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Electrostatics and Magnetotransport in Two-Dimensional Hole Gases by Ge/GeSi Heterostructures

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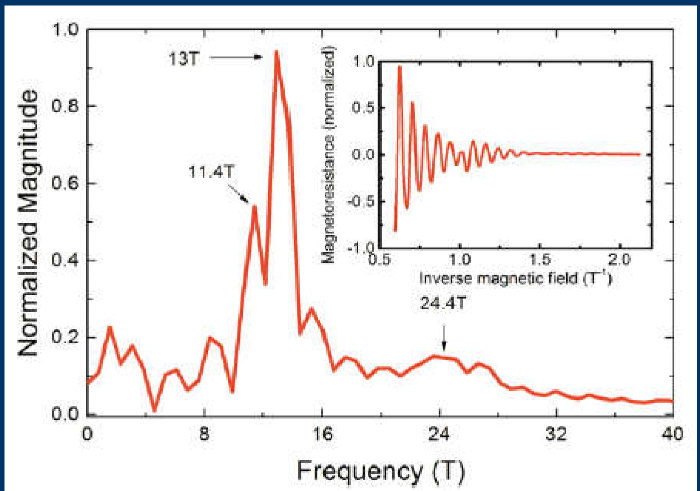
Outline

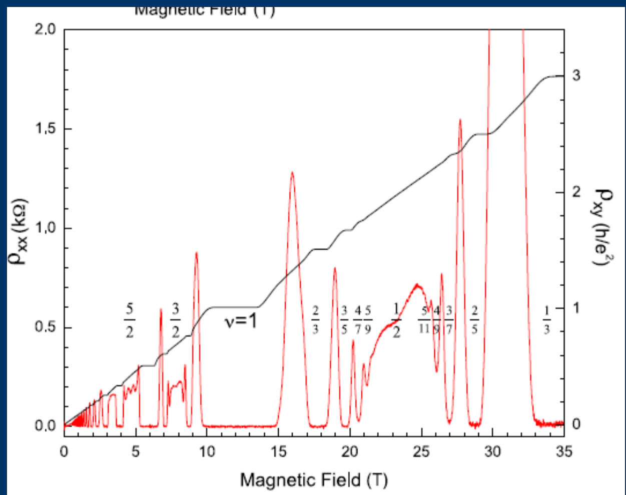
- **Motivation**
  - Two-dimensional hole gases (2DHGs) in un-doped Ge/GeSi heterostructures
- **Experiment**
- **Electrostatics**
  - A cross-over of equilibrium and non-equilibrium
  - An unexpectedly low gate capacitance
- **Magneto-transport properties**
  - Scattering mechanisms
  - Missing even minima of filling factors
  - Higher-subband occupancy
- **Conclusions**

Motivation: Ge/GeSi 2DHGs

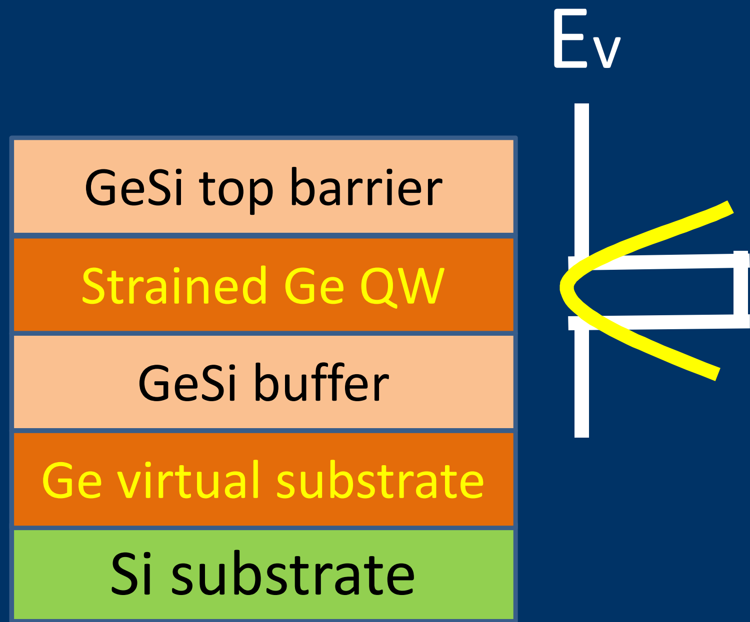
- **2DHGs in Ge/GeSi heterostrucures**
  - High hole mobility enhanced by compressively strain
  - Interesting physics such as
    - ✓ Spin-orbit interaction (Rashba effect)
    - ✓ Fractional quantum hall effect



SOI (2016, SSC)

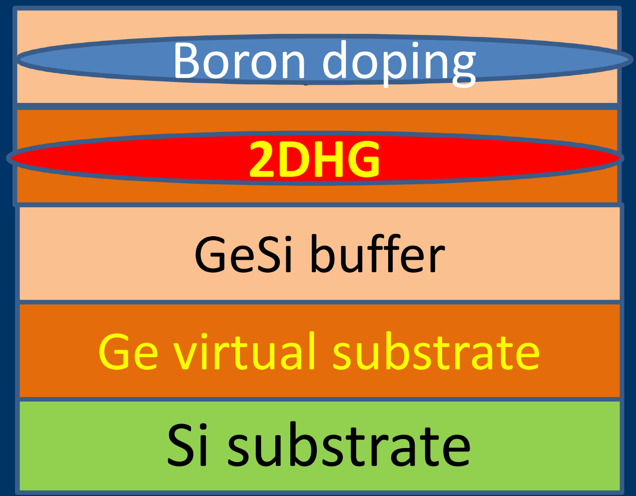


FQHEs (2016, PRL)



