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NTUEE Quantum Electronics Lab

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Weak anti-localization in undoped Ge/GeSn heterostructures

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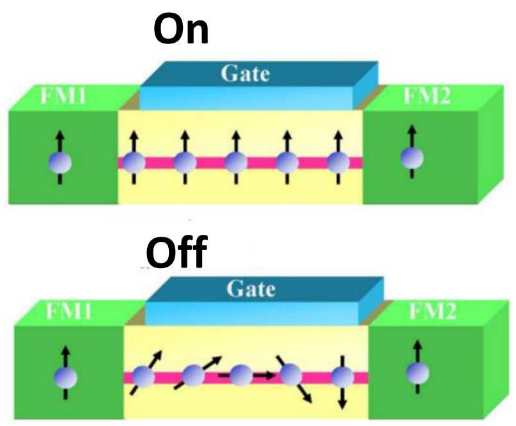
Outline

- Motivation
- Epi structures and device structures
- Magneto-transport at low temperature
- Weak antilocalization and Spin-orbit Coupling
- Conclusions

Motivation

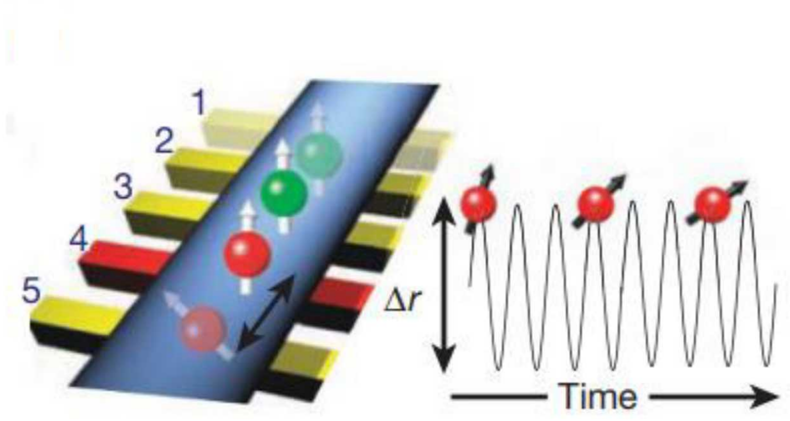
Spin computing devices

Spin-FETs



2010 Proc. IEEE

Spin-orbit qubits

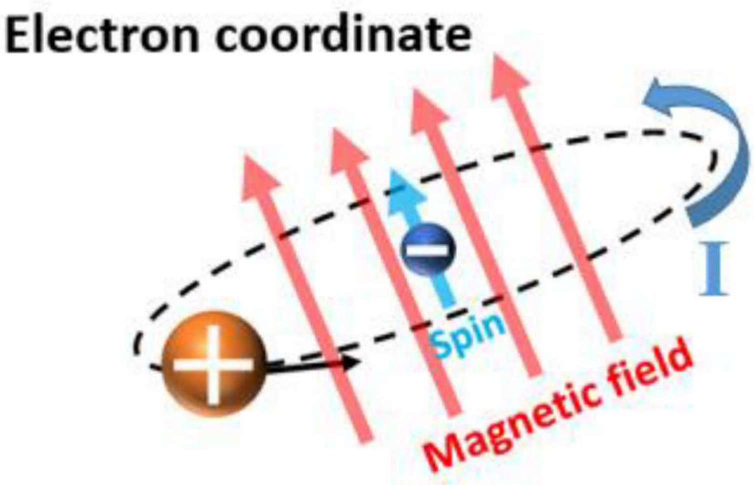


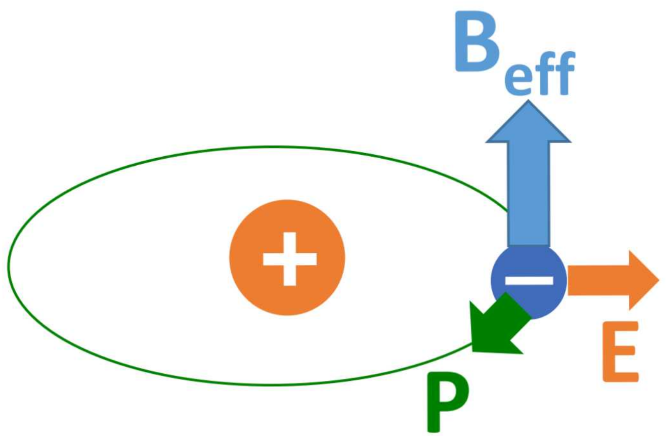
2010 Nature

- ◆ Spin FETs → Manipulate spins via SOC to control on/off
- ◆ Spin-based QC → Manipulate spins via SOC to operate qubits

