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NTUEE Quantum Electronics Lab

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Demonstration of two-dimensional hole gases (2DHG) in strained GeSn quantum wells

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Outline

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- Motivation
- Epi structures and device structures
- Electrical characterization and magneto-transport at low temperature
- Effective mass extraction and simulation
- Conclusions

Motivation

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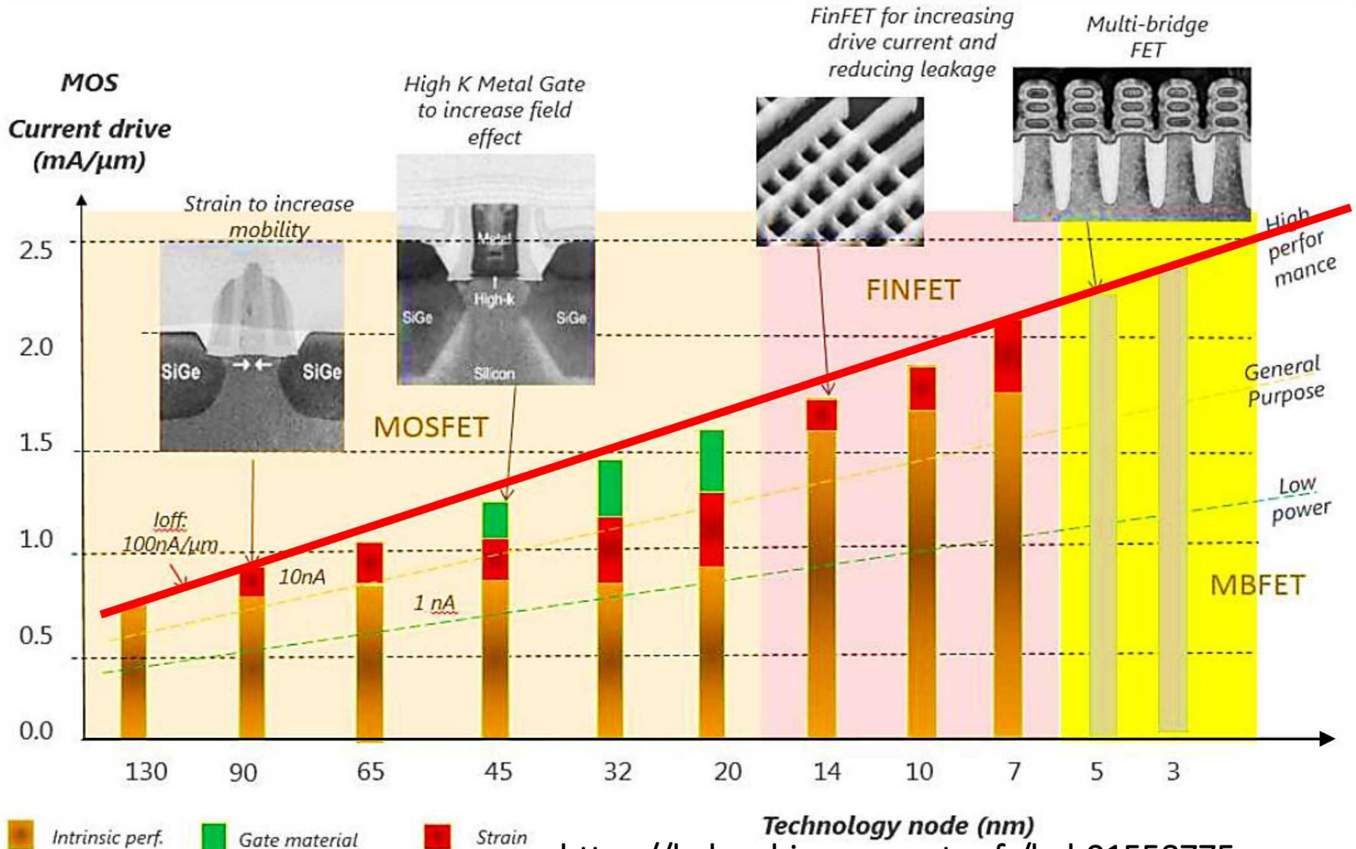

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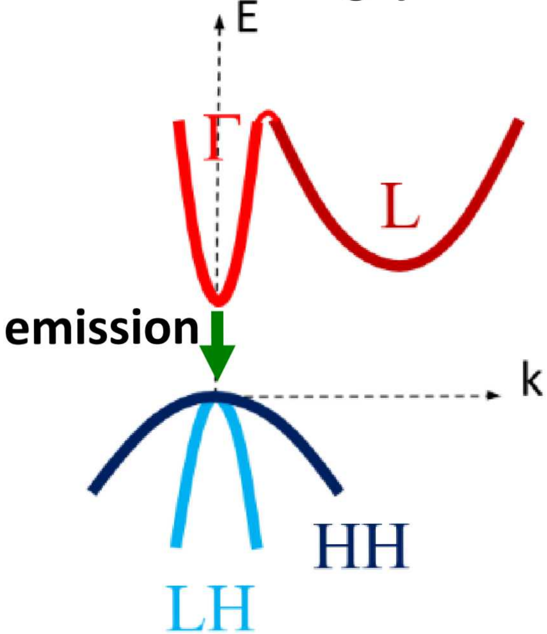
- With the development of Moore's law, higher I_{on} current device is needed
- To achieve high I_{on}, we need high mobility material for channel

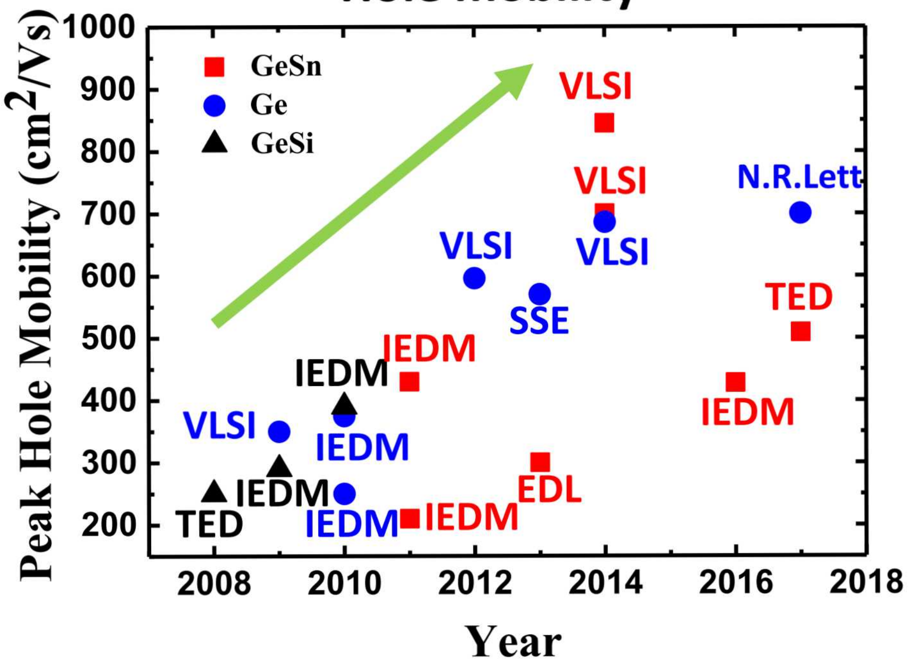
Motivation

Why we choose GeSn?