Motivation: Doped/Undoped Structures

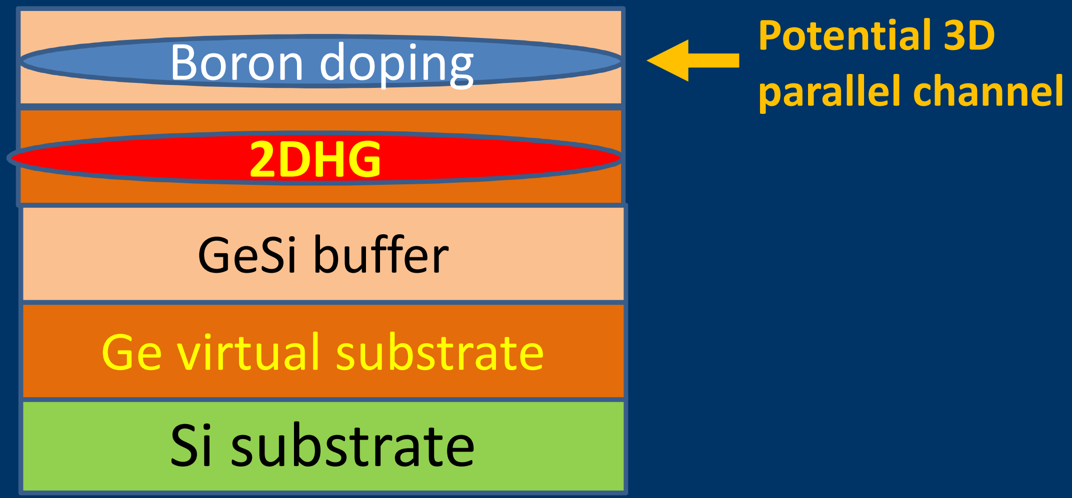
Modulation-doped structure



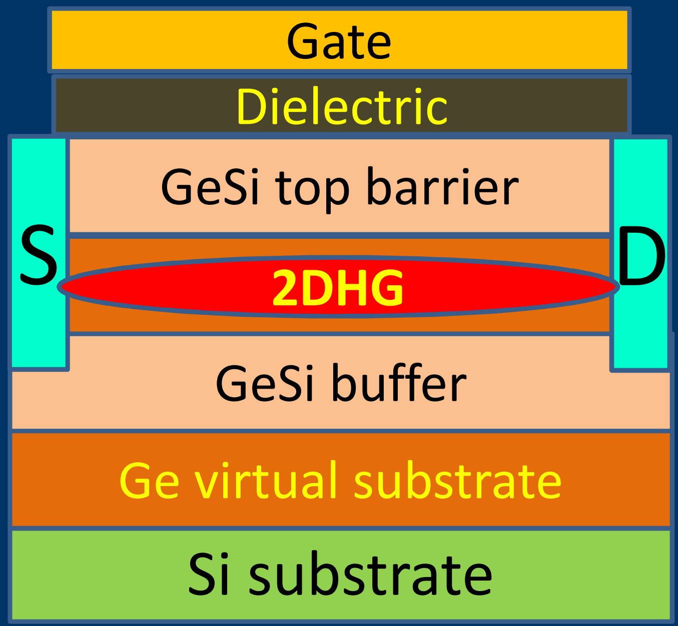
- **Simple implementation**
- **Ultra-high mobility of ~ 1,000,000 cm^2/V-s by Warwick (2011, APL)**

Motivation: Doped/Undoped Structures

Modulation-doped structure



Un-doped structure

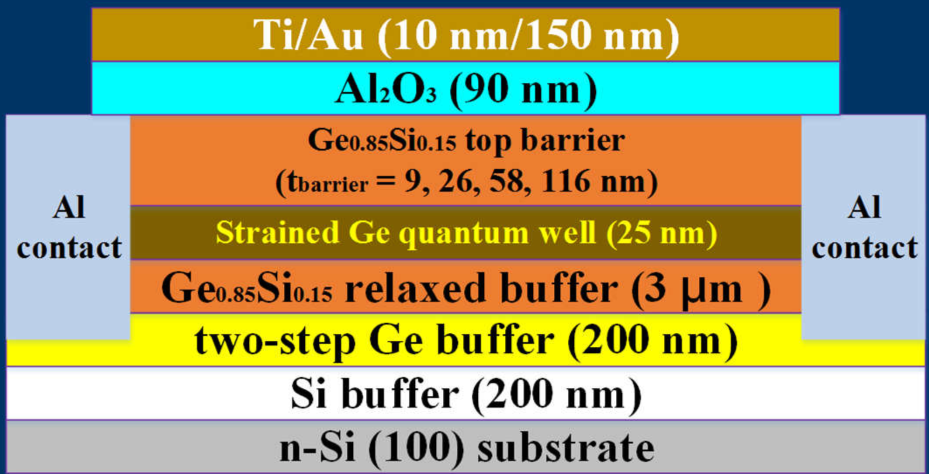


- **Easy device fabrication**
- **Ultra-high mobility (2014, JJAP)**
- **Gate leakage**
- **Potential 3D parallel channel**

- **Impurity-free**
- **Low density regime**
- **QDs and single hole transistors**
- **No 3D parallel channel**

