Giant Anisotropy of Spin Relaxation and Spin-Valley Mixing in a Silicon Quantum Dot

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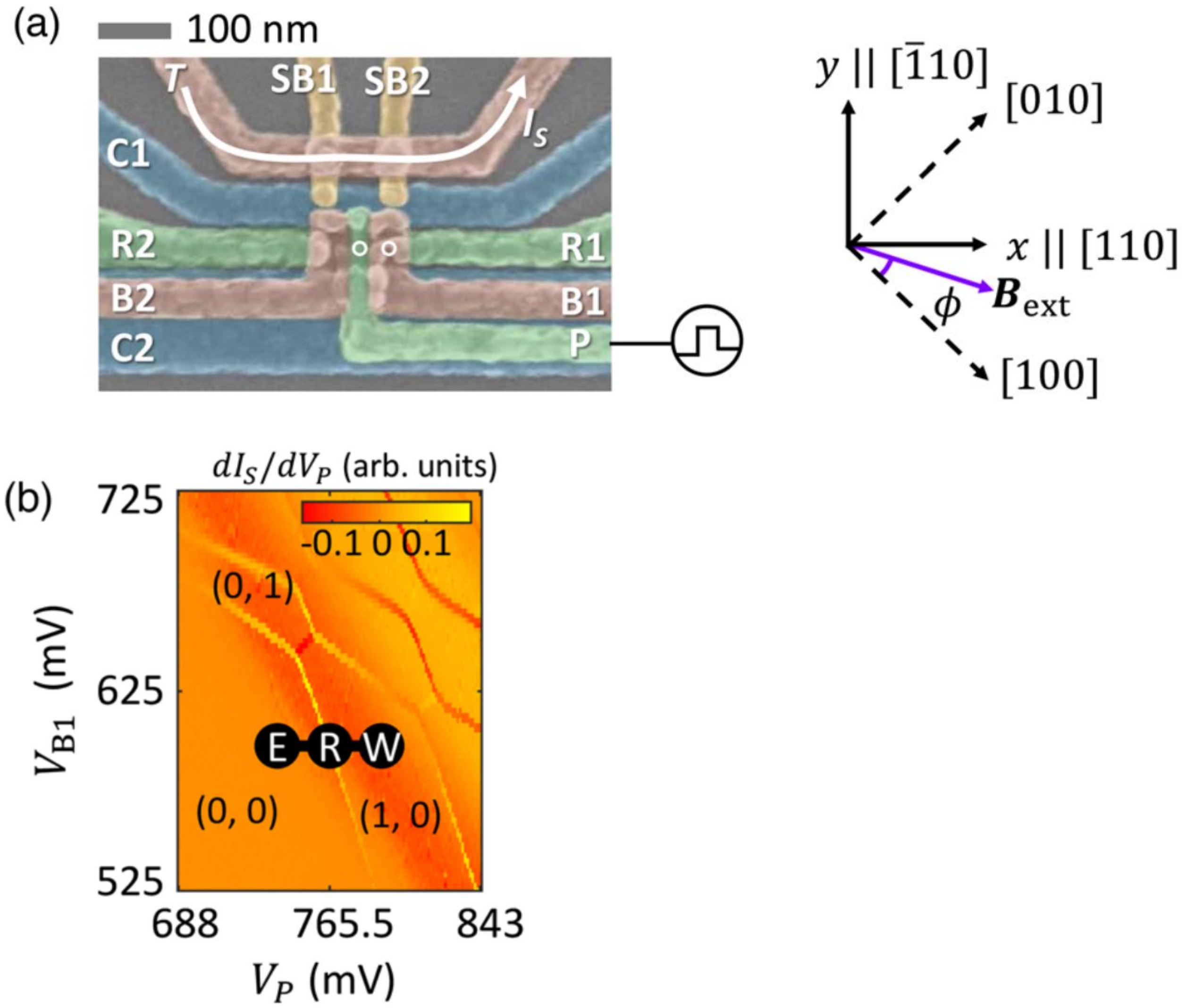
- spin relaxation depends on valley splitting and SOI
- giant anisotropy of T_1 (factor 100) at relaxation „hot spot“
- spin relaxation model
- electric control of valley splitting

