



2018 European Materials Research Society Spring Meeting

Modulation of two-dimensional hole gas density in an undoped Ge/GeSi heterostructure by Ion Implantation

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Outline

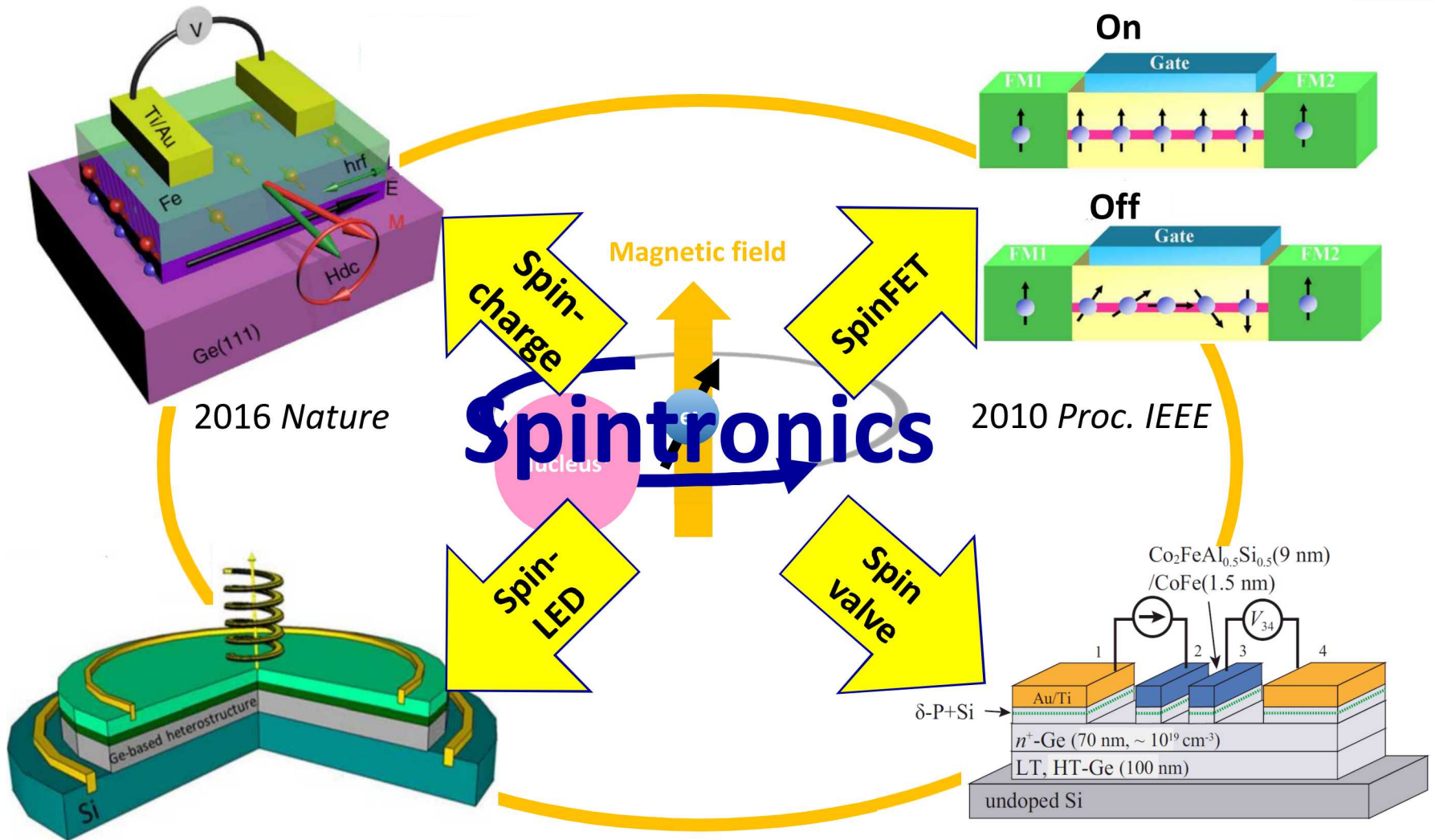
- Motivation
- Epitaxy and Material Analysis
- Device Fabrication
- Electrical Characteristics
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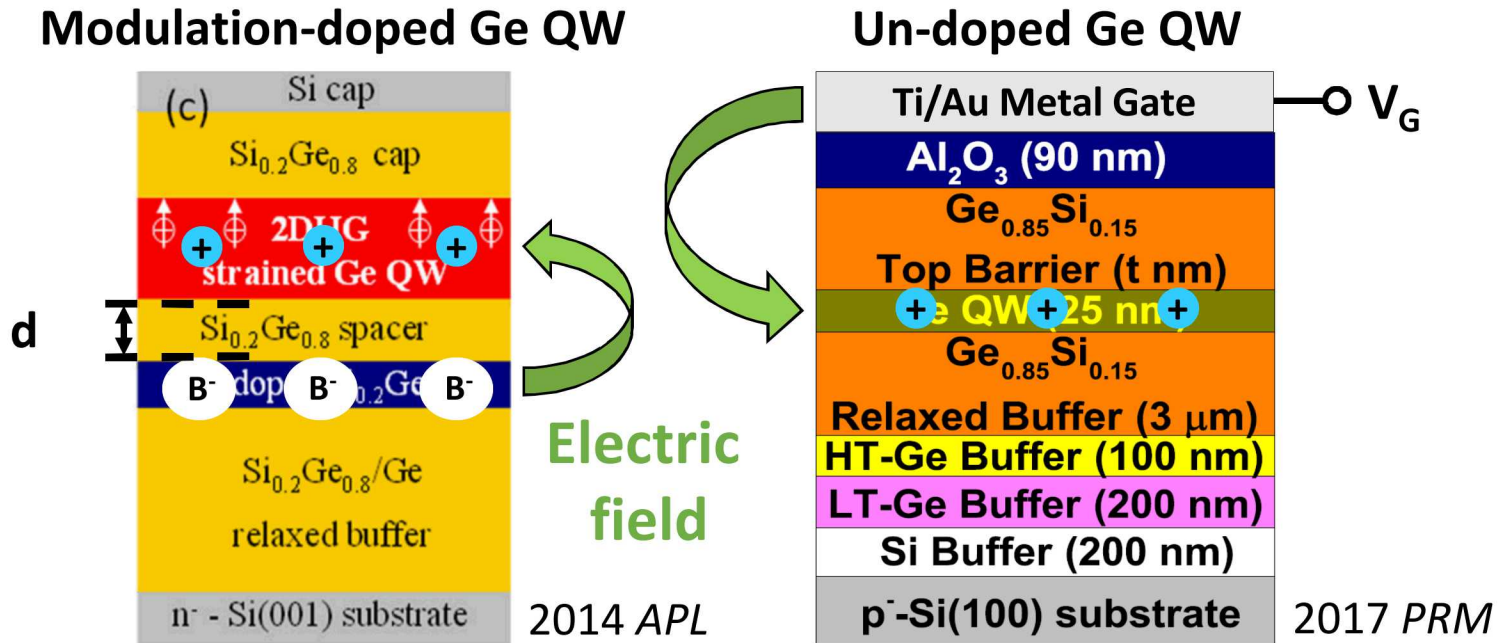
Motivation: Group-IV Spintronics



