University of Basel | Journal Club

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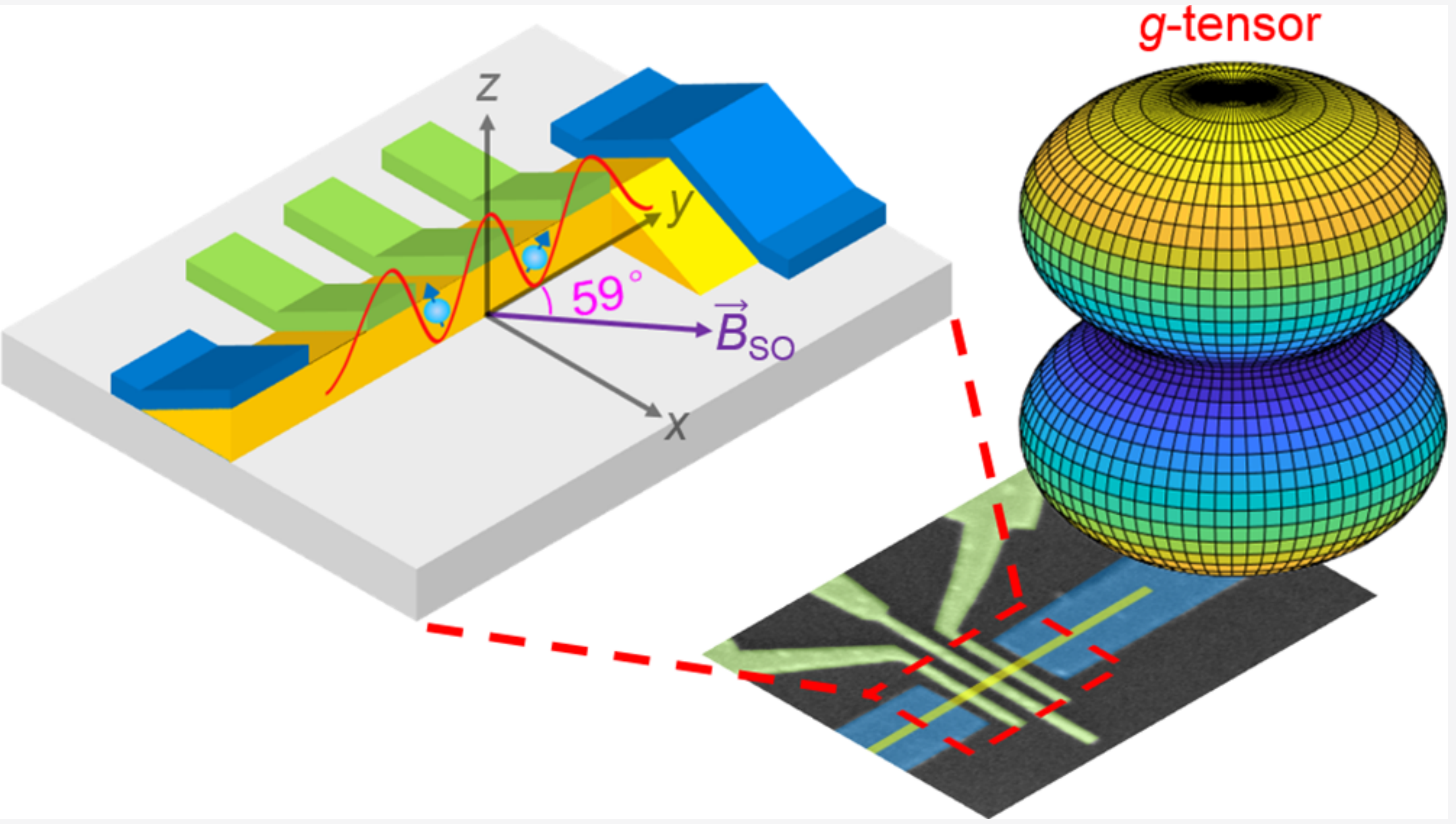
Anisotropic g-Factor and Spin-Orbit Field in a Germanium Hut Wire Double Quantum Dot

ABSTRACT: Holes in nanowires have drawn significant attention in recent years because of the strong spin−orbit interaction, which plays an important role in constructing Majorana zero modes and manipulating spin−orbit qubits. Here, from the strongly anisotropic leakage current in the spin blockade regime for a double dot, we extract the full *g*-tensor and find that the spin−orbit field is in plane with an azimuthal angle of 59° to the axis of the nanowire. The direction of the spin−orbit field indicates a strong spin−orbit interaction along the nanowire, which may have originated from the interface inversion asymmetry in Ge hut wires. We also demonstrate two different spin relaxation mechanisms for the holes in the Ge hut wire double dot: spin-flip co-tunneling to the leads, and spin−orbit interaction within the double dot. These results help establish feasibility of a Ge-based quantum processor.