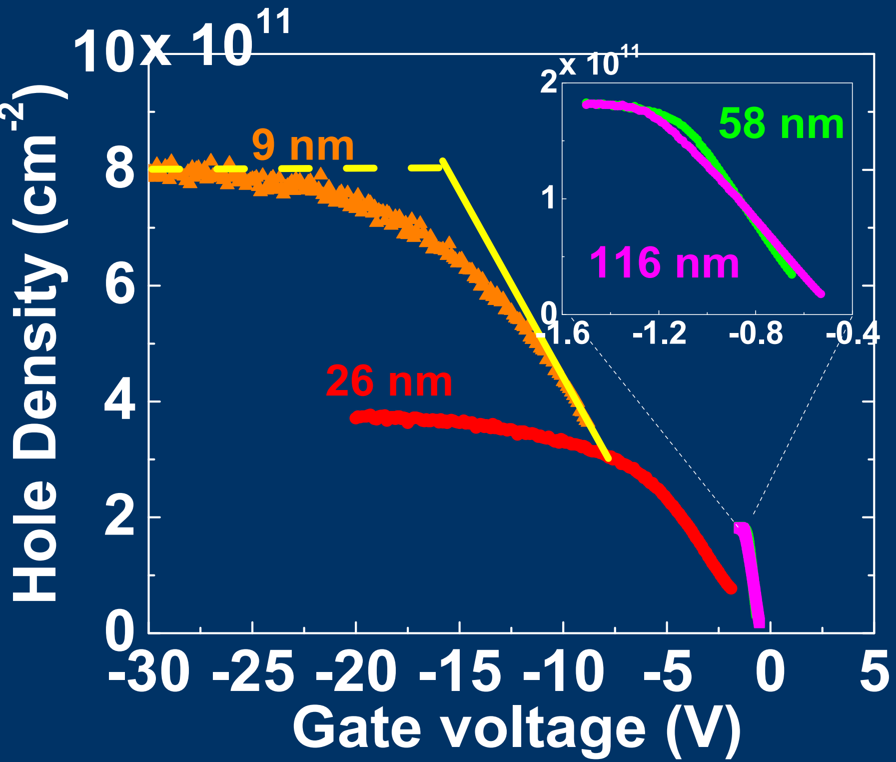
Experiment

Gated Hall bar



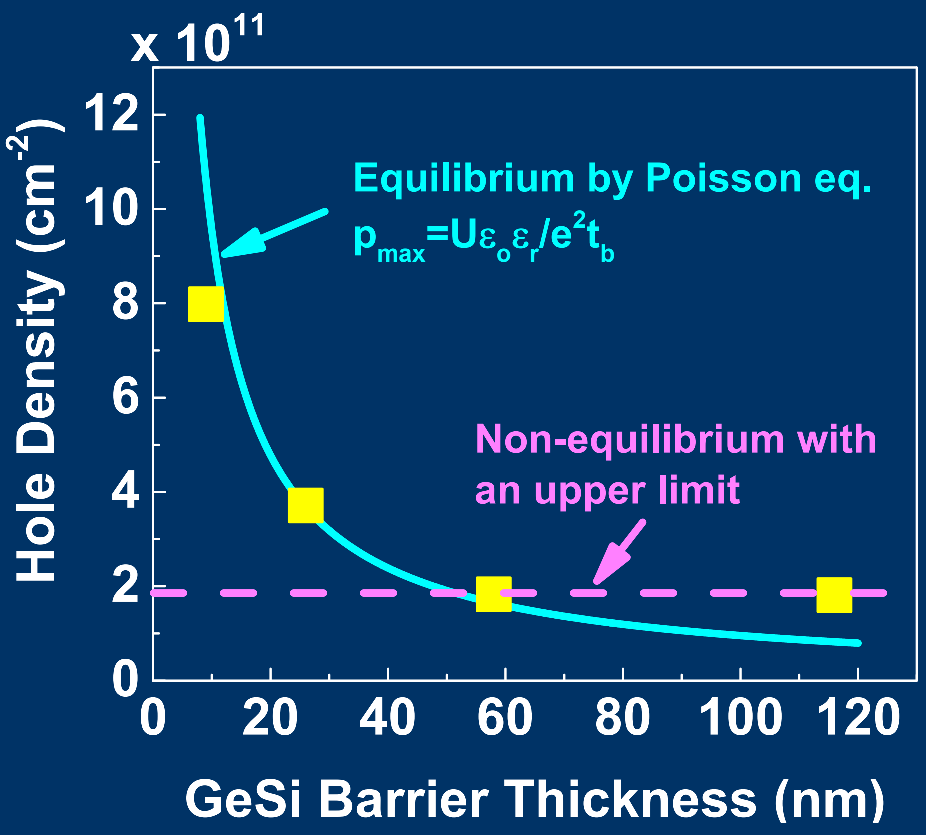
- Al deposition
- RTA to form Ohmic contact
- Al_2O_3 by ALD
- Ti/Au top gate by e-beam
- Hall measurement at 0.3K

Electrostatics: Density Saturation



- **Two stages**
  - Linear stages vs. Saturation
- **Linear stage(Solid lines)**
  - Slope: effective gate capacitance
- **Saturation stage(Dashed Lines)**
  - Deep-channel: (Large $t_{barrier}$)(116 nm, 58nm)
    - ✓ Low, independent with $t_{barrier}$
  - Shallow-channel: (Small $t_{barrier}$) (26 nm, 9 nm)
    - ✓ High, dependent with $t_{barrier}$

Electrostatics: Density Saturation

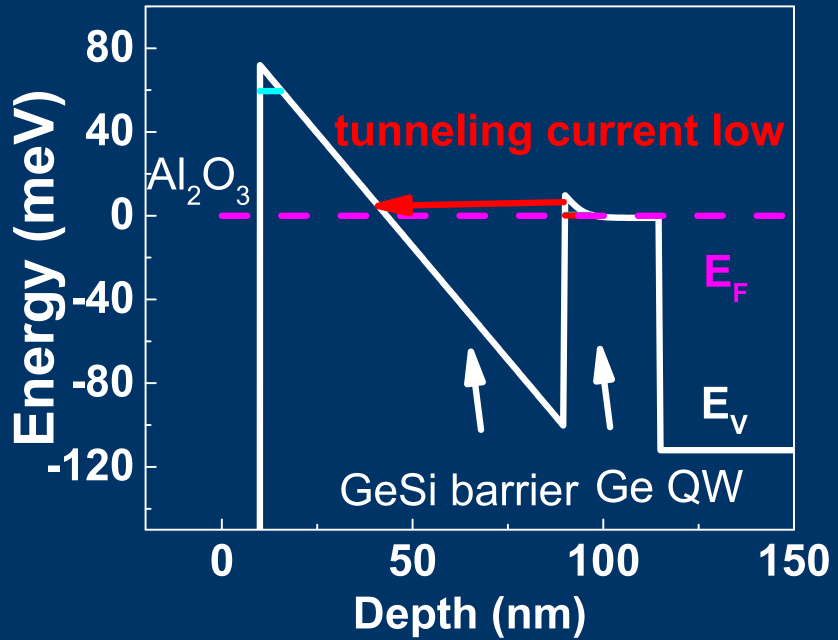


- **Two regimes**
  - Equilibrium vs. Non-equilibrium
- **Deep-channel: Non-equilibrium**
  - reported in Si 2DEG system (Ref. 2011 APL)
  - attributed to surface tunneling to surface capped quantum well
- **Shallow-channel: Equilibrium**
  - matched the calculated equilibrium values well

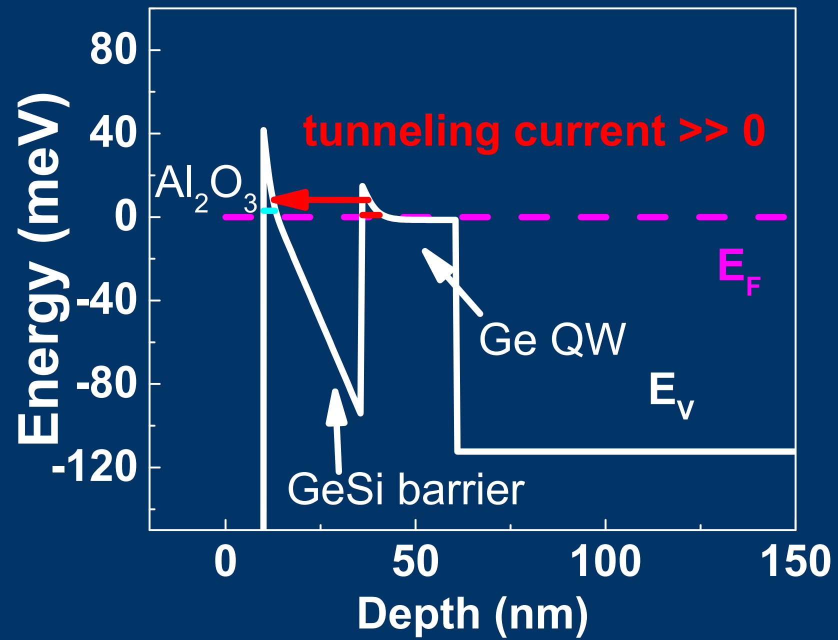
Why crossover from equilibrium to non-equilibrium?