National
Taiwan
University



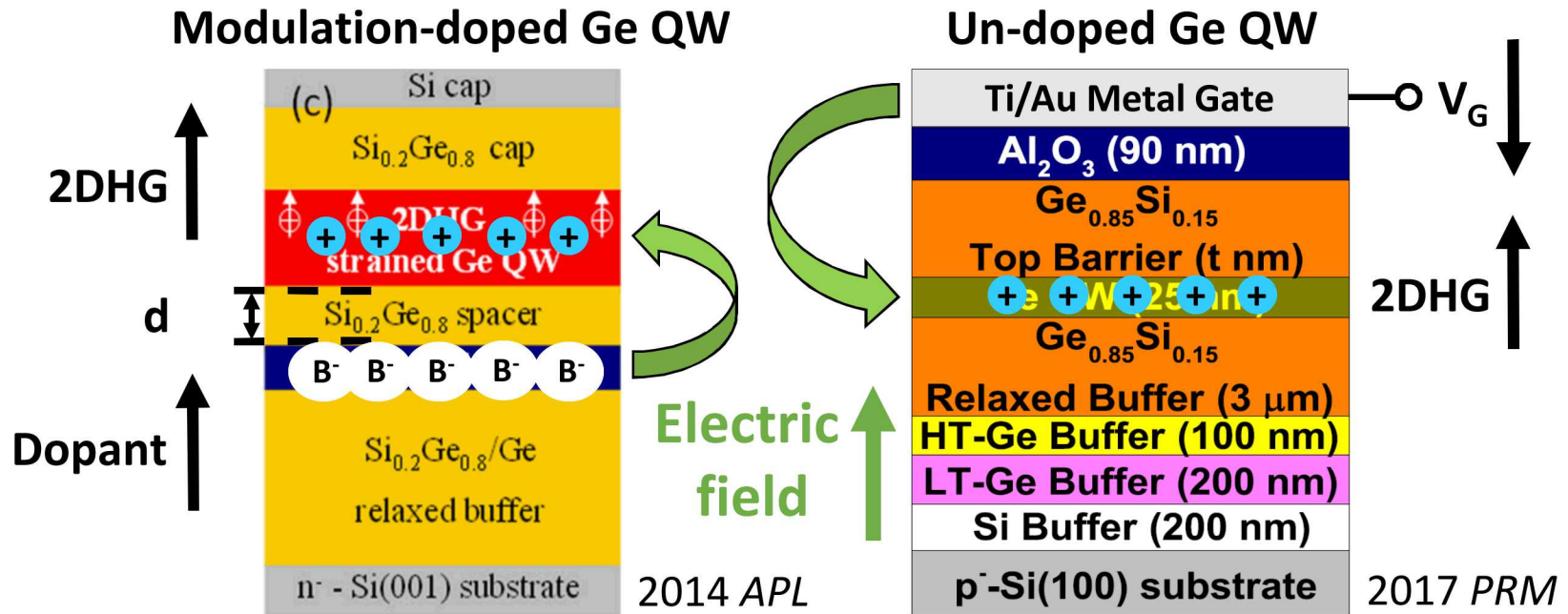
Motivation: Ge Two-Dimensional Hole Gas



Structures	Modulating 2DHG	Disadvantage
Mod.-doped	Dopant density and distance (Regrow new epitaxial layer)	Impurity scattering → mobility ↓
Un-doped	Gate voltage V_G	Poor oxide/GeSi interface



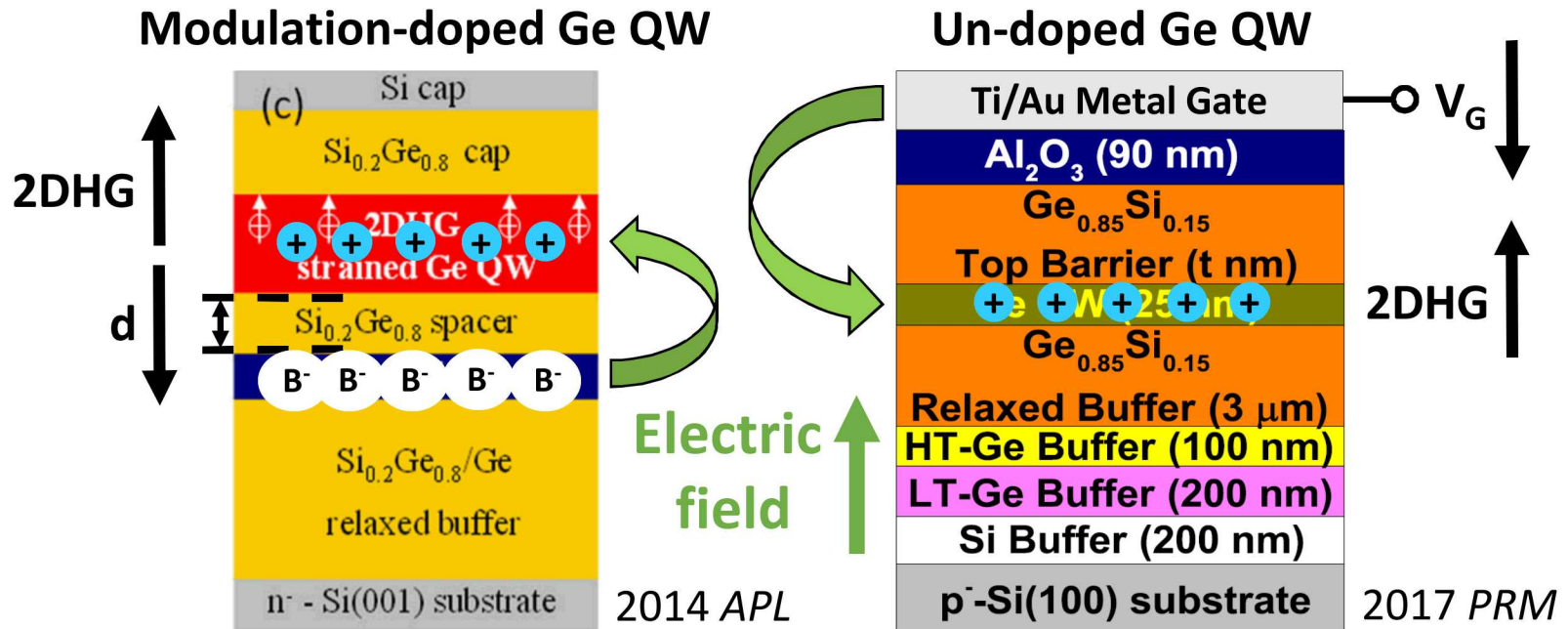
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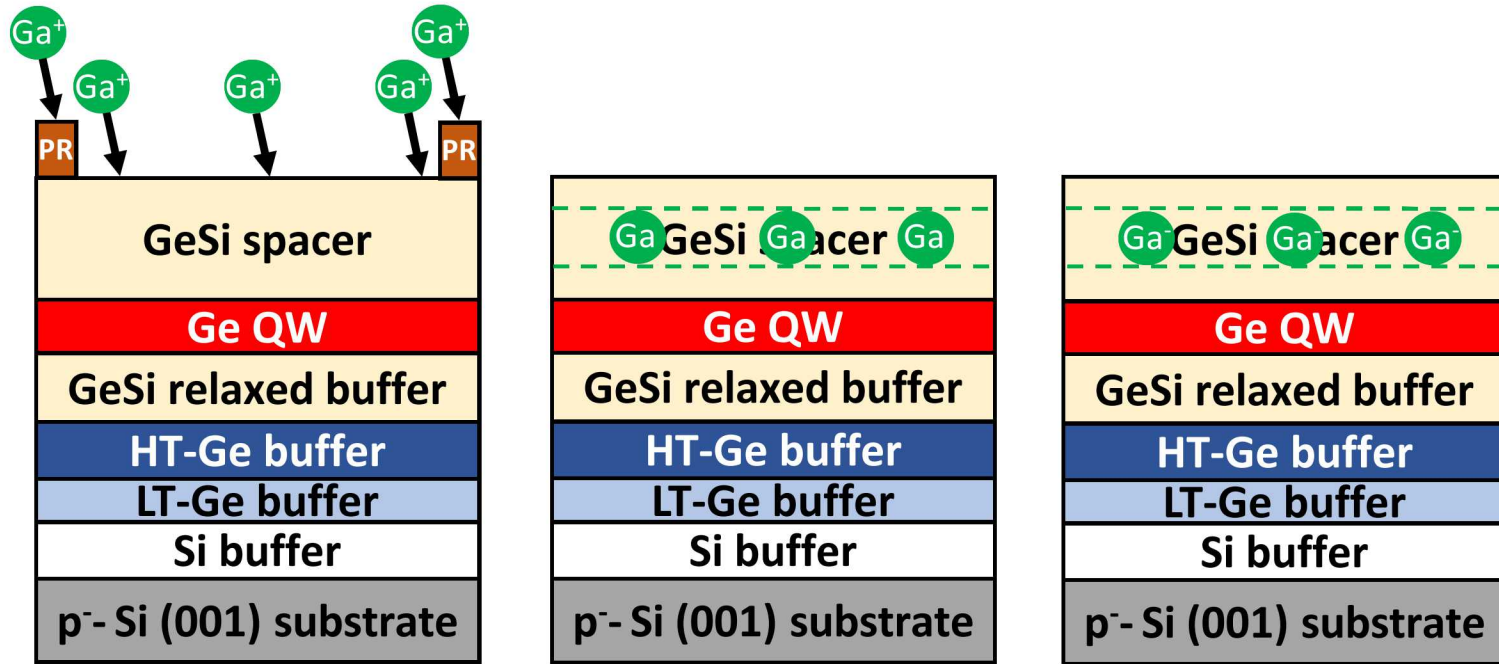