Motivation

Spin manipulation→ SOC





$$H_{SO} = -\mu_B \sigma \left(\frac{\vec{P} \times \vec{E}}{2 m_0 C}\right)$$

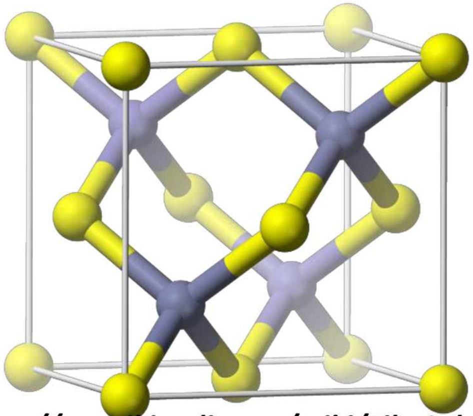
B_{eff}

- e^- will feel an effective magnetic field due to the relative motion between e^- and atom
- Spin orientation changes by the effective magnetic field

Motivation

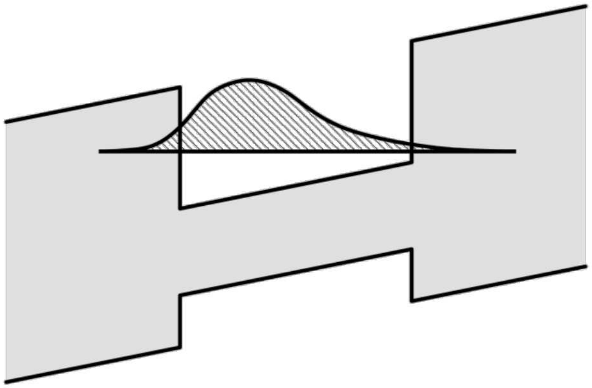
Dresslhaus and Rashba Spin-orbit Coupling

Dresselhaus



https://en.wikipedia.org/wiki/File:Sphalerite-unit-cell-depth-fade-3D-balls.png

Rashba



Winkler, Spin-Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems, 2003.

- **Dresselhaus SOC**
  - → Arising from bulk inversion asymmetry
  - → Exist in zinc blende structure (III-V material)
- **Rashba SOC**
  - → Arising from structure inversion asymmetry
  - → Tunable by external gating

Motivation

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Why focus on GeSn SOC?

	Ge 2DHG (C)	*2014,PRL* Ge 2DHG (C)[24]	*2002,PRB* Si 2DEG[23] (L)
Low Temperature Mobility (cm^2/Vs)	450 000	~5 000	200 000
Rashba spin-orbit parameter α or β	1.0×10^{-28} eVm^3	0.2×10^{-28} eVm^3	5.5×10^{-15} eVm
Rashba spin-orbit energy (meV)	1.4	0.30	~0.001
Lattice mis-match strain	0.8%	2.1%	...

2014,APL

C 0.006
Si 0.044
Ge 0.29
Sn 0.80

Winkler, 2003

Split-off band energy (eV)

Stronger SOC

◆**GeSn is expected to have larger SOC, and is compatible to Si VLSI Technology**

Ge/GeSn Epitaxial Structures

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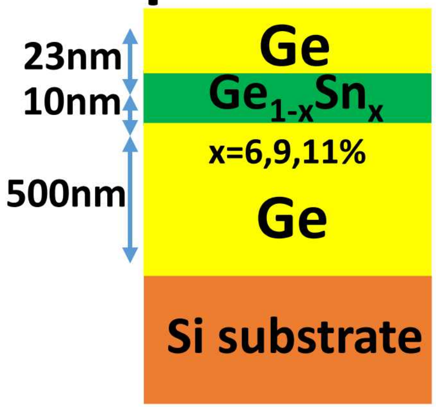
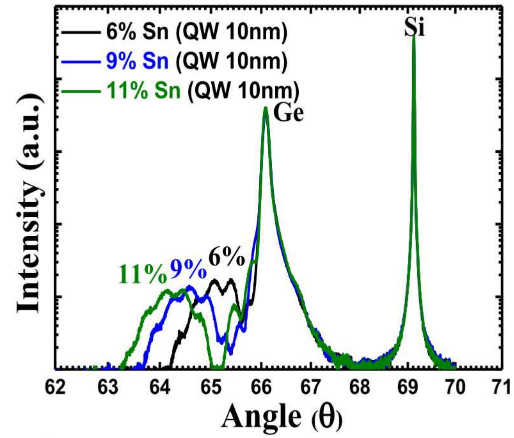
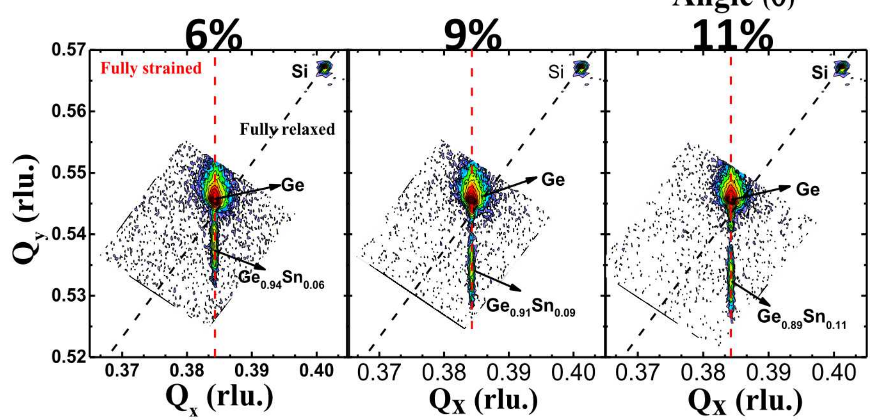
Epi structure