Electrostatics: Density Saturation

- **Deep-channel: low tunneling current**



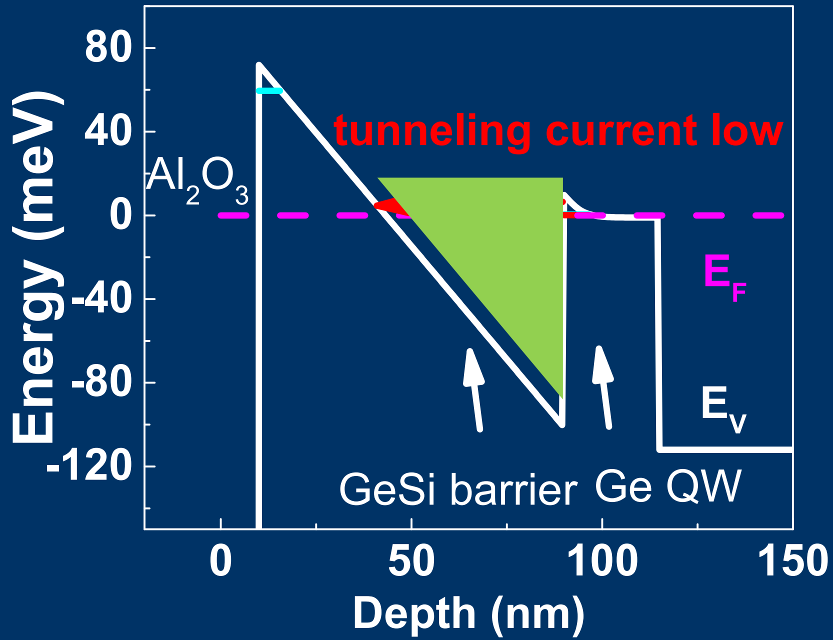
- **Shallow-channel: tunneling current >> 0**



- **Surface hole population: (1) Thermal generation (2) S/D injection (3) surface tunneling**

Electrostatics: Density Saturation

- **Deep-channel: low tunneling current**



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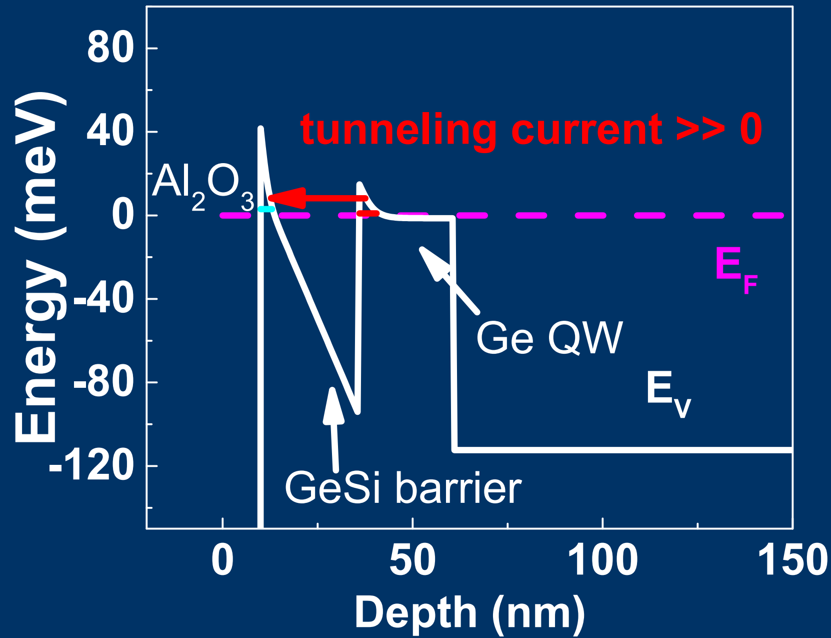
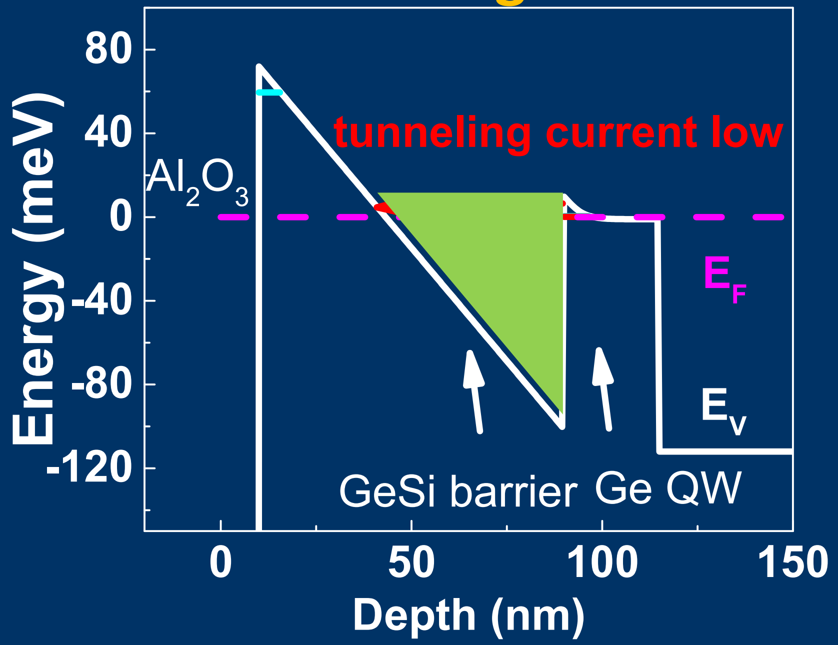


- **Surface hole population- ~~(1)Thermal generation (2) S/D injection~~ (3) surface tunneling**