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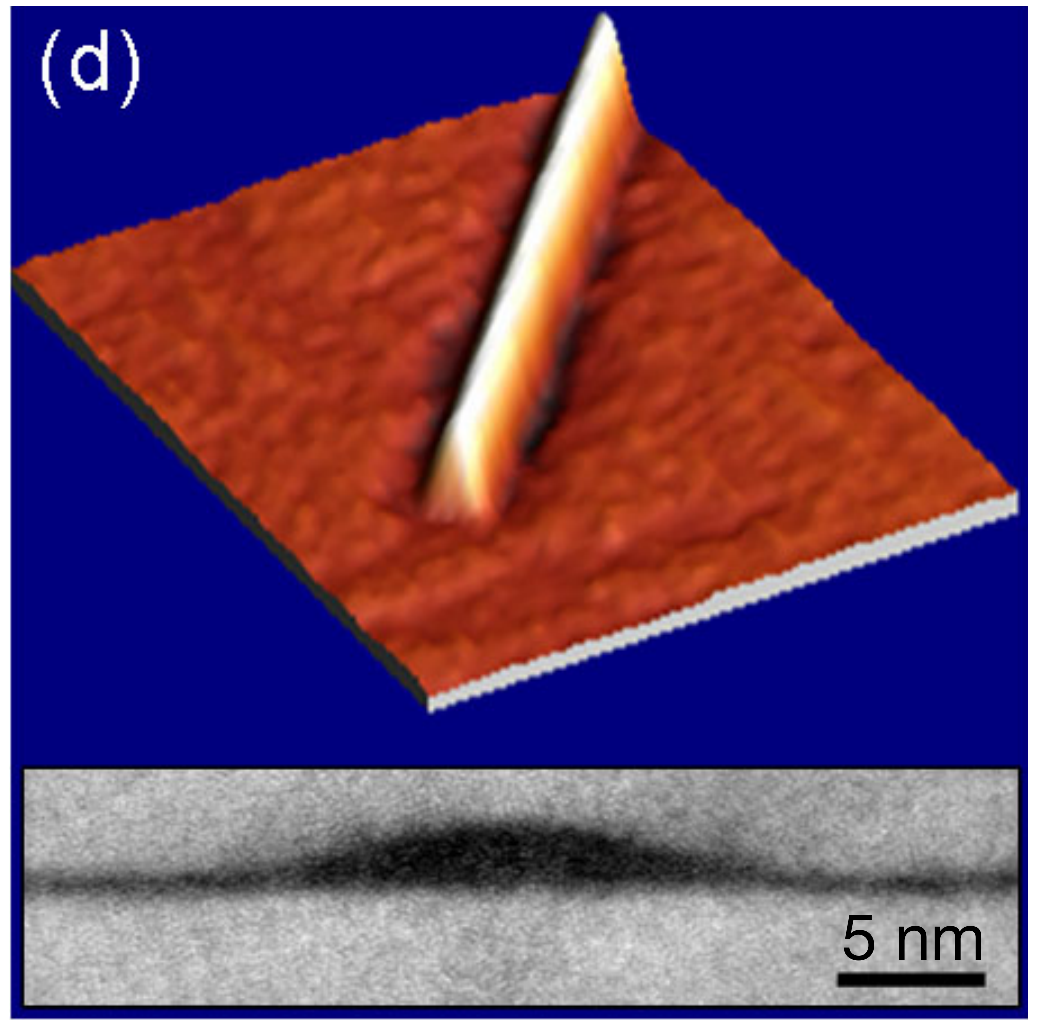
Outline

