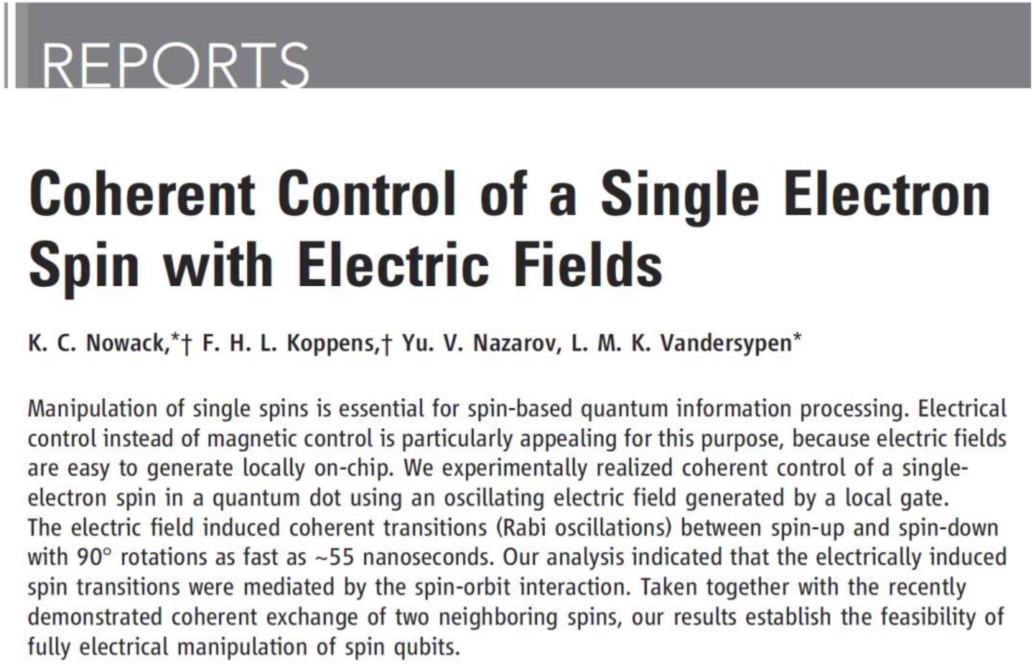


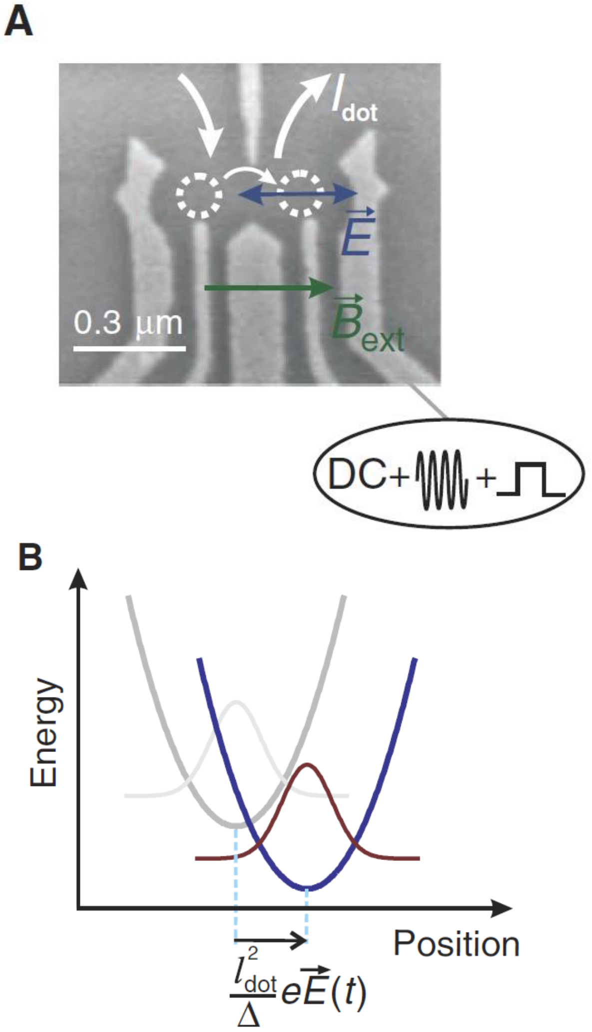
REPORTS

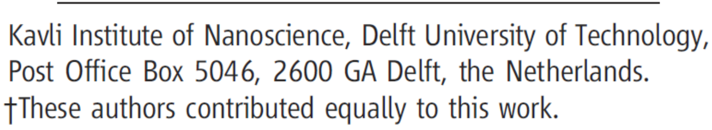
Coherent Control of a Single Electron Spin with Electric Fields

K. C. Nowack,*† F. H. L. Koppens,† Yu. V. Nazarov, L. M. K. Vandersypen*

Manipulation of single spins is essential for spin-based quantum information processing. Electrical control instead of magnetic control is particularly appealing for this purpose, because electric fields are easy to generate locally on-chip. We experimentally realized coherent control of a single-electron spin in a quantum dot using an oscillating electric field generated by a local gate. The electric field induced coherent transitions (Rabi oscillations) between spin-up and spin-down with 90° rotations as fast as ~55 nanoseconds. Our analysis indicated that the electrically induced spin transitions were mediated by the spin-orbit interaction. Taken together with the recently demonstrated coherent exchange of two neighboring spins, our results establish the feasibility of fully electrical manipulation of spin qubits.

