
↓

SIMS

Nitrogen (n-body)



Aluminum (p-body)



Both N and Al atoms were incorporated inside SiO_2 by oxidation

Oxidation of SiC Causes N_{Body}-dependent Q_{fix}

Ox-NO **CVD-NO**

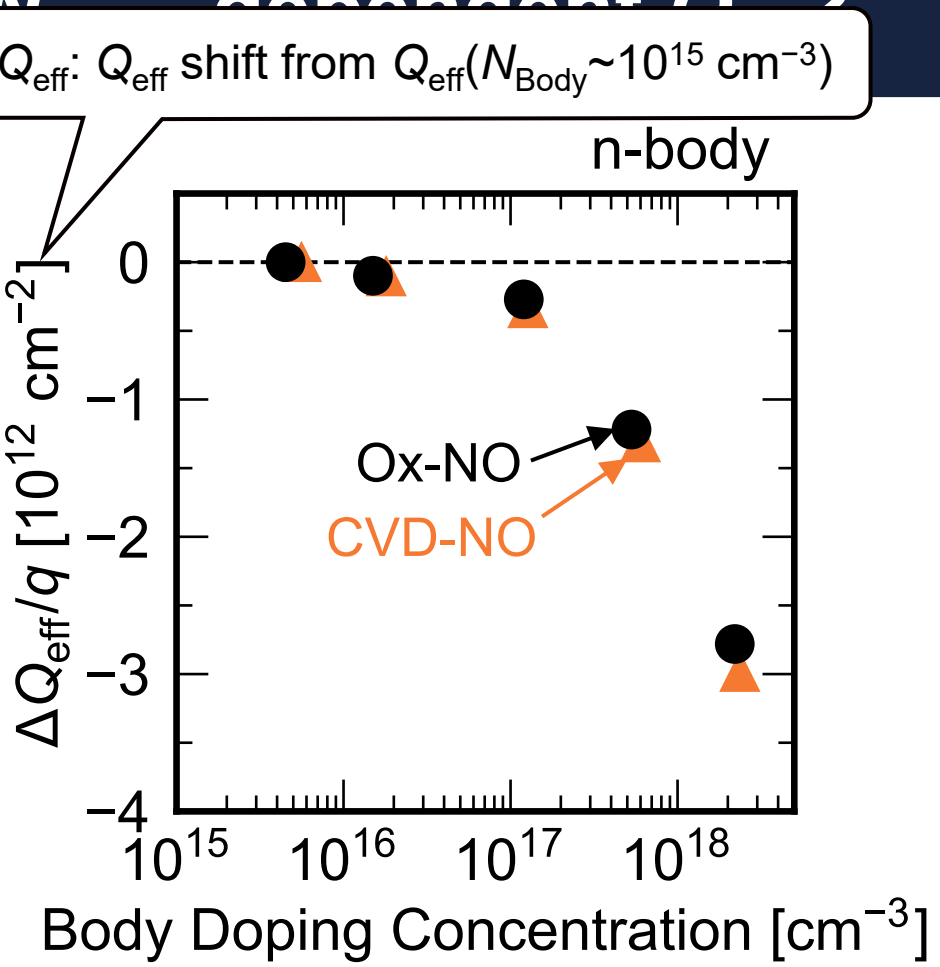
Epitaxial growth & Ion implantation

Post-implantation annealing

Oxidation
1300℃, 20 min

SiO_2 depositon
CVD, 400℃, 30 Pa

Post-oxidation annealing
NO, 1250℃, 70 min



ΔQ_{eff}(CVD-NO) ≃ ΔQ_{eff}(Ox-NO)
→ Oxidation itself does not cause N_{Body}-dependent Q_{fix}