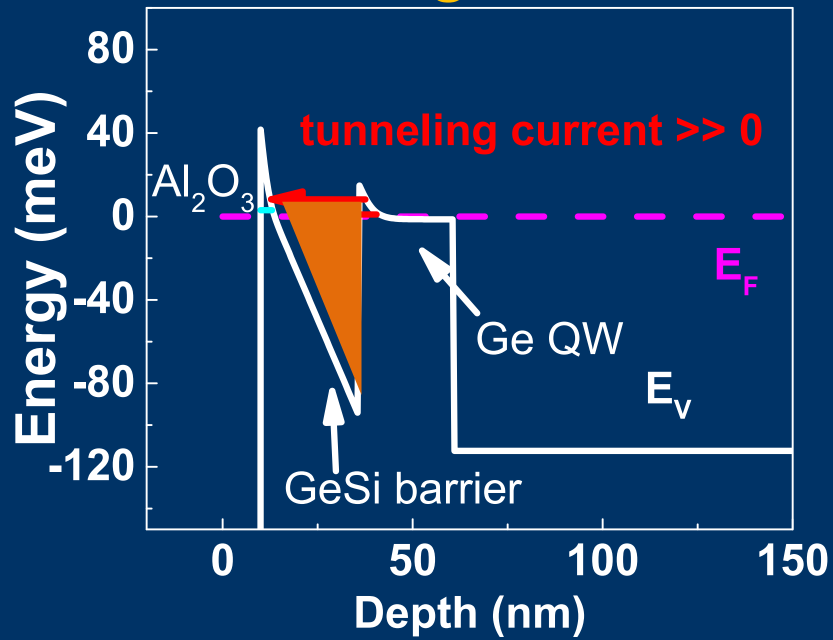
Low T **Poor oxide/semiconductor interface**

Electrostatics: Density Saturation

- Deep-channel: low tunneling current

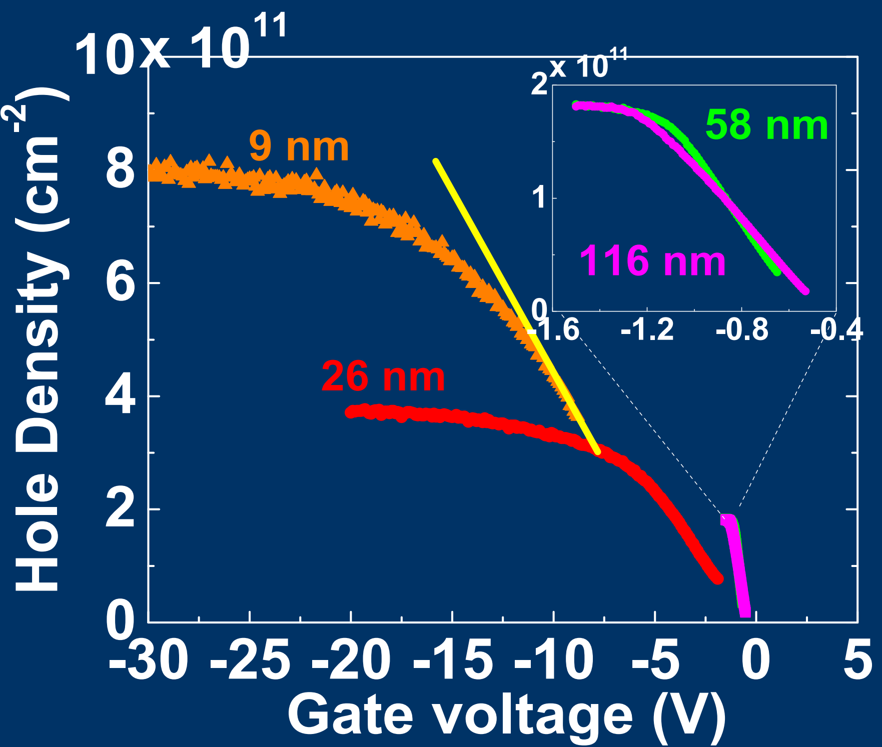


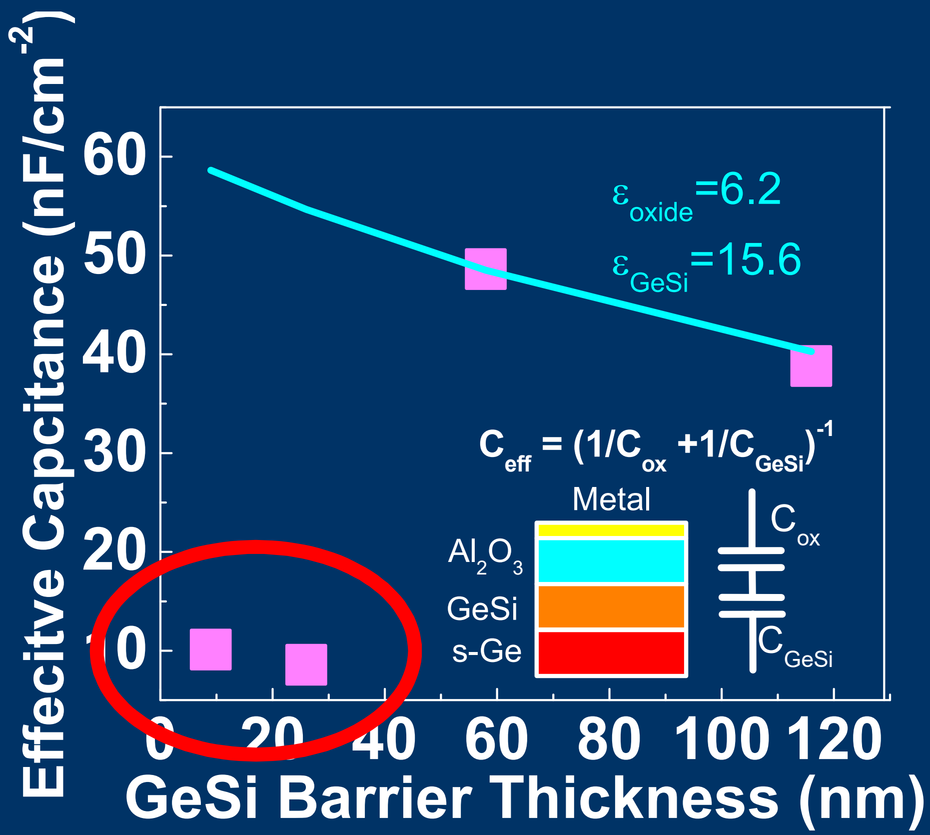
- Shallow-channel: tunneling current >> 0



- Surface hole population- (1)~~Thermal generation~~ (2) ~~S/D injection~~ (3) surface tunneling
- Tunneled carriers will passivate high-density defects, and lead to surface conduction.