Science ***318***, *1430 (Nov 30, 2007)*





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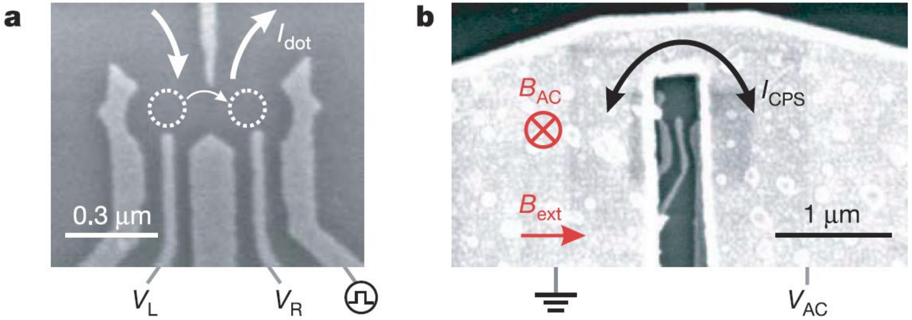
†These authors contributed equally to this work.

Electron Spin Resonance (ESR)

Strip line produces B_{AC}

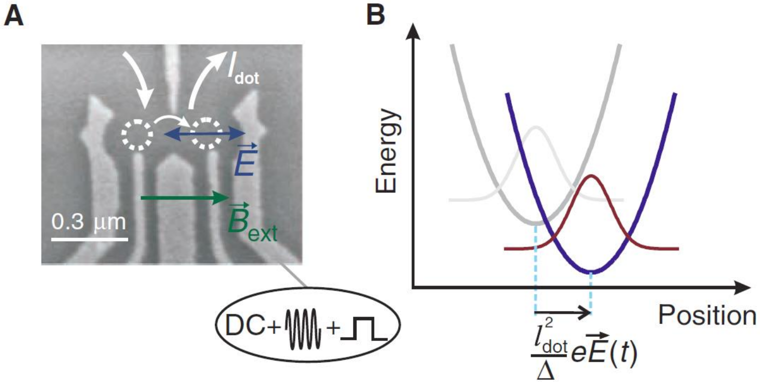


Koppens et al., Nature 2006

$f_{Rabi} \leq 10$ MHz

comparison: SWAP > 1 GHz

Electric dipole spin resonance: spin-orbit coupling



$f_{Rabi} \leq 5$ MHz

Golovach, Borhani & Loss, PRB 2006
Nowack, Koppens et al., Science 2007

other methods
gradients
- nuclear
- micro magnet
- exchange
- g - factor

Exploiting semiconductor spin-orbit coupling

$$|\mathbf{B}_{\mathrm{eff}}(t)| = 2\,|\mathbf{B}_{\mathrm{ext}}|\,\frac{l_{\mathrm{dot}}}{l_{\mathrm{SO}}}\,\frac{e|\mathbf{E}(t)|l_{\mathrm{dot}}}{\Delta}$$

Golovach, Borhani, Loss, PRB 2006

dot orbitals	Δ, ℓ_{dot}
spin-orbit length	ℓ_{SO}
electric field	E(t)

semiconductor spin-orbit lengths	ℓ_{SO} ~ 50 nm to few microns
dot sizes	ℓ_{dot} ~ 10 nm to 100 nm (single charge dot)

$$\lambda_{\pm} = \hbar^2/(2m^*\,|\alpha \pm \beta|)$$

$$H_{SO} = \underline{\alpha(p_x\sigma_y - p_y\sigma_x)} + \underline{\beta(p_x\sigma_y + p_y\sigma_x)}$$

Rashba term
structural asymmetry

Dresselhaus term (linear)
crystal asymmetry

45° rotation

$$\mathrm{H}_{\mathrm{SO}} = (\beta-\alpha)\,p_y\,\sigma_x + (\beta+\alpha)\,p_x\,\sigma_y$$

Typical wafers: $\alpha \sim \beta$

"weak" direction $\alpha - \beta$: slow EDSR < 10 MHz

"strong" direction $\alpha + \beta$: fast EDSR >100 MHz

Rashba term

- Structure inversion asymmetry:

→electric field, QW asymmetry

→doping (effective E-field)

