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Coherent Control of a Single Electron Spin with Electric Fields

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Presented by
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Outline

- Motivation
- Spin control with electric field
- Observations
- Results

Motivation

- the ability to induce transitions between the spin-up and spin-down states
- producing strong oscillating magnetic fields requires
  - specially designed microwave cavities
  - microfabricated striplines
- Challenging

- Electric fields can be generated more easily

- Electric field couples
  - by placing the spin in a magnetic field gradient
  - in a structure with a spatially varying *g*-tensor
  - spin-orbit interaction

- coherent single spin rotations induced by
  an oscillating electric field

Single spin control with electric field
Rabi oscillations

- Definition: oscillations of quantum-mechanical probability amplitudes under the influence of an incident field

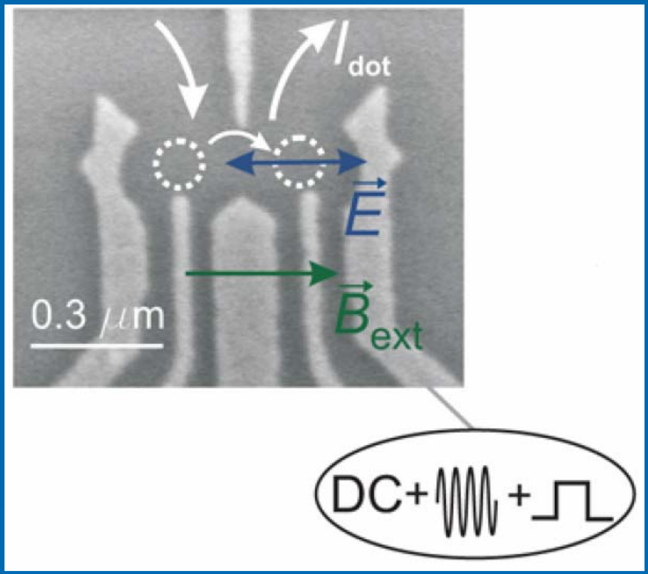
- the **Rabi cycle** is the cyclic behavior of a two-state quantum system in the presence of an oscillatory driving field

- A two-state system has two possible states, and if they are not degenerate energy level the system can become "excited" when it absorbs a quantum of energy

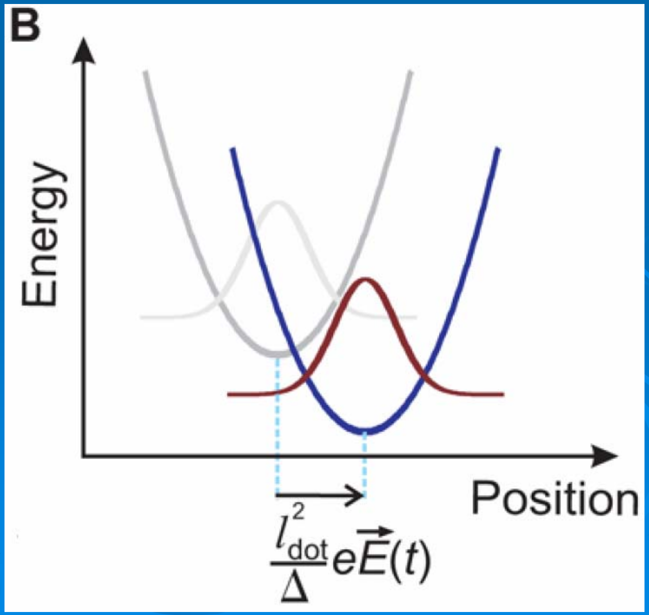
- If the system is initialized in one of these levels, time evolution will make the population of each of the levels oscillate with some characteristic frequency, known as the **Rabi frequency**.

Single spin control with electric field

- Coherent single spin rotations induced by an oscillating electric field
- Experimental set up