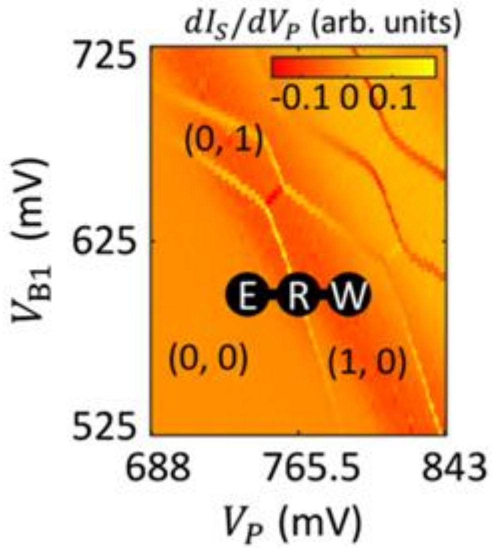
Device

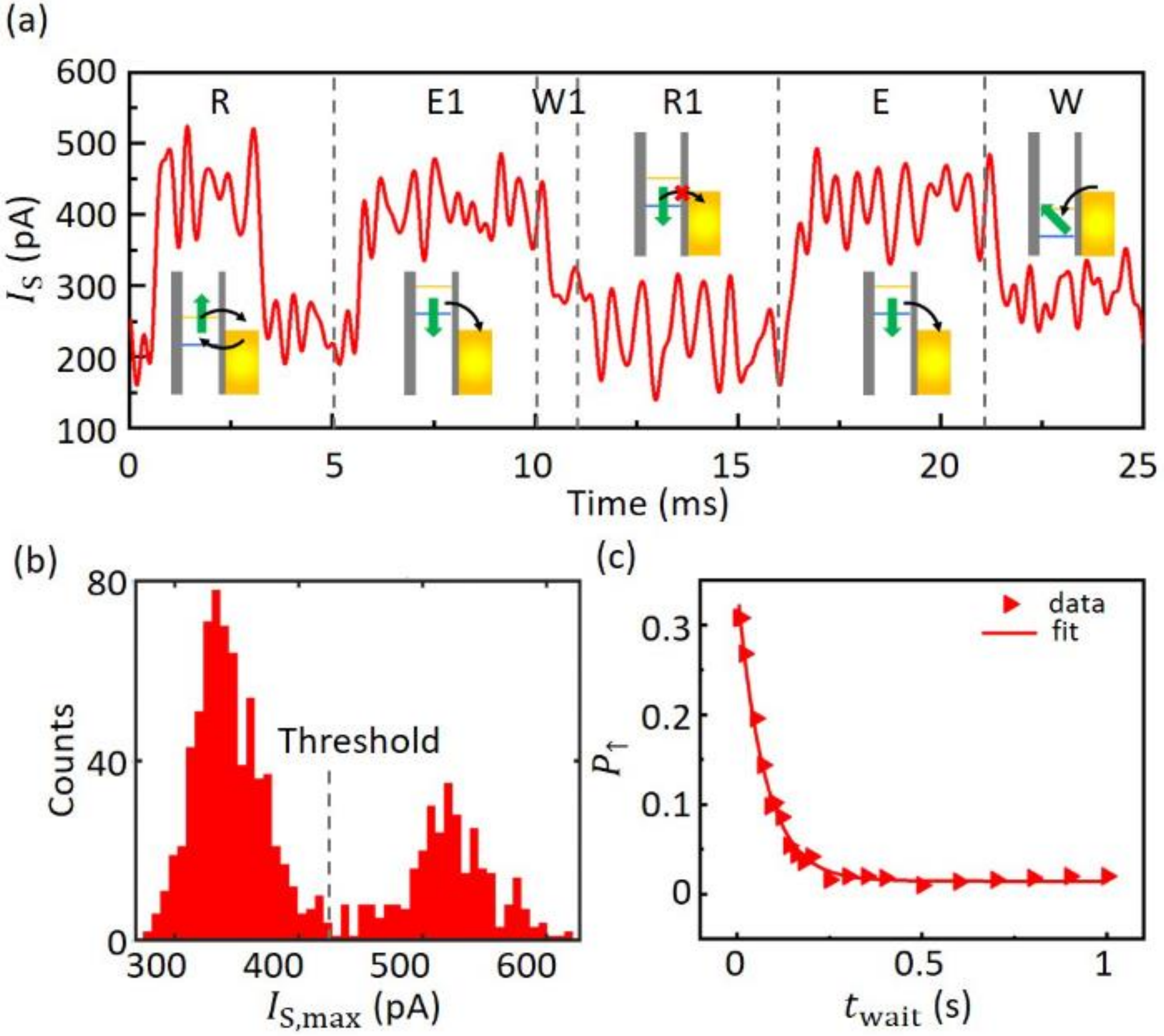
- Si MOS stack:
    - 200mm intrinsic Si wafer
    - 10nm SiO_2
    - 4 layers of Al gates with insulating oxide
- double QD below P and B1
- B-field in-plane rotated by φ from [100]
- SET for charge sensing