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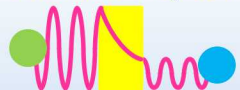


Motivation: Ge Two-Dimensional Hole Gas

ion implantation for modulation doping

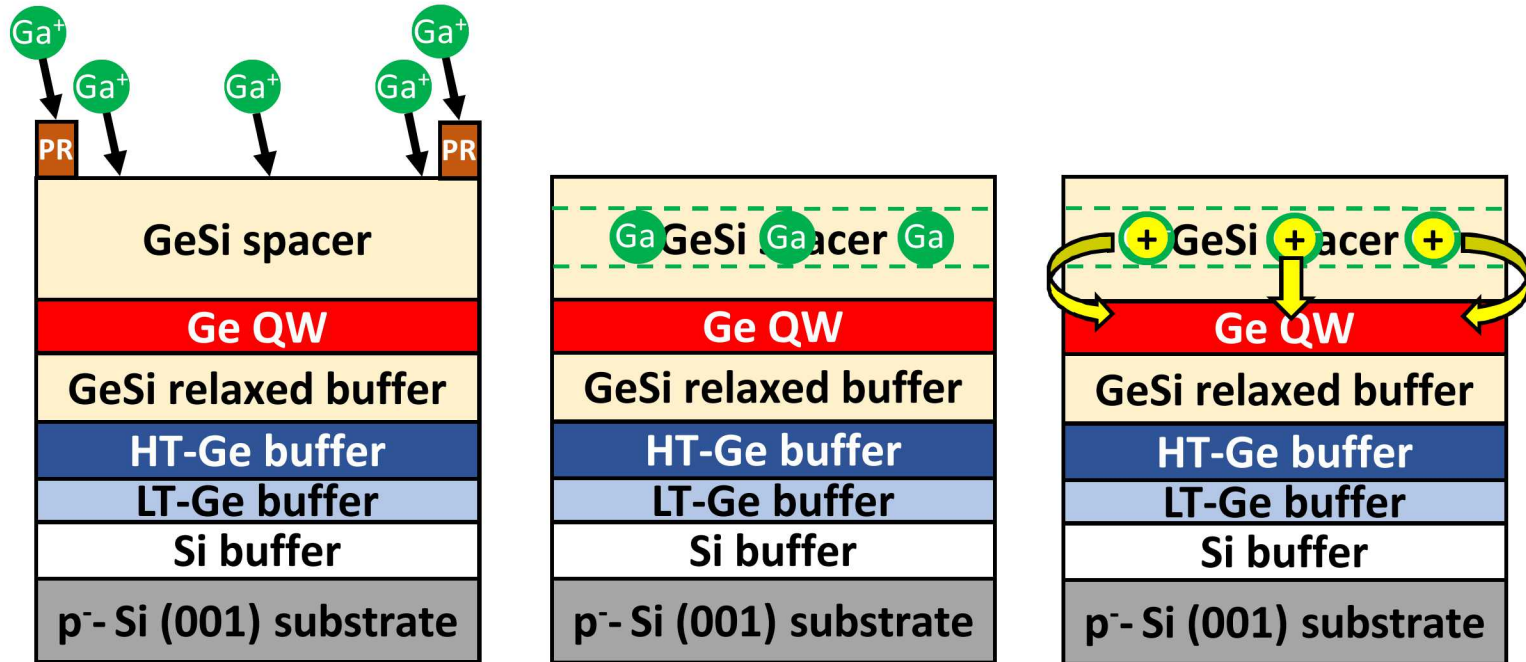


- Gallium ions were implanted into the GeSi top spacer.
- The 2DHG comes from the ex-situ doping layer.
- Modulate the carrier density by changing implantation fluence.

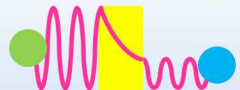


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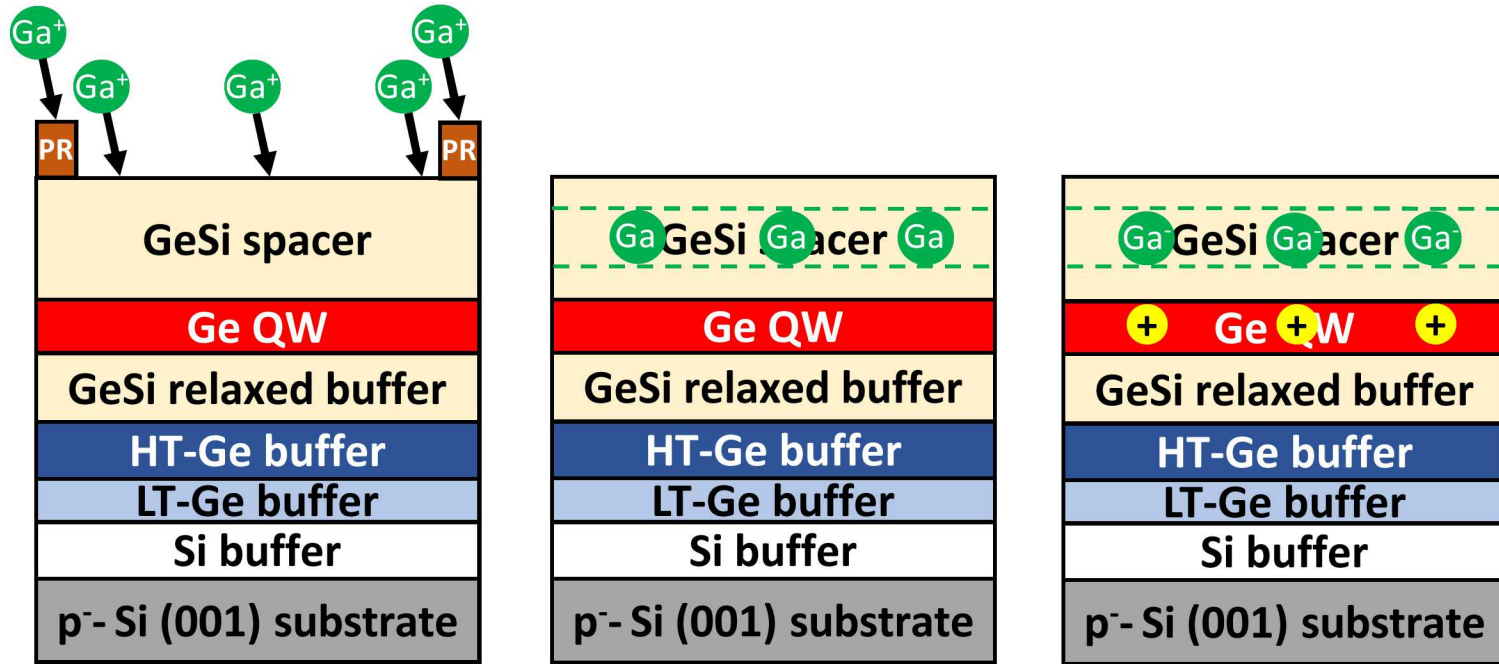