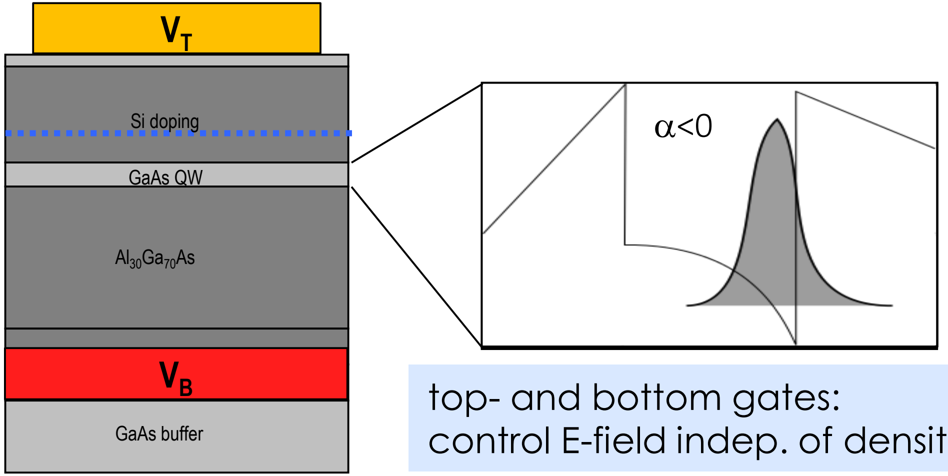
→tilting of the QW with gate

2D Rashba Hamiltonian

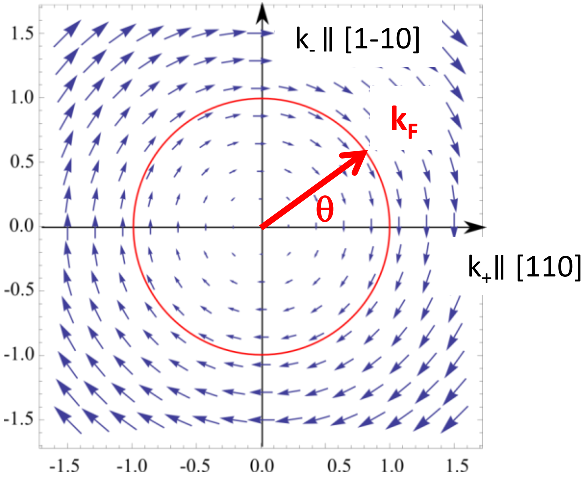
$$\mathcal{H}_R = \alpha(\sigma_x k_y - \sigma_y k_x)$$

$$\alpha \sim E_{\text{eff}}$$

GaAs quantum well



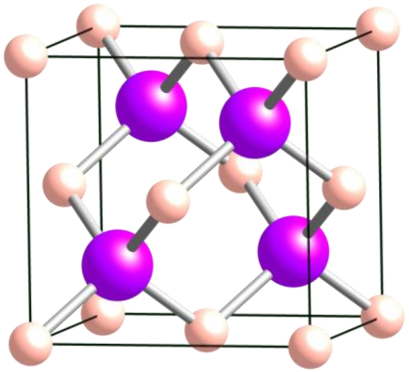
top- and bottom gates:
control E-field indep. of density n



first harmonics

Y. Bychkov and E. Rashba, JETP Letters **39**, 66 (1984)

Dresselhaus term



GaAs,InAs,InSb,.... (III-V compounds)

- zinc-blende structure
- 2 atomic basis, polar semiconductor
- No center of inversion for electric fields → Bulk inversion asymmetry (BIA)

Dresselhaus Hamiltonian in 3D:

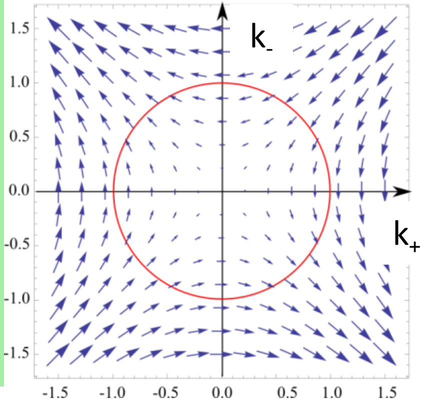
$$\mathcal{H}_D = \gamma(\sigma_x k_x k_y^2 - \sigma_y k_y k_x^2) + \text{cycl. perm.}$$

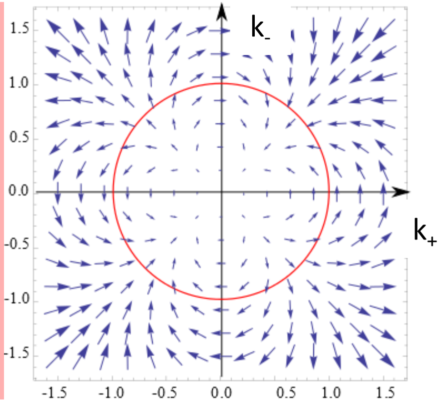
g: Dresselhaus coefficient: material constant

G. Dresselhaus, Physical Review **100**, 580 (1955)

Dresselhaus term in a quantum well

$$H_D = \beta(p_y\sigma_y - p_x\sigma_x)$$





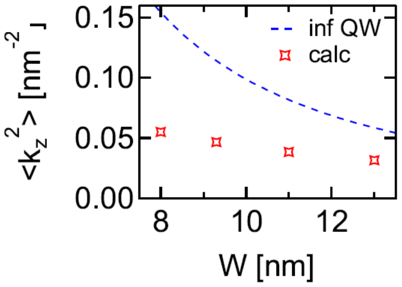
- Coordinate transformation [110] main axes
- quantum well: quantize z-direction($\langle k_z \rangle = 0$)
- Rewrite in polar coordinates

$$\mathcal{H}_D = k_F\left[(\beta\sin(\theta) + \beta_3\sin(3\theta))\sigma_+ - (\beta\cos(\theta) + \beta_3\cos(3\theta))\sigma_-\right]$$

density n
gate tunable

$$\beta = \gamma\underline{\langle k_z^2\rangle} - \gamma\frac{\pi n}{2} \qquad \beta_3 = \gamma\frac{\pi n}{2}$$

well width



→ β and β_3 are density dependent!