Spin read-out

- 3-step pulse sequence
  - load electron of random spin + wait
  - read-out spin-up probability (Elzerman)
  - empty QD
- spin-up probability decays with T_1





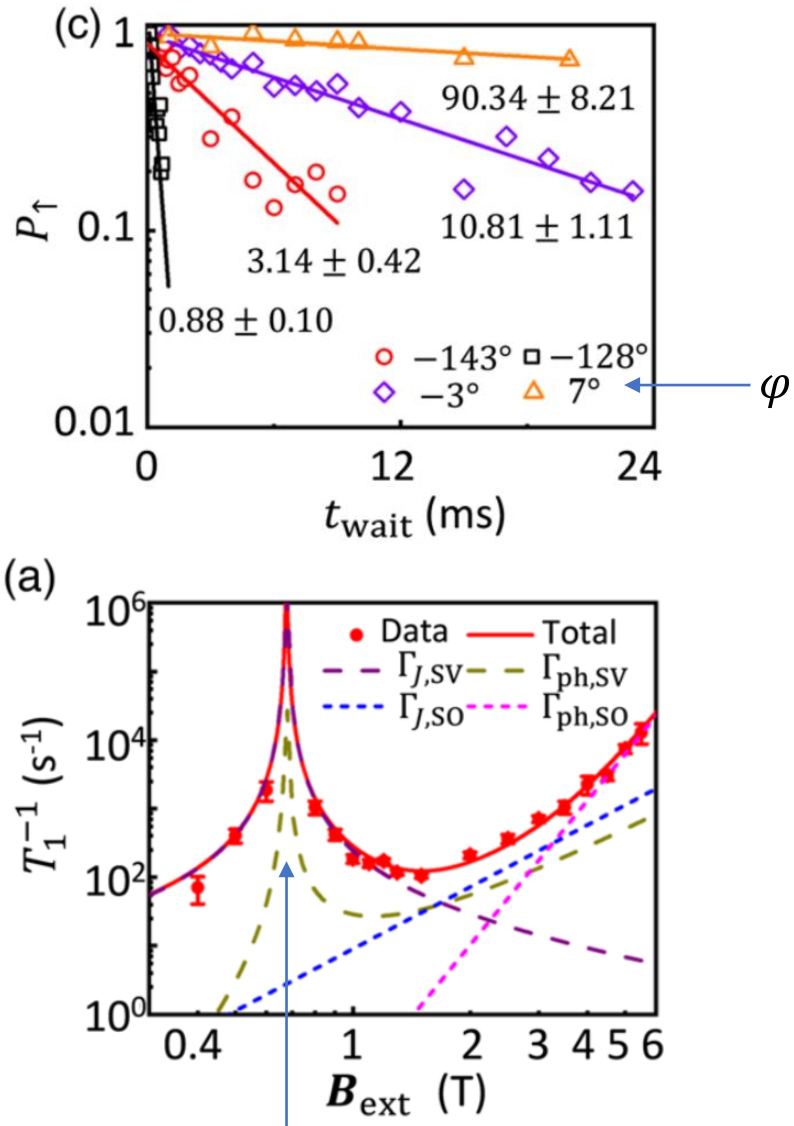
T_1 Spin Relaxation

- T_1 shows strong anisotropy (2 orders of magnitude)
- T_1 also depends on $|B|$

$$T_1^{-1} = \Gamma_{J,\mathrm{SV}} + \Gamma_{\mathrm{ph,SV}} + \Gamma_{J,\mathrm{SO}} + \Gamma_{\mathrm{ph,SO}} + \Gamma_{\mathrm{const}}, \qquad (1)$$

SV = spin-valley mixing
SO = spin-orbit mixing
J = Johnson noise
ph = phonon noise

- relaxation model includes Johnson and phonon noise as well as spin-orbit and spin-valley mixing
- contribution of decay channels are fitted
- fast relaxation for $E_Z = E_{VS}$ via SV and at high $|B|$ via SO