Possible Origin of N_{Body}-Dependent Fixed Charges

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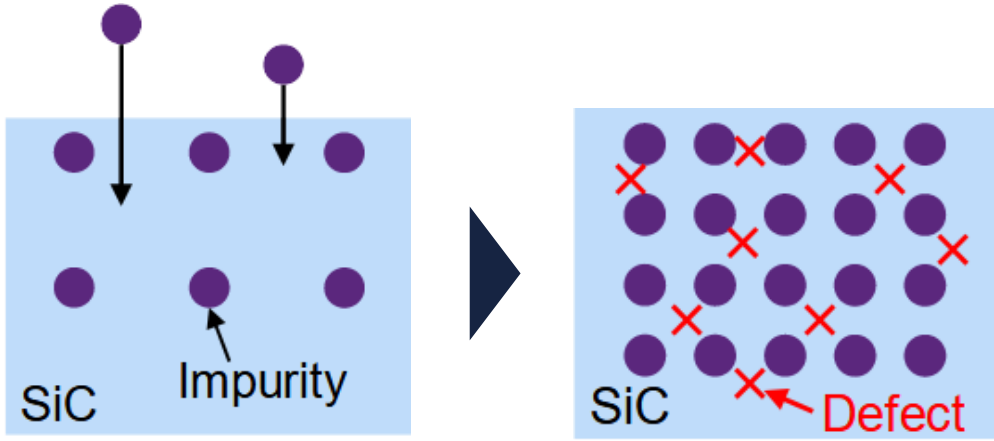
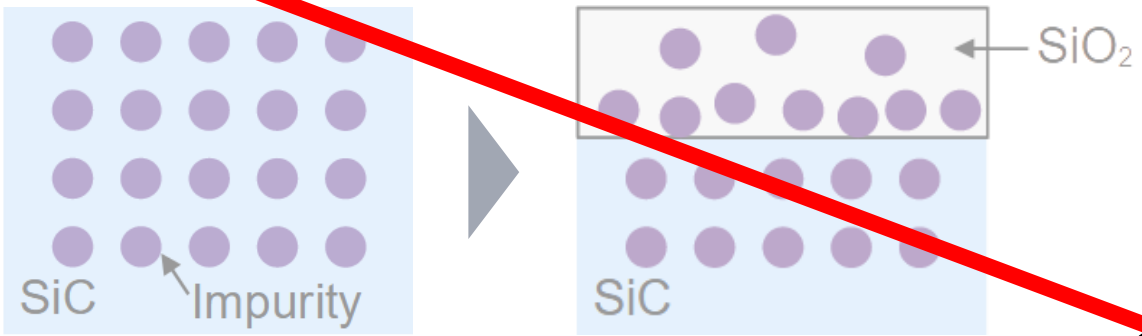
Ion implantation causes defects in SiC
→Generated defects create Q_{fix}?



~~SiC is replaced by SiO_2 via oxidation~~
~~→Impurities incorporated inside SiO_2 create Q_{fix}?~~



Ion Implantation Causes N_{Body}-dependent Q_{fix}?

Impl-CVD-NO

Epitaxial growth
N_{Body}=10^{15} cm^{-3}

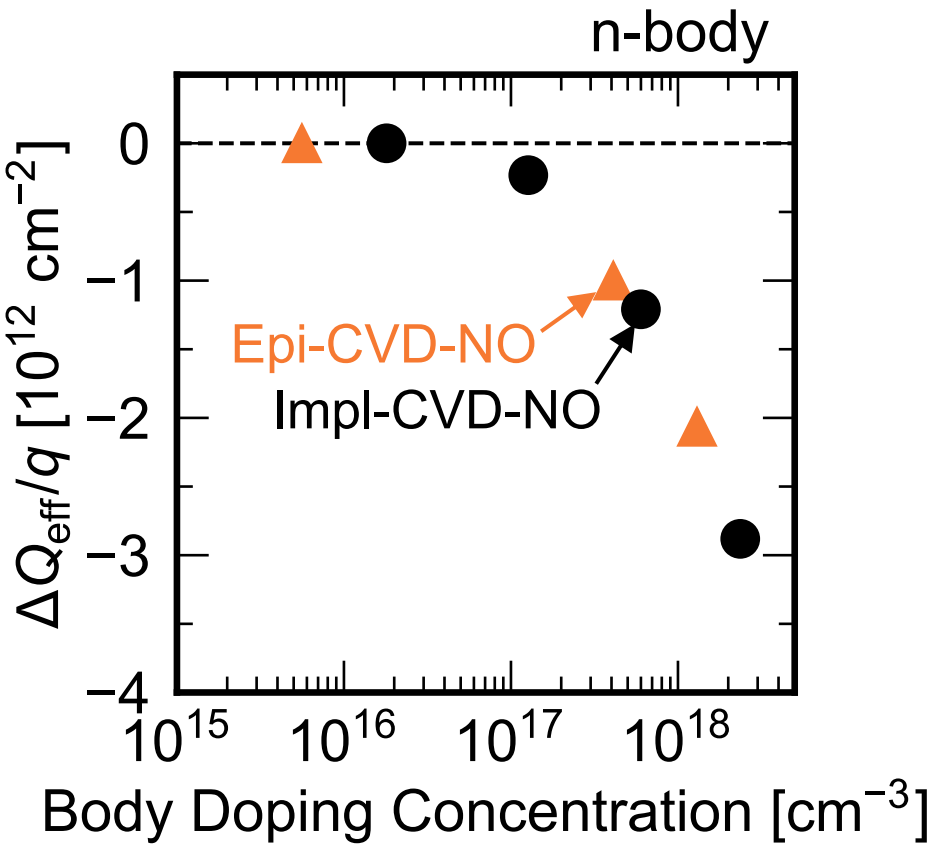
Ion implantation
& Post-implantation annealing
N_{Body}= 10^{16}~10^{18} cm^{-3}

Epi-CVD-NO

Epitaxial growth
N_{Body}=10^{15}~10^{18} cm^{-3}

SiO_2 formation (CVD)