Direct band gap



Hole mobility



- GeSn is a direct band gap material
  → Better emission efficiency (No need phonon assist)
- GeSn shows higher hole mobility than Ge and GeSi
  → GeSn has smaller m^*

Motivation

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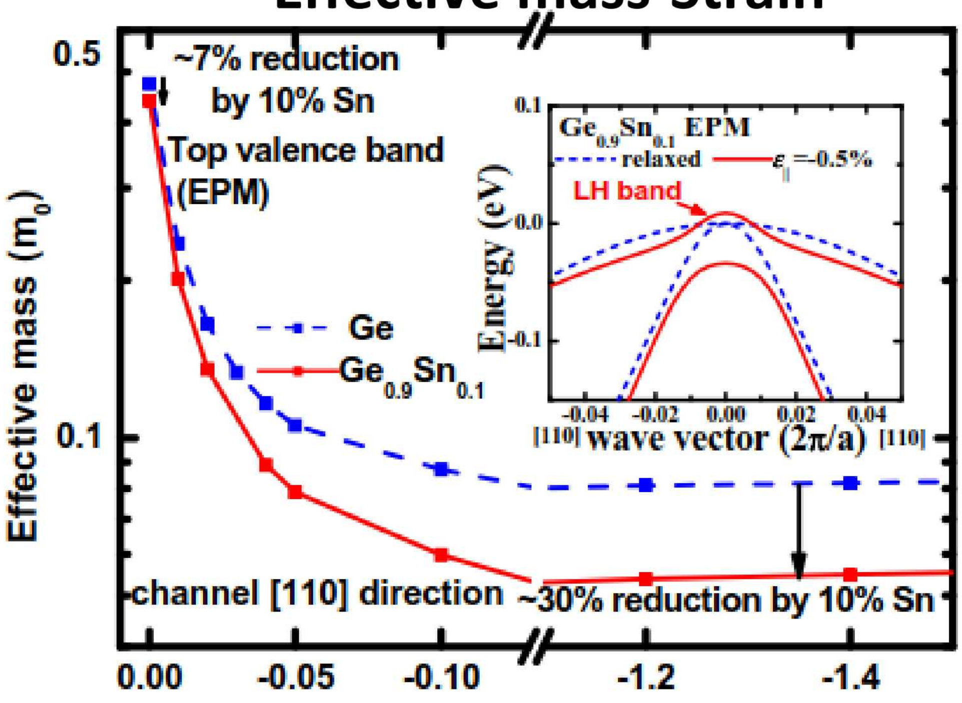
GeSn has smaller m*

Effective mass-Strain



IEDM (2016)

- m* ↓ with compressive strain, due to the deformation of HH-LH band
- Adding Sn into Ge can increase strain and hence decrease m*

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Ge/GeSn Epitaxial Structures

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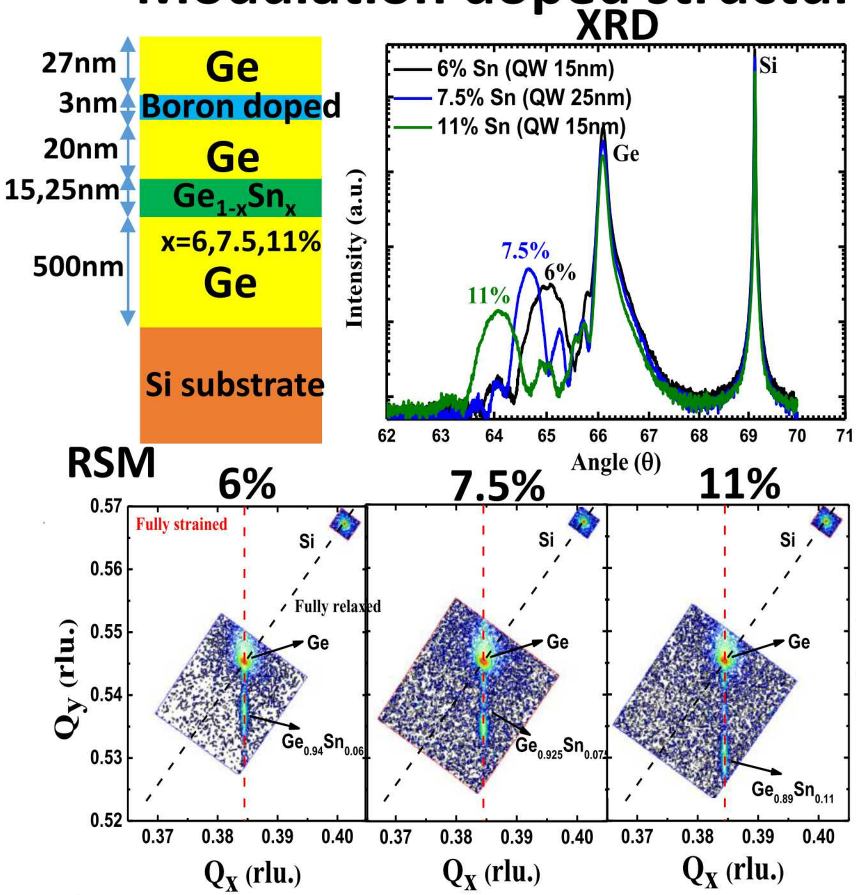
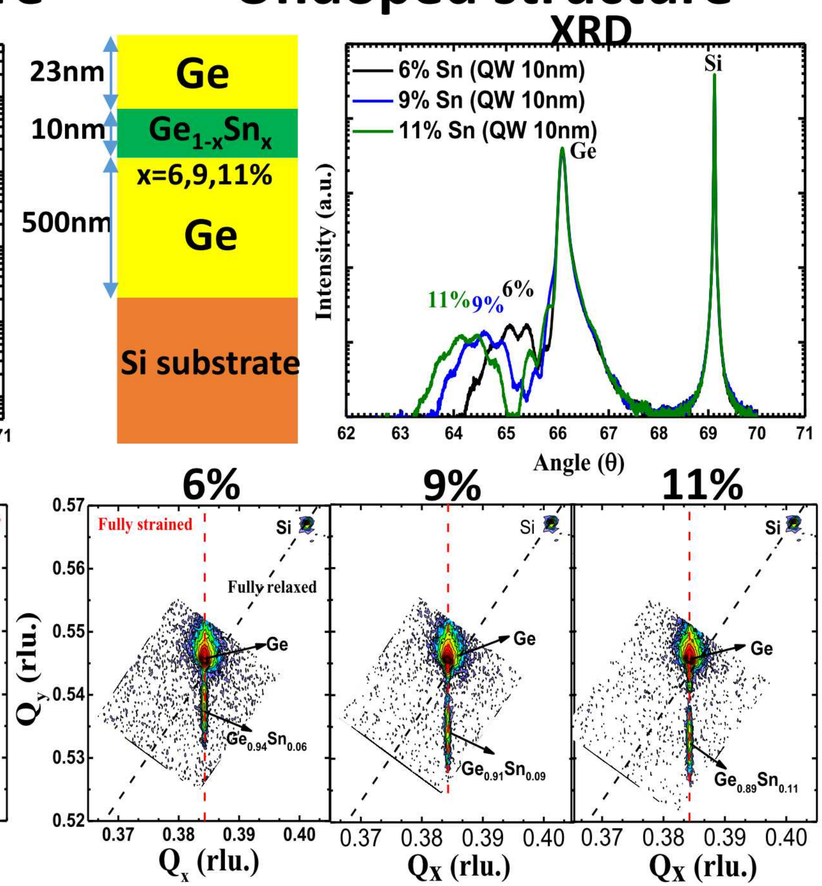
Modulation doped structure

Undoped structure





- The XRD gives [Sn]=6,7.5,11% for doped samples, and [Sn]=6,9,11% for undoped samples
- The RSM results show that the GeSn is fully strain on Ge layer

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Device Structure (Undoped)

