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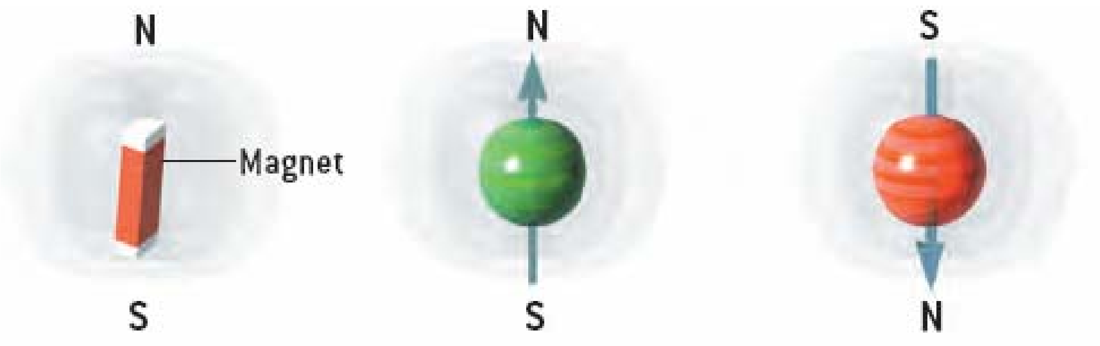
Single Spin Magnetic Resonance and Related Phenomena in Si Field Effect Transistors



or how to measure a single electron spin

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KITP, UCSB

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Acknowledgements

- *D. Mozyrsky (LANL,T-4)*
- *M. Hastings (LANL, T-13)*
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- *Experiment: H.W. Jiang's group at UCLA*

REFS:
Phys. Rev. Lett. **90**, 018301 (2003) - ESR - theoretical scheme
Phys. Rev. Lett. **91**, 078301 (2003) - experiment (B-dep)
Nature **430**, 435 (2004) - experiment (1 spin ESR)
Phys. Rev. B **71**, 165115 (2005) - Kondo + lattice
cond-mat/0312503 - Fermi-edge + lattice
Phys. Rev. B ***73**, 035104 (2006)* - polaronic molecular switch

Outline

Introduction: Single Spin Magnetic Resonance

Random Telegraph Noise in Field Effect Transistors

- *A scheme for Electron Spin Resonance: Theory*
- *A scheme for Electron Spin Resonance: Experiment*
- *Single Spin Measurement*

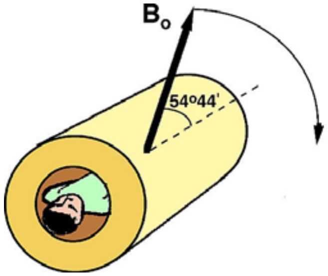
Inconsistency between expected and observed tunneling rates: Polaronic slowdown

Low temperature magnetic anomalies: Possible Kondo Effect

Summary and Open problems

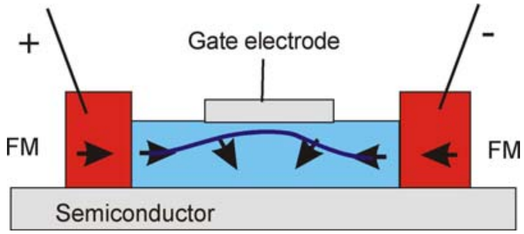
Applications of Spin measurement

Magnetic Resonance Imaging (MRI)



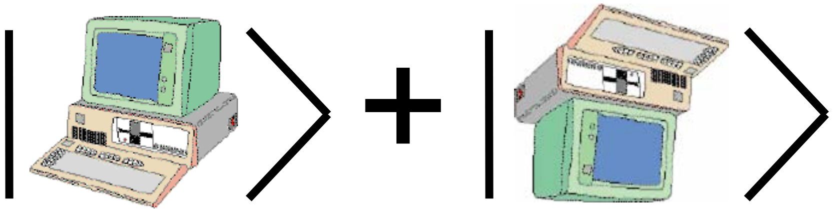
$> 10^{10}$ spins

Spin – Effect Devices (Spin Transistors)