→ **Dresselhaus SOI can be gate-tuned**

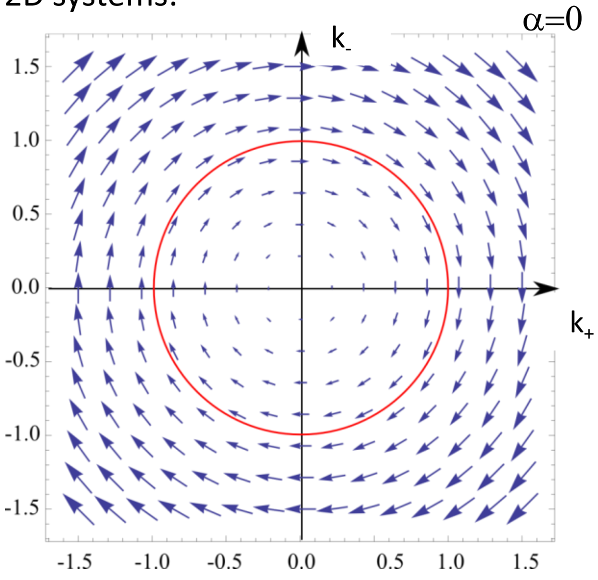
first harmonics

third harmonics

Iordanskii, Lyanda-Geller&Pikus, JETP Lett. **60**, 206 (1994)
Pikus&Pikus, PRB**51**, 16928 (1995)

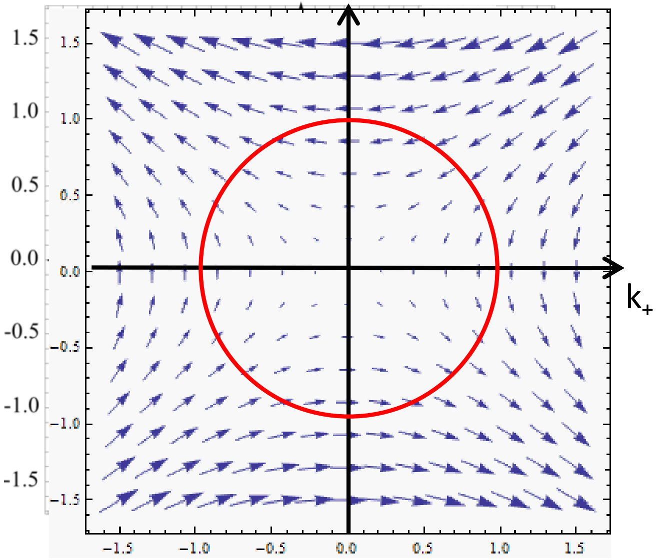
The Persistent Spin Helix

2D systems:



Rashba α

+



Dresselhaus β

first harmonics

~~third harmonics~~

J. Schliemann, J.C. Egues and D. Loss, PRL 2003

A. Bernevig, J. Orenstein, S. Zhang, PRL 2006

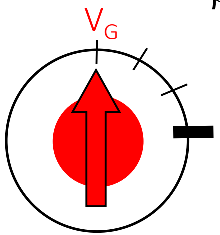
The Persistent Spin Helix

2D systems:

$$\alpha(V_G) = \beta(V_G)$$

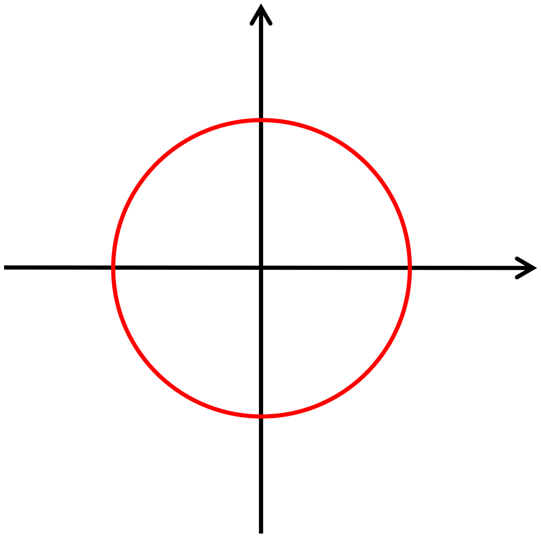
$\alpha=0$

increasing α
β fix



→ Persistent spin helix (PSH) regime at $\alpha=\beta$
→ UNIAXIAL spin orbit field