XRD





- [Sn]=6,9,11% and thickness = 10 nm by XRD
- GeSn is fully strain on Ge layer with ϵ = -0.57%,-0.96%,-1.24%

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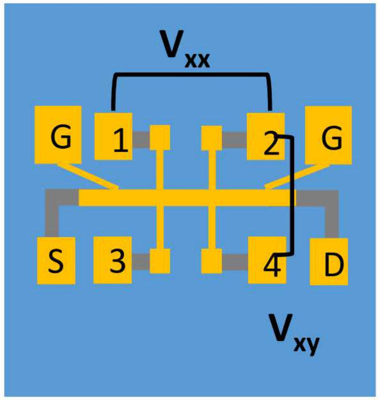
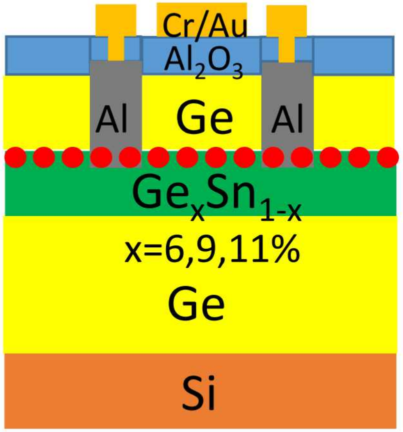
Device Structure

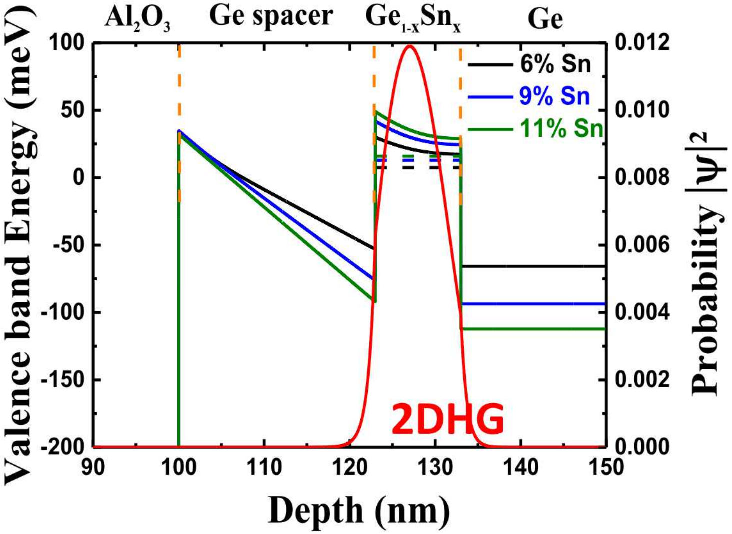
Top view



Side view



Simulation band diagram



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

Hall measurement at T=1.2K

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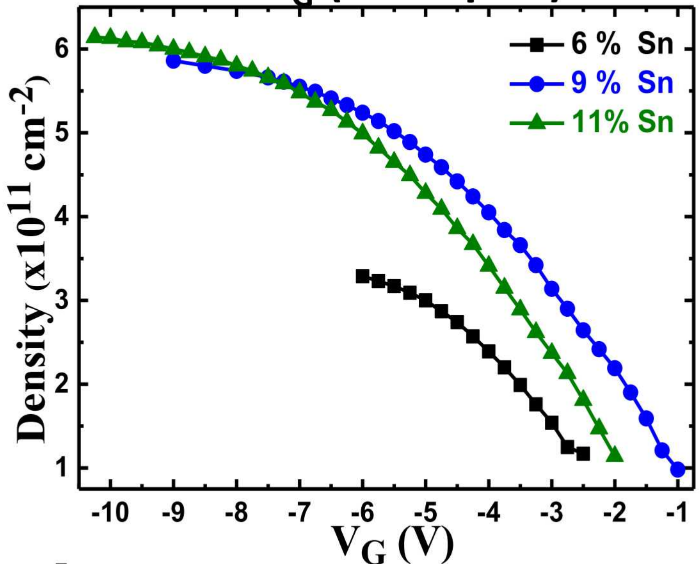
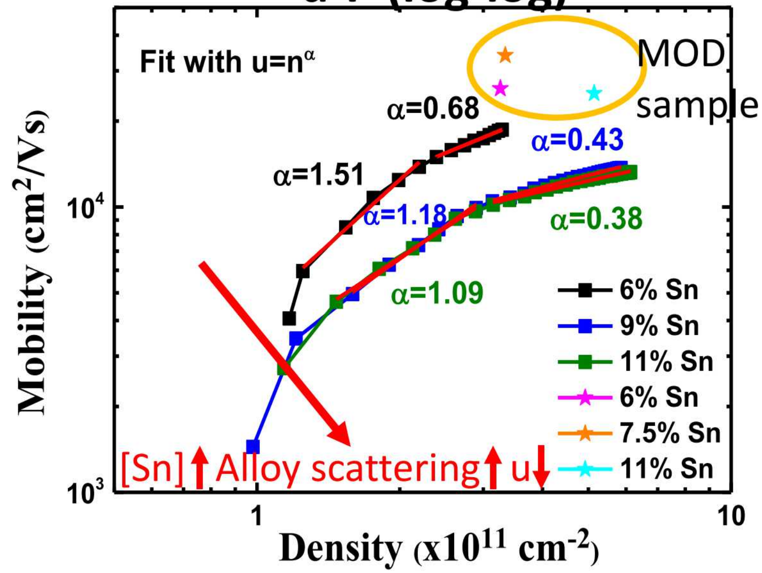
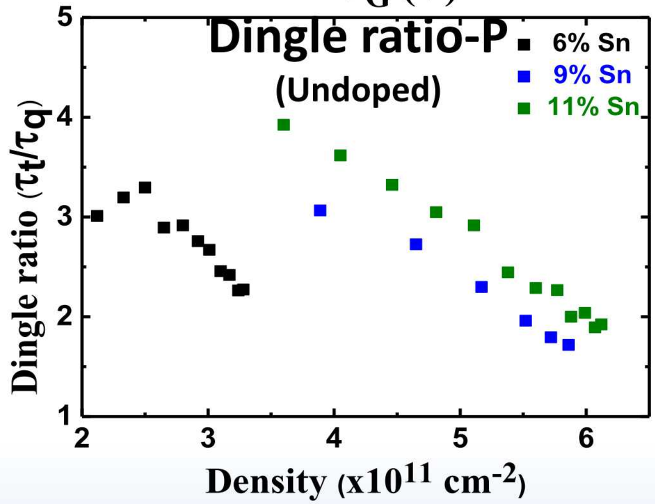
P-V_G (Undoped)