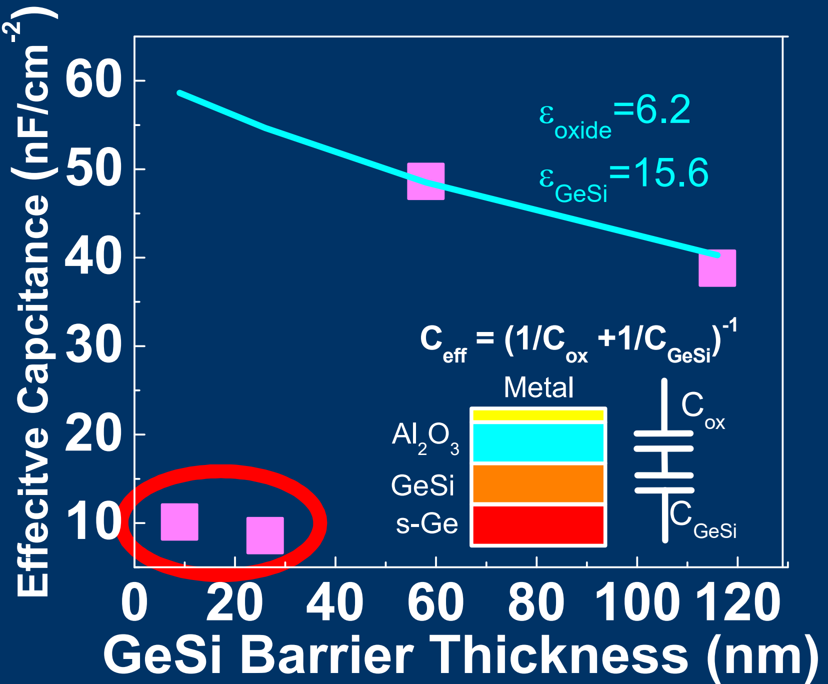
Electrostatics: Unexpectedly Low Capacitance

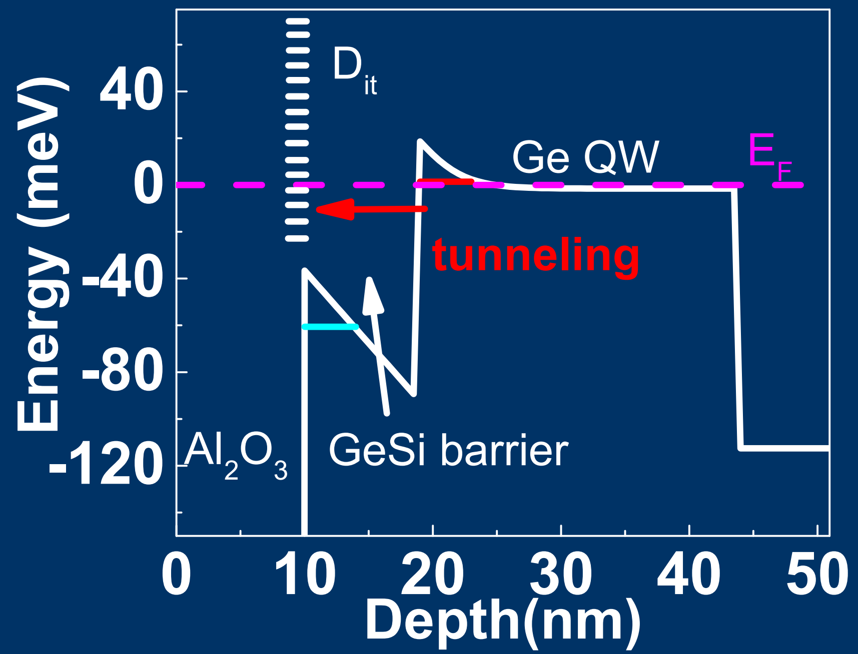




Unexpectedly low C_{eff}

Electrostatics: Unexpectedly Low Capacitance





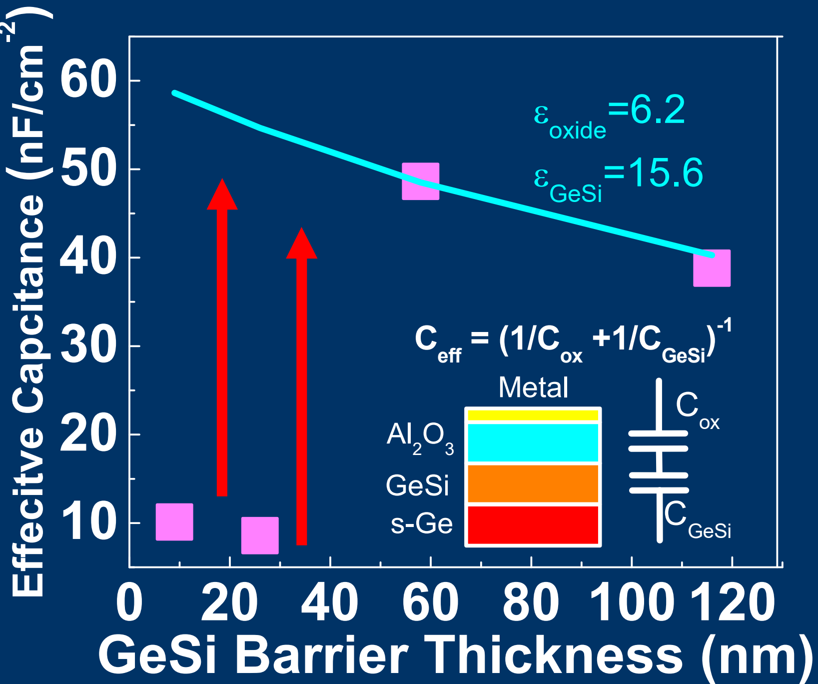
Unexpectedly low C_{eff}

- **High-density interface traps**
- **Hole loss due to surface tunneling**
- **only count mobile charges for C_{eff}**