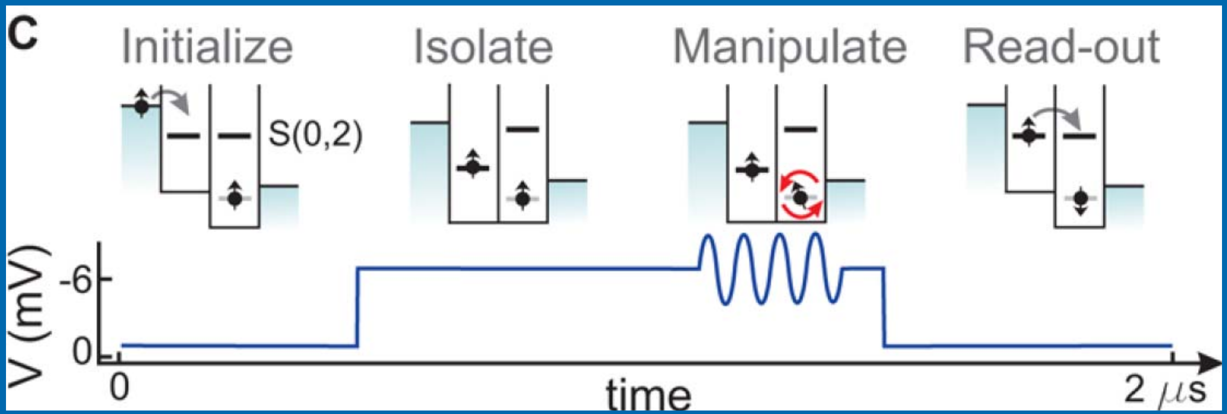


• Metallic Ti Au gates are deposited on top of a GaAs heterostructure
• 2DEG 90 nm below the surface
• Electron is confined in dot and an adjacent quantum dot, containing one electron is for read-out
• a dc voltage can be applied fast pulses and microwaves to the right side gate (as indicated)



• ac electric field is generated through excitation of one of the gates
• electron wavefunction around its equilibrium position is periodically displaced
• Δ-orbital energy splitting
• l_{dot}=ħ/ ($m^*\Delta$) ½ - size of the dot,

Single spin control with electric field

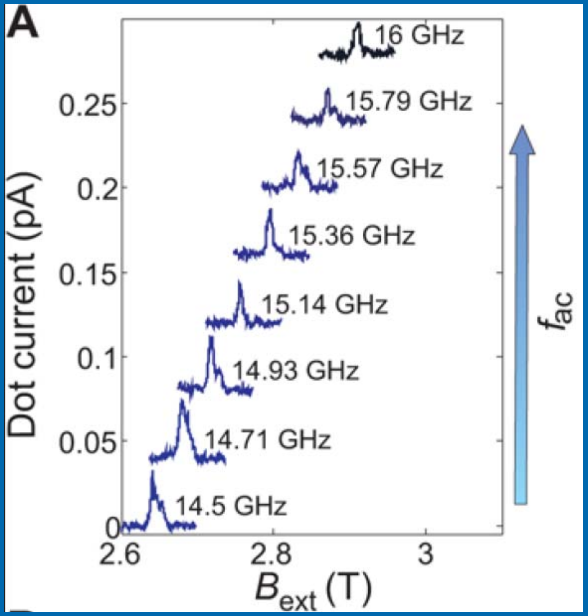


- Manipulation and detection scheme
  - Combination of a voltage pulse and burst, *V*(*t*), applied to the right side gate
  - The device is initialized in a spin-blockade regime
  - Two excess electrons, one in each dot, spin triplet state
  - Two spins are isolated by a gate voltage pulse - electron tunneling between the dots or to the reservoirs is forbidden
  - One of the spins is rotated by an ac voltage burst applied to the gate, over an angle
  - Read-out stage allows the left electron to tunnel to the right dot
  - Tunneling of one electron to the right reservoir contributes to the current.
  - Cycle is continuously repeated
  - Current flow - proportional to the probability of having antiparallel spins after excitation.

Single spin control with electric field

- Signatures of single spin flip
- Microwave burst is applied to the right dot and current flow is observed as a function of external magnetic field
- finite current flow is observed around the single-electron spin resonance condition
- $|\mathbf{B}_{ext}| = hf_{ac}/g\mu_B$