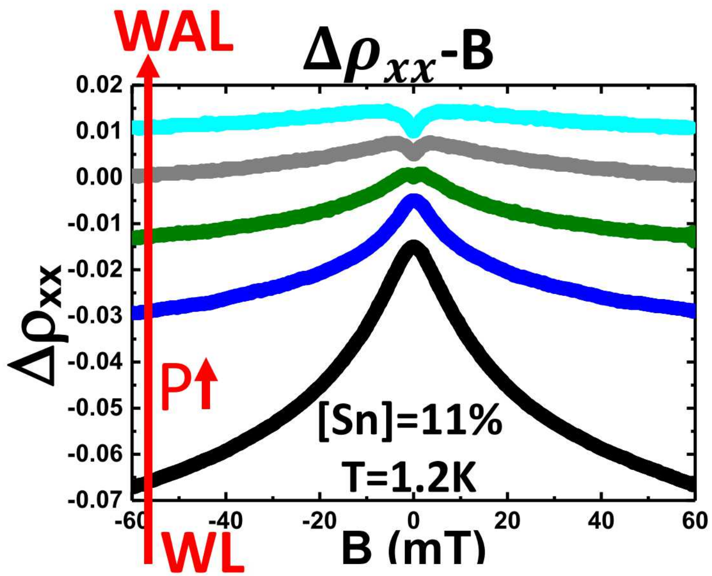
u-P (log-log)

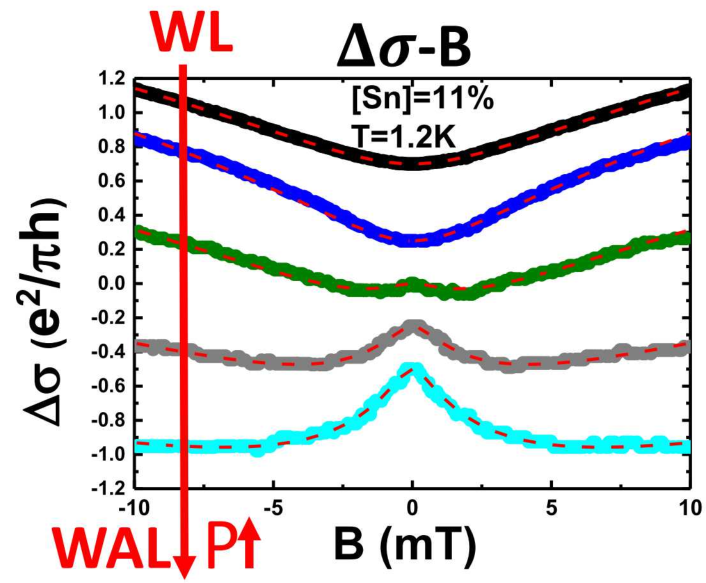


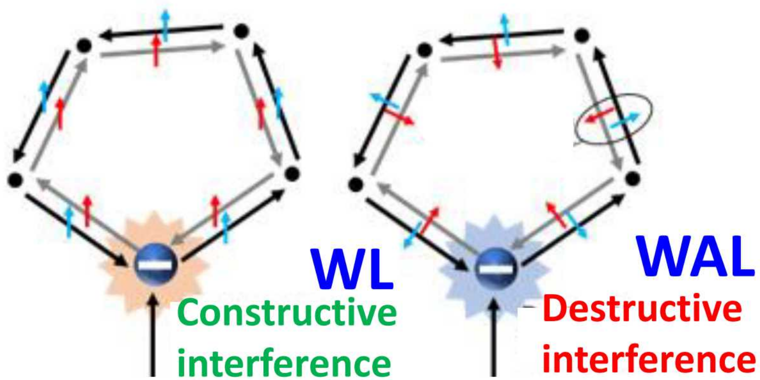


- Hole density increase with V_G and saturated at high bias
- $0.5 \cong \alpha \leq 1.5$ and small dingle ratio
  → Background charge scattering
  (large angle scattering)