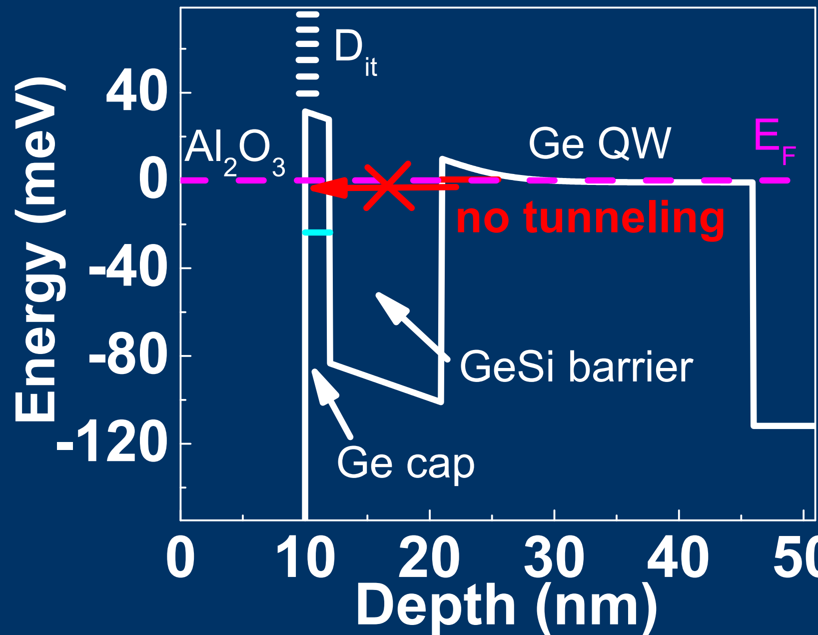
National Taiwan University

NTUEE QEL

Electrostatics: Unexpectedly Low Capacitance



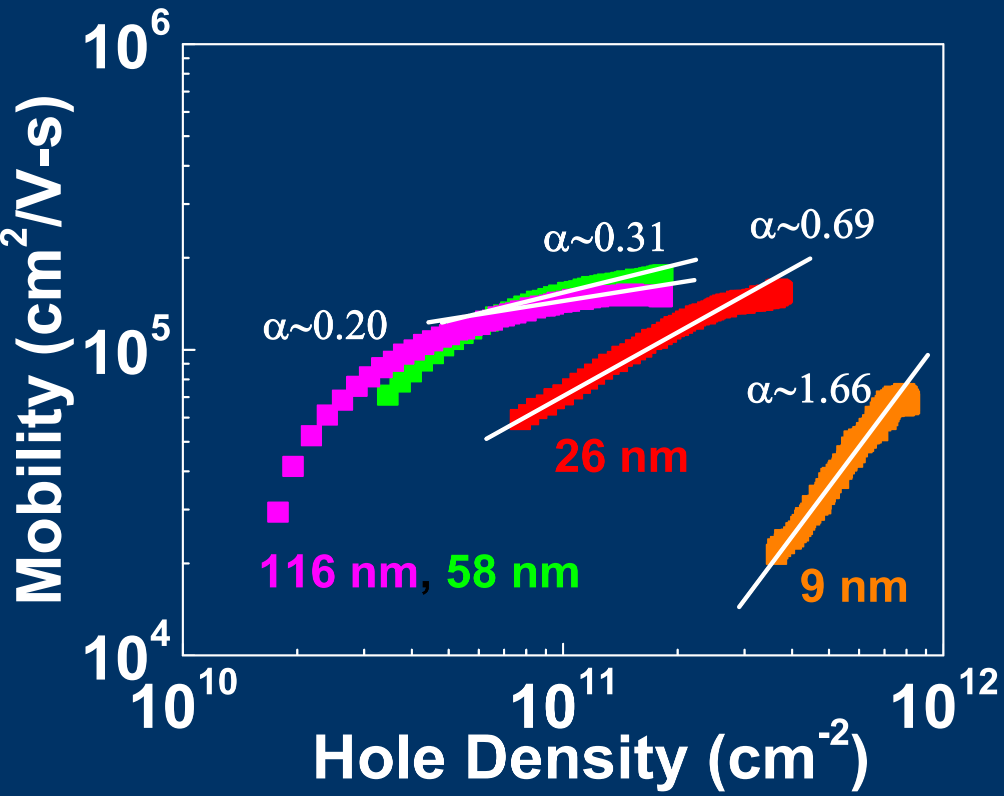
Mobility is sacrificed, gate efficiency doesn't improve



How to suppress surface tunneling?

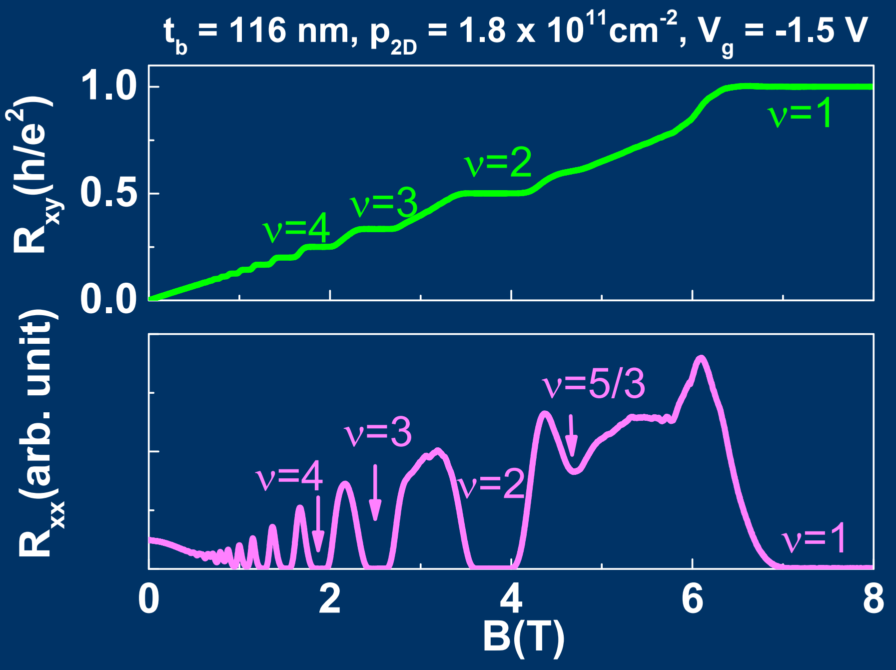
- $Ge_{1-x}Si_x$, x up -> tunneling barrier up
- Ge cap -> no energy alignment

