Controlling spin-orbit interactions in silicon quantum dots using magnetic field direction

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Silicon quantum dots are considered as an excellent platform for spin qubits, partly due to their weak spin-orbit interaction. However, the sharp interfaces in the heterostructures induce a significant spin-orbit interaction which degrade the performance of the qubits or, when understood and controlled, could be used as a powerful resource. To understand how to control this interaction we build a detailed profile of the spin-orbit interaction of a silicon metal—oxide—semiconductor double quantum dot system. We probe the Stark shift, g-factor and g-factor difference for two single electron quantum dot qubits as a function of external magnetic field and find that they are dominated by spin-orbit interaction originating from the vector potential, consistent with recent theoretical predictions. Conversely, by populating the double dot with two electrons we probe the mixing of singlet and spin polarized triplet states during electron tunneling, dominated by momentum term spin orbit interactions. Finally, we exploit the tunability of the Stark shift of one of the dots to reduce its sensitivity to electric noise and observe an expected increase in T_2^*.

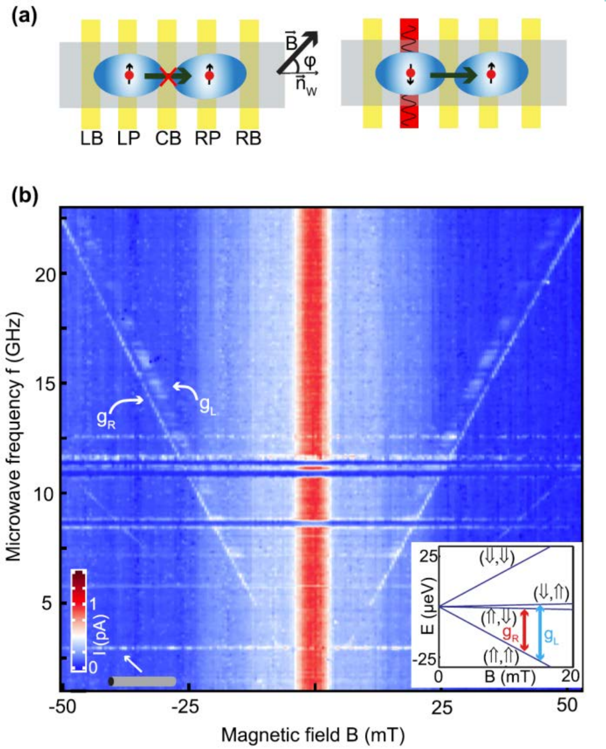
FAM, 24 / 8 / 2018

Leon Camenzind

Outline & Motivaton

Motivation

- SOI in (purified) Si
- G-factor control :
  - Adressability
  - Tuning/detuning f. global MW field
  - Sensitivity to electric noise (T_2)



Nadj-Perge, S. *et al.* Spectroscopy of spin-orbit quantum bits in indium antimonide nanowires. *Phys. Rev. Lett.* **108,** 1–5 (2012).

SO Hamiltonian & Outline

$$H_{SO} = \alpha(k_x\sigma_y - k_y\sigma_x) + \beta(k_x\sigma_x - k_y\sigma_y)$$

Magnetic field

$$k_x = -i\frac{d}{dx} + eA_x/\hbar \qquad \vec{A} = |B| \times (z, -z, 0)$$

spin-flip tunneling
leakage from $\mathrm{S} \rightarrow \mathrm{T}^-$

Hofmann, *et al.*
Anisotropy and Suppression of Spin-Orbit Interaction in a GaAs Double Quantum Dot, *PRL* 119 (2017)