Post-oxidation annealing
NO, 1250℃, 70 min



ΔQ_{eff}(Epi-CVD-NO) ≃ ΔQ_{eff}(Impl-CVD-NO)
→ Ion implantation does not cause N_{Body}-dependent Q_{fix}

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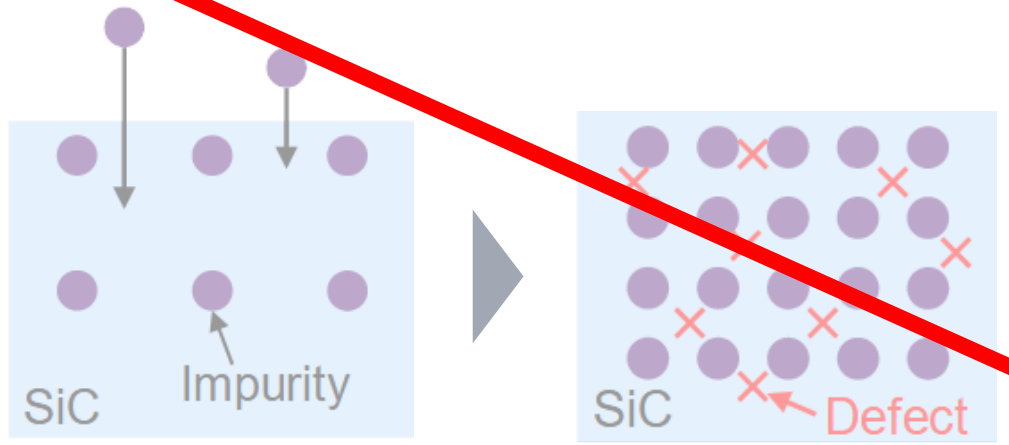