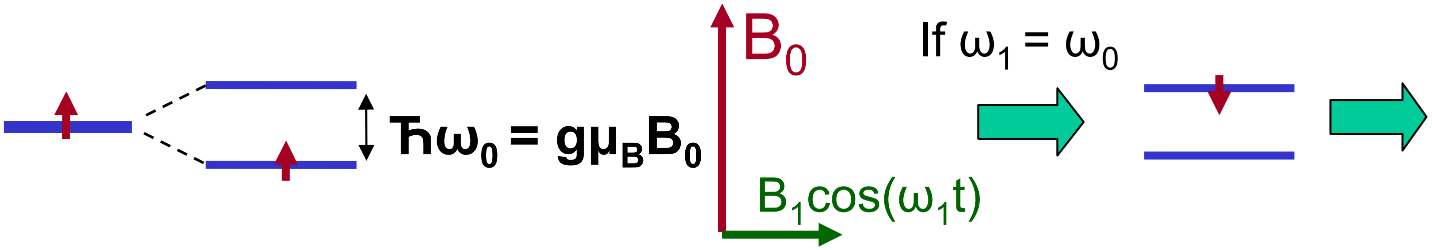
$> 10^{3}$ spins

Quantum Computing



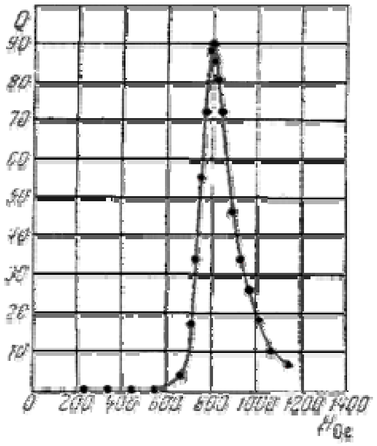
1 spin

Electron Spin Resonance

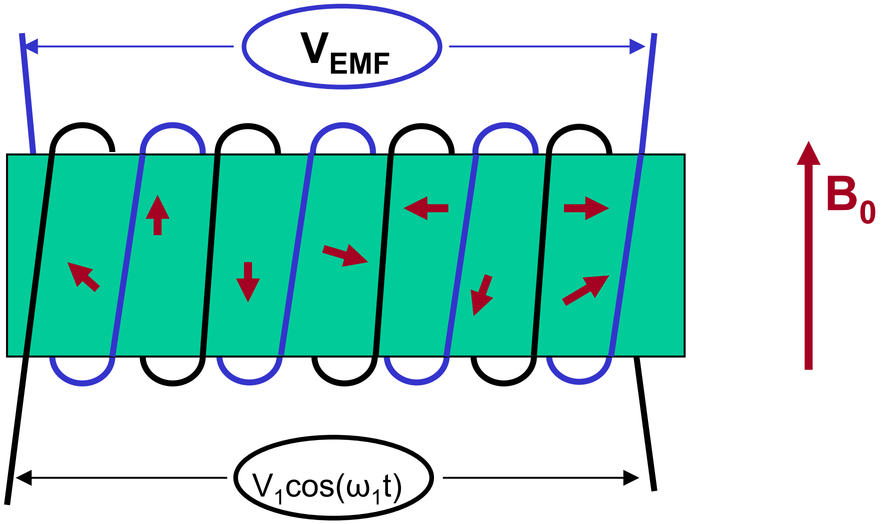


spin rotates with Rabi frequency ~ B_1

Experiment



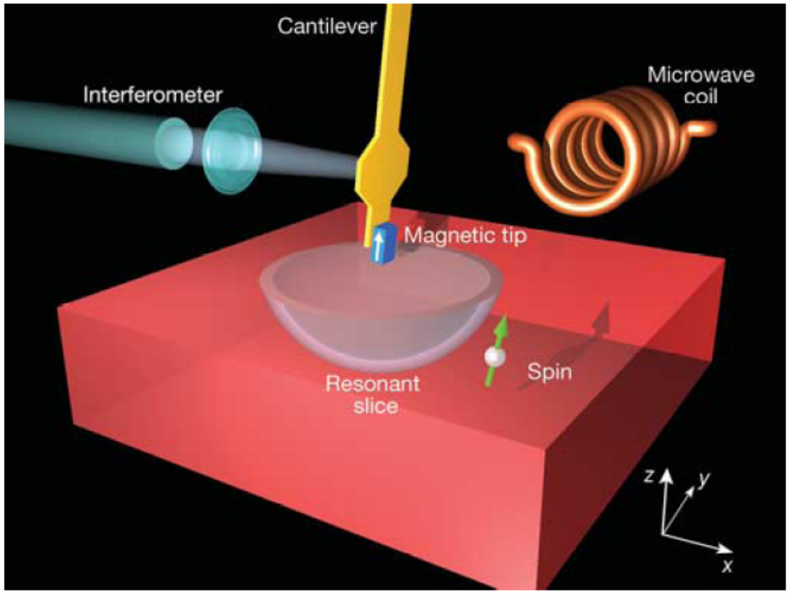
Rabi , Zacharias, Millman, Kusch (1939)

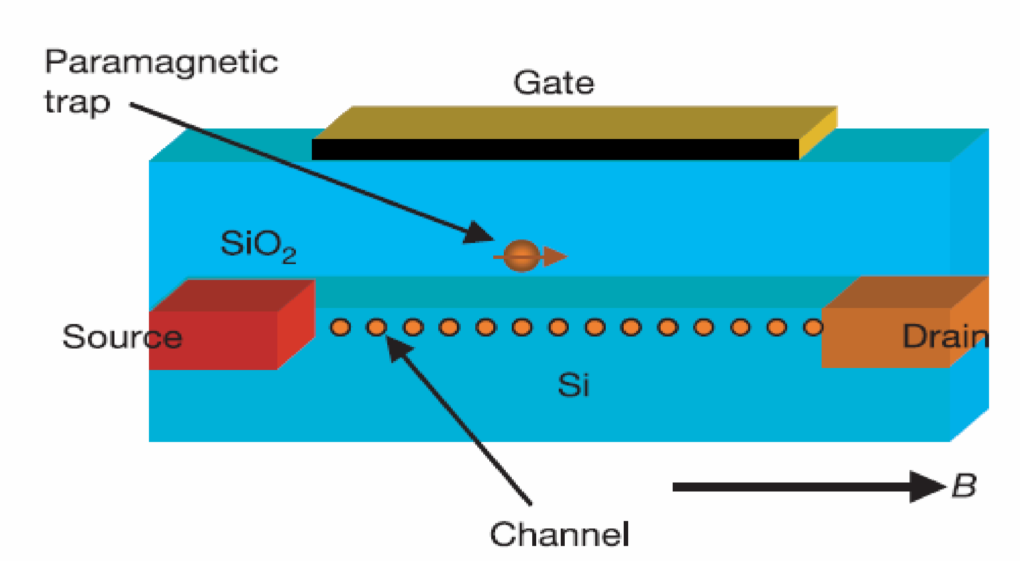


Single Spin Resonance: MRFM and Paramagnetic Traps in FETs

Magnetic Resonance Force Microscopy (MRFM)