Weak Antilocalization Effect







HLN formula *2012,PRL*

$$\Delta\sigma(B)-\Delta\sigma(0) = \frac{e^2}{2\pi^2\hbar}\left\{\psi\left(\frac{1}{2}+\frac{B_\varphi}{B}+\frac{B_{SO}}{B}\right) + \frac{1}{2}\psi\left(\frac{1}{2}+\frac{B_\varphi}{B}+\frac{2B_{SO}}{B}\right) - \frac{1}{2}\psi\left(\frac{1}{2}+\frac{B_\varphi}{B}\right) - \ln\frac{B_\varphi+B_{SO}}{B} - \frac{1}{2}\ln\frac{B_\varphi+2B_{SO}}{B} + \frac{1}{2}\ln\frac{B_\varphi}{B}\right\}$$

- The $\Delta\rho_{xx}$ shows the transition from WL→WAL when P↑
- The red-dashed line shows the fitting result with HLN formula

Characteristic Time/Length

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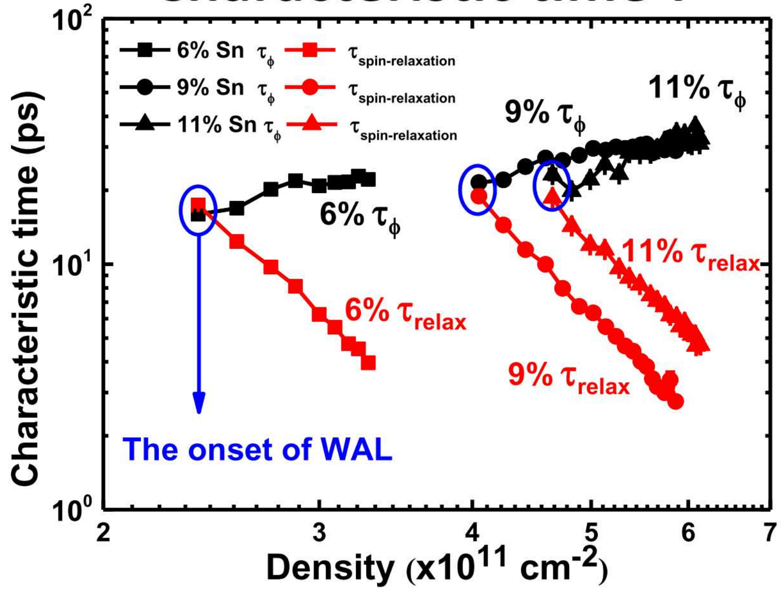
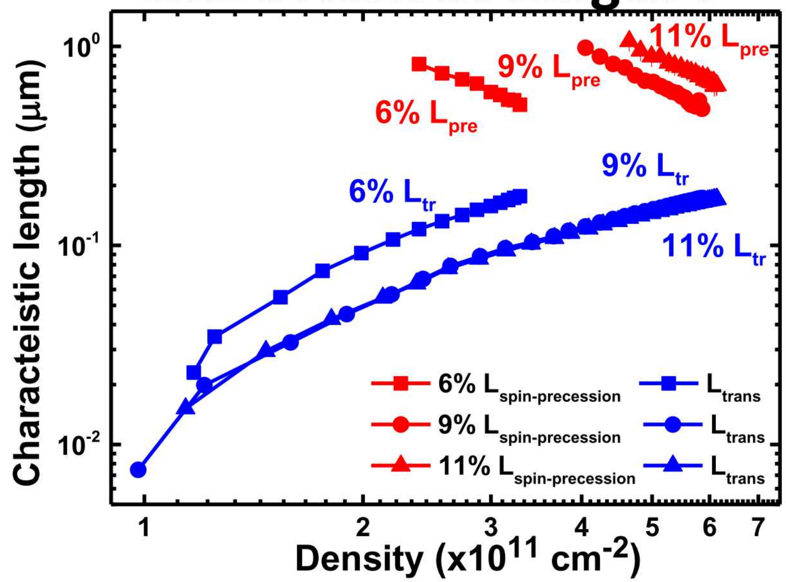
Characteristic time-P