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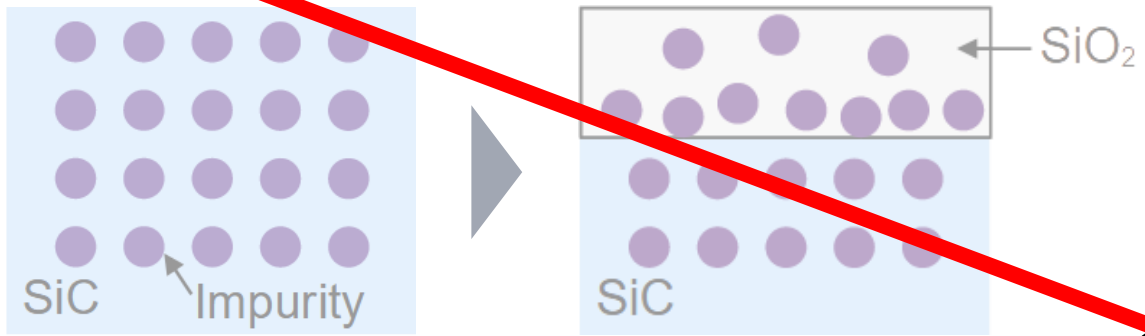
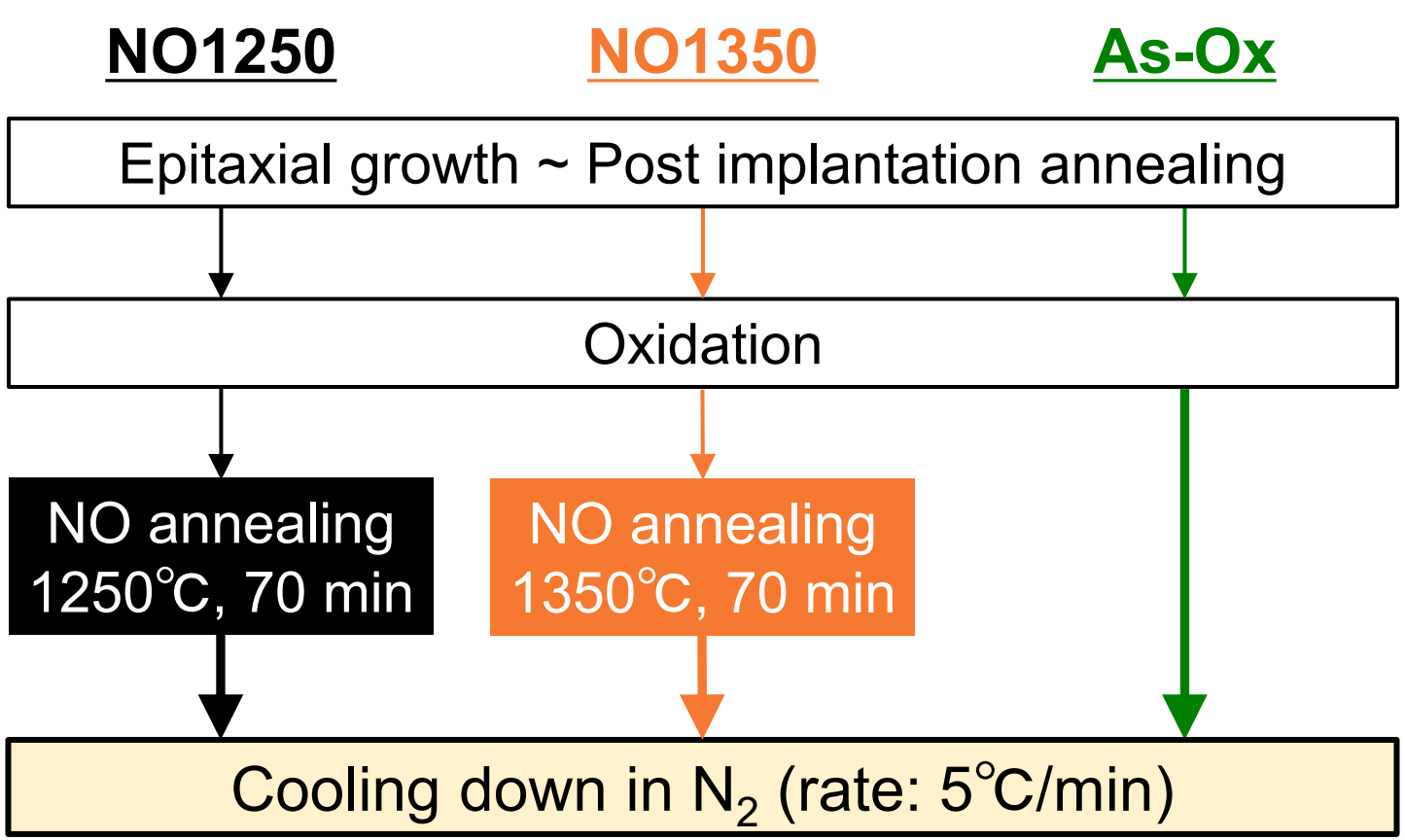
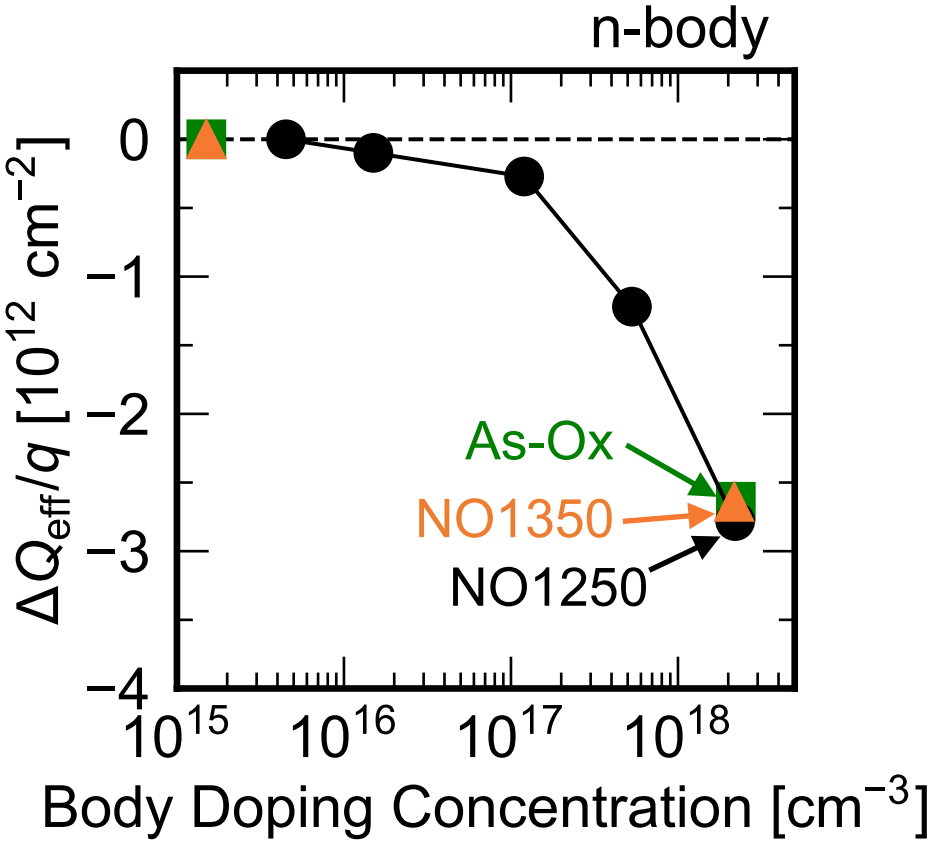


NO Annealing Causes N_{Body}-dependent Q_{fix}?