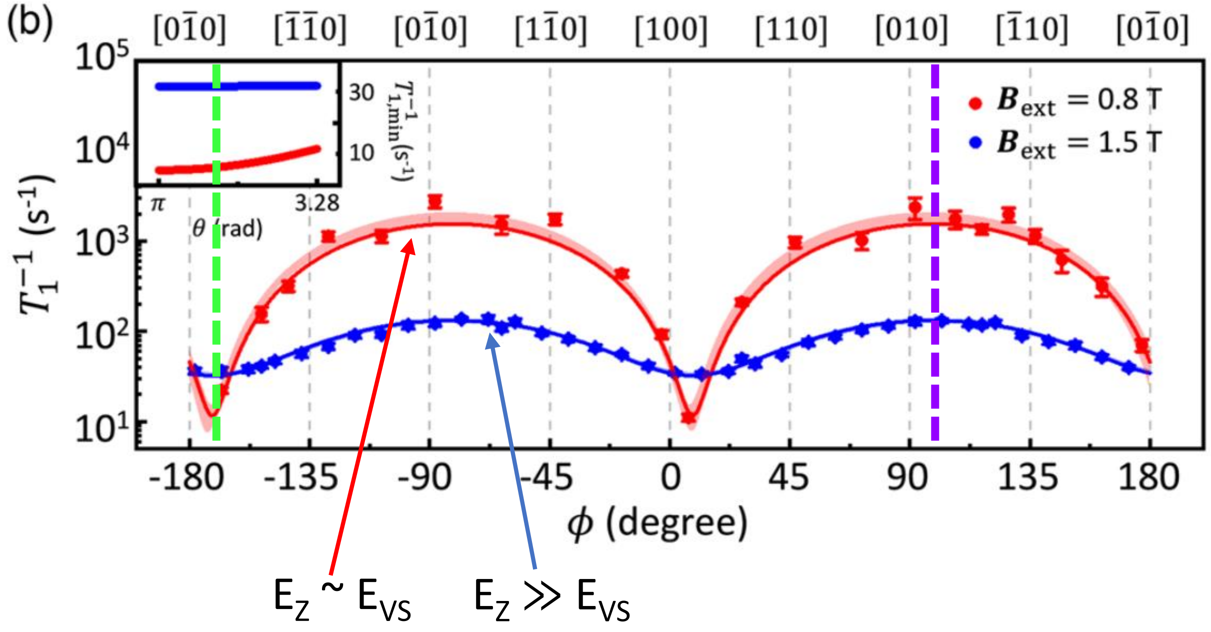


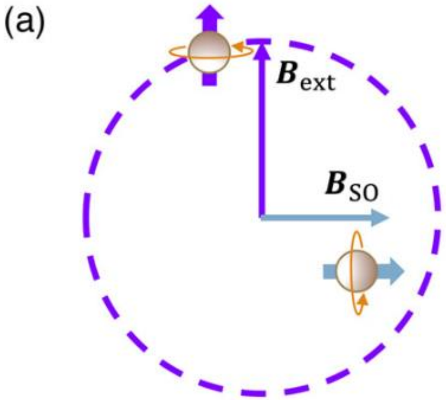
$E_Z = E_{VS}$ = 78ueV

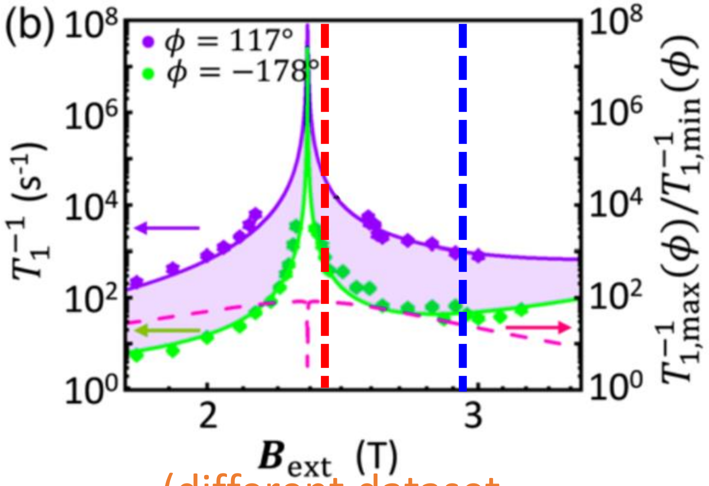
T_1 Anisotropy – Simple Model

- anisotropy with 180° period
- larger for $E_Z \sim E_{VS}$ -> probably caused by SV mixing
- simple model:
  - high relaxation when effective B_{SO} of SV is orthogonal to B
  - zero relaxation for B_{SO} || B
  - ➢ explains 180° period, but NOT shift of minima and relatively high relaxation rate at minima