Characteristic length-P



$$B_{SO(\phi)} = \frac{\hbar}{4eD\tau_{SO(\phi)}}$$

DP spin-relaxation mechanism

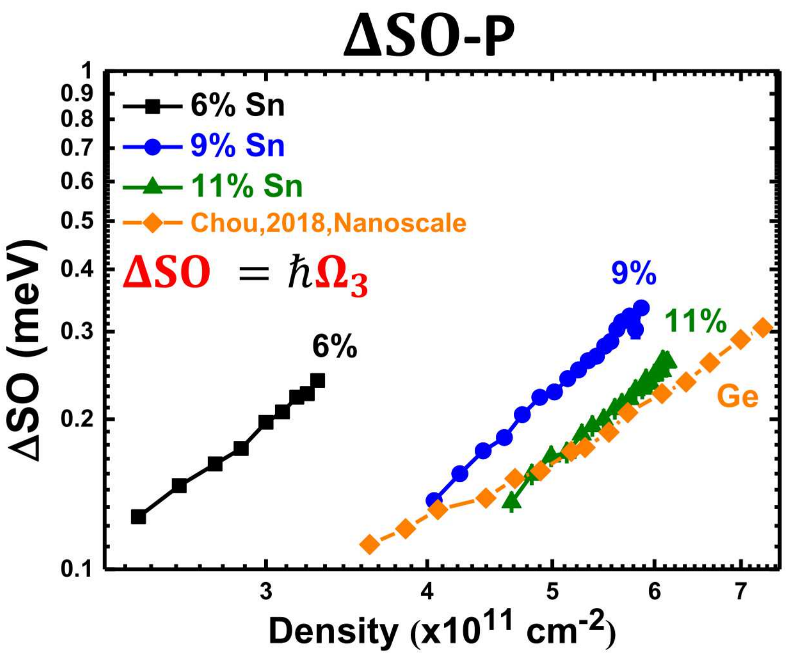
$$\frac{1}{\tau_{SO}} = 2|\Omega_3|^2\tau_{trans}$$

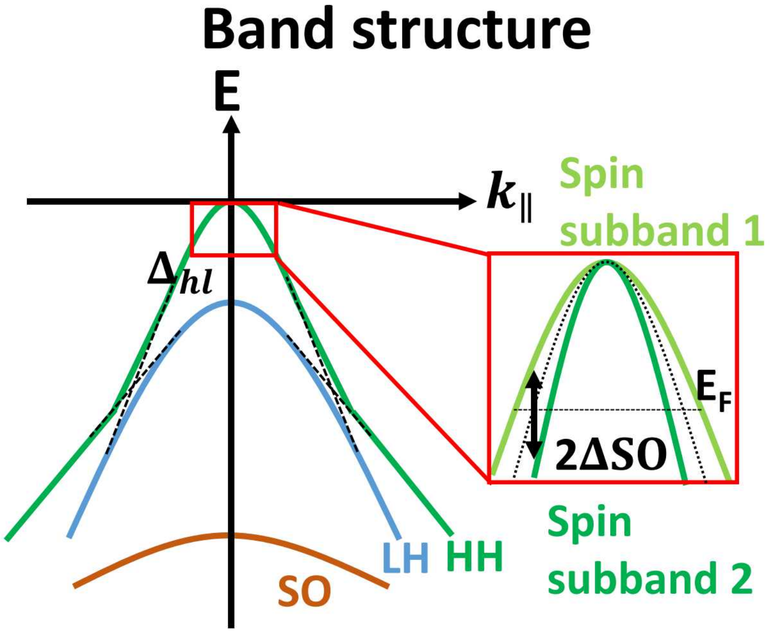
Spin precession frequency

2018,Nanoscale.

- [Sn]↑, τ_{relax}↑, SOC↓ → Due to strain effect
- $L_{precess} < L_{transport}$ (spin-diffusive regime) → HLN is eligible