Rashba α



Dresselhaus β

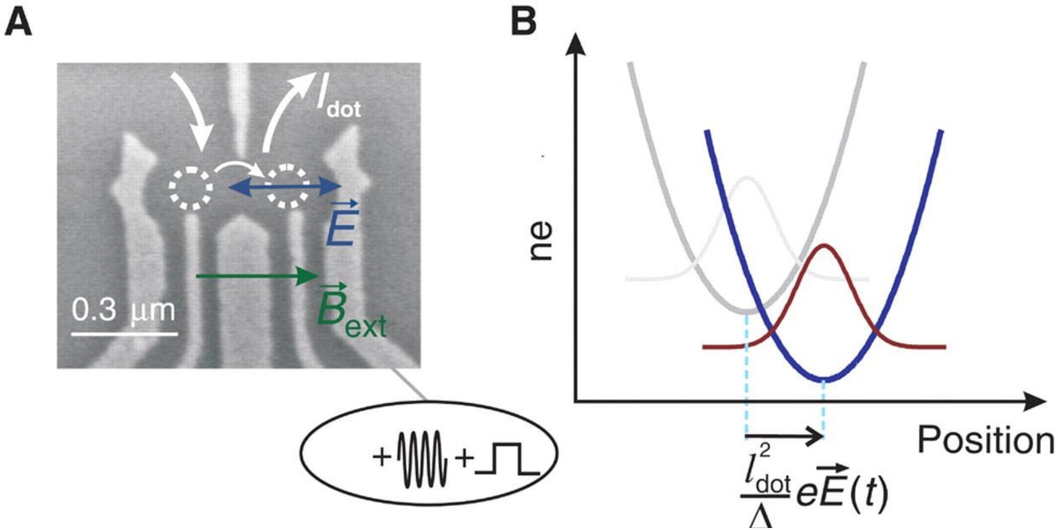
first harmonics

~~third harmonics~~

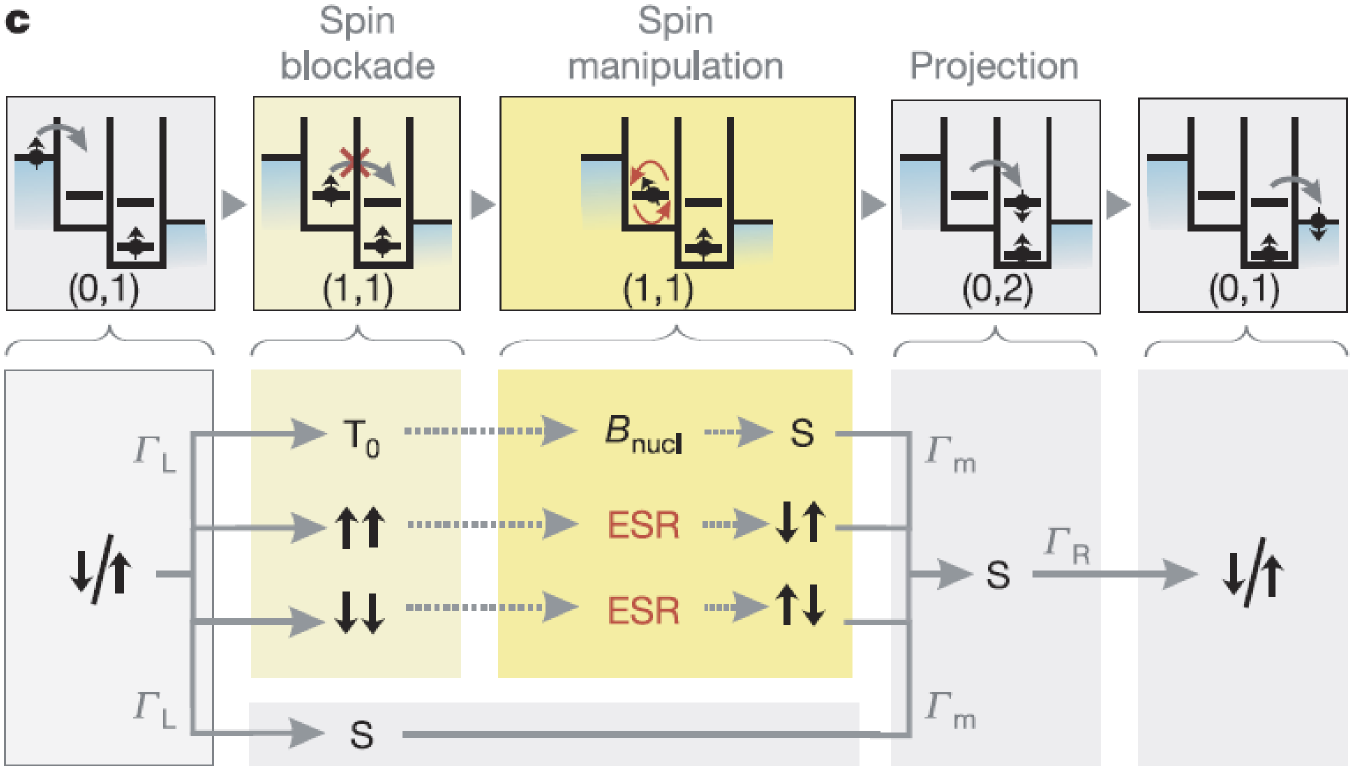
J. Schliemann, J.C. Egues and D. Loss, PRL 2003
A. Bernevig, J. Orenstein, S. Zhang, PRL 2006

Device and Pulse Scheme

Fig. 1. (A) Scanning electron micrograph of a device with the same gate structure as the one used in this experiment.