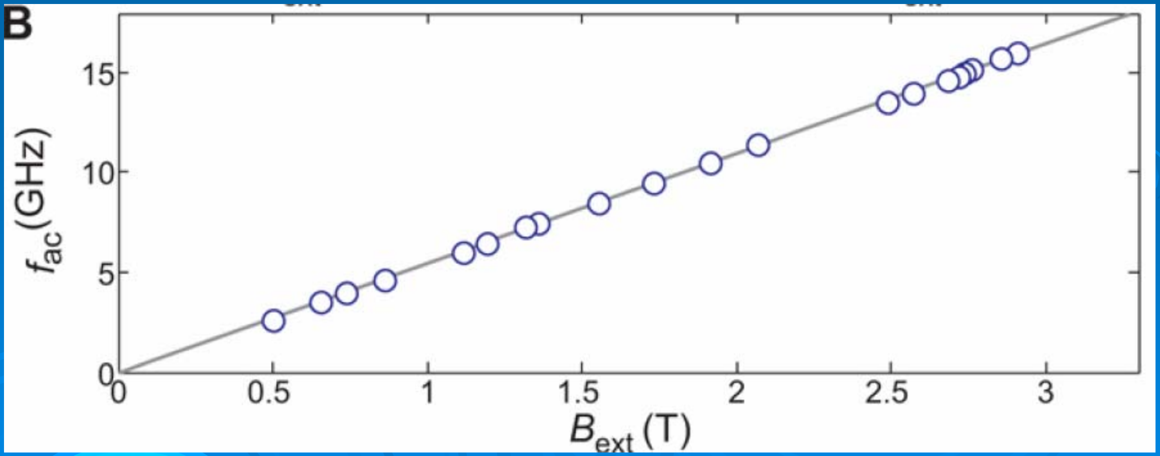
Single spin control with electric field



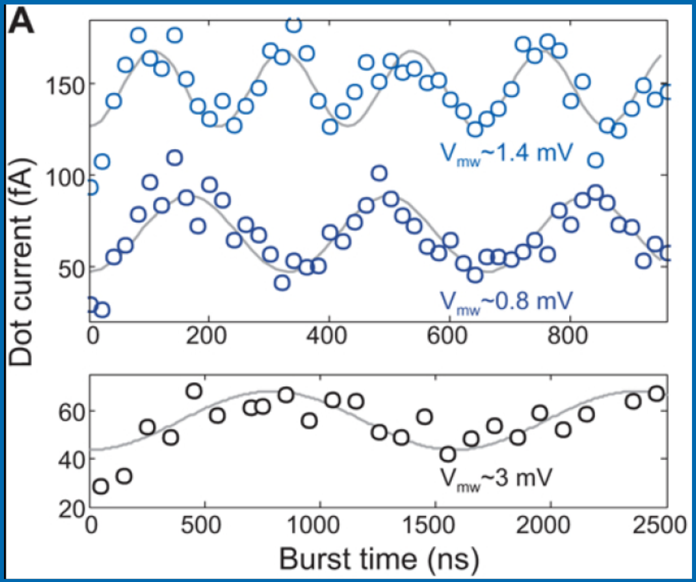
The current averaged over 40 magnetic field sweeps is given for different excitation frequencies

microwave burst length of 150 ns
microwave amplitude *V*mw- 0.9−2.2 mV

Position of resonant response over wider frequency and field ranges



Single spin control with electric field
Demonstration of coherent control of the spin



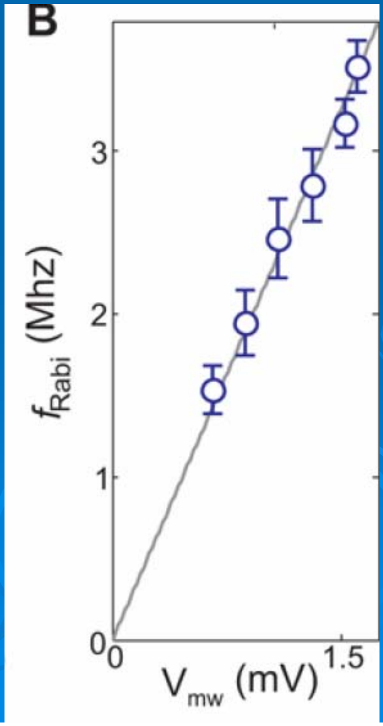
the length of the microwave bursts was varied, and the current level monitored.

- Rabi oscillations at 15.2 GHz (blue) and 2.6 GHz (black)
- Two oscillations at 15.2 GHz are measured at different amplitude of the microwaves *V*mw leading to different Rabi frequencies.

The maximum current oscillates as a function of burst length.

Linear dependence of the Rabi frequency on applied microwave amplitude measured at *fac* = 14 GHz

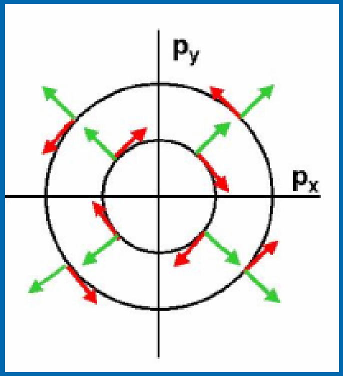
oscillation frequency is linear with the driving amplitude



Single spin control with electric field
Spin orbit mediated tranasition

- an ac electric field can cause single spin transitions in various ways
- the oscillating electric field gives rise to effective magnetic field - **B**eff(*t*),
- Beff(t) acts on the spin, oscillating in the plane perpendicular to **B**ext
- Oscillation frequency $f_{ac} = g\mu_B|\mathbf{B}_{ext}|/h$
- The spin-orbit interaction in a GaAs heterostructure
  - $H_{SO} = \alpha(p_x\sigma_y - p_y\sigma_x) + \beta(-p_x\sigma_x + p_y\sigma_y)$,
  - α and β are Rashba and Dresselhaus spin-orbit coefficients
  - $p_{x,y}$ and $\sigma_{x,y}$ are the momentum and spin in the *x* and *y in (100) and (010)*