Single dot quantities
Renormalization of g-factor and Stark-Shift

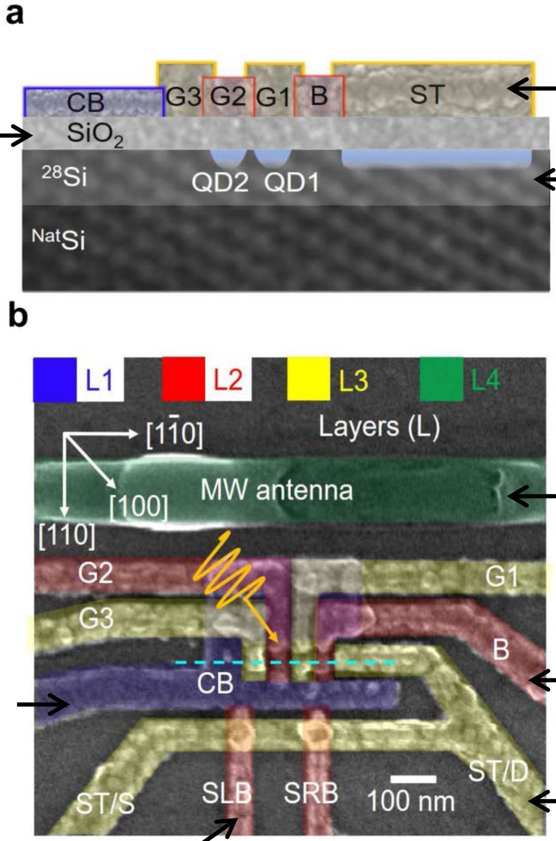
Side note: in Si bulk no real Dresselhaus (BIA).
Interface inversion → term with same symmetry

Golub, L. E. & Ivchenko, E. L.
Spin splitting in symmetrical SiGe quantum wells. *Phys. Rev. B* **69** (2004).

Outline

- Device, Setup & Charge stability
- g-factor anisotropy due to SOI
- Local g-factor difference
- Tuning of Stark-Shift and T_2^*
- Singlet-Triplet Mixing

Veldhorst device



Al gates, ox.

5.9nm

Purified, 800ppm

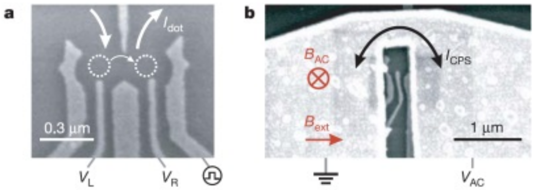
ESR/EDSR (Discontinuity)

Confinement Barrier

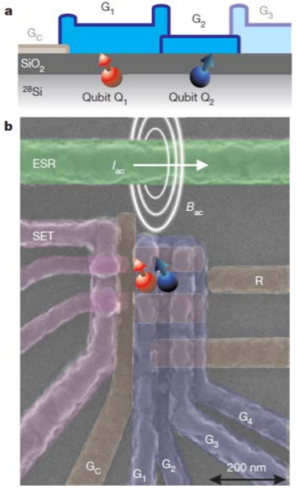
Barrier

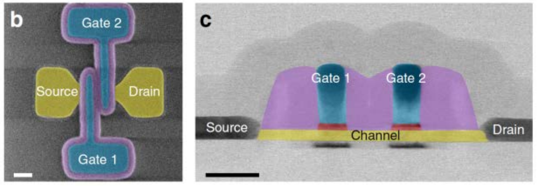
Sensor Topgate /Reservoir

Sensor Barriers



Koppens, F. H. L. *et al.* Driven coherent oscillations of a single electron spin in a quantum dot. *Nature* **442** (2006).