➢ more sophisticated model needed







(different dataset, E_{VS} = 268ueV)

T_1 Anisotropy – Complex Model

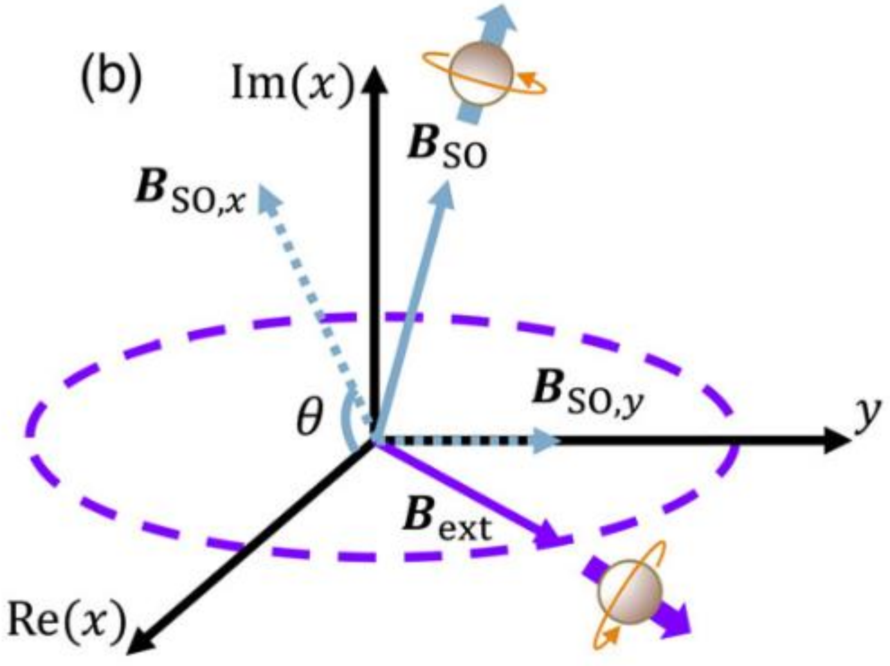
- B_{SO} from spin-valley mixing:

Rashba/Dresselhaus SOI parameter

$$\boldsymbol{B}_{\mathrm{SO}} = \frac{i m^* E_{\mathrm{VS}}}{\hbar \gamma}\left(\alpha_m r_y^{-+}\hat{\boldsymbol{x}} + \alpha_p r_x^{-+}\hat{\boldsymbol{y}}\right). \qquad (2)$$

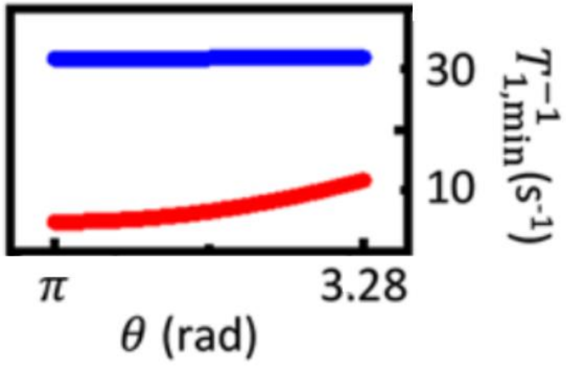
inter-valley matrix elements (complex)

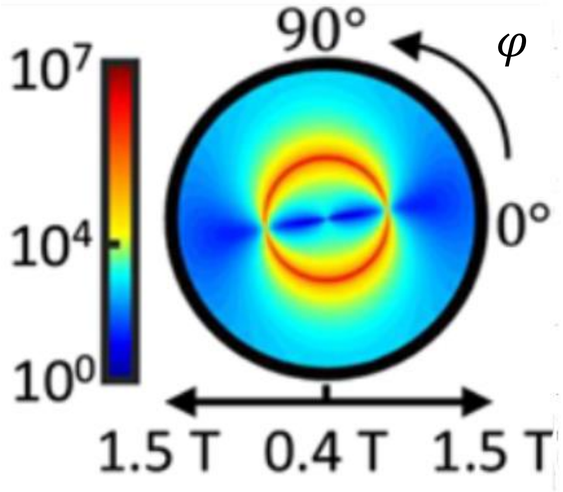
- define **R** = $B_{SO,x}$ / $B_{SO,y}$ = $Re^{i\theta}$
- finite θ reduces anisotropy (B_{SO} || B not possible anymore)
- minima are shifted for finite θ