Electron Spin Resonance in a Field Effect Transistor (FET)



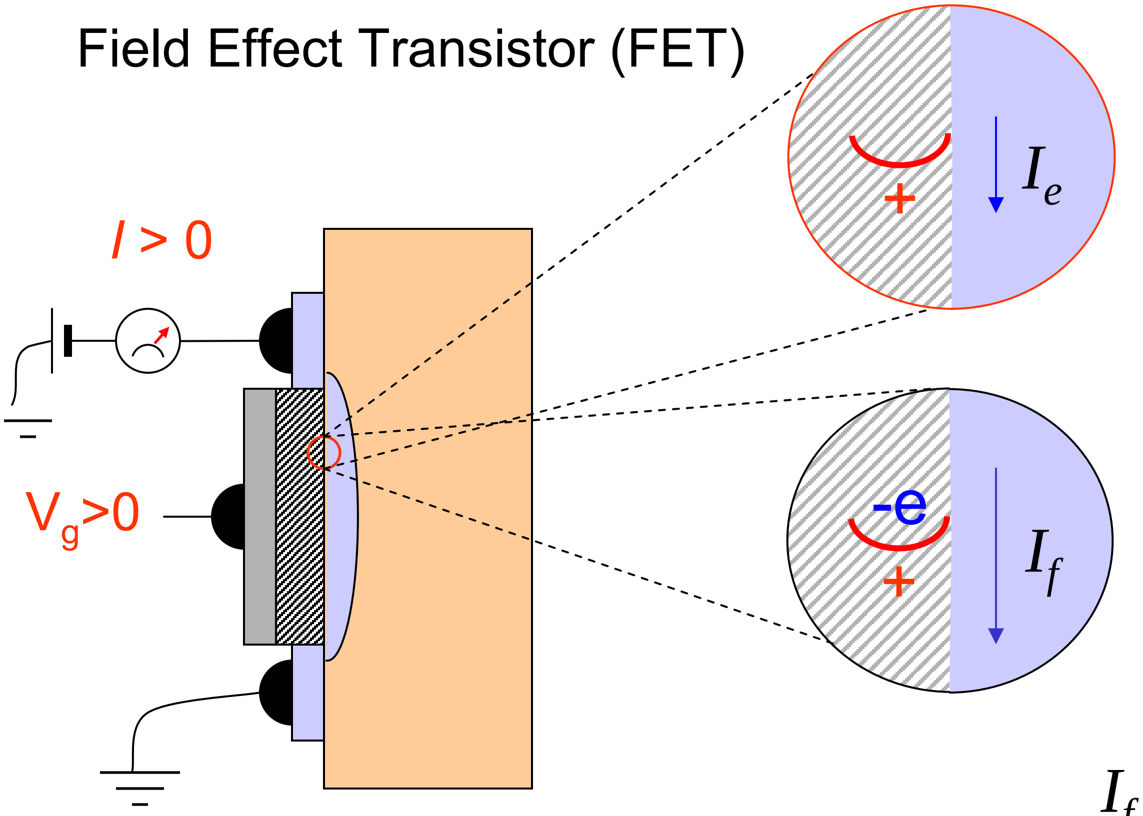


Rugar, Budakian, Mamin & Chui, **Nature 430**, 329 (2004)

Xiao, Martin, Yablonovitch & Jiang, **Nature 430**, 435 (2004)

Traps in Field Effect Transistors and Random Telegraph Signals

Field Effect Transistor (FET)