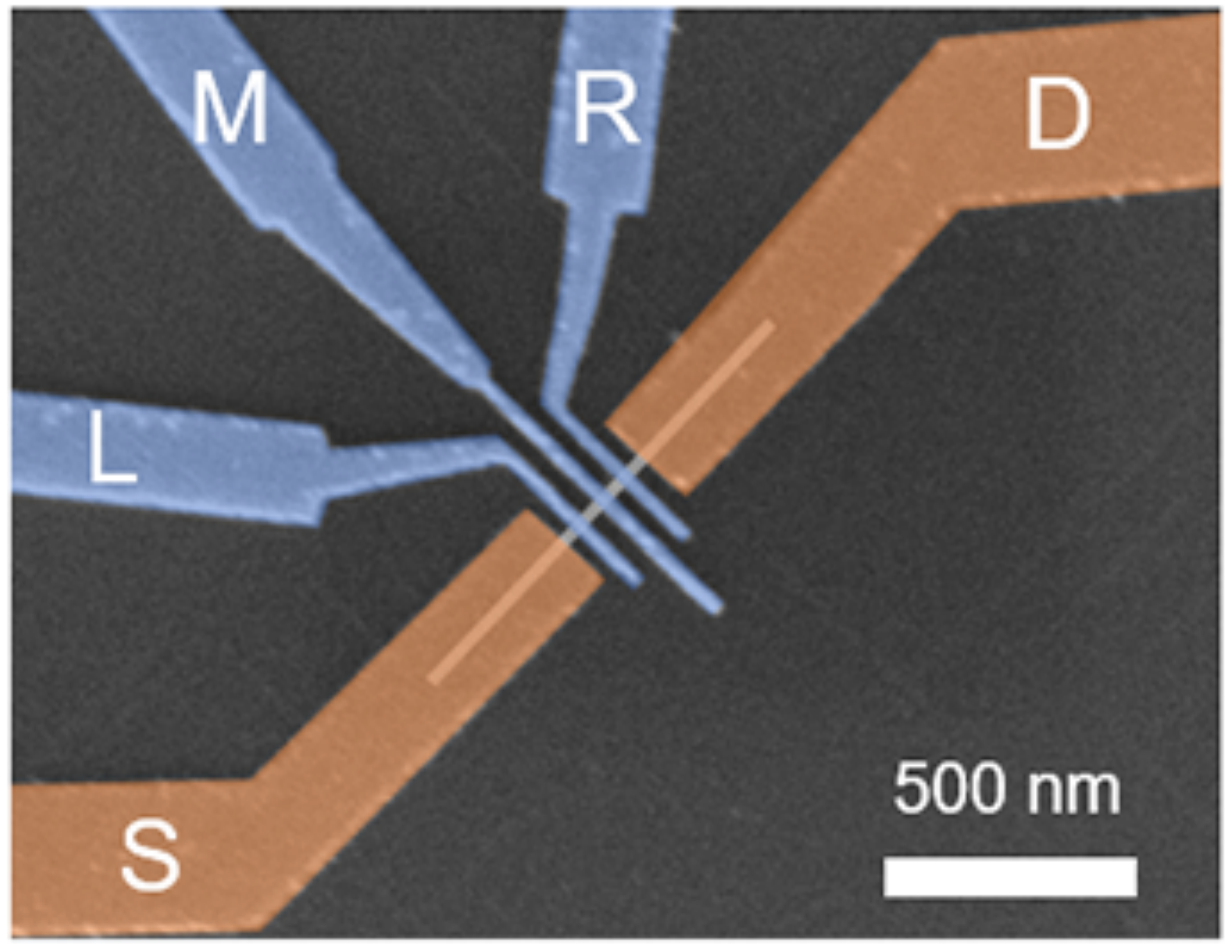
- Device
- Experimental Method: **PSB —> look at (anisotropic) leakage**
- Dominant leakage #1: **spin-flip cotunneling** —> in-plane g-factor
- Dominant leakage #2: **SOI** —> extract: **i)** B_{SO}, **ii)** out of plane g-factor**, iii)** g-anisotropy
- **Ratio** of (Direct-) Rashba & Dresselhaus **SOI**
- Conclusion