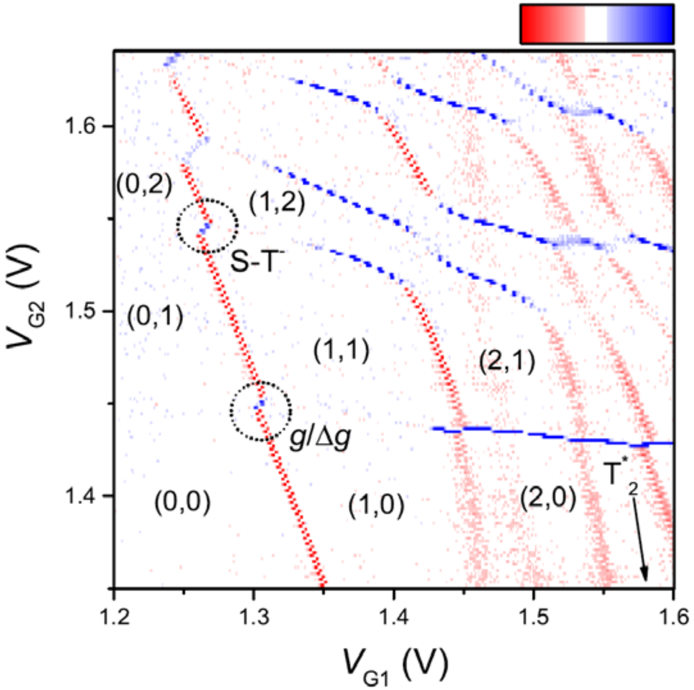


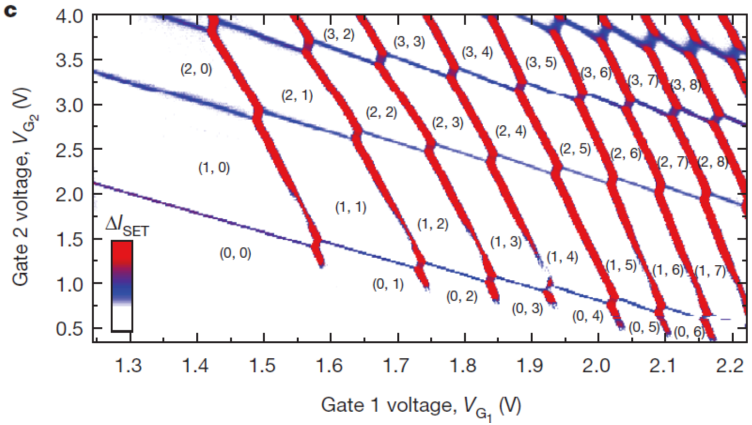


Maurand, De Franceschi *et al.*
A CMOS silicon spin qubit.
Nat. Commun. **7,** 13575 (2016).

Veldhorst, Laucht, Morello, Dzurak, *et al.*
A two-qubit logic gate in silicon. *Nature* **526,** 410 (2015).

Charge Stability Diagram



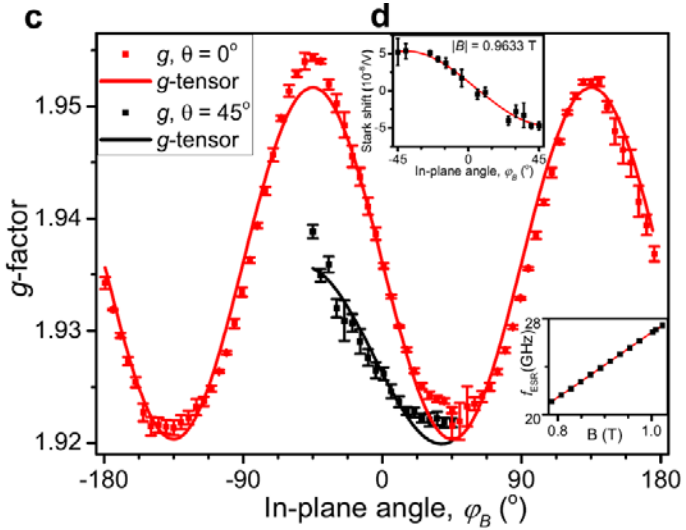


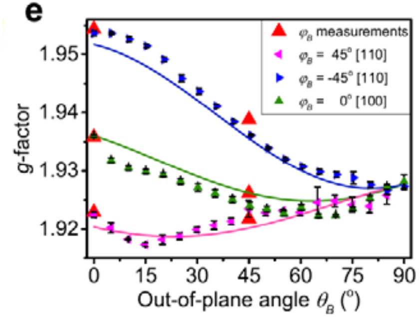
Veldhorst, Laucht, Morello, Dzurak, *et al.*
A two-qubit logic gate in silicon. *Nature* **526,** 410 (2015).