Spin-subband splitting

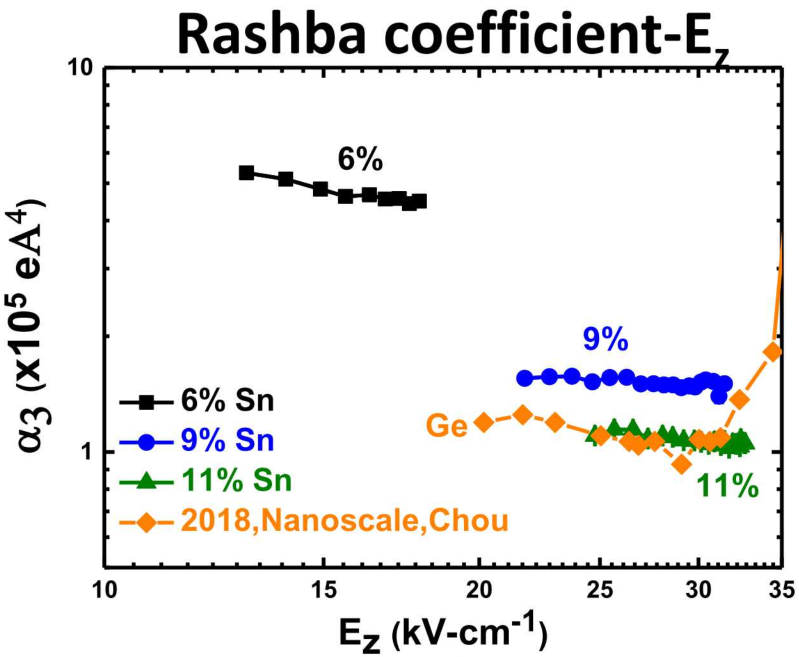


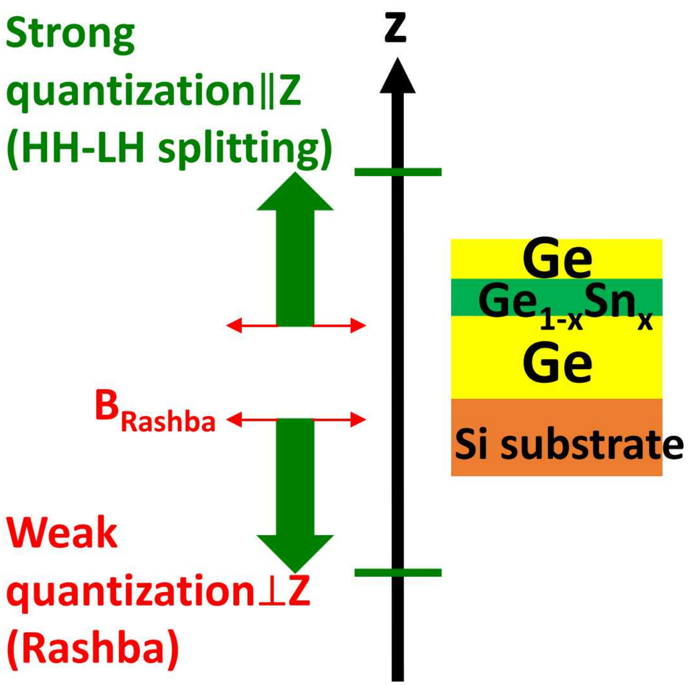


Spin-splitting due to Rashba SOC

- [Sn]↑, ΔSO↓, SOC↓ → Due to strain effect
- Spin degeneracy of HH band broken by SOC

Rashba Coefficient Extraction





$$\Delta SO = \alpha_3 E_z (k_F)^3$$

$$H_{SO} = \alpha_3 E_z i (k_-^3 \sigma_+ - k_+^3 \sigma_-)$$

2018,Nanoscale

$$\alpha_3 = a\gamma_3(\gamma_2+\gamma_3)\frac{e\hbar^4}{m_0^2}\left[\frac{1}{\Delta_{11}^{hl}}\left(\frac{1}{\Delta_{12}^{hl}}-\frac{1}{\Delta_{12}^{hh}}\right)+\frac{1}{\Delta_{12}^{hl}\Delta_{12}^{hh}}\right]$$

2004,APL

- [Sn]↑, α_3↓ → HH-LH splitting affects Rashba SOC
- HH-LH splitting quantized in z direction
  B$_{Rashba}$ quantized in x-y plane

} Δ_{hl}↑α↓

Conclusions

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- Demonstration of magneto-transport in Ge/GeSn QW structures
- Clear transition from WL→WAL, and Rashba coefficient, spin-subband splitting energy has extracted
- The experiment result shows a negative strain effect on SOC

Acknowledgements

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- National Taiwan University (NTU)
- Ministry of Science and Technology (MOST)
- Center for Integrated Nanotechnologies (CINT)
- Sandia National Laboratories

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Thank you very much!