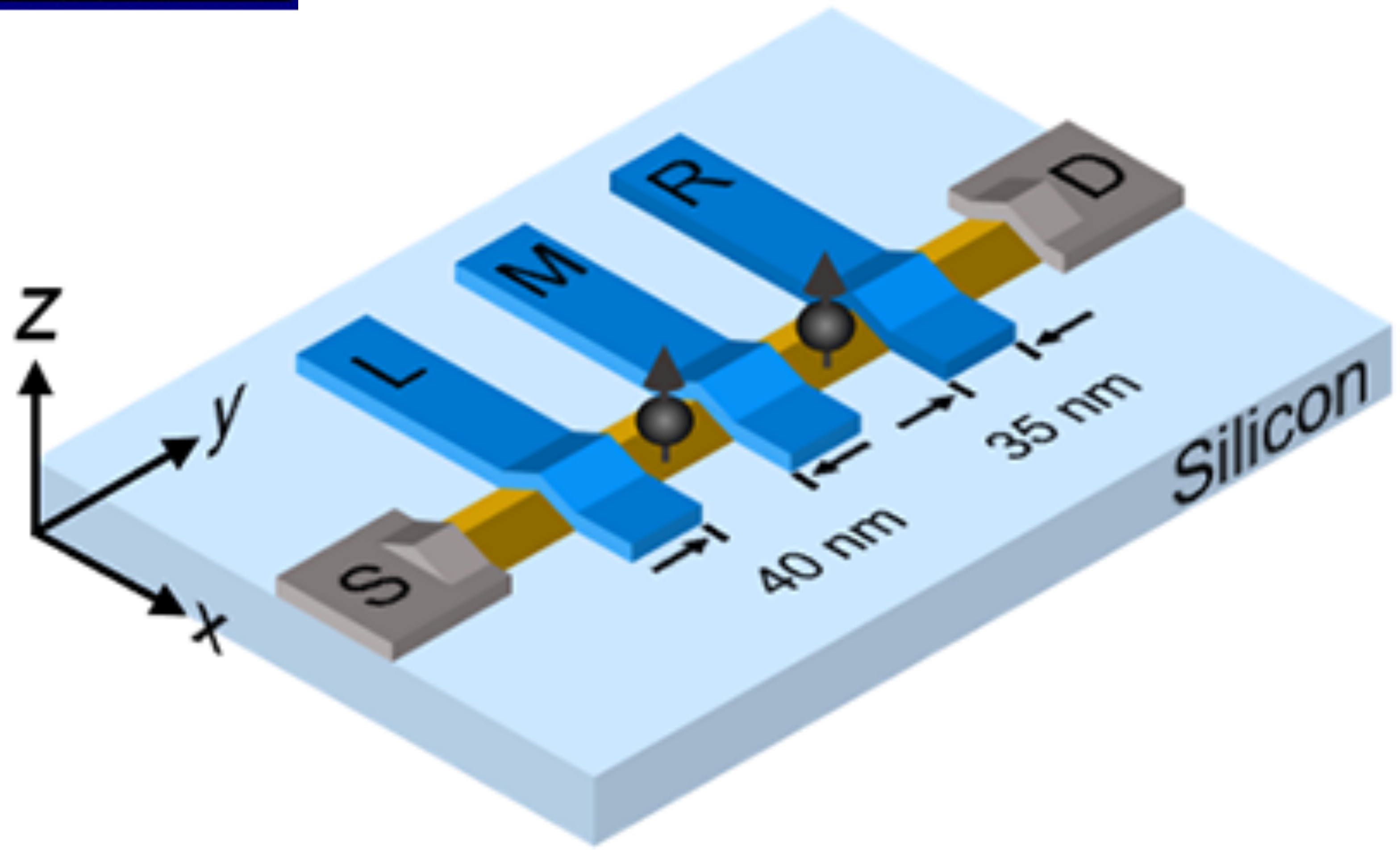
Device

- Monolithically grown Ge hut wires (HW) on Si along [100] or [010]
- 2 nm tall, 1 µm long
- 30 nm Pd ohmic contacts (prior bHF - dip)
- 20 nm Al_2O_3 dielectric
- 5 top gates with 75 nm pitch, Ti/Pd 3/25 nm
- Measured in dilution refrigerator @ 15 mK (mixing chamber), (hole temperature 40 mK)



[1]