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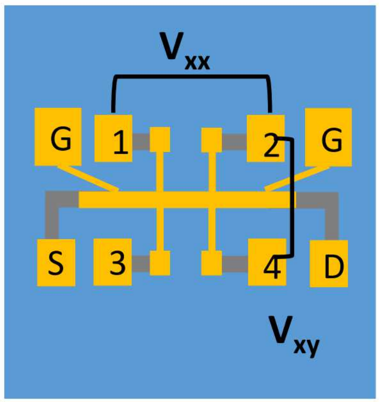
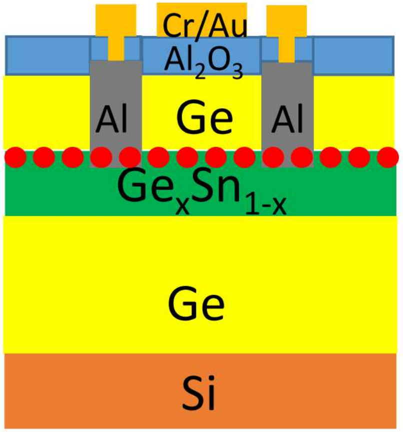
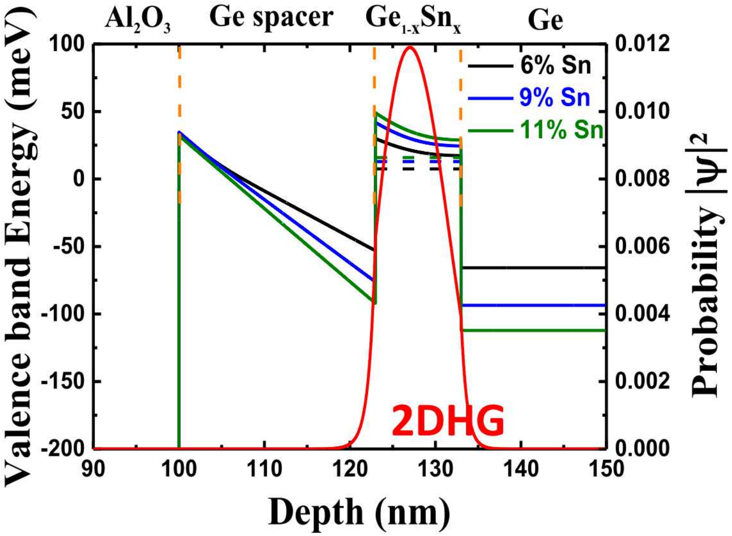
Top view



Side view



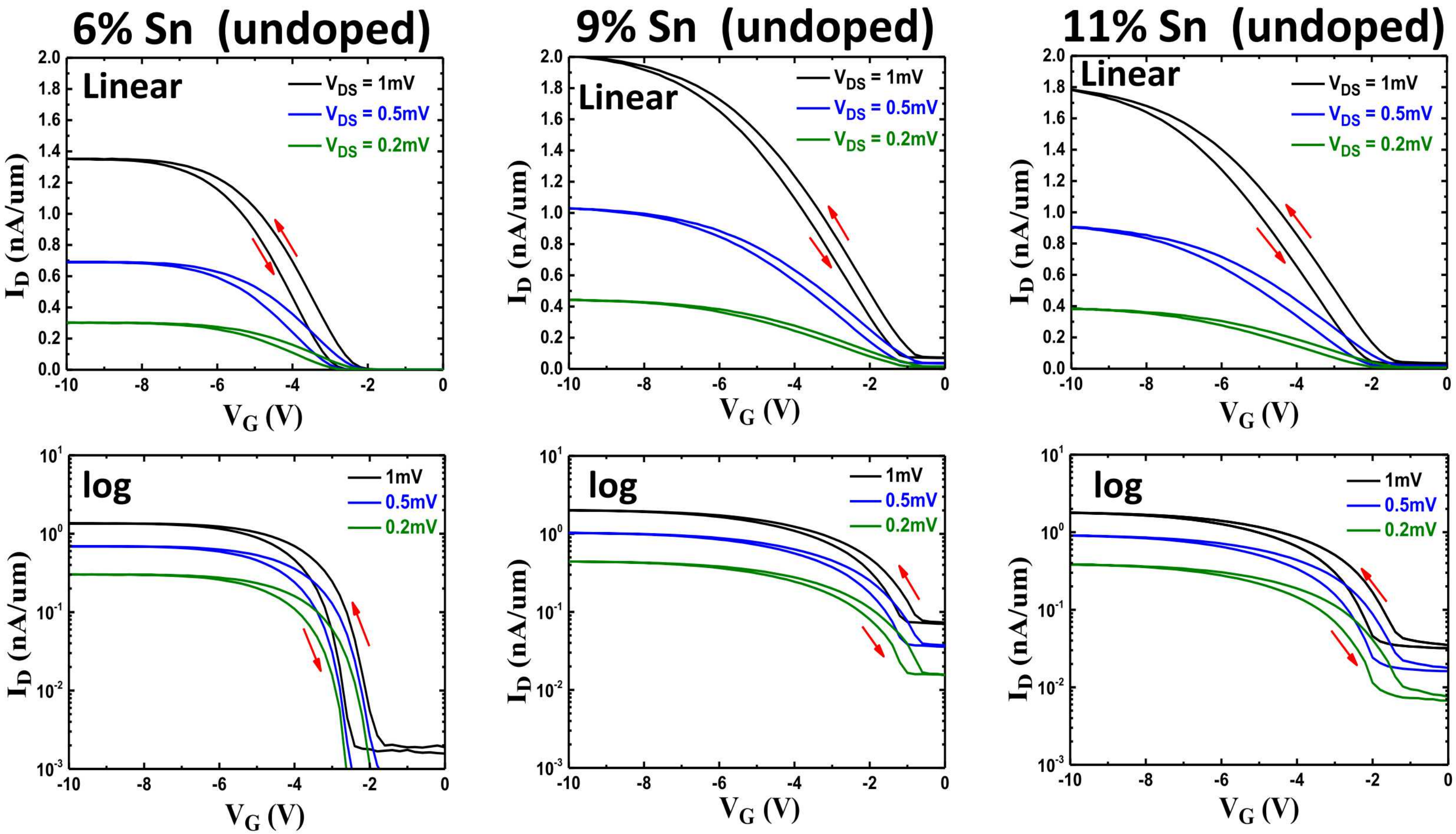
Simulation band diagram



- Two-dimensional hole gas (2DHG) formed in the GeSn quantum well
- Band diagram simulated by Schrodinger + Poisson
  - → Valence band offset at Ge/GeSn creates a QW
  - → [Sn]↑ Valence band offset↑ Quantum confinement↑

Electrical Characterization

I_D-V_G at 4 K



- I_D-V_G curve shows transistor characteristics

Hall measurement at T=1.2K

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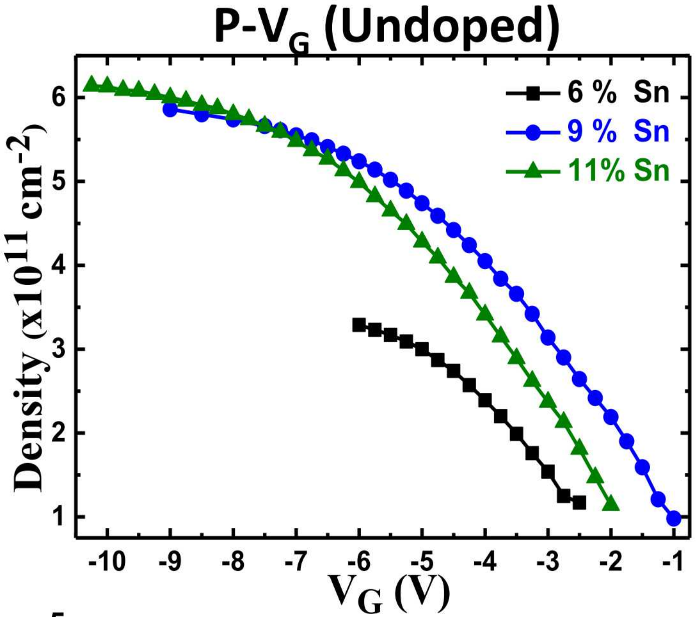