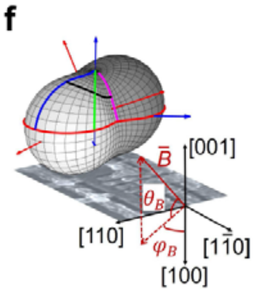
Topics

1. gfactor anisotropy & difference
2. T_2^*: Charge noise sucessibility due to Stark Shift
3. Singlet-Triplet Mixing

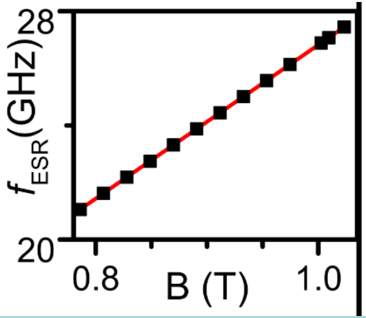
g-factor anisotropy







$\theta_B = 0°$*: in-plane*
$\varphi_B = 0°$*: [100]*



Measurement:
Single-dot ESR frequency $f_{\mathrm{ESR}}(B)$ using Elzerman readout

$$g\mu_B B = hf_{ESR}$$

G-Tensor:

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

[1]
In Si: almost diagonal

$$\beta_g^* = \frac{e\langle z\rangle\beta_g}{\hbar} \;\; (\textit{same for } \alpha_g^*) \;, \quad \langle z\rangle = 1.68\ nm$$

reconstruction

$$\hat{g}_1 = 1.9 \times I + \begin{pmatrix} 36.0 & -15.7 & -5.7 \\ -15.7 & 36.0 & -0.3 \\ -5.7 & -0.3 & 28.0 \end{pmatrix} \times 10^{-3},$$

strain?

$$\beta_g = 4.31 \pm 0.27 \times 10^{-15}\ eV\ cm$$

For α_g*: check* $dg/d\langle z\rangle$ *→ Stark shift*

[1] Jock, R. M. *et al.* A silicon metal-oxide-semiconductor electron spin-orbit qubit. *Nat. Commun.* **9** (2018).

Stark shift measurement

In-plane variation

$$\delta g \approx 2\frac{|e|\langle z\rangle}{\mu_B \hbar}\left(-\alpha_g + \beta_g \sin 2\varphi_B\right)$$

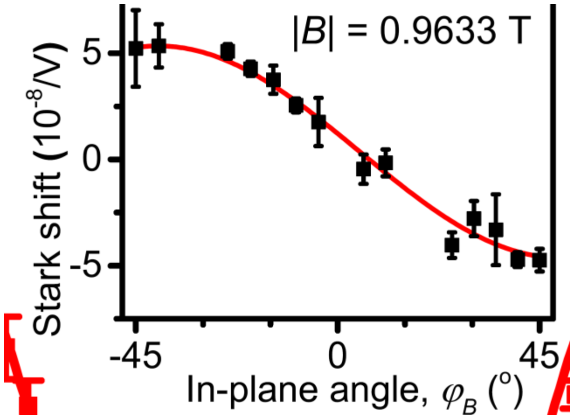
Measure g-factor for different topgate voltages (load level depth) →

$$\frac{dg}{dF_z} = 2\frac{|e|}{\mu_B \hbar}\frac{d\langle z\rangle}{dF_z}\left(-\alpha_g + \beta_g \sin 2\varphi_B\right)$$