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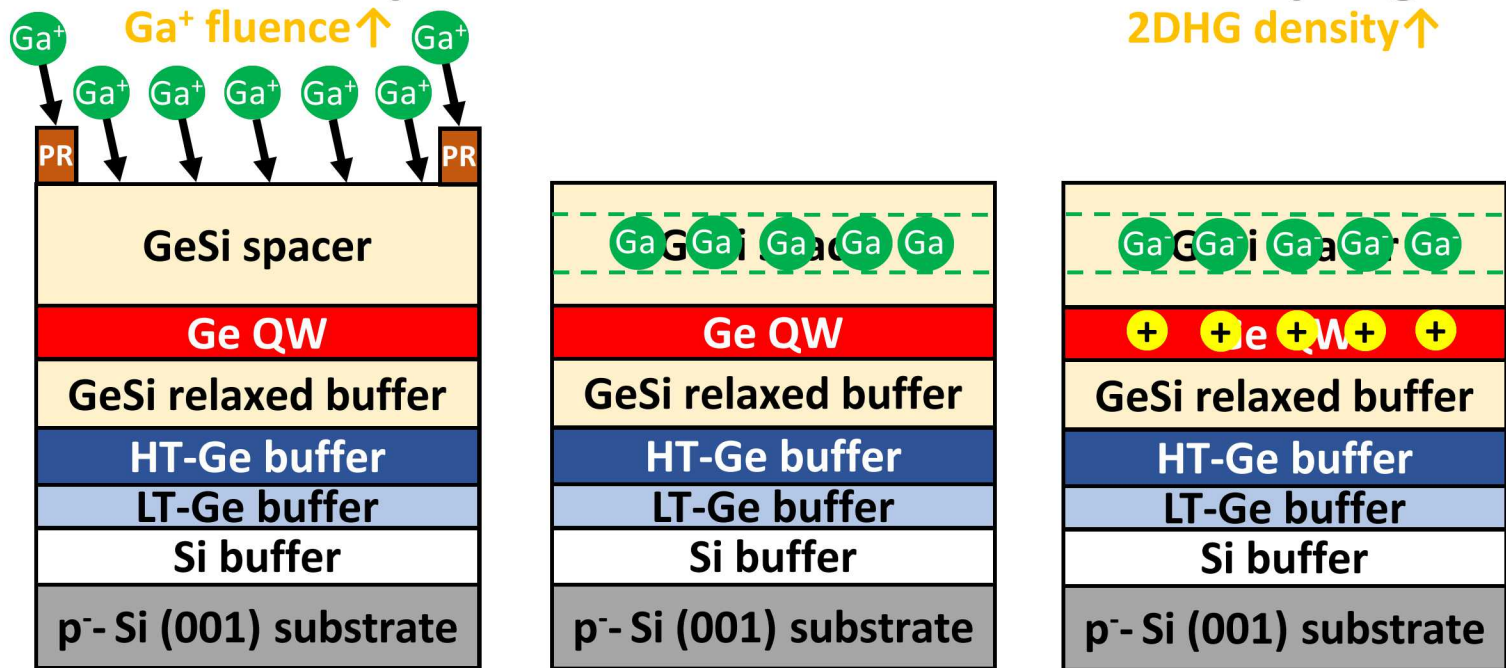


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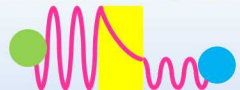


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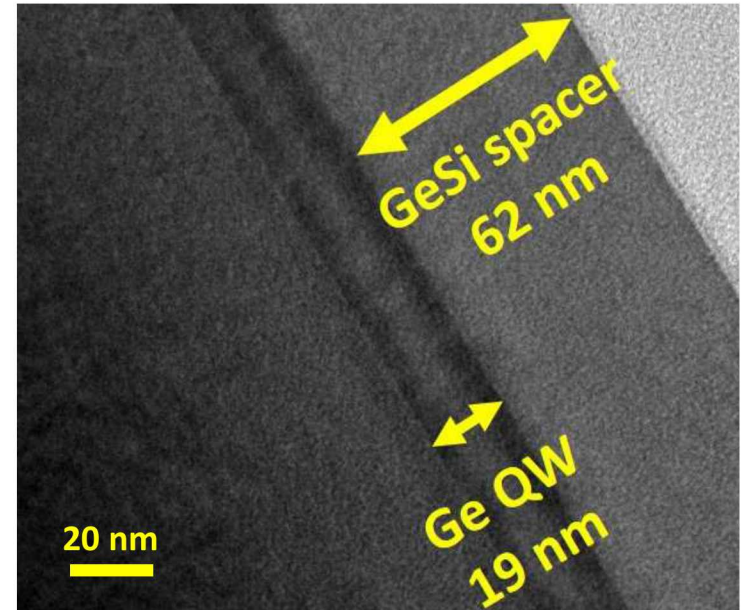
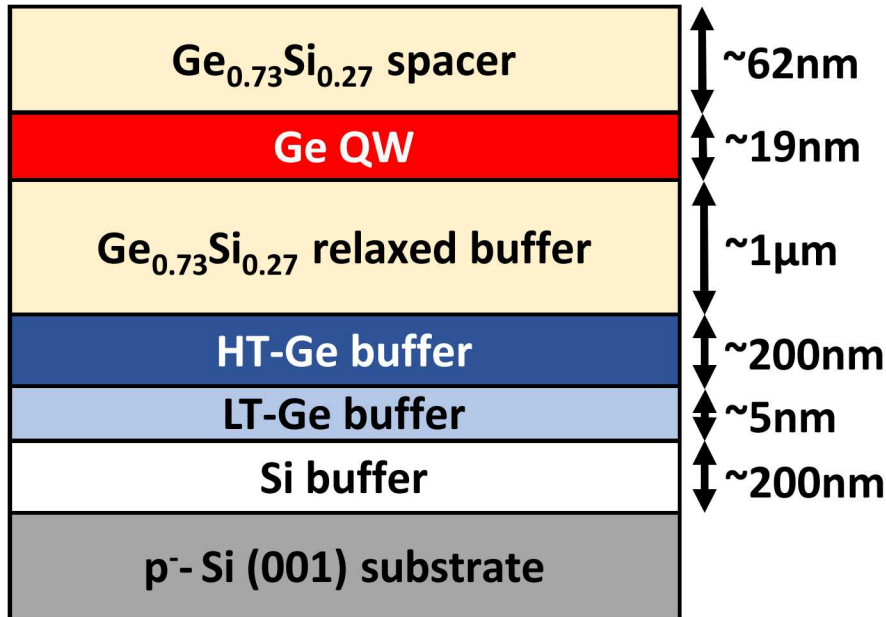