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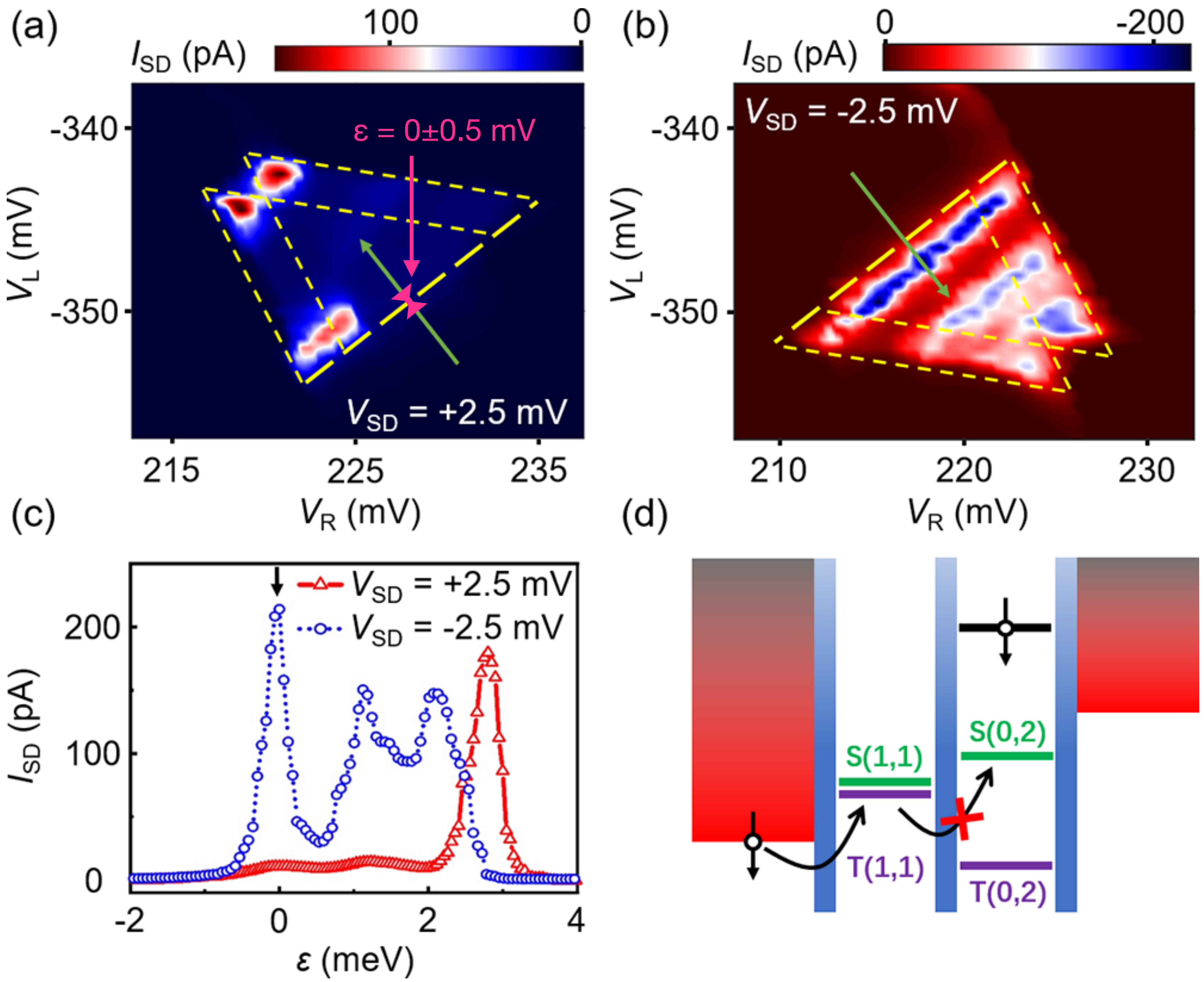
Experimental Method

- Consider a **double quantum dot** (DD) with Pauli Spin-Blockade (**PSB**)
- Determine dominant spin relaxation mechanism based on the leakage current I_{leak} (lifting of PSB)
- Determine in-plane g-factors by **fitting the spin-flip cotunneling peaks (SFC)** from leakage current I_{leak}
- Fix **|B|** and analyse angular dependence of I_{leak} on **B**(ϕ,δ). Extract $\mathbf{B_{SO}}$ from the anisotropy of I_{leak} .



In-Plane g-Factors

- Investigate **ε vs. Bx / By / Bz**

$$I_{\mathrm{leak}} = \boxed{\frac{4ecg^*\mu_B B}{3\sinh\frac{g^*\mu_B B}{k_B T}}} + \boxed{I_{SO}^0 \frac{B^2}{B^2 + B_C{}^2}} + \boxed{I_B}$$