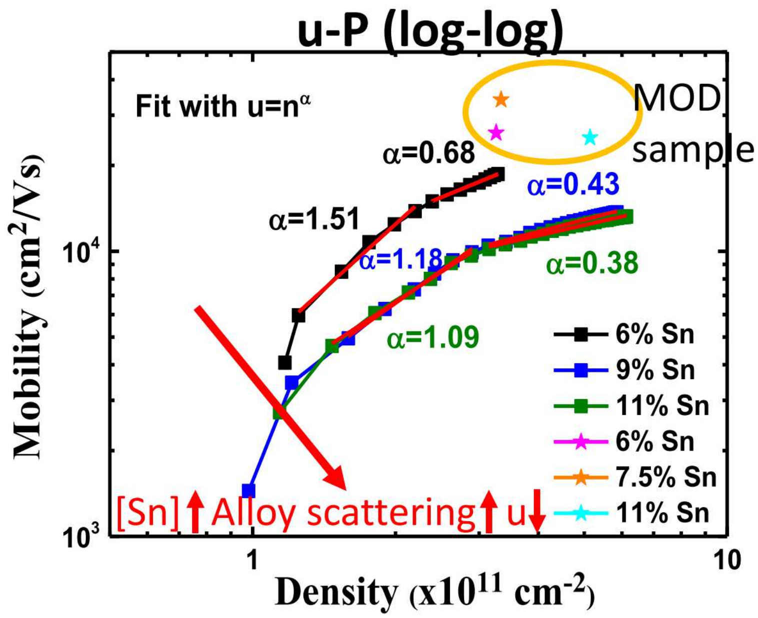

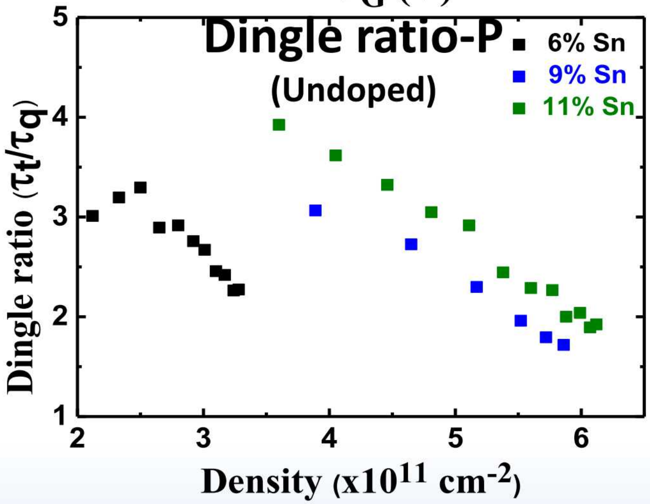

- Hole density increase with V_G and saturated at high bias
- $0.5 \cong \alpha \leq 1.5$ and small dingle ratio
  → Background charge scattering
  (large angle scattering)

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SdH oscillation and Quantum Hall effect

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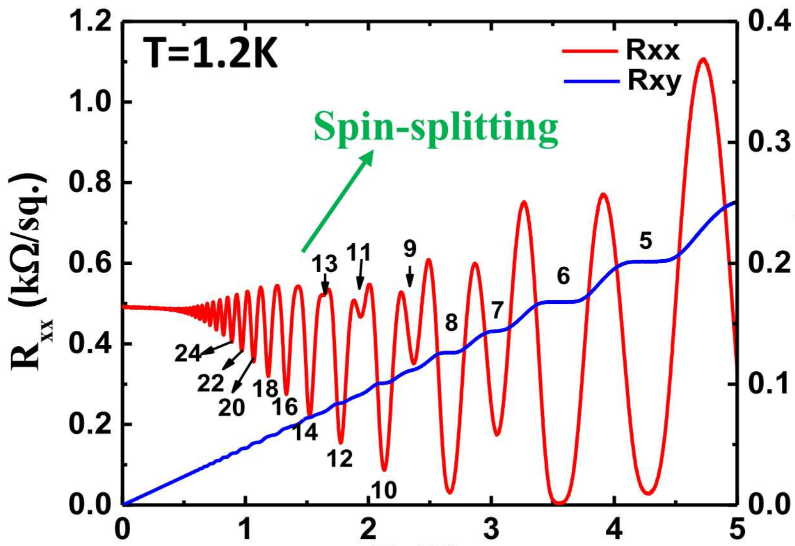
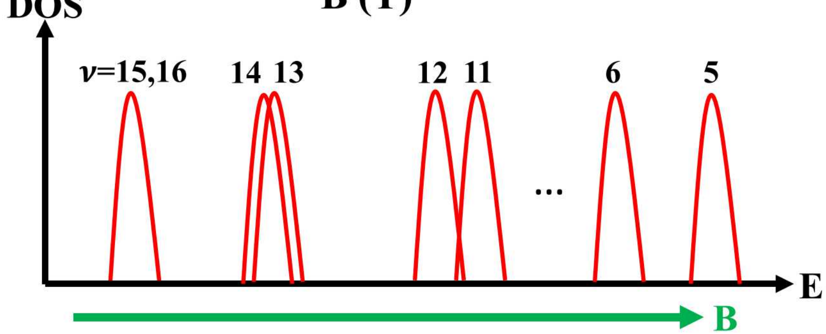
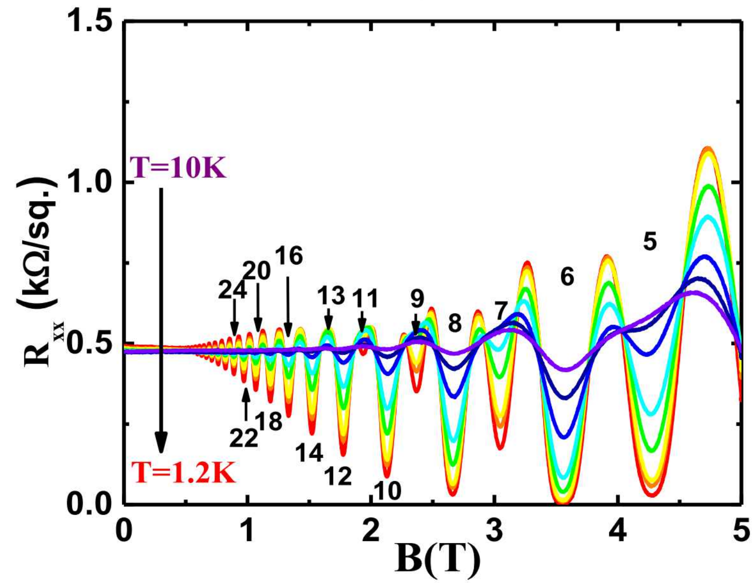
MOD sample (Sn 11%)





MOD sample (Sn 11%)



$$\Delta\rho_{xx(norm)} = \frac{\rho_{xx}(B) - \rho_{xx}(B=0)}{\rho_{xx}(B=0)}$$

$$= 4\frac{aT}{\sinh(aT)} e^{-b} \cos(\Phi) \quad \text{(2012,LTP)}$$

$$a = \frac{2\pi^2 m k_B}{\hbar e B} \quad b = \frac{m\pi}{eB\tau_q}$$

- Integer quantum hall effect and spin-splitting observed at T=1.2K
- Clear temperature-dependent SdH oscillation observed