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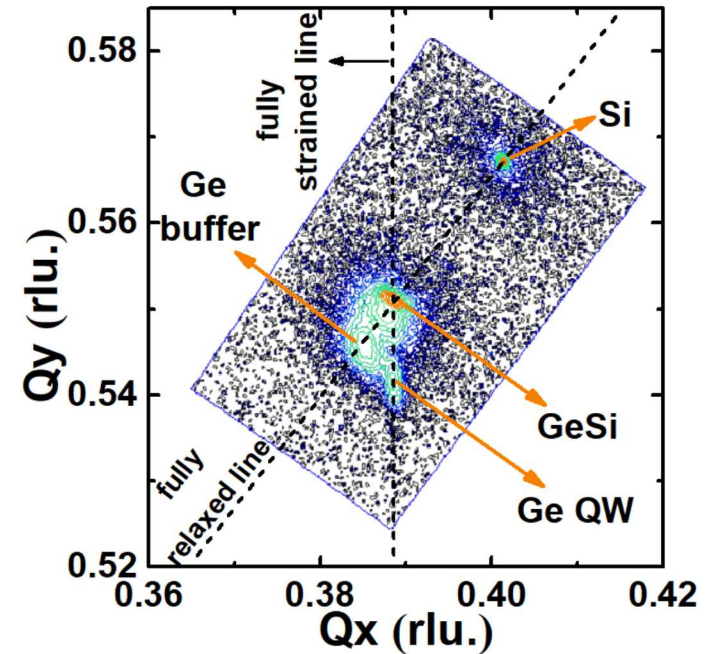
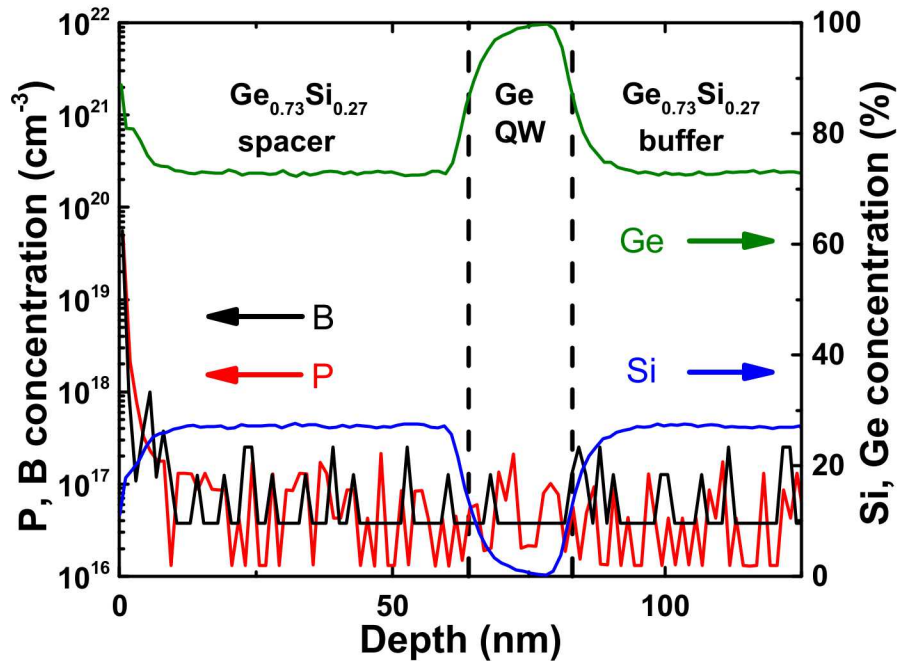


Epitaxy Structure before Ion Implantation



- Reduced pressure chemical vapor deposition (RPCVD)
- Precursor: germane (GeH₄) and silane (SiH₄) at 450°C
- XTEM => no observable threading dislocation ($\leq 10^6 \text{ cm}^{-2}$)

Depth Profile and Strain Condition before Ion Implantation

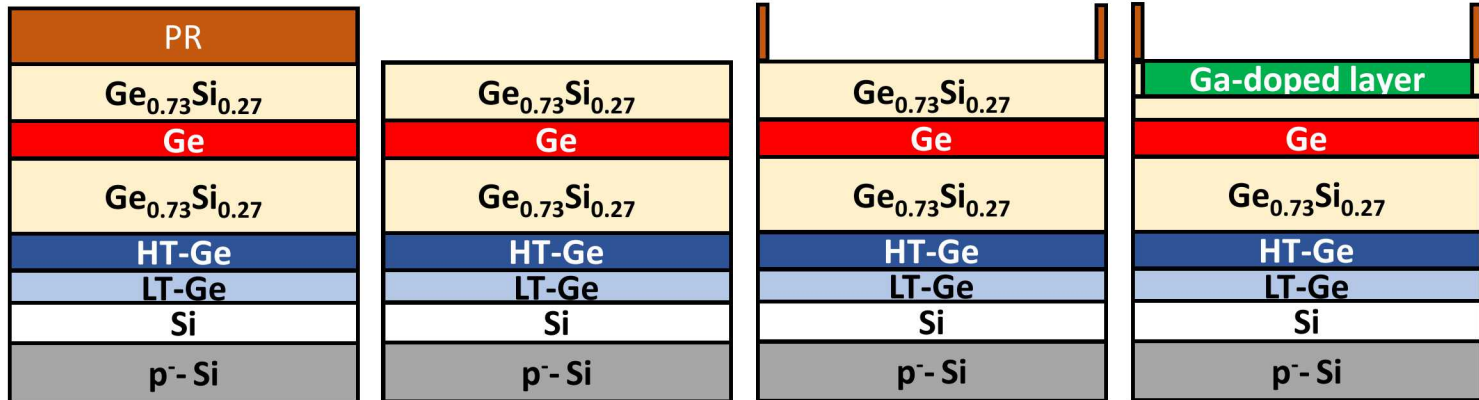
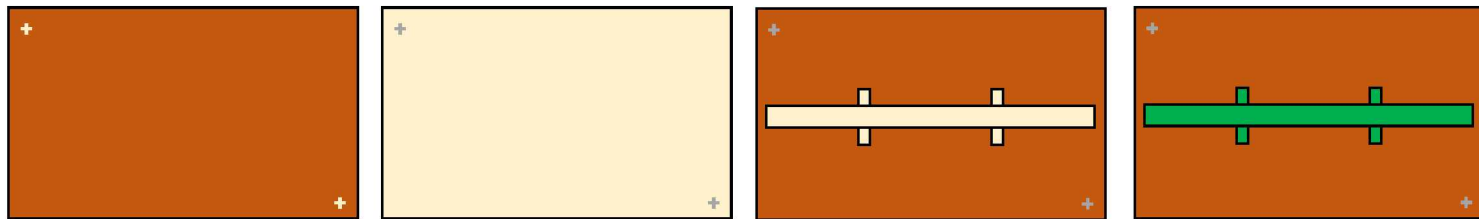


- SIMS: $[\text{Ge}]=73\%$, $[\text{Si}]=27\%$ in GeSi buffer layer
- Boron, phosphorous: detection limit ($< 5 \times 10^{16} \text{ cm}^{-3}$)
- Fully relaxed GeSi buffer layer and fully strained Ge QW layer