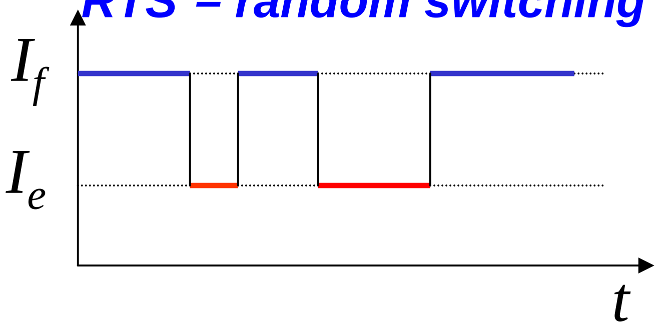


empty trap (positive)
higher resistance

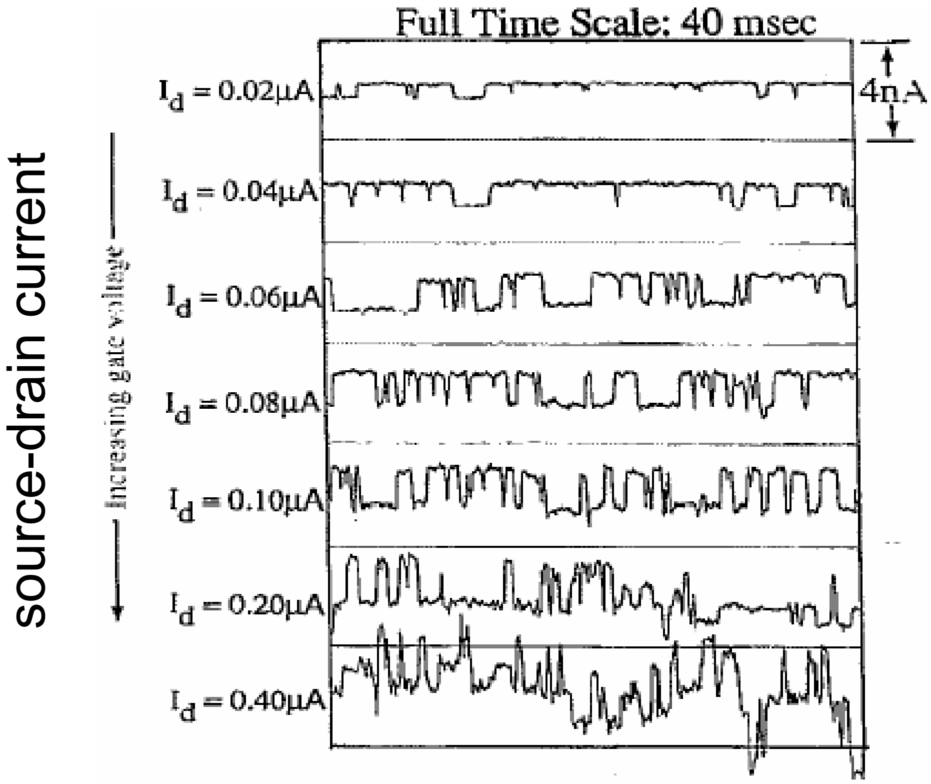
or

filled trap (neutral)
lower resistance

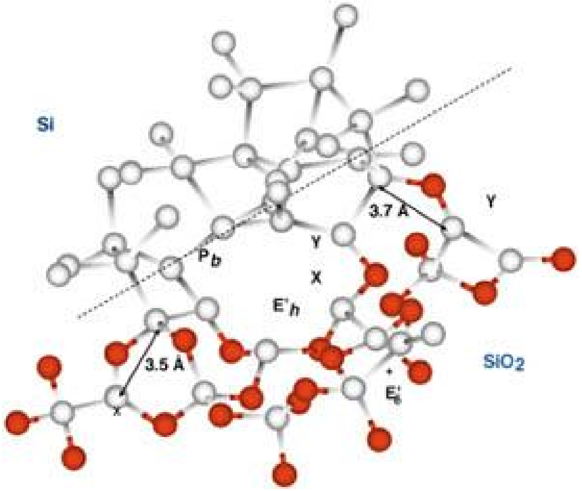
RTS – random switching



Random Telegraph Signal (RTS) – experiment



Defects at Si - SiO_2 interface



Ming-Horn Tsai, Hirotaka Muto,[a] and T. P. Ma
Appl. Phys. Lett. **61** (14), 5 October 1992

A Setup for Electron Spin Resonance(ESR)

At $T = 0$, $B_1 = 0$:

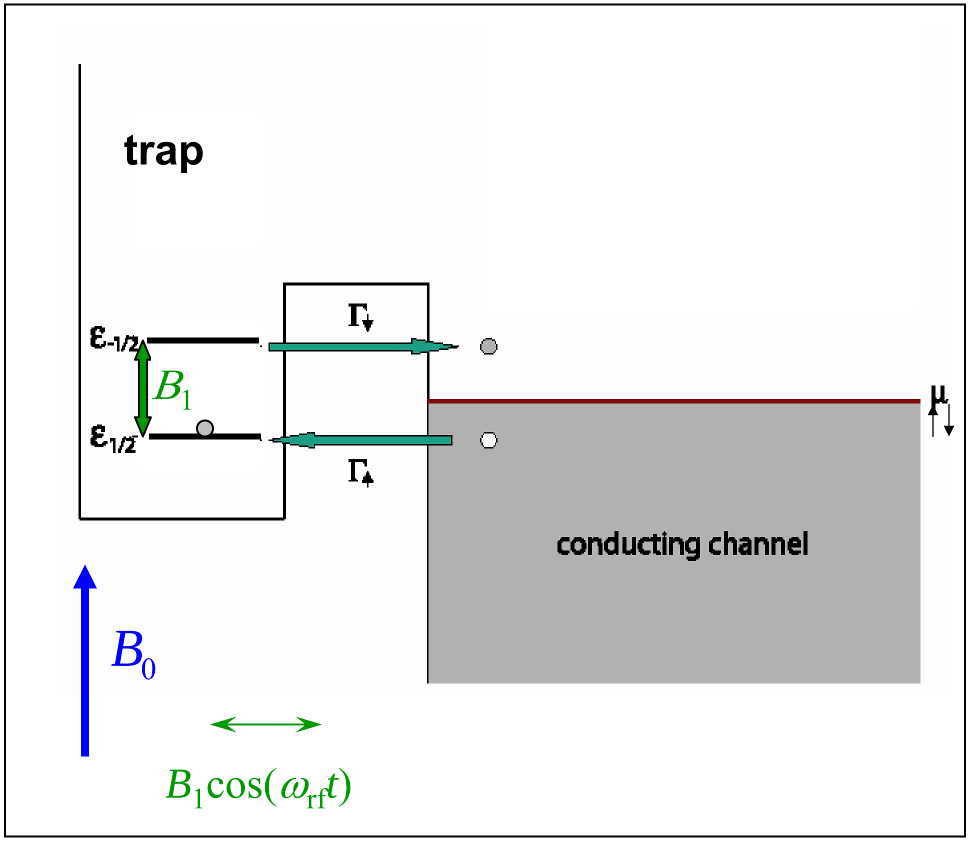
trap is filled if $\varepsilon_{1/2} < \mu$
trap is empty if $\varepsilon_{1/2} > \mu$

No RTS

At $T = 0$ and resonant $B_1(t)$:

trap can be filled if $\varepsilon_{-1/2} < \mu$
e^- is promoted $\varepsilon_{1/2}$ -> $\varepsilon_{-1/2}$
e^- can escape if $\varepsilon_{1/2} > \mu$

Electron Spin Resonance -induced RTS!