Effective mass extraction

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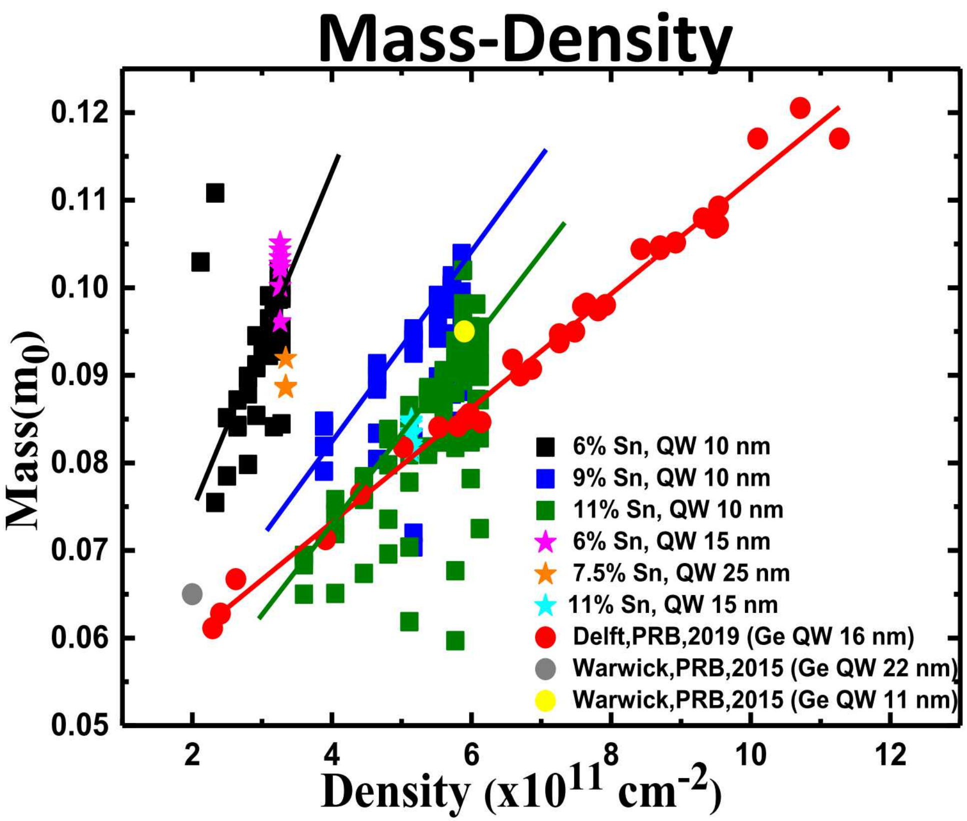

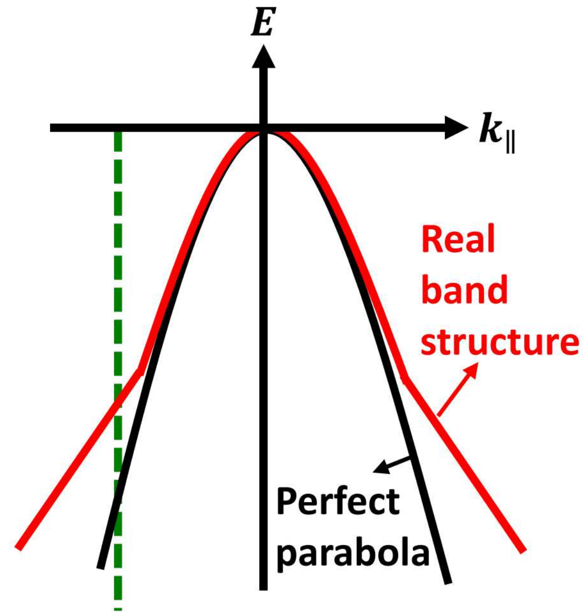

At high k state

Curvature < Curvature

$m^* > m^*$

◆ P↑, m^*↑ → Valence band non-parabolicity

Band non-parabolicity

$\rightarrow \frac{\hbar^2 k^2}{2m^*} = E(1 + \alpha E)$ (1st order)