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Device Fabrication for Electrical Characteristics

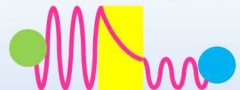


Defining
alignment mark

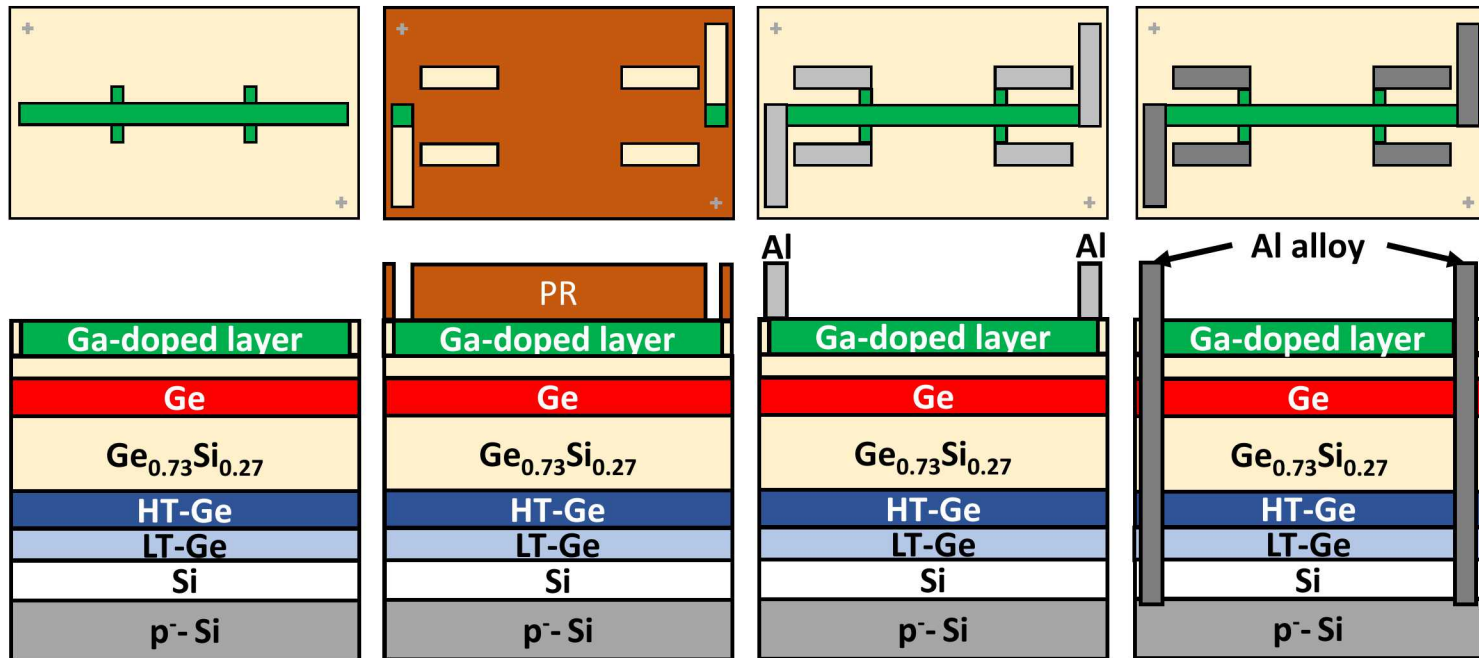
Reactive ion
etching

Defining
channel region

Ga ion
implantation



Device Fabrication for Electrical Characteristics



Rapid thermal
annealing
(550°C, 1 hr)

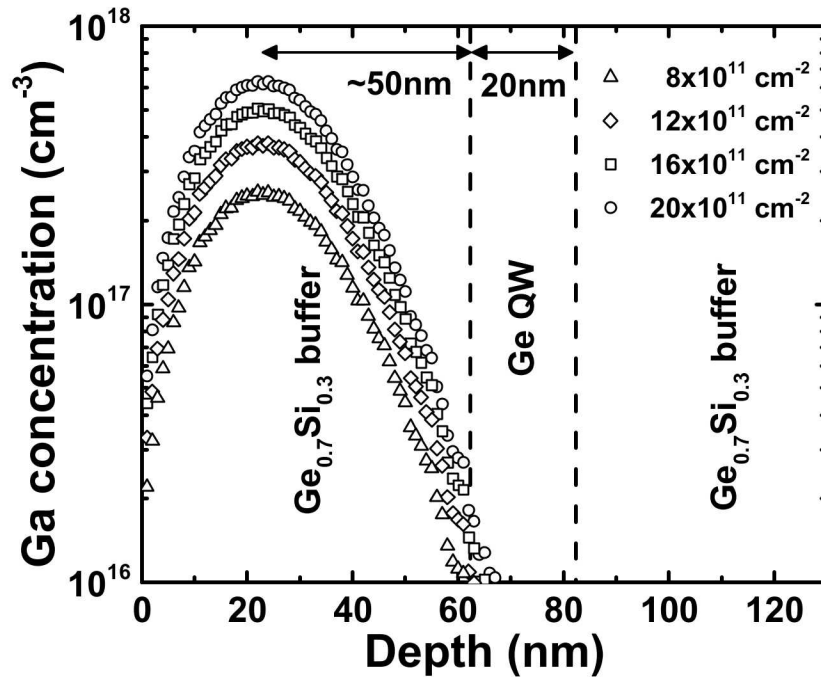
Defining
contact region

Al deposition
(250 nm)

Rapid thermal
annealing
(490°C, 30 s)



Simulation of Gallium Implantation Profile



Sample number	Ion fluence (cm ⁻²)
1	8 x 10 ¹¹
2	12 x 10 ¹¹
3	16 x 10 ¹¹
4	20 x 10 ¹¹