Stark Shift

Offset

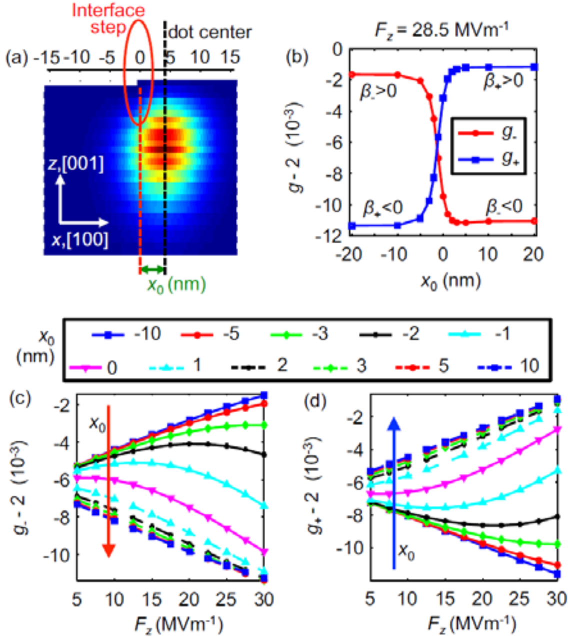
Amplitude



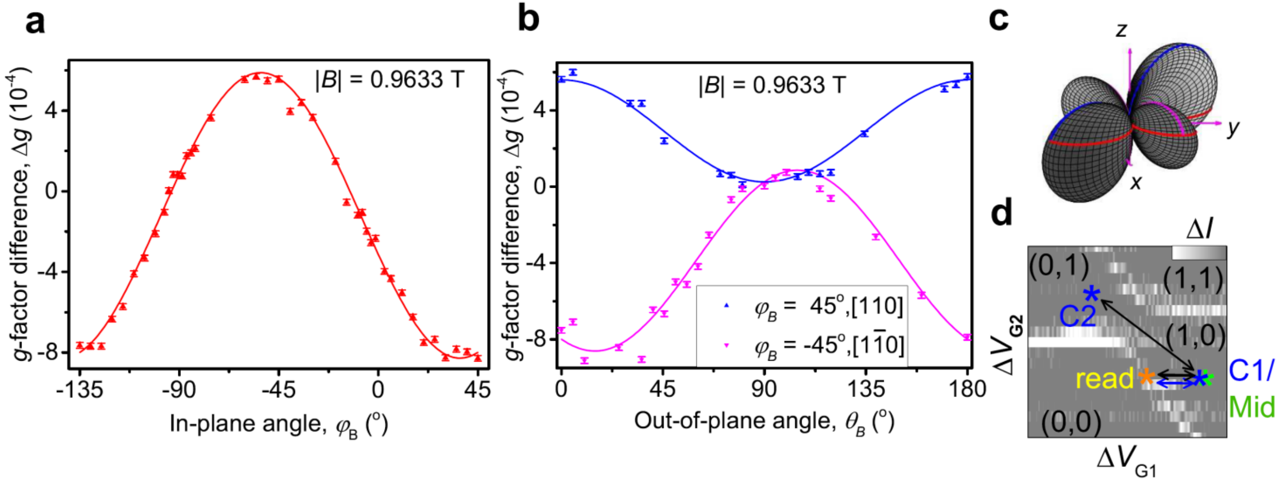
$$\Rightarrow \frac{\alpha_g}{\beta_g} = 0.071 \Rightarrow \alpha_g = 3.05 \pm 0.19 \times 10^{-16}\ eVcm$$

Ferdous, R. *et al.*
Interface-induced spin-orbit interaction in silicon quantum dots and prospects for scalability.
Phys. Rev. B **97**, 1–5 (2018).