spin-flip cotunneling

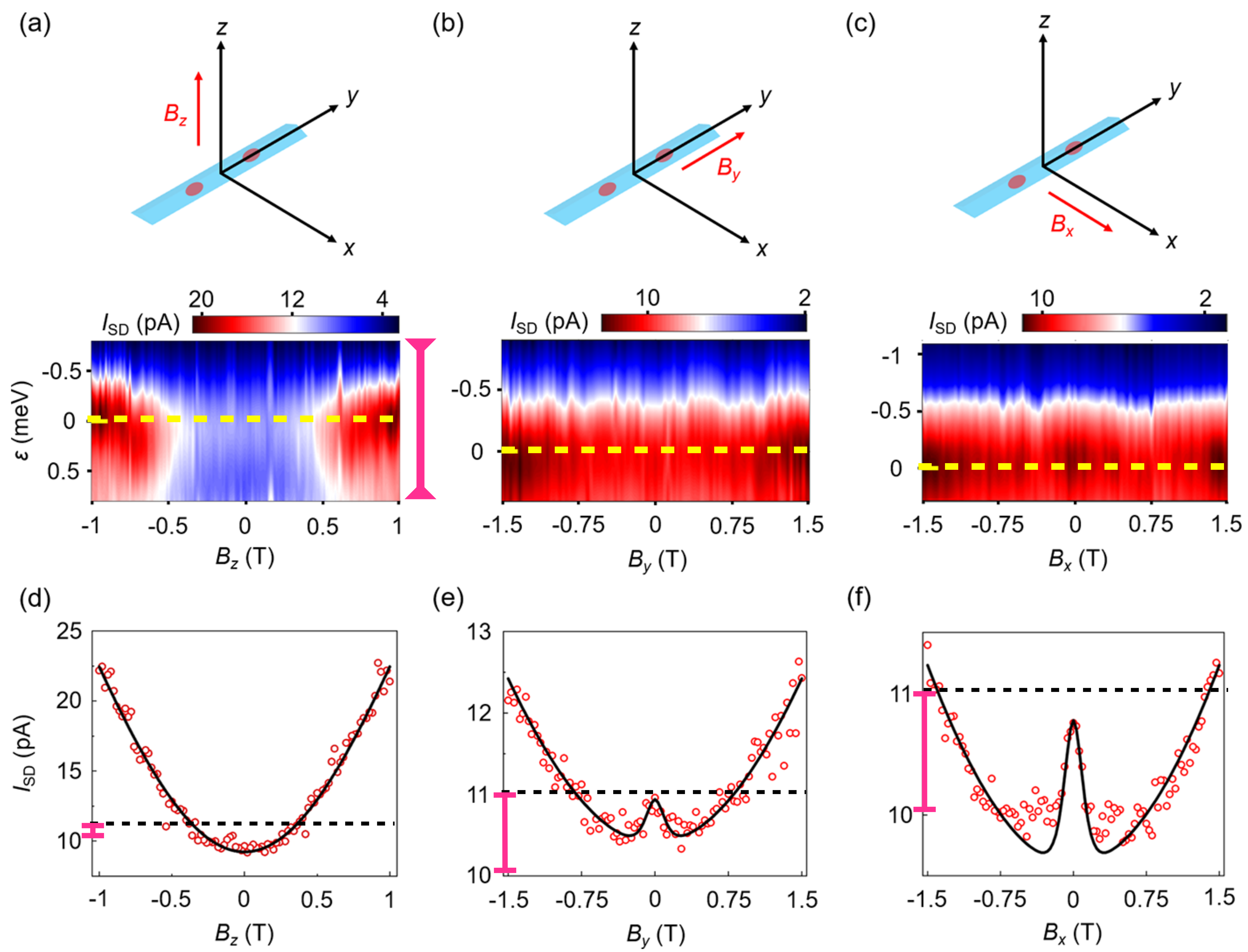
SOI-induced leakage

other: e.g. Δg

$$c = \frac{h}{\pi}[\{\Gamma_l/\Delta\}^2 + \{\Gamma_l/(\Delta - 2U_M - 2eV_{SD})\}^2]$$

$$\hat{g} \approx \begin{pmatrix} 1.2 & 0 & 0 \\ 0 & 1.2 & 0 \\ 0 & 0 & g_z \end{pmatrix}$$

- **$g^*_x = g^*_y = 1.2 \pm 0.2$**
- **B_{Cx} = 9 T, B_{Cy} = 6.5 T, B_{Cz} = 1.7 T**



Diagonal g-tensor

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- **Rashba SOI** leads to **corrections of the in plane g-factor**
- **Dresselhaus SOI** will lead to off-diagonal elements g_{xy} which are negligible **due to strong z-confinement** ($g_{xy} \approx 0.1$)

$$\hat{g} \approx \begin{pmatrix} 1.2 & 0 & 0 \\ 0 & 1.2 & 0 \\ 0 & 0 & g_z \end{pmatrix}$$

—> B is a good probe for g, (g || B)

$$\hat{g} = \begin{pmatrix} g_{\parallel} - \frac{2\alpha_g^*}{\mu_B} & \frac{2\beta_g^*}{\mu_B} & g_{xz} \\ \frac{2\beta_g^*}{\mu_B} & g_{\parallel} - \frac{2\alpha_g^*}{\mu_B} & g_{yz} \\ g_{xz} & g_{yz} & g_{\perp} \end{pmatrix}$$

- α^*_g, β^*_g ~ $\Delta z << 1$

- g_{xz}, g_{yz} from strong in-plane E-fields due to e.g.: strain from expansion mismatch when cooling down. -> 🤔

[2]

Dominant SOI-Regime

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- Fix **B = 0.8 T**, away from SFC, where SOI dominates
- **B_C** not only related to the effective g-factor but also to the angle between **g·B** and **B_{SO}**