Back up slide

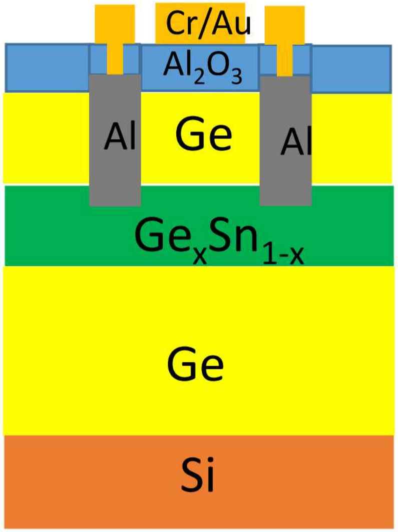
Fabrication Process flow

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

Undoped



D'yakonov-Perel (DP) spin relaxation

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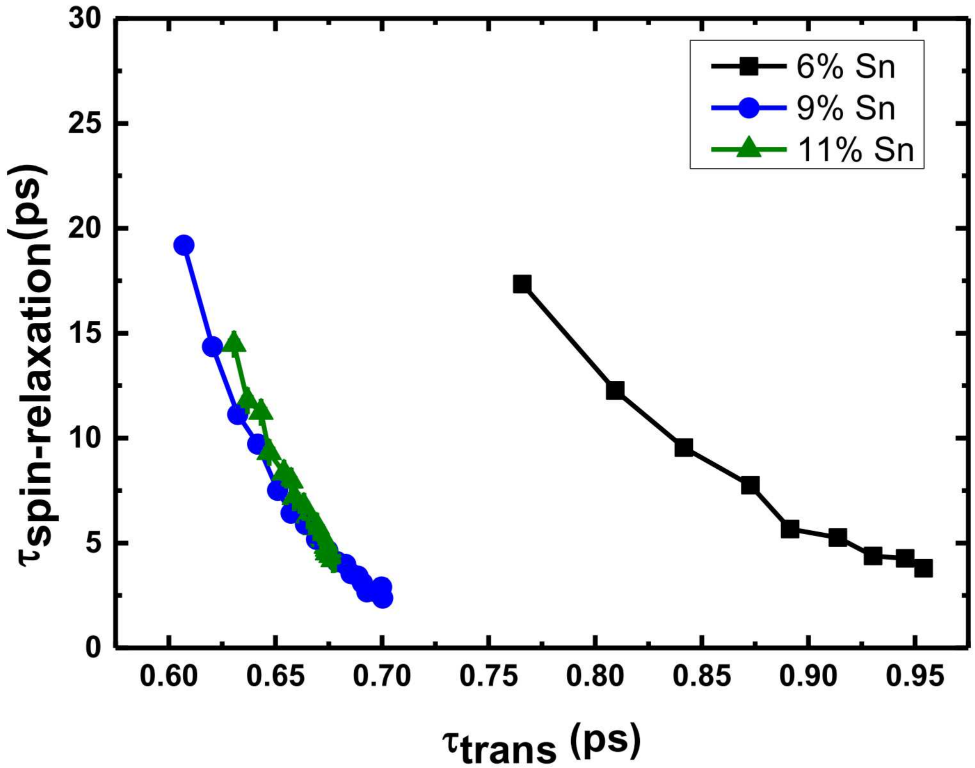
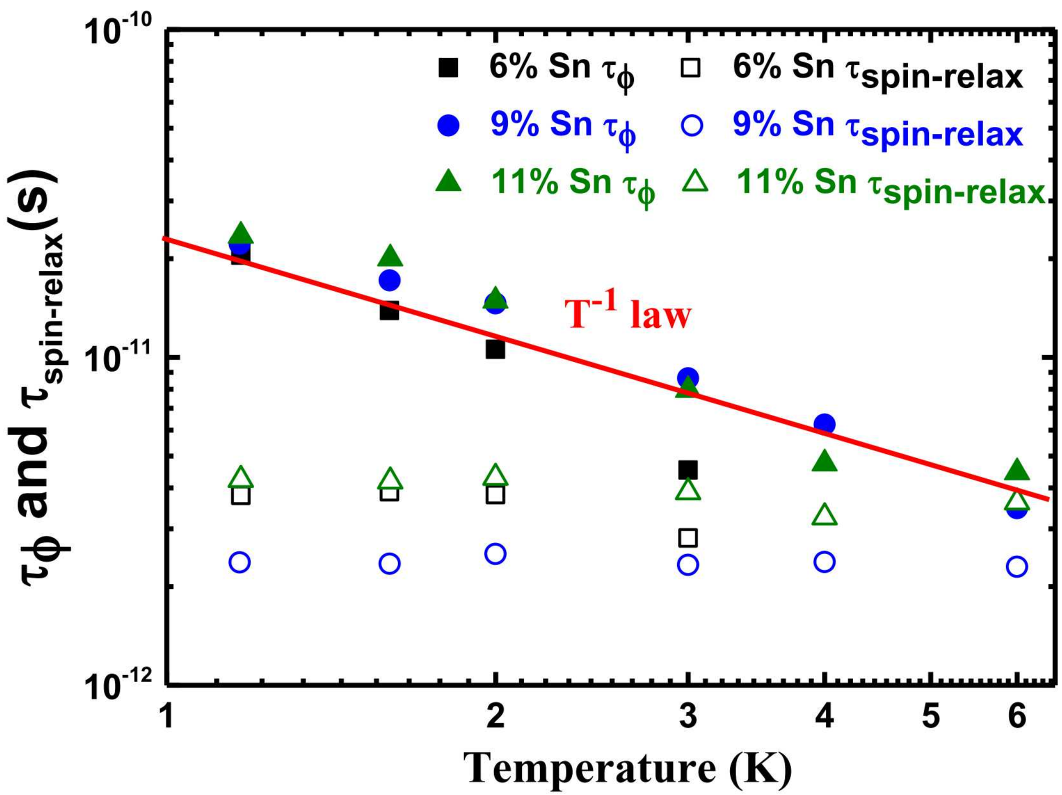


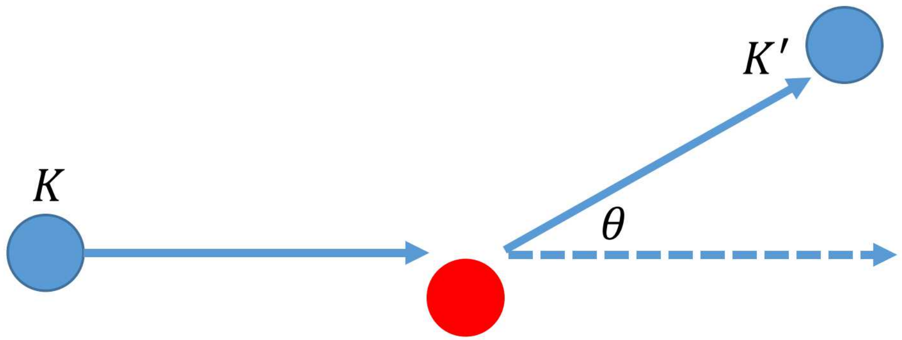
- $\tau_{spin-relax}$ is inverse proportional to τ_{trans}
  → An indication of DP spin-relaxation mechanism

Temperature Dependence



- $\tau_\phi \propto T^{-1}$ → e⁻-e⁻ interaction dephasing is dominant
- $\tau_{spin-relax}$ is independent of temperature

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