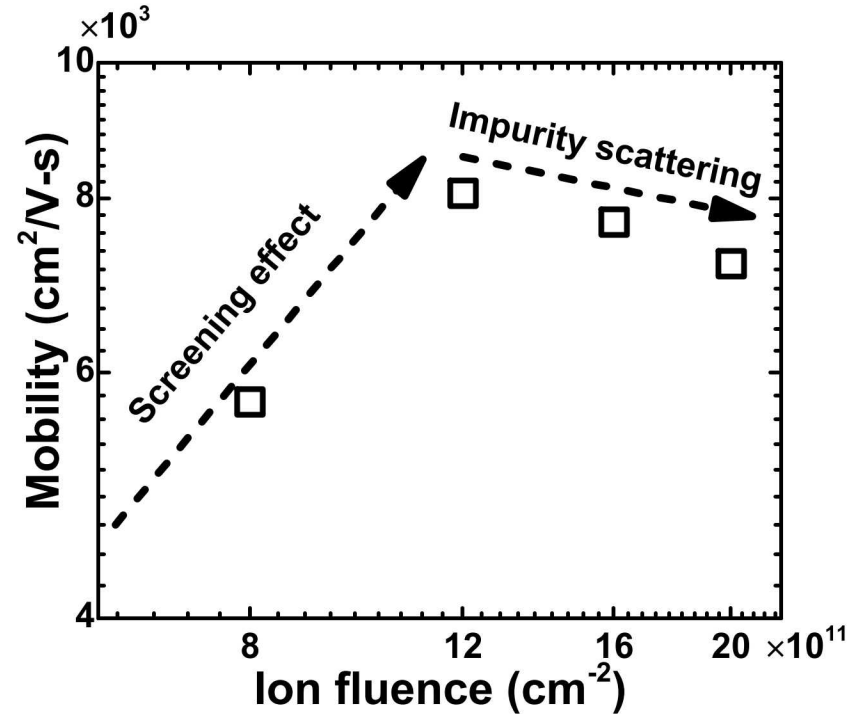
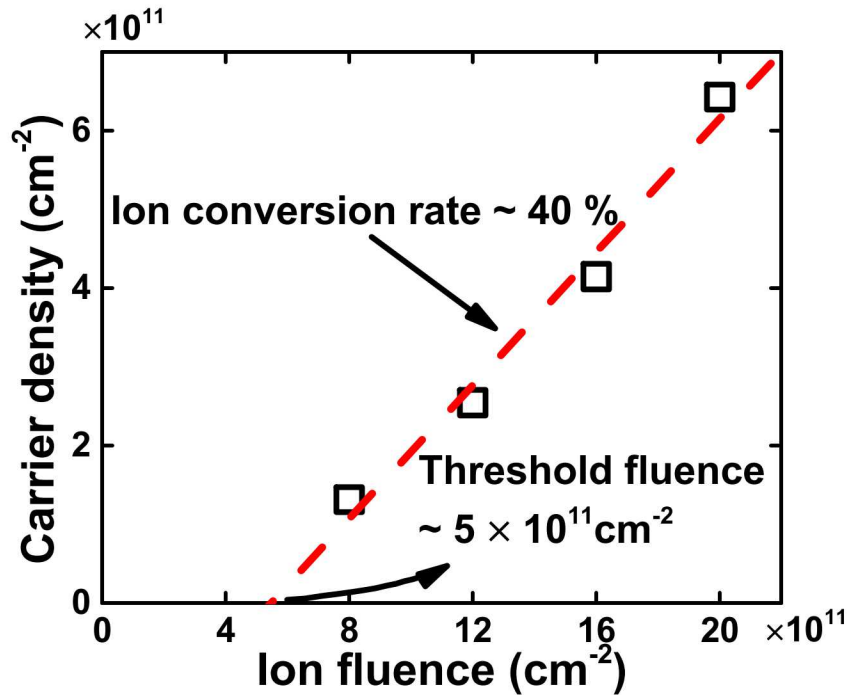
Tilt=7° Energy=40 keV

- Distance between gallium (Ga) peaks and QW ↑ (↓) → carrier in Ge QW ↓ (remote scattering ↑)
- Ga fluence ~ 10¹² cm⁻² → typical density of 2DHG



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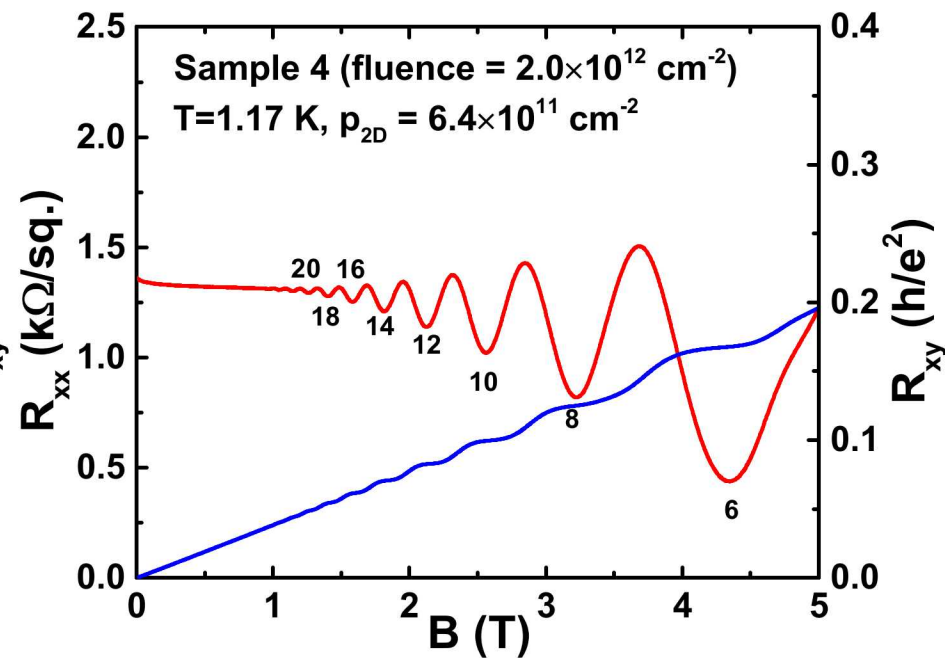
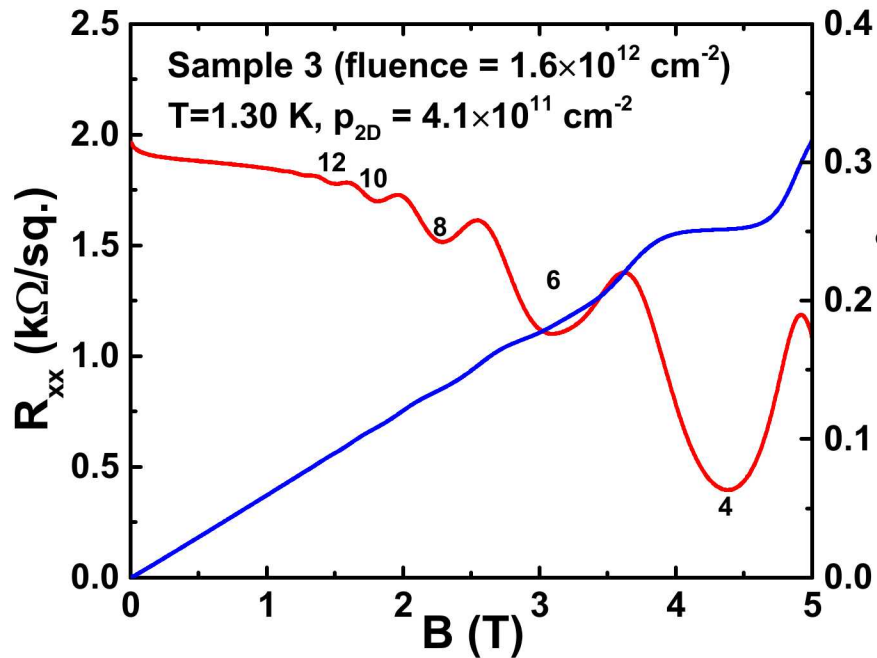
Hall measurement at 1.5 K



- The carrier density is linear to ion fluence.
- Ion fluence $< 12 \times 10^{11} \text{cm}^{-2}$ \rightarrow screening effect dominate;
 $> 12 \times 10^{11} \text{cm}^{-2}$ \rightarrow impurity scattering dominate.