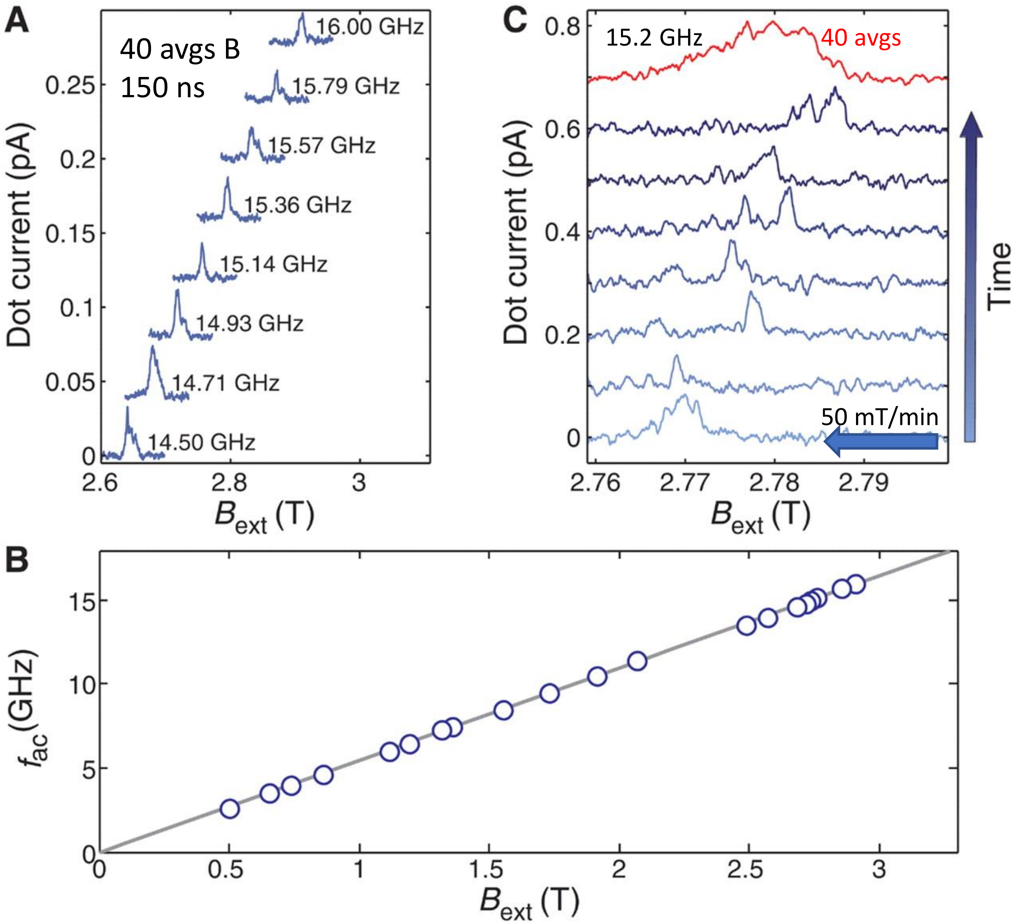


Using Pauli Spin Blockade for Spin Readout



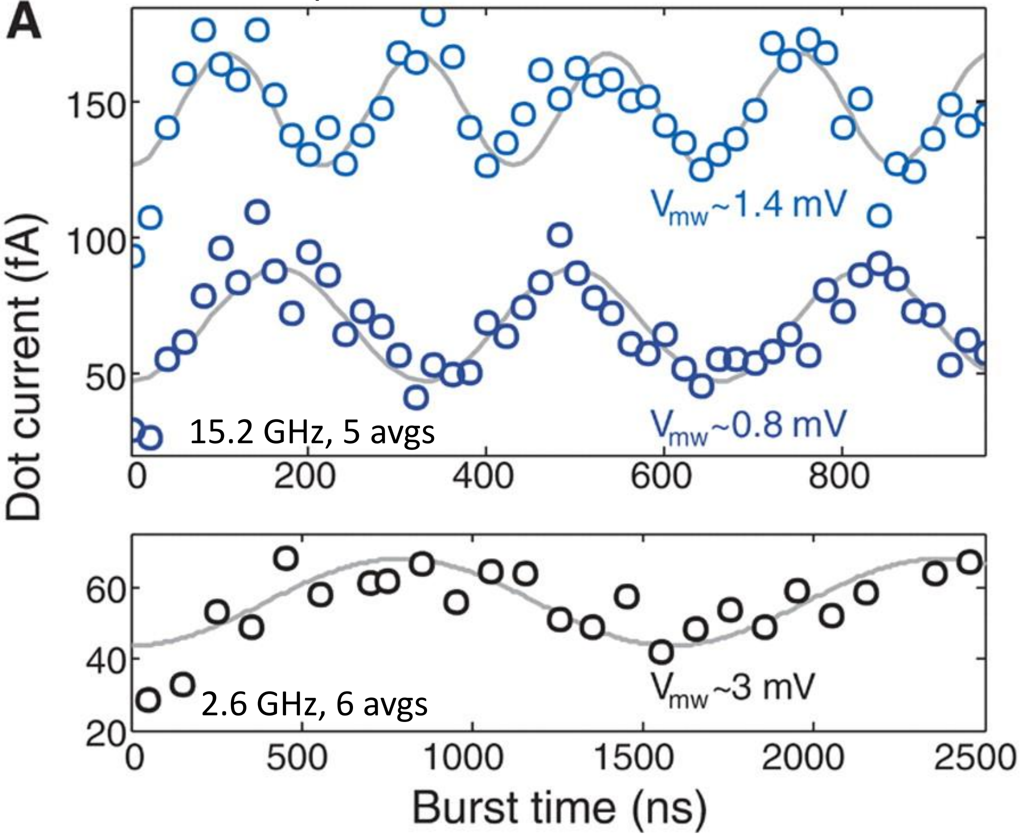
ESR signature and B-field noise

Fig. 2. (A) The current averaged over 40 magnetic field sweeps is given for eight different excitation frequencies, with a microwave burst length of 150 ns.