- ΔQ_{eff} is independent of NO annealing temperature
- Similar N_{Body}−ΔQ_{eff} relation in **As-Ox**

→ Post-oxidation annealing itself does not cause N_{Body}-dependent Q_{fix}

Influence of Cooling Rate on Q_{fix}

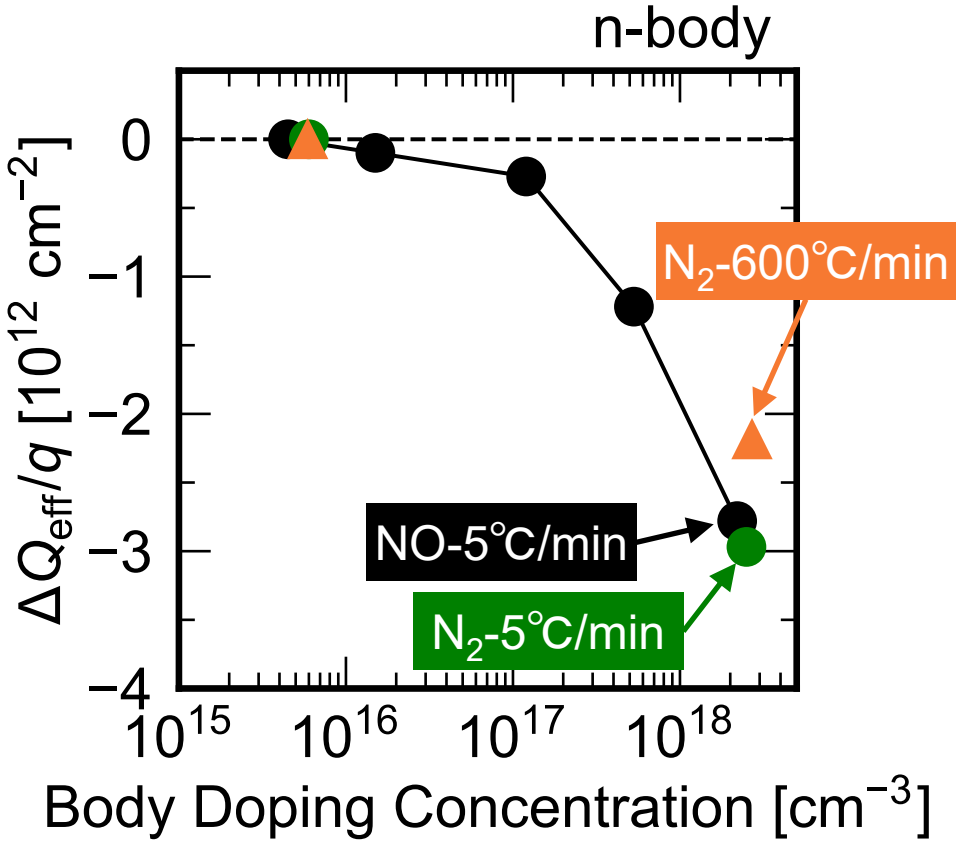
NO-5℃/min **N_2-600℃/min** **N_2-5℃/min**

Epitaxial growth ~ Post implantation annealing

Oxidation

NO annealing	N_2 annealing	N_2 annealing
1250℃, 70 min	1400℃, 45 min	1400℃, 45 min
*5℃/min cooling	*600℃/min cooling	*5℃/min cooling