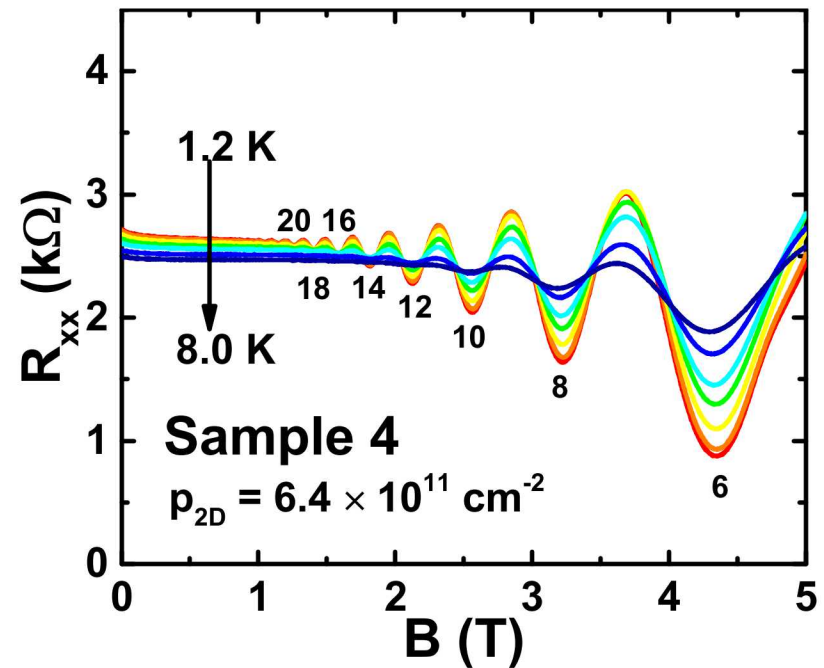
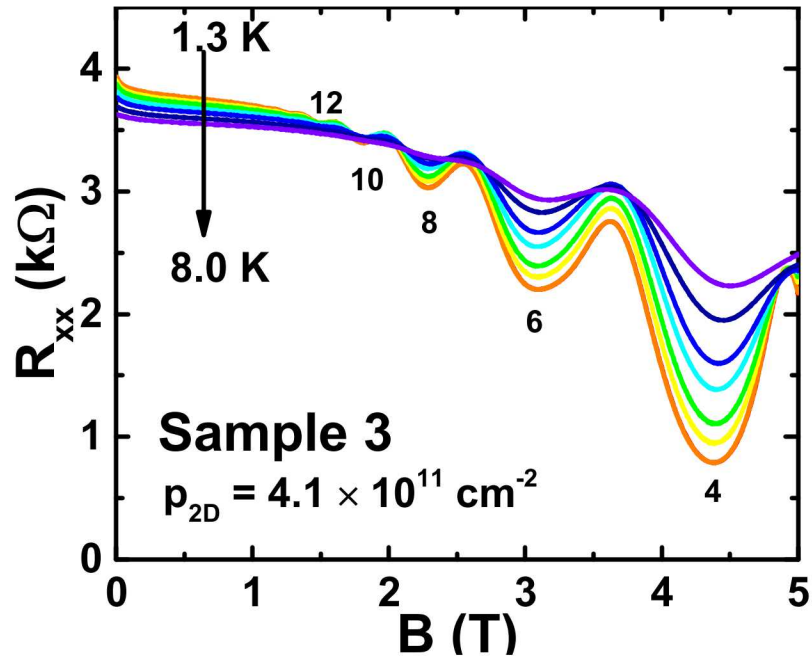
Quantum Hall effect and Shubnikov de-Hass (SdH) Oscillations



- Quantum Hall plateau \rightarrow 2D carriers
- The SdH oscillations are more obvious in sample 4.
- Fluence $\uparrow \rightarrow$ carrier $\uparrow \rightarrow$ filling factor \uparrow

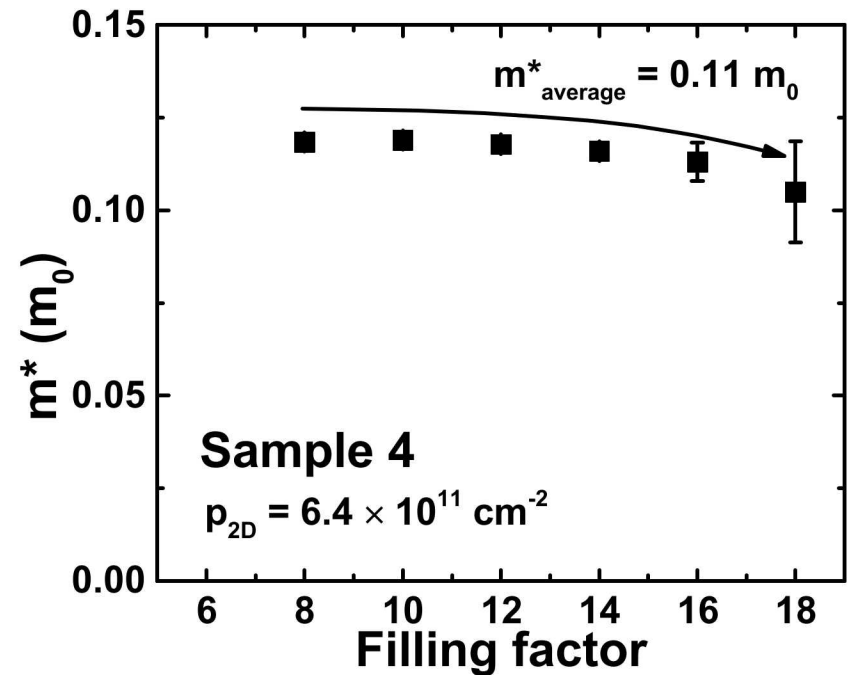
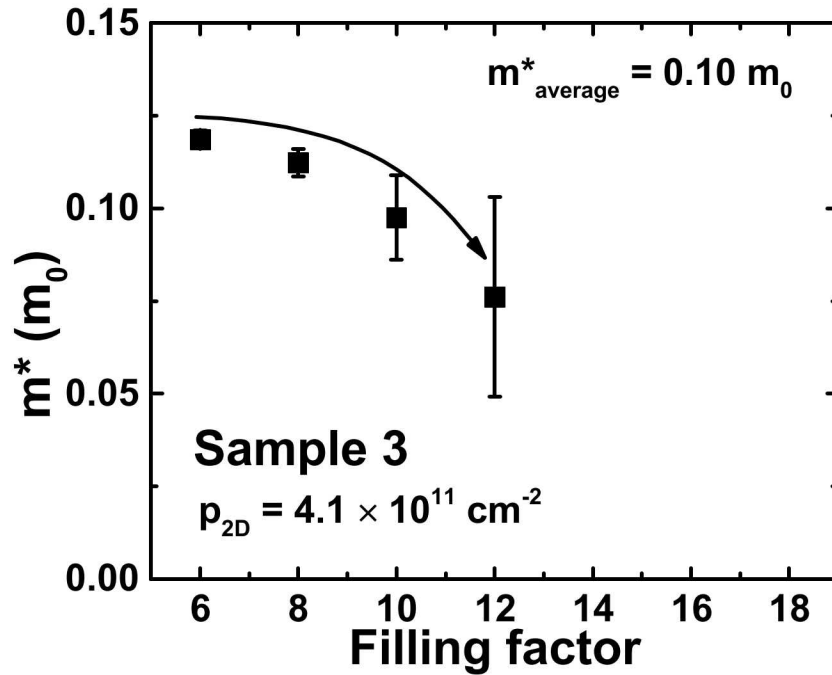


Temperature Dependence of SdH Oscillations

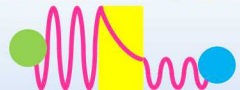


- Effective mass can be extracted from the temperature-dependent SdH oscillations.
- Well-resolved SdH oscillations → good sample quality

Effective Mass



- Magnetic field dependence of effective mass (?)
- Slightly density dependence of effective mass
 - Non-parabolic valence band structure (?)



Summary

- Ga ion implantation to realize modulation-doped Ge 2DHG in an undoped Ge/GeSi heterostructure.
- 40 % activation rates of implanted Ga ions were achieved with carrier density of $1.3 \sim 6.4 \times 10^{11} \text{ cm}^{-2}$ and maximum mobility of $8,000 \text{ cm}^2/\text{V}\cdot\text{s}$.
- Well-resolved SdH oscillations and quantum Hall plateaus were observed with effective masses extracted ($m^* \sim 0.11 m_0$).

Acknowledgement

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