Rabi Oscillations

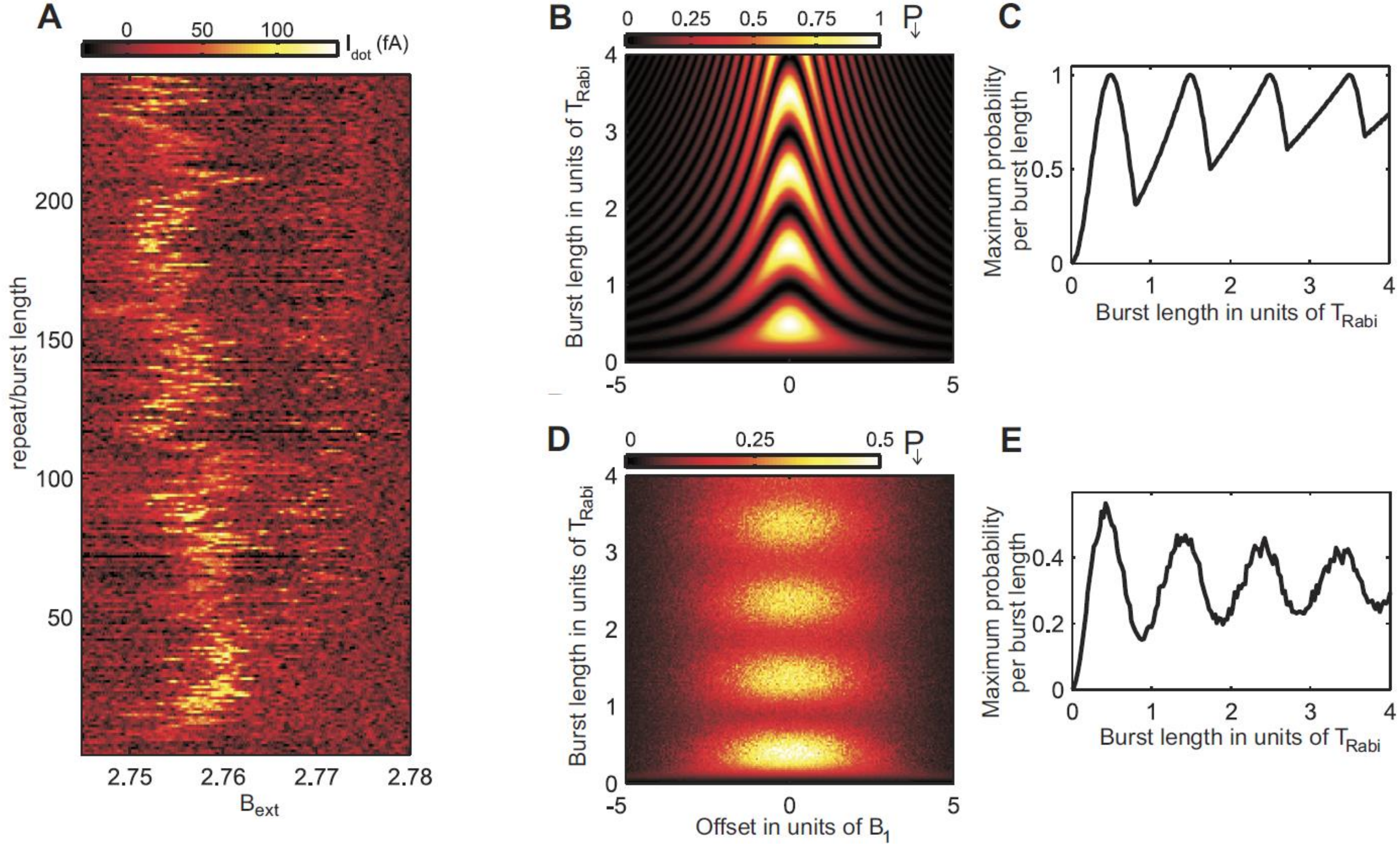
ca. 1 hour per trace



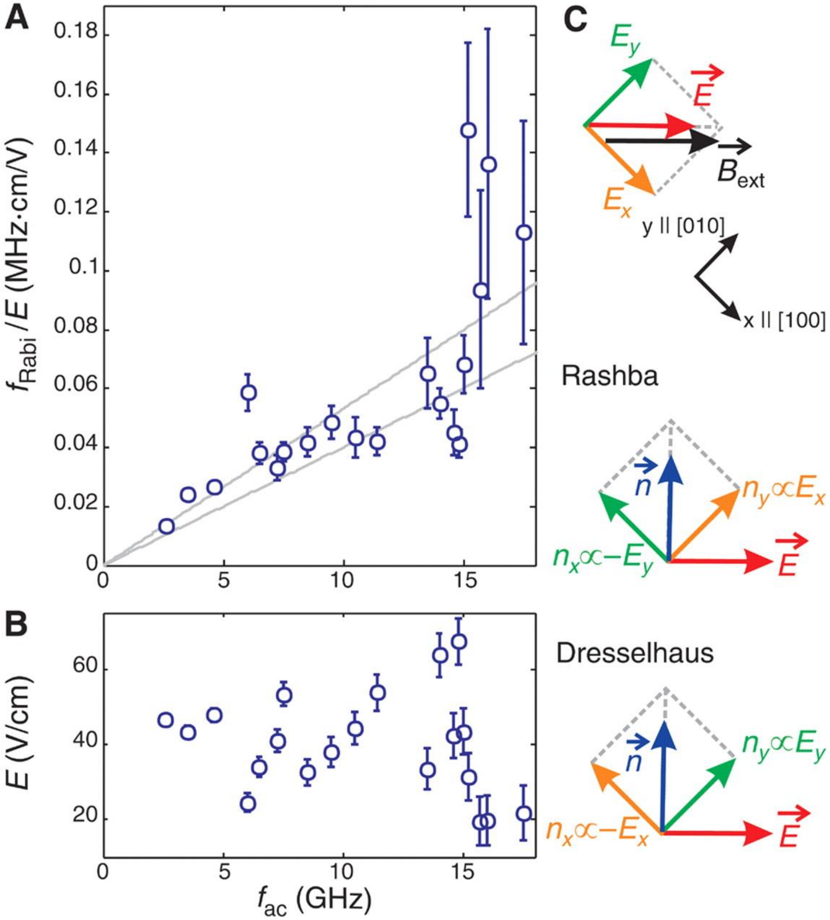
15.2 GHz, 5 avgs

2.6 GHz, 6 avgs

Chevrons with B-field noise



Determining the EDSR Mechanism

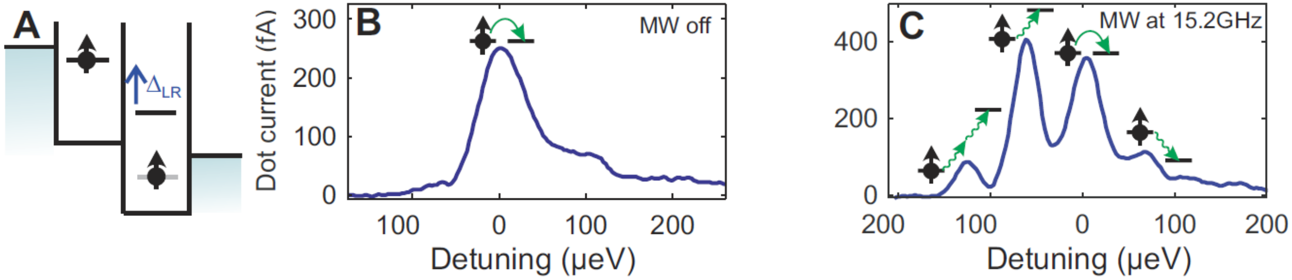


$$|\mathbf{B}_{\mathrm{eff}}(t)| = 2\,|\mathbf{B}_{\mathrm{ext}}|\,\frac{l_{\mathrm{dot}}}{l_{\mathrm{SO}}}\,\frac{e|\mathbf{E}(t)|l_{\mathrm{dot}}}{\Delta}$$

dot orbitals	Δ, ℓ_{dot}
spin-orbit	ℓ_{SO}
electric field	$E(t)$

challenge: E-field vs. freq.

Calibrating the E-field: Photon Assisted Tunneling