*Cooling rate from annealing temperature to 800℃

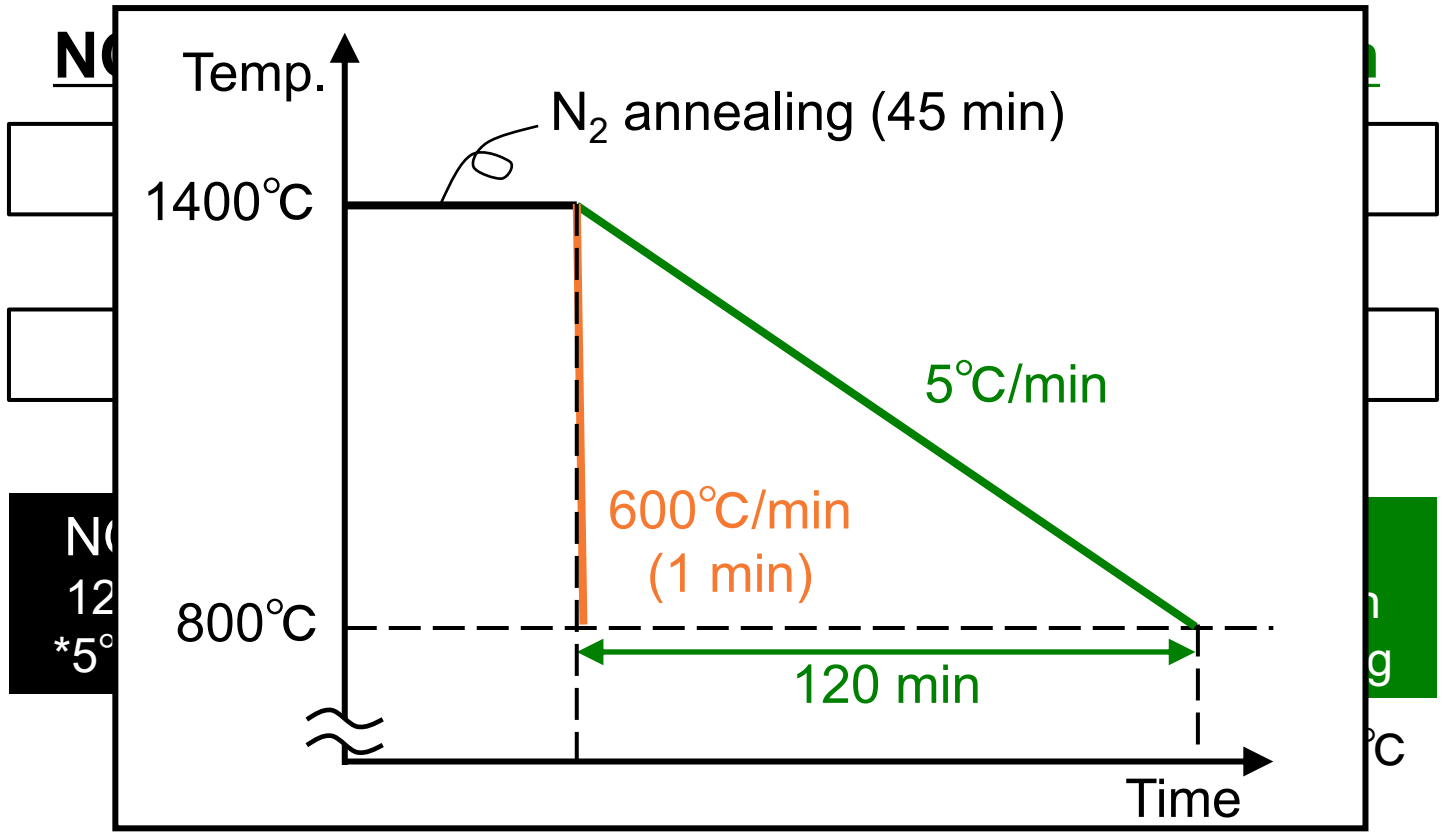


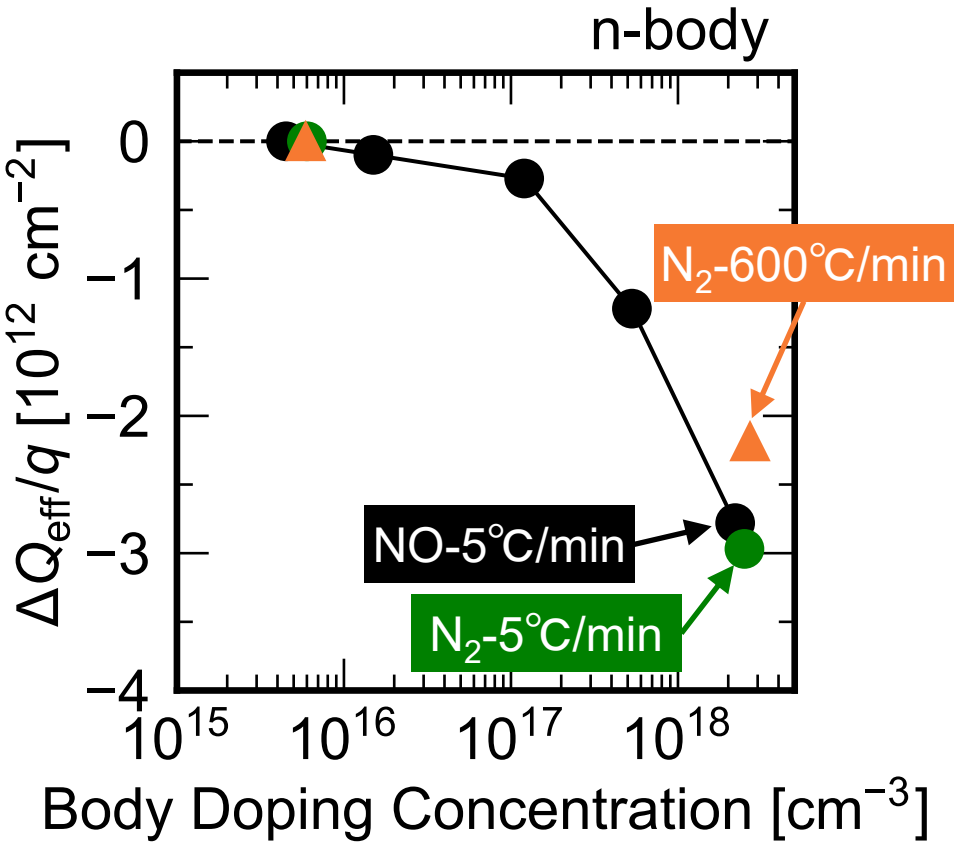
ΔQ_{eff}(600℃/min) < ΔQ_{eff}(5℃/min) @ $N_{Body}=2\times10^{18}$ cm^{-3}