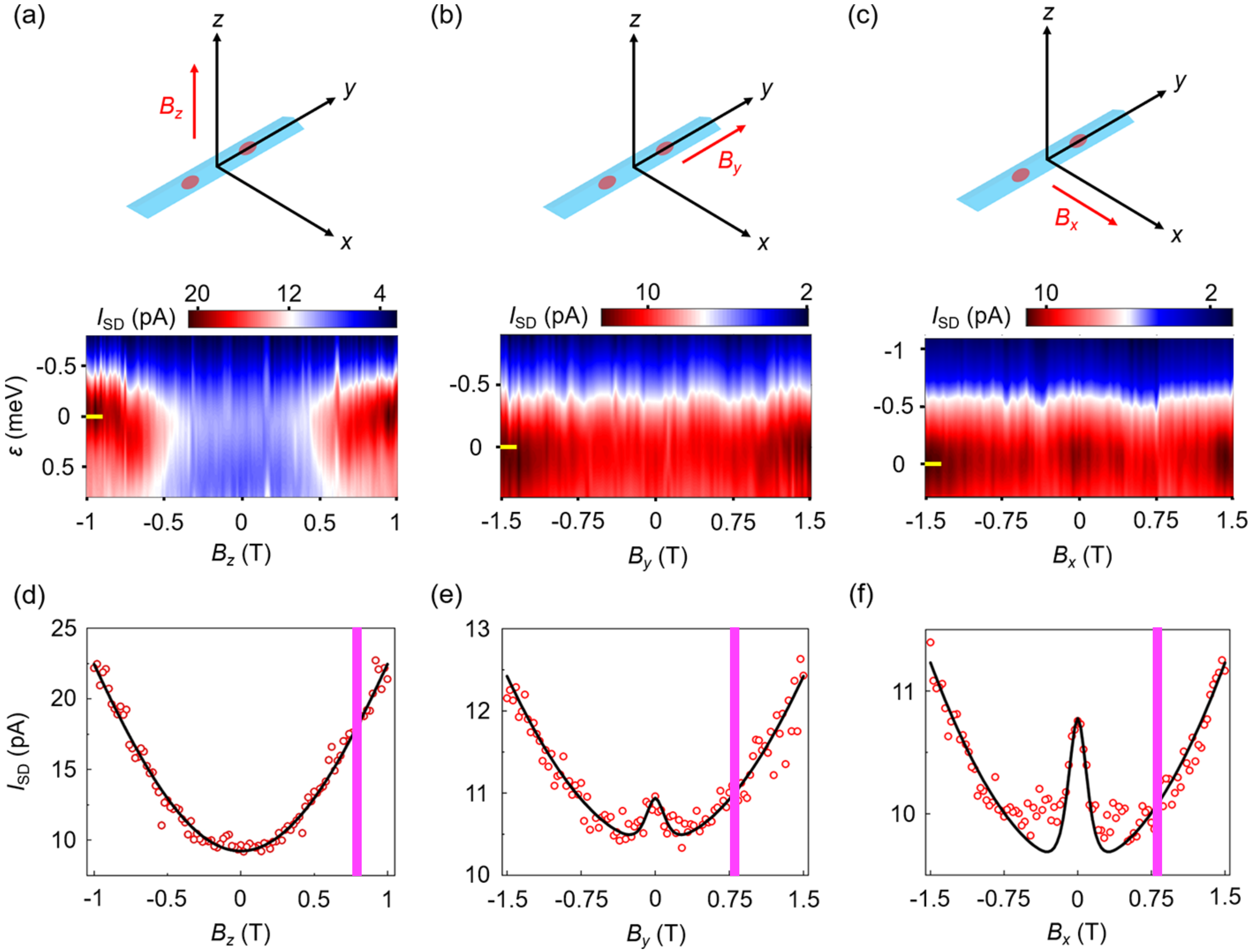
$$B_C = \frac{B_C^0}{g^* \sin\alpha}$$

$$I_{leak} = \frac{4ecg^*\mu_B B}{3\sinh\frac{g^*\mu_B B}{k_B T}} + I_{SO}^0 \frac{B^2}{B^2 + B_C^2} + I_B$$

SFC not relevant

$$I_{leak} = I_{SO}^0 \frac{B^2}{B^2 + \left(\frac{B_C^0}{g^* \sin\alpha}\right)^2} + I'_B$$