The trap occupation number is *modified* by resonant $B_1(t)$

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Quantum rate equations for ESR-RTS

I. Martin, D. Mozyrsky & H.-W.Jiang, Phys. Rev. Lett. **90**, 018301 (2003)

$$H = \sum_s \left(\epsilon_s n_s + \frac{U}{2} n_s n_{-s}\right) + \sum_{q,s} \epsilon_{qs} c^\dagger_{qs} c_{qs} + \sum_{q,s} T_q \left(c^\dagger_{qs} c_s + c^\dagger_s c_{qs}\right) + H_{\mathrm{rf}}(t)\,.$$

$$H_{\mathrm{rf}}(t) = \frac{\omega_R}{2}\left(c^\dagger_{1/2} c_{-1/2} e^{i\omega_{\mathrm{rf}} t} + h.c.\right)$$

– rotating wave approx

$$\left.\begin{aligned}
\dot{\sigma}_0 &= -\Gamma_\uparrow \sigma_0 + \Gamma_\downarrow \sigma_{\downarrow\downarrow}\,, \\
\dot{\sigma}_{\uparrow\uparrow} &= \Gamma_\uparrow \sigma_0 + i(\omega_R/2)\left(e^{i\omega_{\mathrm{rf}} t}\sigma_{\uparrow\downarrow} - e^{-i\omega_{\mathrm{rf}} t}\sigma_{\downarrow\uparrow}\right)\,, \\
\dot{\sigma}_{\downarrow\downarrow} &= -\Gamma_\downarrow \sigma_{\downarrow\downarrow} - i(\omega_R/2)\left(e^{i\omega_{\mathrm{rf}} t}\sigma_{\uparrow\downarrow} - e^{-i\omega_{\mathrm{rf}} t}\sigma_{\downarrow\uparrow}\right)\,, \\
\dot{\sigma}_{\uparrow\downarrow} &= -i(E/\hbar)\sigma_{\uparrow\downarrow} - \Gamma_\downarrow/2\sigma_{\uparrow\downarrow} \\
&\quad + i(\omega_R/2)e^{-i\omega_{\mathrm{rf}} t}\left(\sigma_{\uparrow\uparrow} - \sigma_{\downarrow\downarrow}\right)\,.
\end{aligned}\right\}$$

equations of motion
for trap density matrix

$$\boxed{\sigma_0 + \sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow} = 1}$$

Average FET channel resistivity: $\boxed{\rho = \rho_e \sigma_0 + \rho_f (1 - \sigma_0)}$

Resonance in average resistance

$$\rho(B_0) = \rho_f + \frac{(\rho_e - \rho_f)\,\omega_R^2}{4(g\mu_B B_0/\hbar - \omega_{\rm rf})^2 + \Gamma^2 + 3\omega_R^2}$$

Application of resonant rf $B_1(t)$ modifies the average channel resistivity by changing the RTS ***statistics***

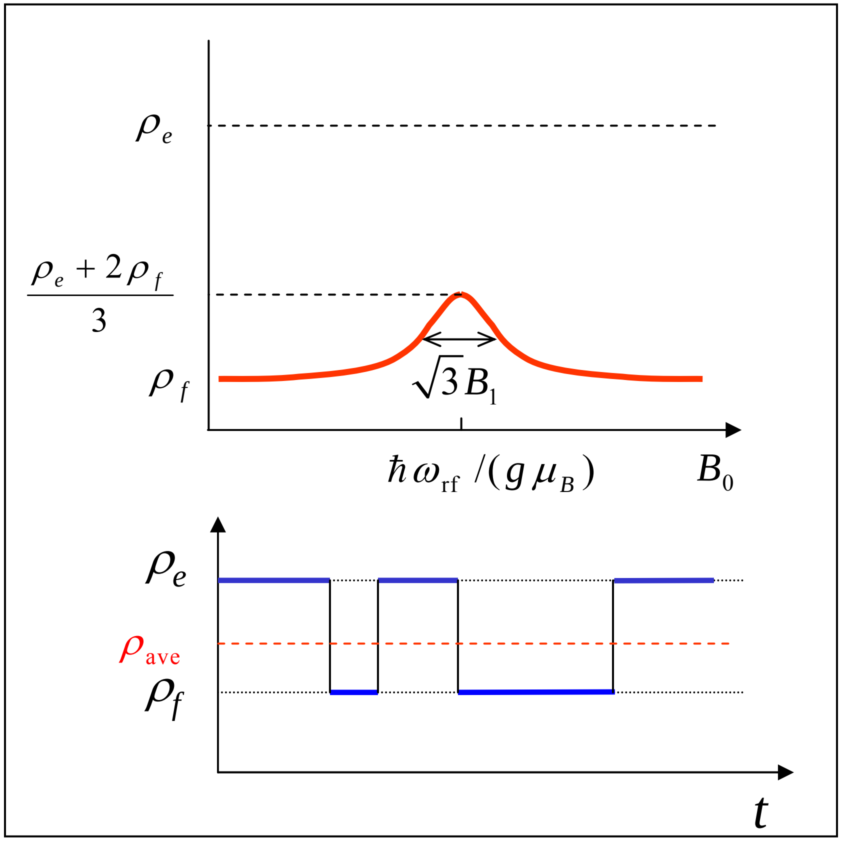
In presence of dephasing $1/T_2' >> \Gamma$:

peak width:

$$(1/T_2')\sqrt{1 + 3\omega_R^2 T_2'/(2\Gamma)}$$

peak height:

$$1/[3 + 2\Gamma/(\omega_R^2 T_2')]$$

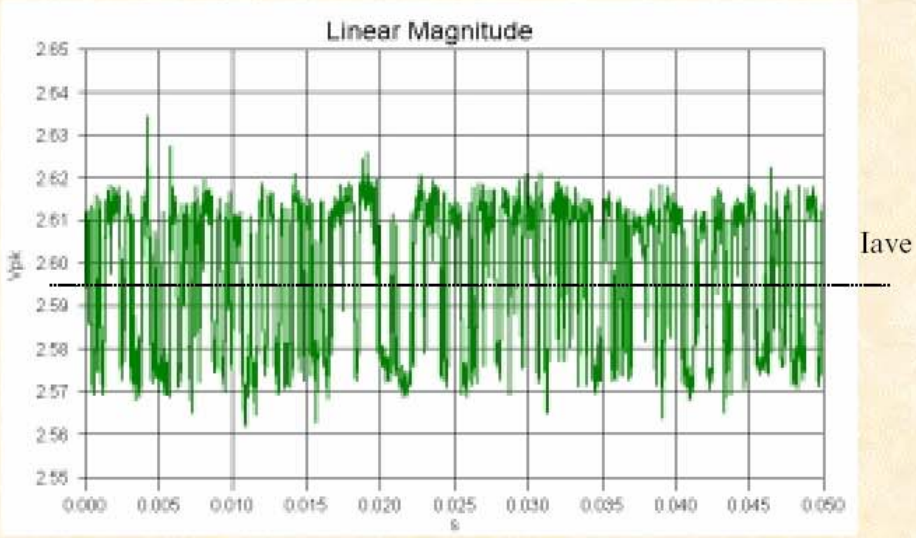


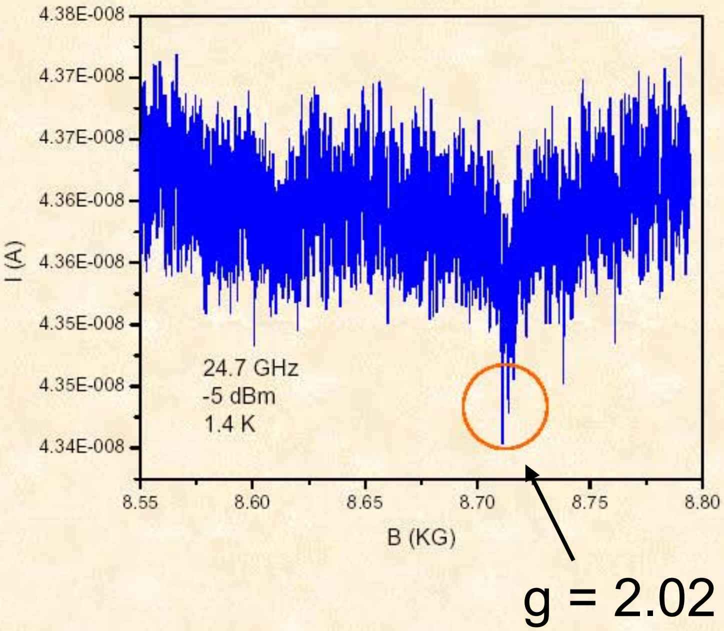
ESR-RTS Experiment –average current

*(M. Xiao et al., Nature **430**, 435, 2004)*

Measure average current: reflects the statistical occupation change:

$$I_{avr} = I_h * p_h + I_l * p_l$$

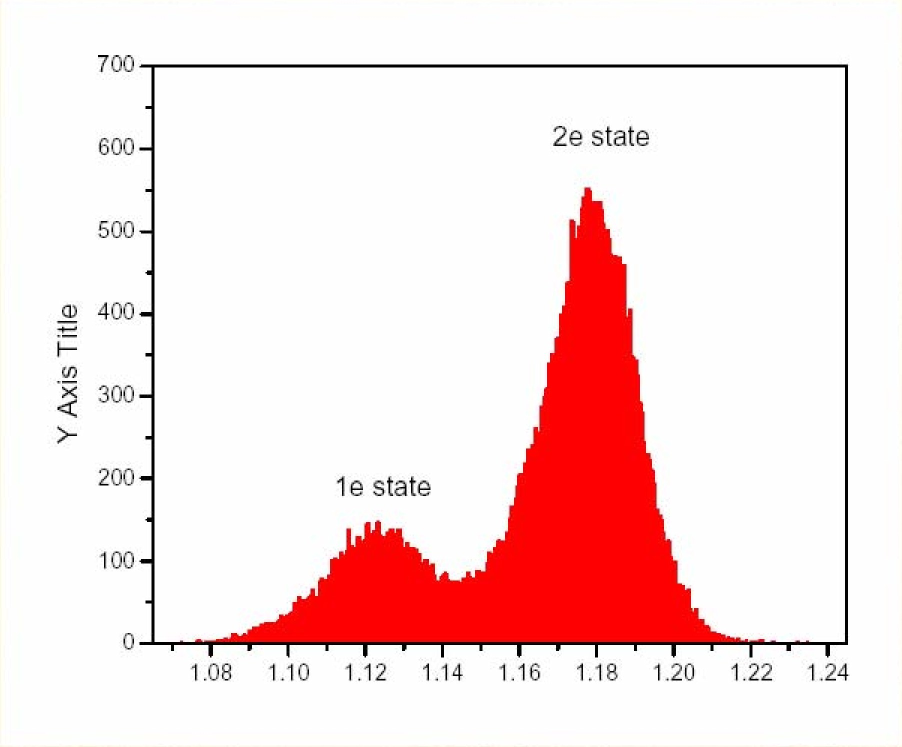




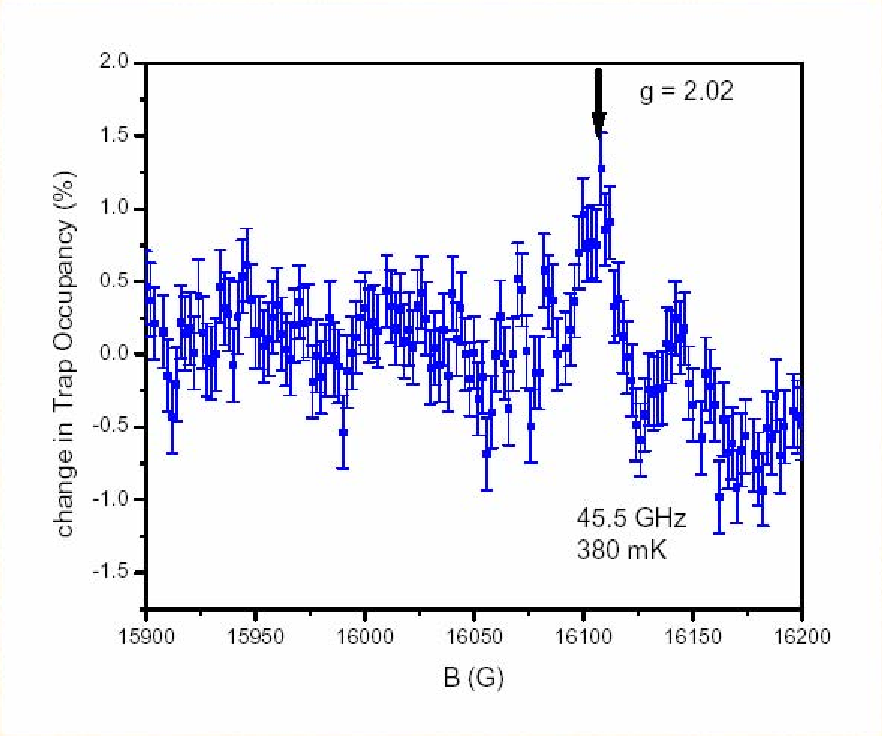
Only observed in the RTS region.

ESR-RTS Experiment – trap occupancy (HWJ)

Observed a change in the trap occupation probability

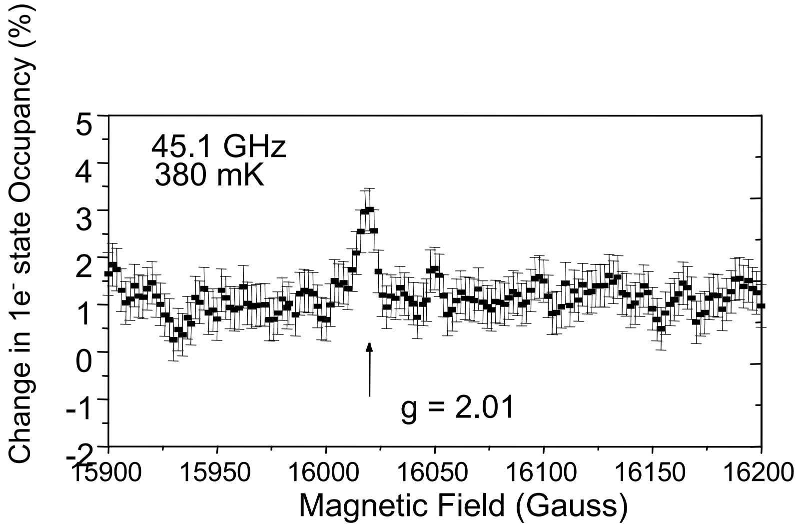


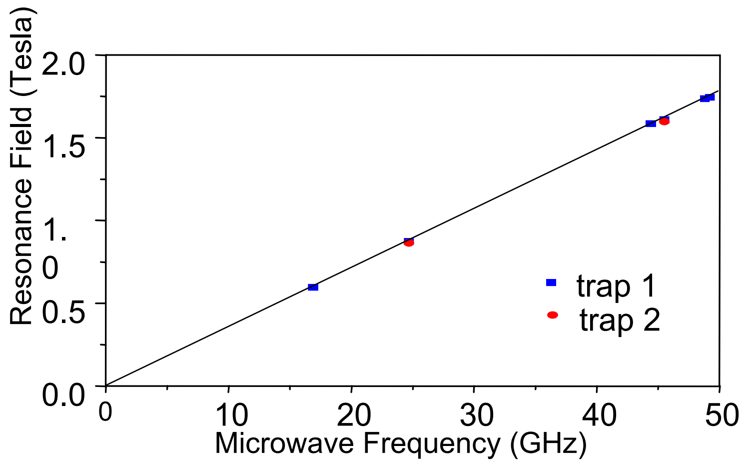
histogram of the raw data



obtained after the time-domain analysis

Surprise I: Signal changes sign for larger microwave power!