Originate from band mixing

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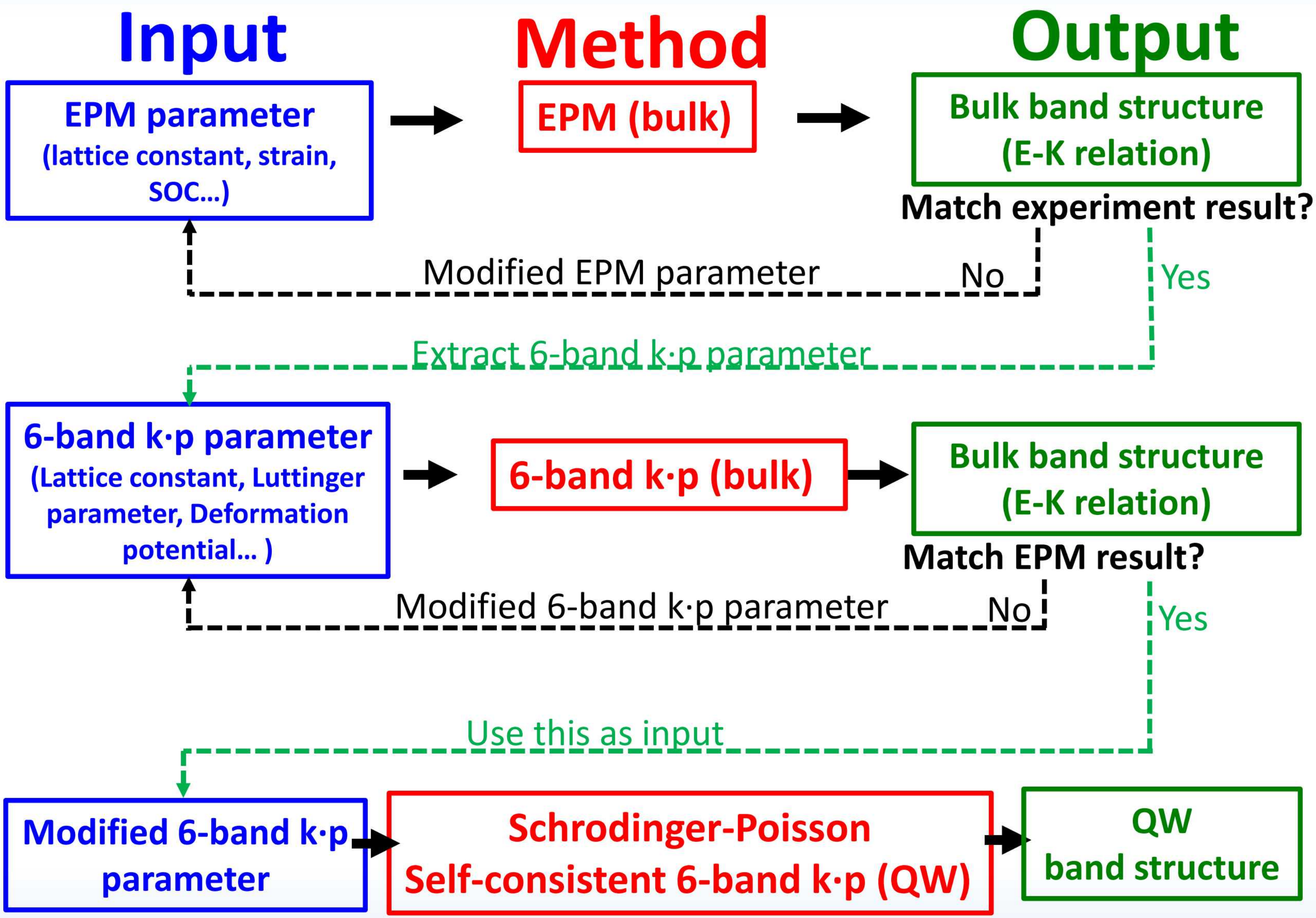
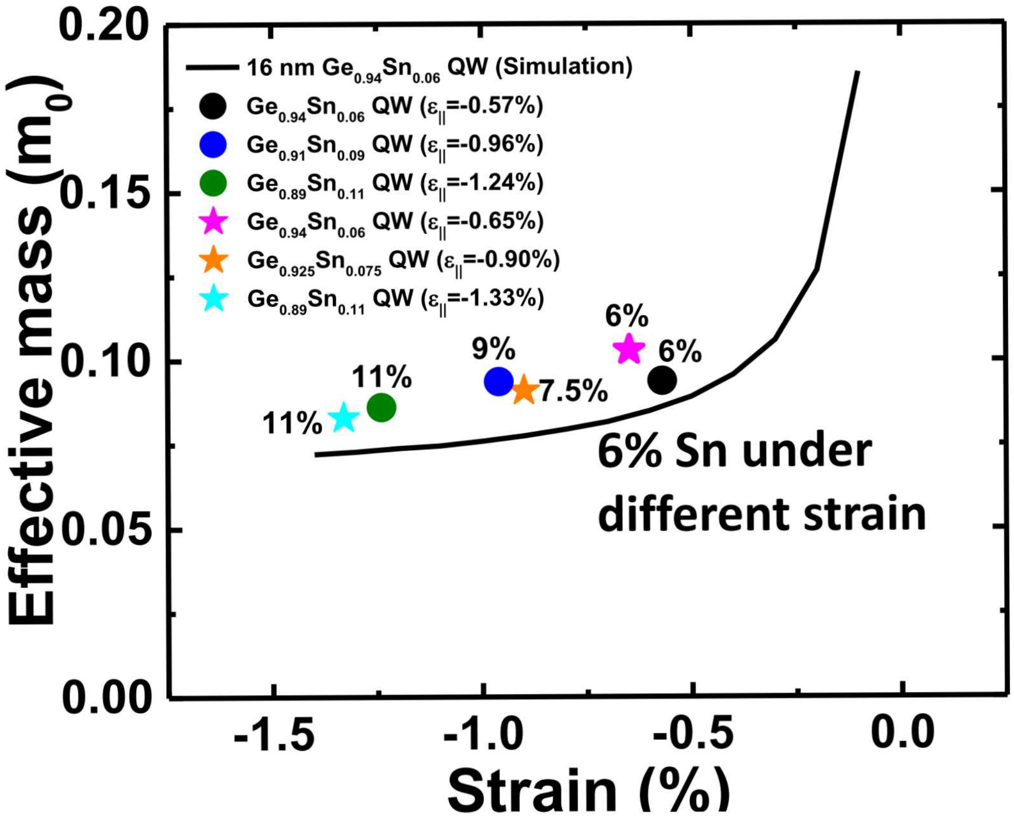
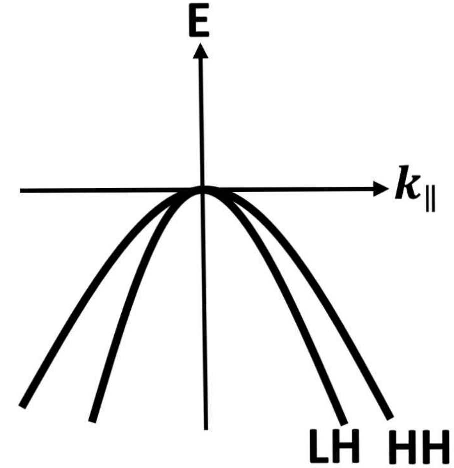
Effective mass simulation



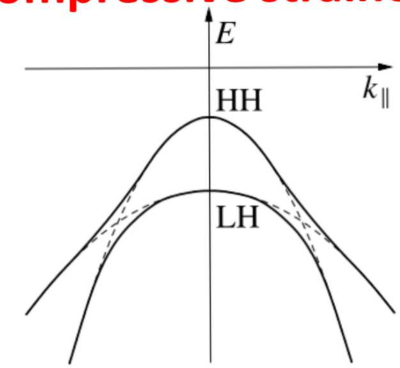
Effective mass simulation



Relaxed GeSn



compressive strained GeSn



◆ Strain↑, m*↓ → Due to deforming of HH-LH band

Conclusions

- Demonstration of enhancement-mode FETs in Ge/GeSn QW structures
- Clear SdH oscillation and Integer Quantum Hall effect observed at high magnetic fields and low temperatures
- Effective mass extraction from temperature-dependent SdH oscillations and the simulation of strain effect on m^*

Acknowledgements

- National Taiwan University (NTU)
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- Sandia National Laboratories

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Thank you very much!

Back up slide

Fabrication Process flow

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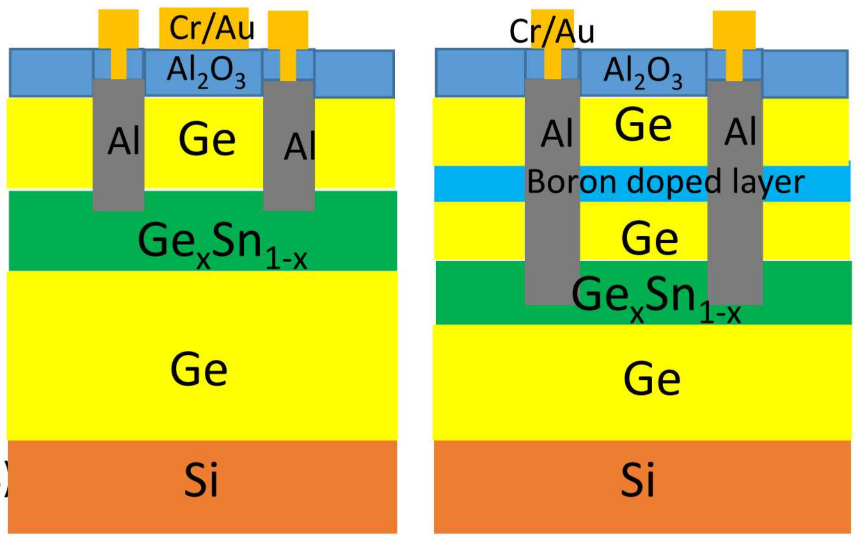
Fabrication process flow of Hall-bar

Undoped
- Deposit Al as contact
- Grow Al_2O_3 by ALD
- Open via by BOE
- Deposit Cr/Au
- Etch back to define gate and contact