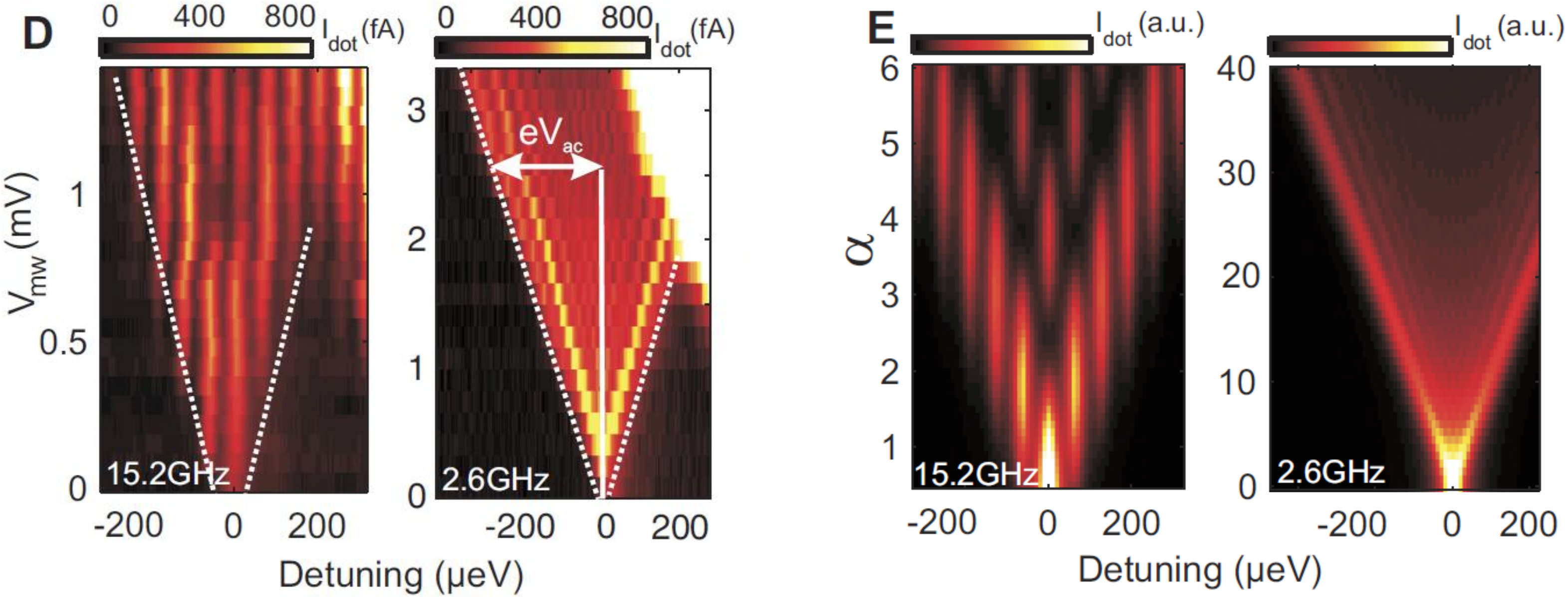


$$\alpha = (eV_{ac})/hf_{ac}$$

$$\tilde{\Gamma}(E) = \sum_{n=-\infty}^{+\infty} J_n^2(\alpha)\Gamma(E + nhf_{ac})$$

n-th order Bessel funct.

envelope ca. $\alpha \sim n$



Conclusions

Demonstration of electric dipole spin resonance

- Rabi frequencies up to 5 MHz / 200 ns
- Consistent with B-scaling as expected for spin-orbit
- Nuclear spins clearly visible

Improvements, outlook:

- suppressing PAT
- higher B-fields
- optimized gate layout
- materials with stronger spin-orbit coupling
- individual addressing of spin in array
- single shot read out