*



Rotate B-field

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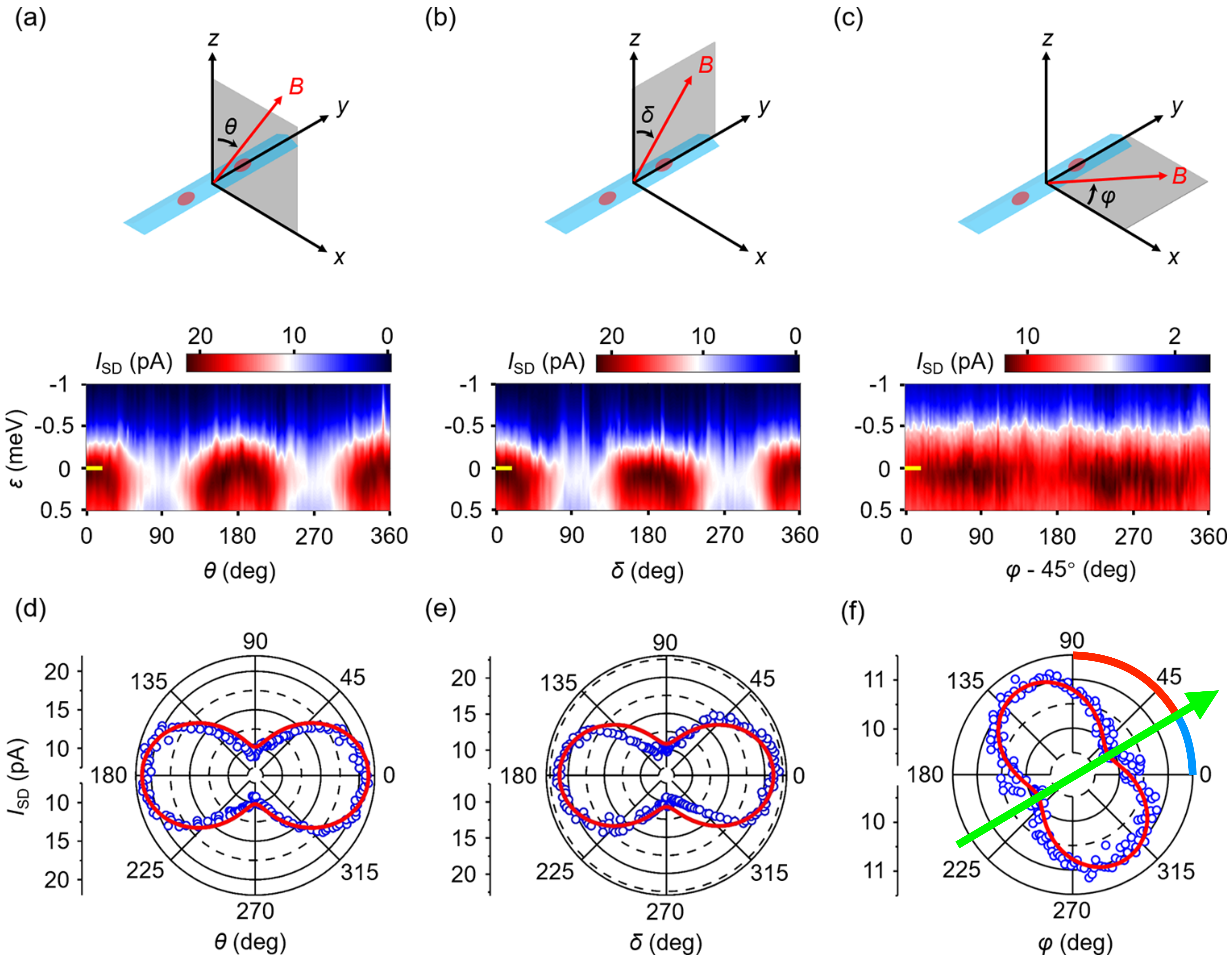
- The extreme anisotropy of I_{leak} can be explained by:

1. x-z, y-z plane: **high g-factor anisotropy**

2. x-y plane: change in the angle between **B** and $\mathbf{B_{SO}}$.

- Fit with * yields $\mathbf{g^*_z = 3.9 \pm 0.1}$

- Spin-orbit field direction at 59° ± 5° from y-axis



Rashba-Dresselhaus Ratio

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- Since the QDs are elongated along y, it is assumed GS-WF is most likely along k_y (smallest confinement, lowest energy)
- Simplify SOI-Hamiltonian such that it **only contains terms in k_y**
- Spin-orbit field expressed by **(α,β,0)**
- DRSOI controllable by E-field + with DSOI one can find **operational sweet spots**

$$H_{SO} = \alpha k_y \sigma_x + \beta k_y \sigma_y$$

$$\beta / \alpha = \tan 31^\circ \approx 0.6$$

MJC: Don't quite see it for DSOI since k_x might play a role due to strong z confinement (?)

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Conclusions

- Measured leakage current (caused by lifting PSB) through a double quantum dot in a Ge HW
- Observed two PSB lifting mechanisms:
  i) spin-flip cotunneling **ii)** SOI
- High **anisotropy of leakage current** from SOI, could be attributed to **g-factor anisotropy** and the angle between $\mathbf{B_{SO}}$ and $\mathbf{g \cdot B}$
- **SOF at 59° to y-axis**, (large interface SOI)

Thank you for your attention!