Single spin control with electric field
Rashba and Dresselhaus spin orbit couplings



- α – Rashba spin orbit coefficient
  - lack of inversion symmetry in vertical confinement
  - $H_R = \alpha\, [p \times \sigma]\, .n$
  - σ = vector of Pauli spin matrices
  - n= unit vector perpendicular to the plane of the 2DEG
  - α = strength of spin-orbit splitting
  - a momentum- dependent effective magnetic field make the spins (red arrows) to align perpendicularly to the momenta (green arrows)

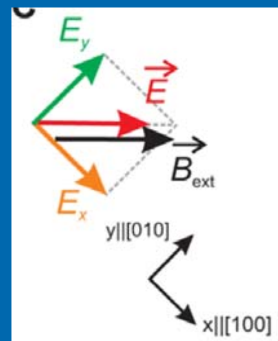
- β - Dresselhaus spin orbit coefficient
  - lack of inversion symmetry of zinc-blend crystal

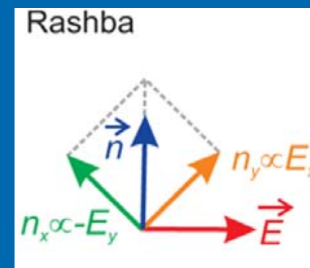
Single spin control with electric field

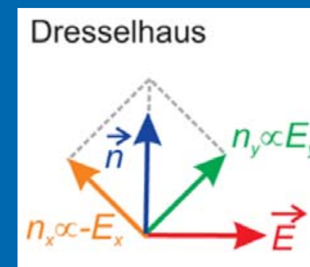
effective magnetic field, acting on the spin, is proportional and orthogonal to the field applied

$$\mathbf{B}_{\text{eff}}(x,y) = \mathbf{n} \otimes \mathbf{B}_{\text{ext}}; n_x = \frac{2m^*}{\hbar}(-\alpha y - \beta x);$$

$$n_y = \frac{2m^*}{\hbar}(\alpha x + \beta y); n_z = 0$$







•Electric field **E**(*t*) will periodically and adiabatically displace electron wave function by **x**(*t*) = (*el*dot ^{2}/Δ) E(t)

•Electron spin will feel an oscillating field **B**eff(*t*) ⊥ **B**ext through the dependence of **B**eff on the position.

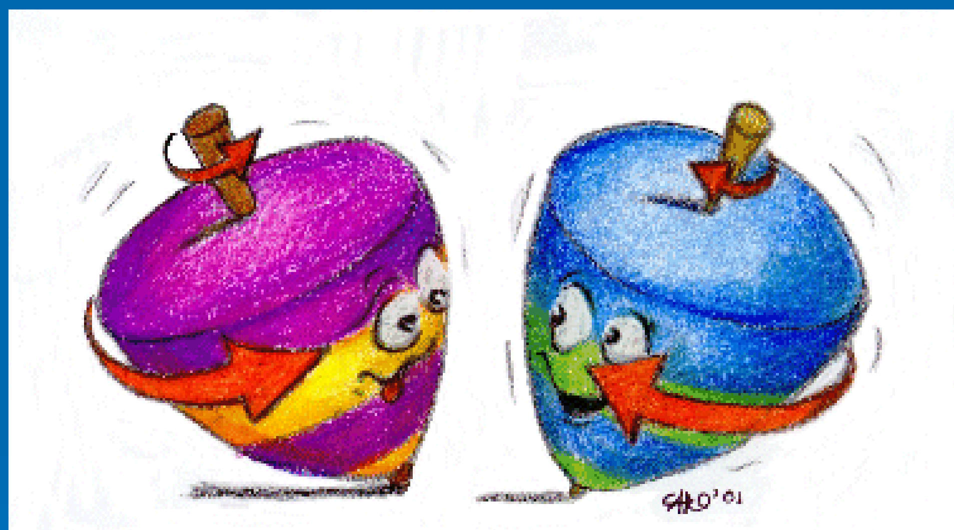
•The direction of **n** can be constructed from the direction of the electric field and together with the direction of **B**ext determines how effectively the electric field couples to the spin.

•The Rashba contribution always gives **n**⊥**E**,

•The Dresselhaus contribution depends on the orientation of the electric field with respect to the crystal axis. For the sample orientation, the Dresselhaus contribution is also orthogonal to the electric field

•This is why both contributions will give **B**eff ≠ 0 and lead to coherent oscillations

Thank you for your attention



The electron as "Spinning top"