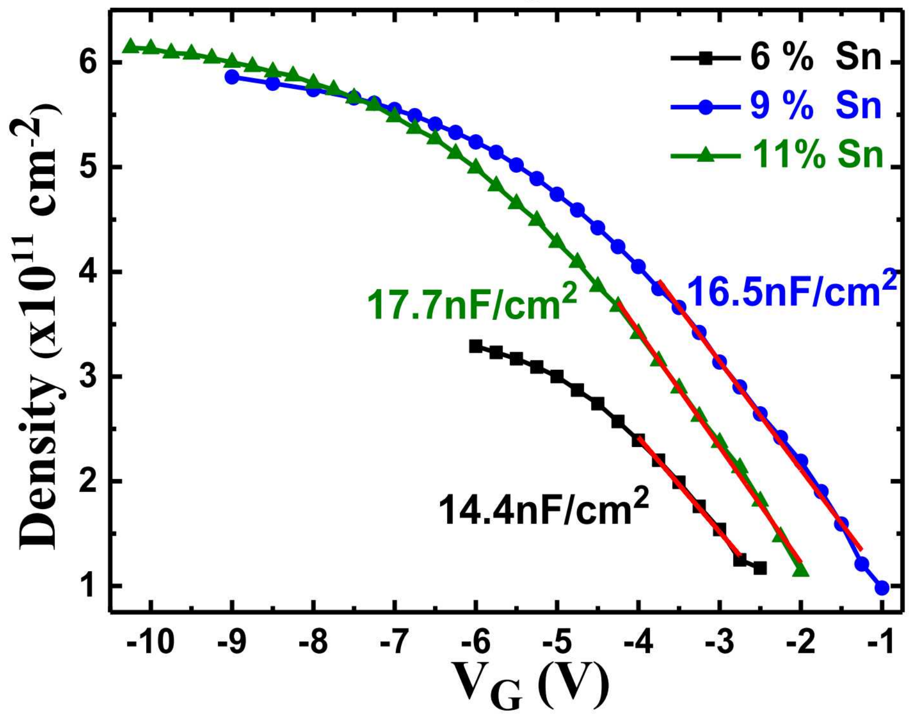
Doped
- Mesa
- Implant Boron
- Annealing (370°C 300s)
- Deposit Cr/Au
- Lift off

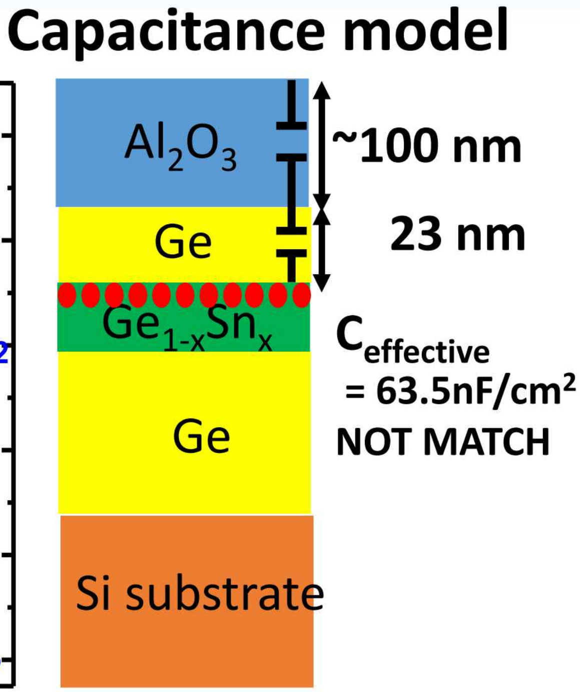
◆ No Gate for doped sample

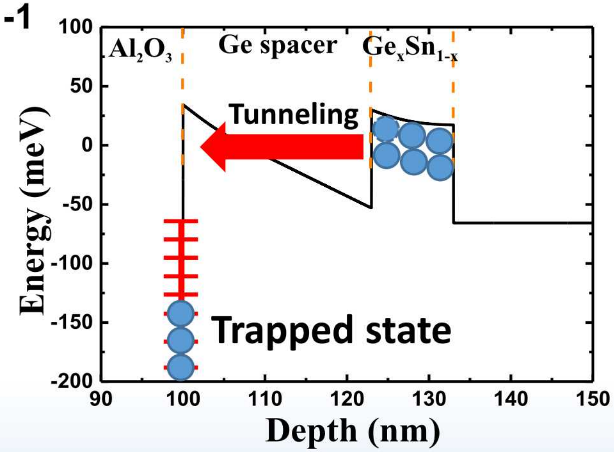
Undoped **MOD**



Hall measurement at T=1.2K



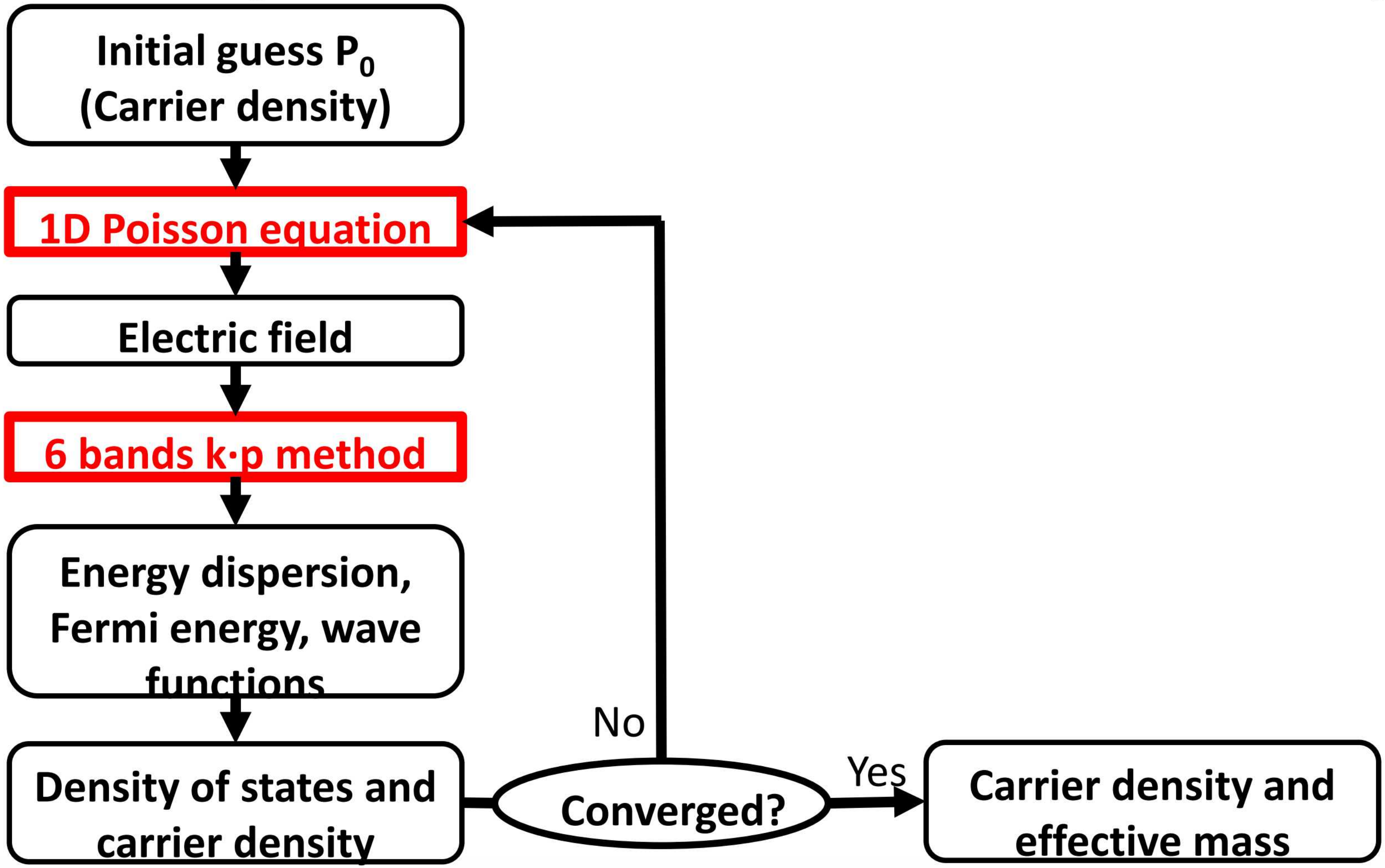




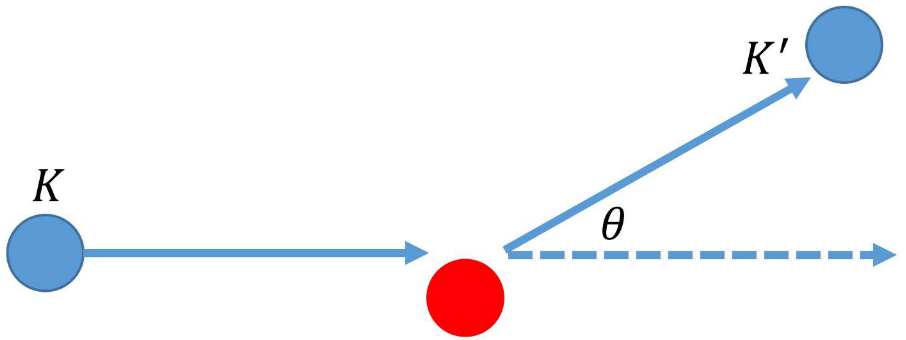
Probable reason : The induced carrier tunnel to the trapped state, since the immobile carrier can not measure by Hall measurement → Q=CV