- 600℃/min : Final interface formed at 1400℃
- 5℃/min : Final interface formed at a lower temperature (<1250℃)

→ Q_{fix} depends on body doping & final annealing temperature

Influence of Cooling Rate on Q_{fix}





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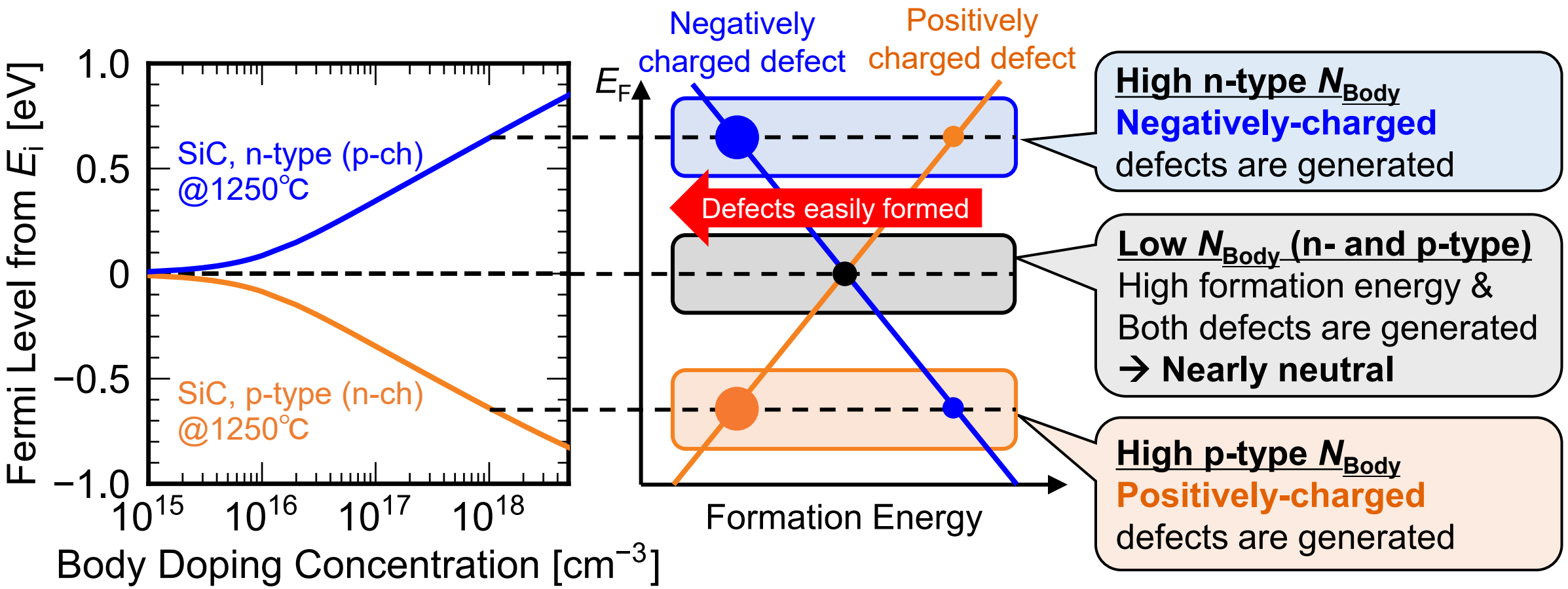
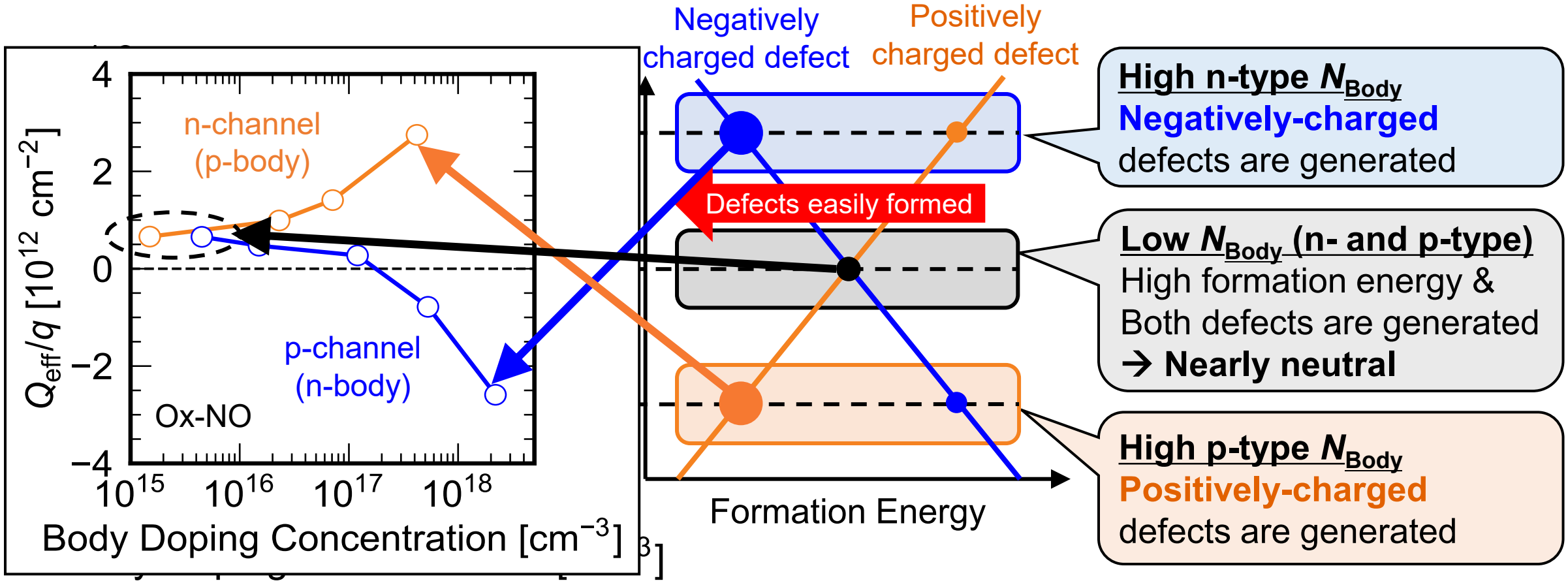
Proposed Model of Fixed Charge Generation