Monatomic steps at the Si/SiO2 interface

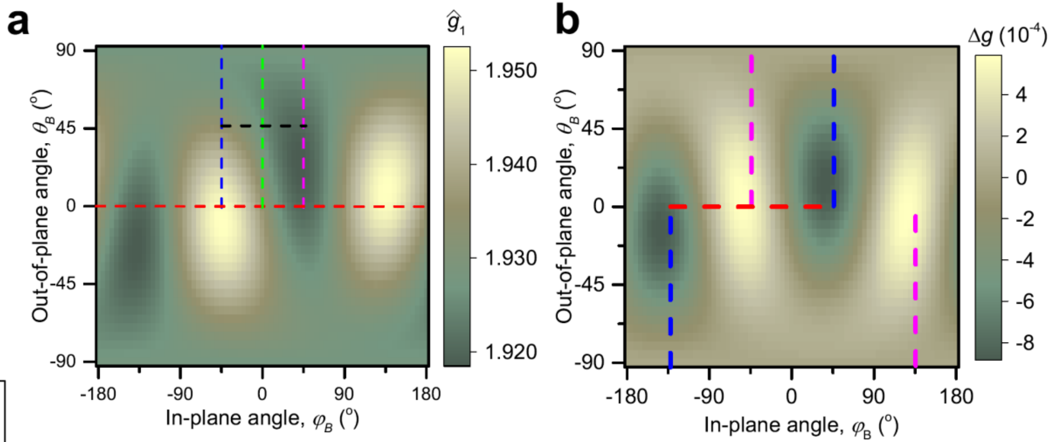


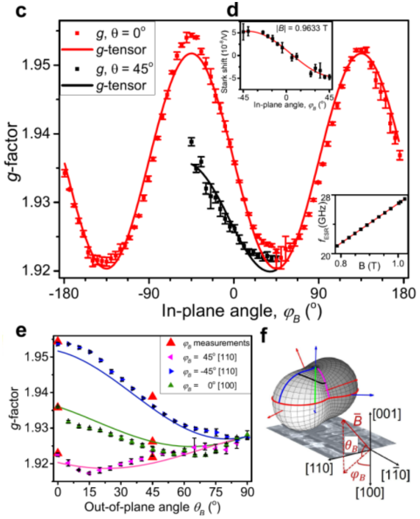
G-factor difference



- Local differences surface roughness and lattice imperfections: different SOI
- Measure Qubit1: read/init -> C1 (ESR) -> read.
- Measure Qubit2: read/init -> C1 -> C2 (ESR) –> C1 -> read
- Adressability

Reconstructed g-tensors

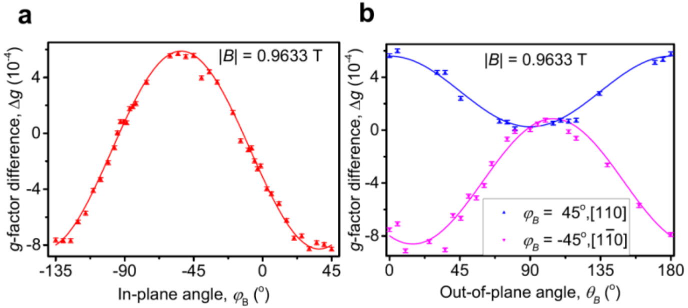




$$\hat{g}_1 = 1.9 \times I + \begin{pmatrix} 36.0 & -15.7 & -5.7 \\ -15.7 & 36.0 & -0.3 \\ -5.7 & -0.3 & 28.0 \end{pmatrix} \times 10^{-3},$$

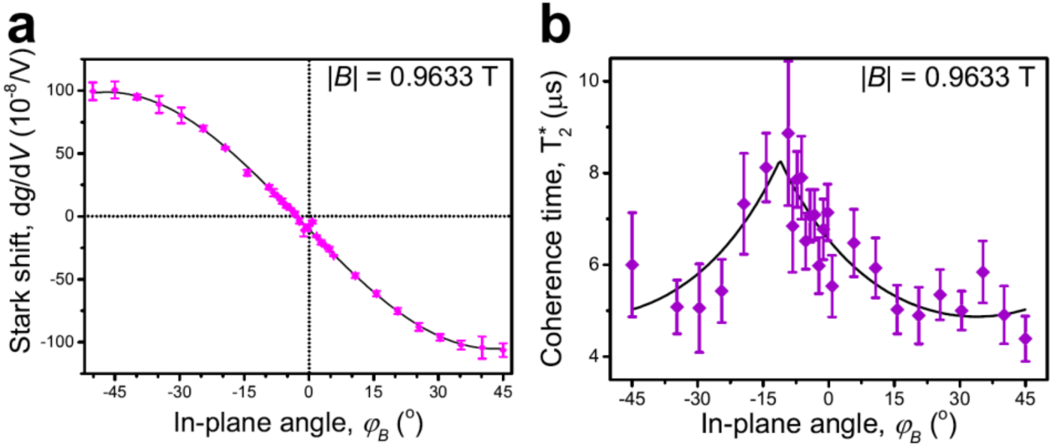
$$\hat{g}_2 = 1.9 \times I + \begin{pmatrix} 36.0 & -16.4 & -5.8 \\ -16.4 & 36.0 & -0.3 \\ -5.8 & -0.3 & 28.0 \end{pmatrix} \times 10^{-3},$$