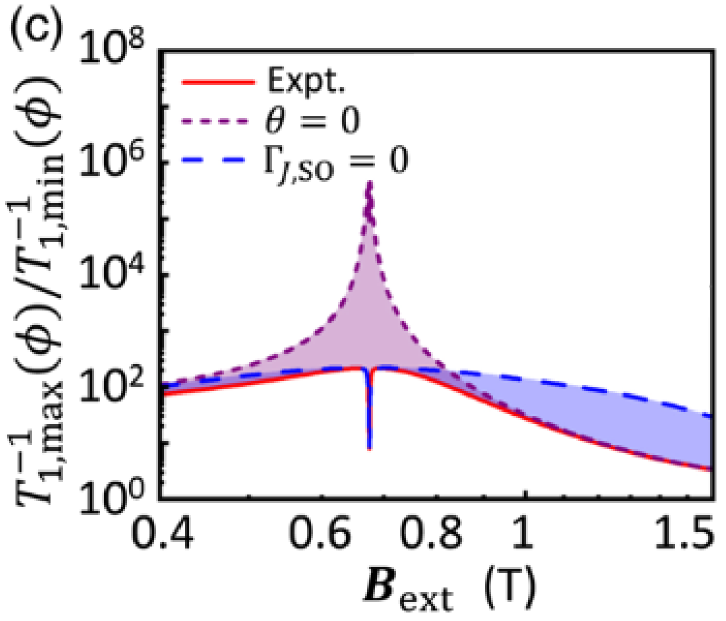


T_1 Anisotropy Limits

- T_1 at minimum angle is limited by finite θ
- anisotropy at small B is limited by non-real R
- anisotropy at high B is limited by $\Gamma_{J,SO}$

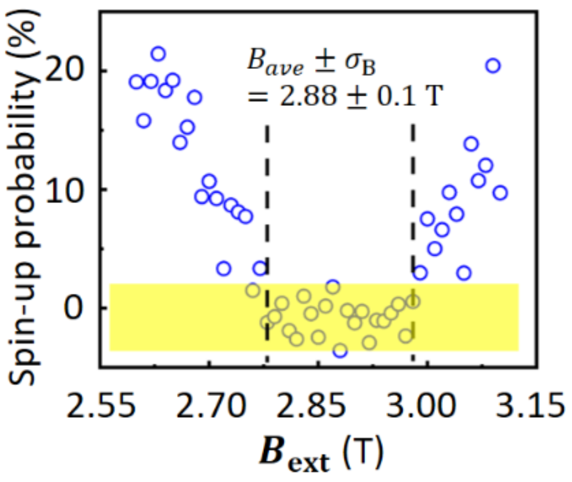


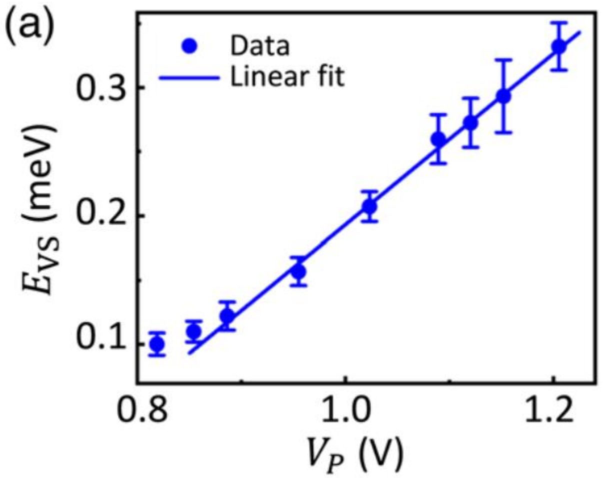




Valley Splitting

- measurement of the valley splitting energy:
  - measure spin-up probability vs B-field
  - sudden dip at B_{ave} indicates $E_Z = E_{VS}$
- valley splitting is tuned linearly by plunger gate voltage by a factor of ~3.5





Conclusion

- spin relaxation induced by spin-valley (low B) and spin-orbit mixing (high B)
- giant anisotropy of T_1 (factor 100) at relaxation „hot spot“
- anisotropy is tuned with B
- model fits very well to measurement results
- electric control of valley splitting from 80 to 300ueV
- „sweet spot“ of B-field orientation for slow qubit relaxation?