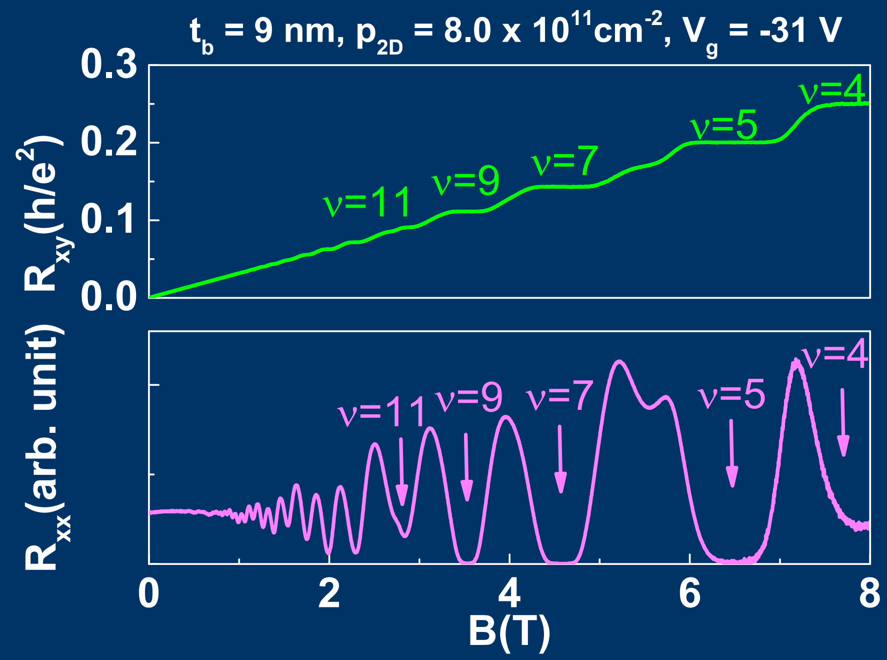
Magnetotransport: Scattering Mechanisms



- **as $t_{barrier}$ ↓ Mobility ↓**
  - ➢ stronger remote impurity scattering
- **as t_b ↑ Mobility = Density $^{\alpha}$, α ↓**
  - ➢ background impurity scattering dominates
- **9 nm device mobility still up to ~70,000 $cm^2/V\text{-}s$**
  - ➢ high-quality material, interface not too rough

Magnetotransport: Shubnikov-de Hass oscillations



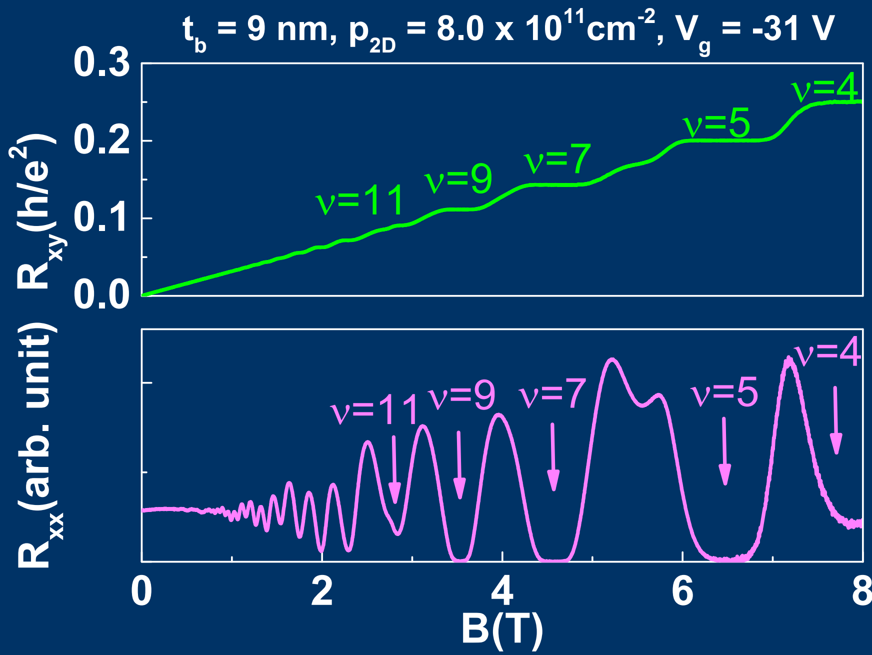


Clear zeros & A fractional QH state
-> High quality of our material

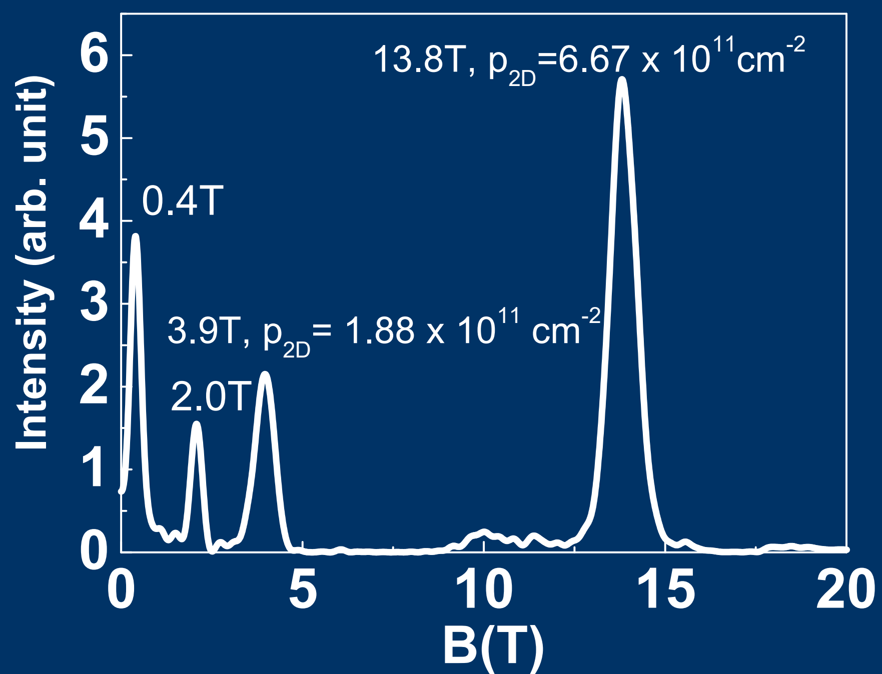
Missing even minima:

- **Large-g factor due to SOC**
- **Disordered Landau broadening**

Magnetotransport: Second Subband Occupancy



Fourier Analysis of SdH data



- **Low frequency peaks:**
  - **second and higher subband occupancy due to high 2DHG density**

Conclusions

- A cross-over of equilibrium and non-equilibrium 2DHG density was reported for the first time, and attributed to the surface tunneling.
- This surface tunneling also leads to much smaller effective capacitance for the shallow-channel devices.
- High-quality 2DHG in un-doped Ge/GeSi structures was achieved by CVD with shallow-channel (9 nm), high-mobility(~70,000 cm^2/V-s), missing even minima, and second subband occupancy.

Acknowledgement

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