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



Stark Shift induced T_2^*

Meas. at (3,0) transition:



- Charge noise + Stark Shift → fluctuation of f_{ESR} → Decoherence T_2^*
- T_2^* measured using Ramsey interferometry
- Voltage noise from top gate

$$T^*_{2\sigma_V} = \frac{\sqrt{2}\hbar}{\Delta F_Z \left|\frac{dg}{dF_Z}\right| \mu_B B}$$

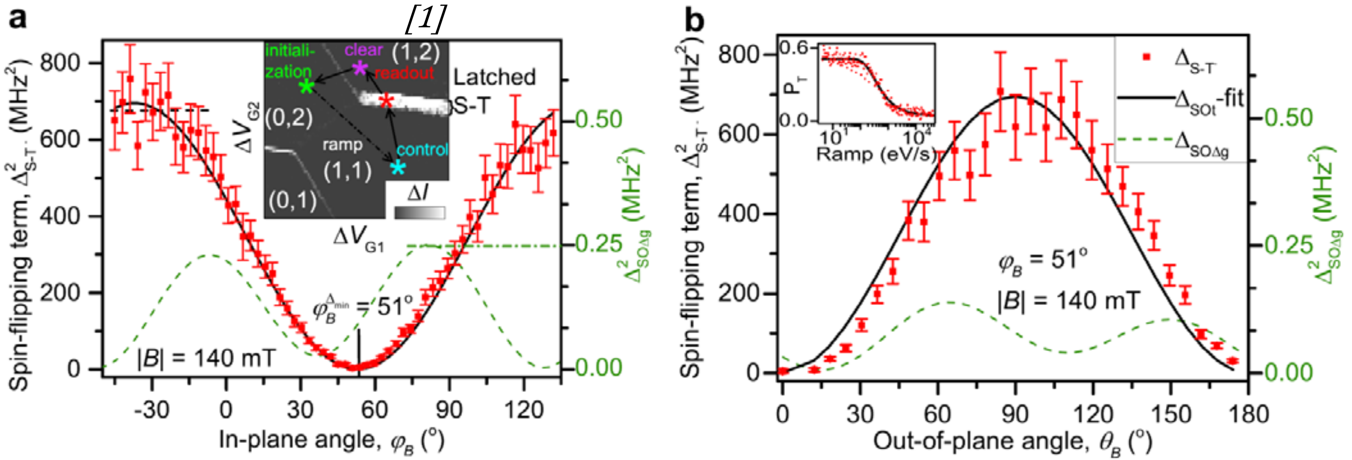
ΔF_Z: Standart deviation of electric field along z [1]

- $\alpha \approx \beta \sin 2\varphi_B$ for $\varphi_B \approx 3°$ → $\left|\frac{dg}{dF_Z}\right| = 0$ → less sucessible to charge noise
- $T^*_{2,other} \sim 8\mu s$ (very short here), max $T^*_{2,\sigma_V} \sim 15\mu s$

[1] Ferdous, R. *et al.* Interface-induced spin-orbit interaction in silicon quantum dots and prospects for scalability. *Phys. Rev. B* **97,** 1–5 (2018).

Singlet and Triplet Mixing

[1]



Singlet-triplet mixing: $\Delta_{S-T}(\xi) = -\cos(\xi)\,\dfrac{\delta E_Z^x + i\delta E_Z^y}{\sqrt{2}} + \Delta_{SOt}\sin(\xi)$ $\qquad \xi = -\arctan\left(\dfrac{2t_c}{E_Z}\right)$

different Zeeman

Spin-flip tunneling [2]

Local nuclear environment
(e.g. GaAs: used for $S - T_0$ qubit, DNP)
here: purified!

local
g-factor variations
(local SOI)