Proposed model based on Fermi level during high-temperature annealing

1. Low N_{Body} : Q_{fix}(p-body) ≈ Q_{fix}(n-body)
2. High N_{Body} : Positive Q_{fix} for p-body (n-ch) & Negative Q_{fix} for n-body (p-ch)

Proposed Model of Fixed Charge Generation



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2. High N_{Body} : Positive Q_{fix} for p-body (n-ch) & Negative Q_{fix} for n-body (p-ch)

Outline

Summary

Doping-dependent fixed charges

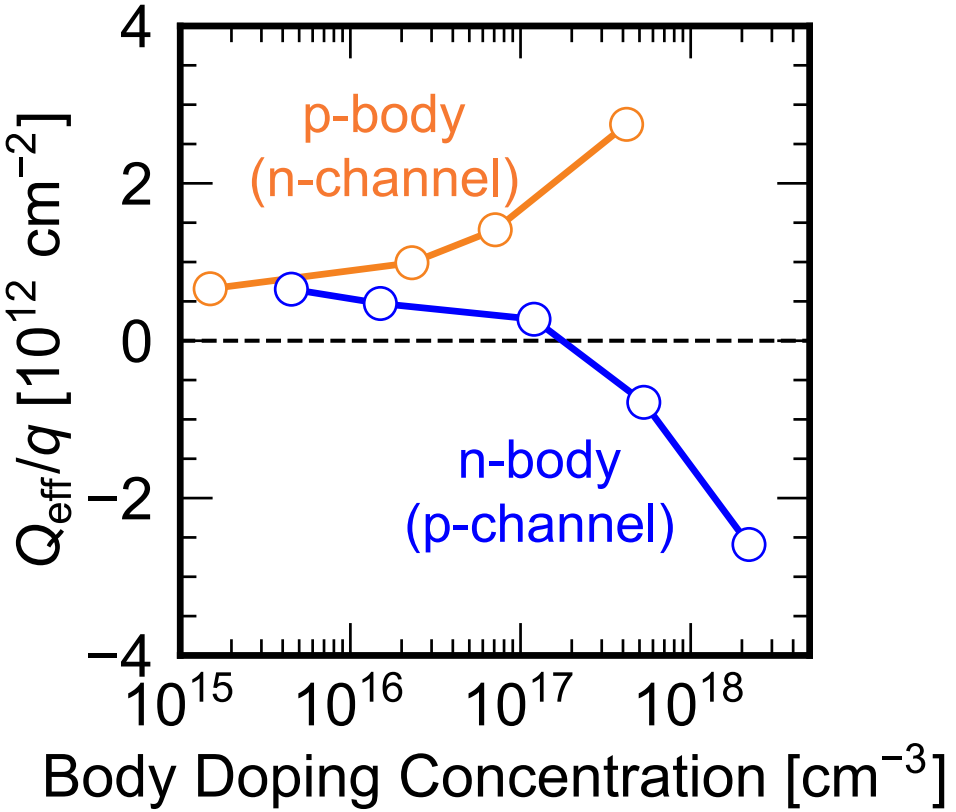
Lightly-doped bodies

Q_{fix}(p-body) ≈ Q_{fix}(n-body) ≈ 5×10^{11} cm^{-2}

Heavily-doped bodies

- p-body (n-channel): Positive Q_{fix}
- n-body (p-channel): Negative Q_{fix}

Due to defect formation during high-T annealing (E_F-related?)



Doping-dependent Q_{fix} should be considered in SiC MOSFETs