Simulation

Schrodinger-Poisson Self-consistent 6-band k·p



Dingle-ratio



$$\alpha = \frac{\tau_{trans}}{\tau_q} = \frac{\frac{1}{\tau_q}}{\frac{1}{\tau_{trans}}} = \frac{\int w(k,k')}{\int w(k,k')(1-\cos(\theta))}$$

- **Remote charge scattering (small angle scattering)**
  →Dingle ratio↑
  Background charge scattering (large angle scattering)
  →Dingle ratio close to unity

Electrical characterization

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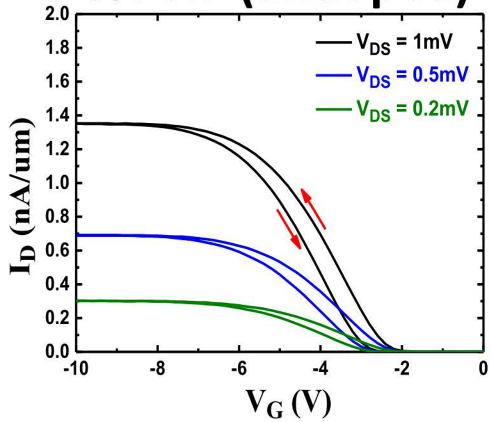
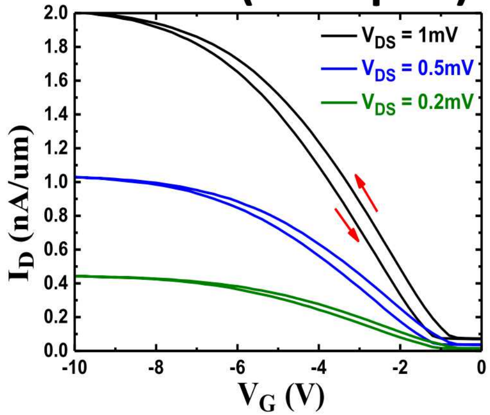
I_D-V_G at 4 K

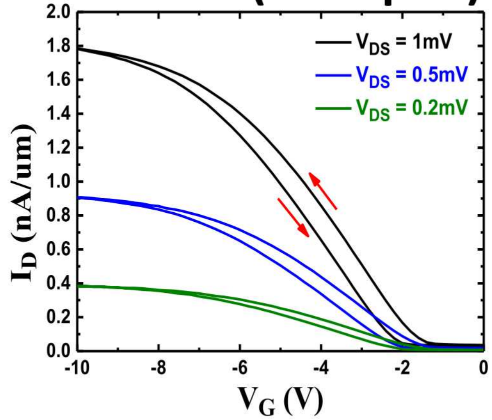
6% Sn (undoped)



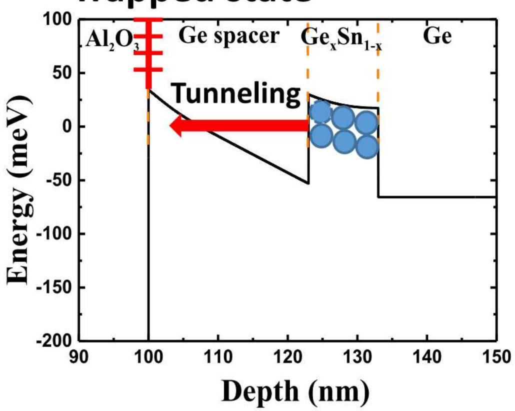
9% Sn (undoped)



11% Sn (undoped)

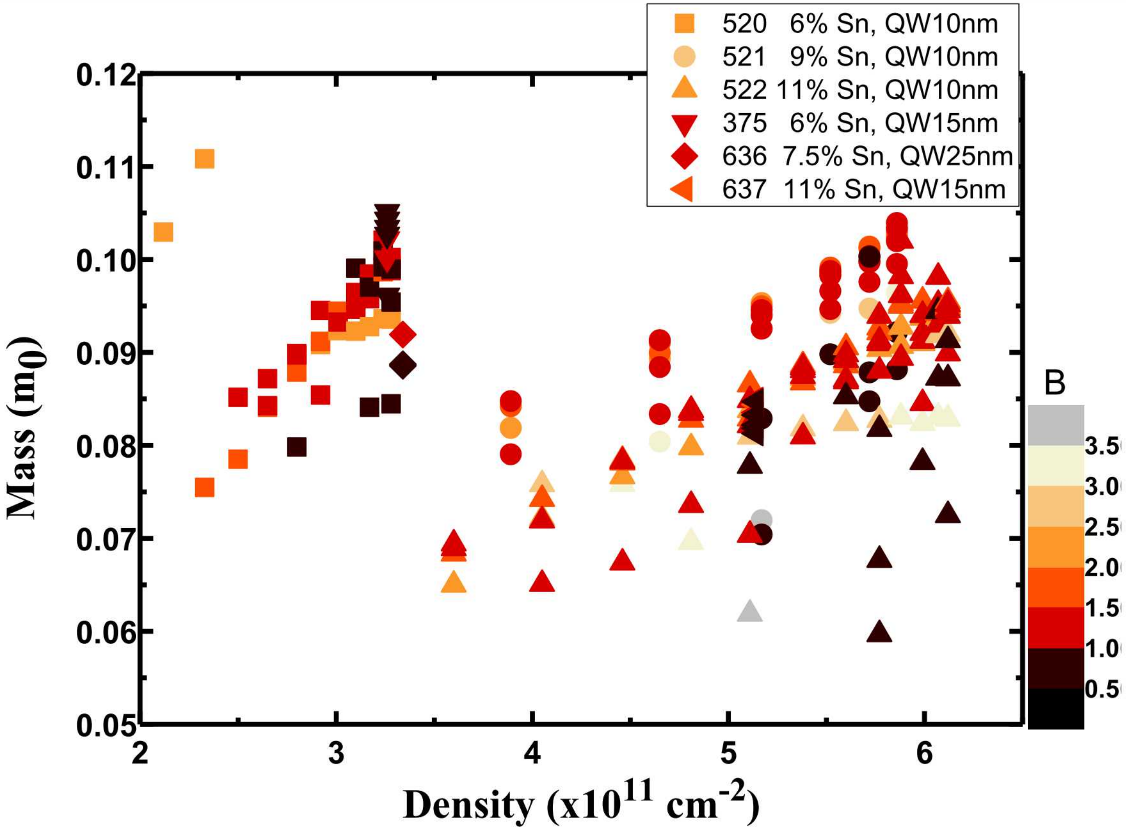


Trapped state



- I_D saturate at high gate bias
  → Surface tunneling* *APL (2017)

Effective mass extraction



From this plot, we can see that the intermediate magnetic field gives more reasonable m^*

For large and small B, the deviation is big