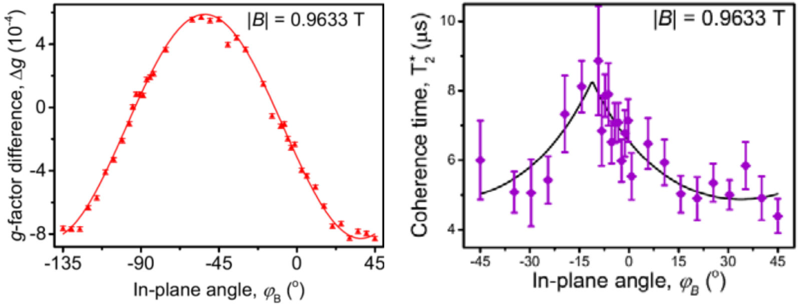
[1] Harvey-Collard, P. *et al.* High-Fidelity Single-Shot Readout for a Spin Qubit via an Enhanced Latching Mechanism. *Phys. Rev. X* **8** (2018).
[2] Hofmann, *et al.*, Anisotropy and Suppression of Spin-Orbit Interaction in a GaAs Double Quantum Dot, *PRL* 119 (2017)

Conclusions

- (small) g-factor anisotropy due to anisotropic SOI was found
- .. having implications on T_2^* limited by charge noise due to Stark shift (local interface property)

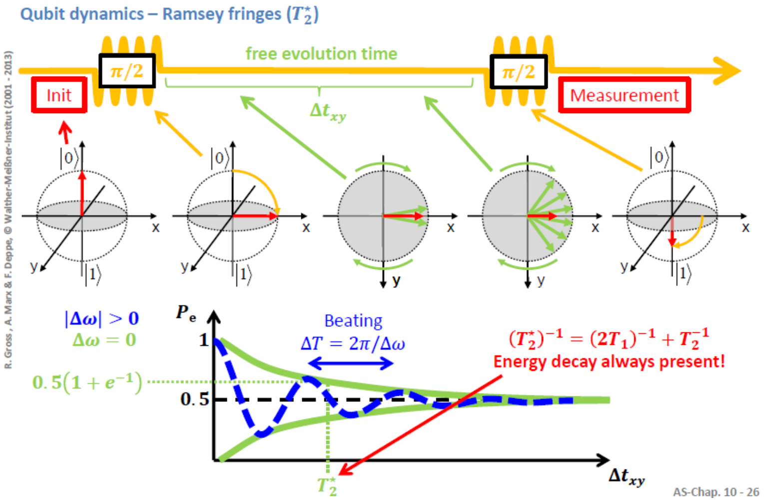
- Source of Singlet-Triplet ($S - T_-$) mixing identified as spin-flip tunneling

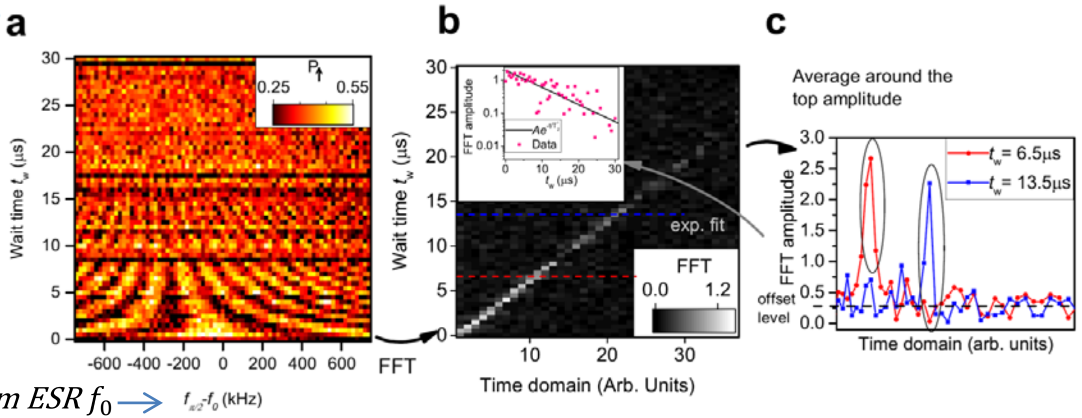
- Trade off: maximal T_2 or adressability (Δg)



Thank you for your attention

Coherence Time – Ramsey interferometry





Detuning from ESR f_0 →

G-factor difference