- *Signal changes sign when* $\Gamma \sim \omega_{Rabi}$
- *Improved signal-to-noise*
- *Tunneling rate is reduced on the resonance*

Nature, **430**, 435 (2004)

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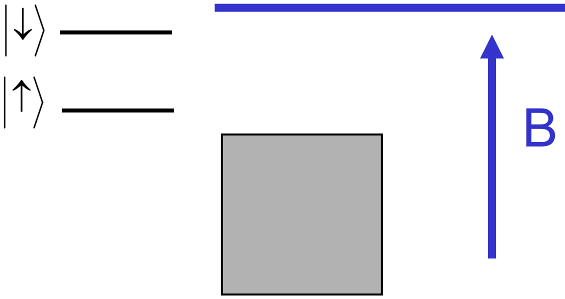
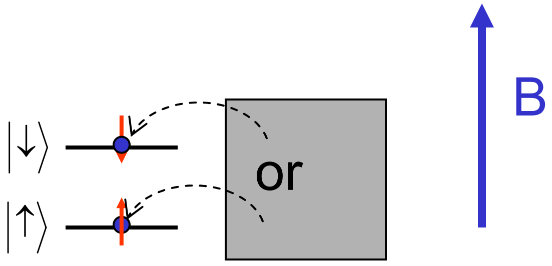
Traps for Quantum Computing
A Readout Scheme

1.



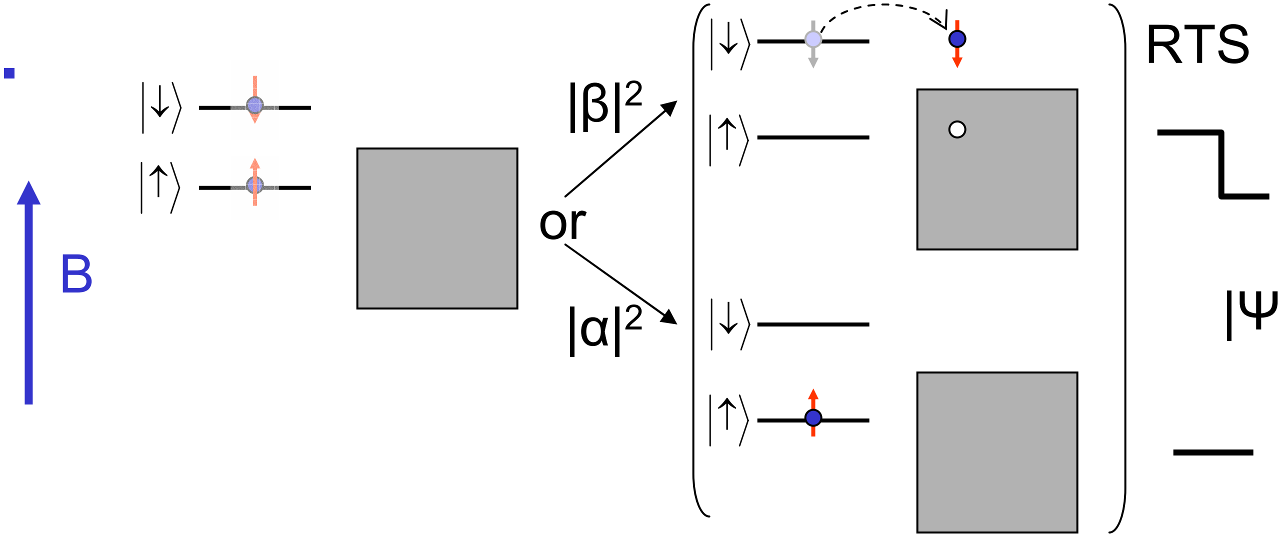
|Ψ> = 0

2.



|Ψ> = α|0> + β|1>

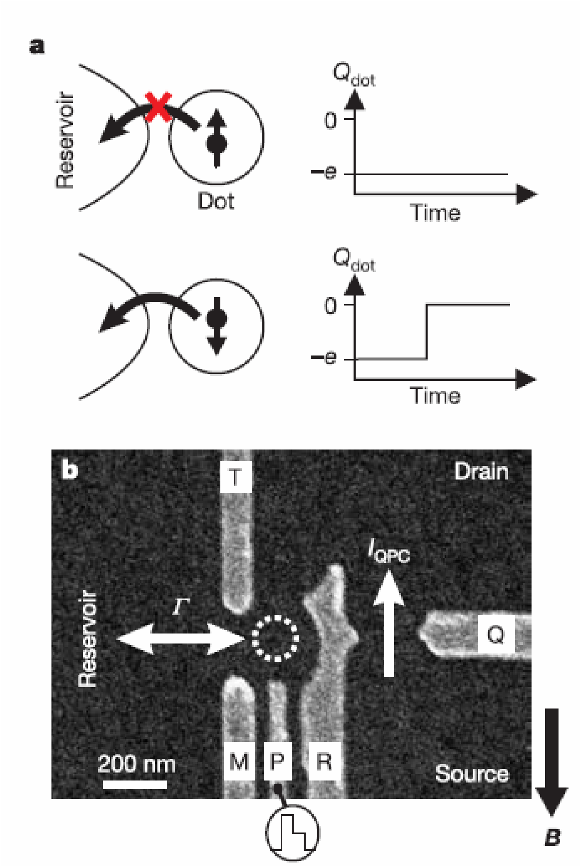
3.

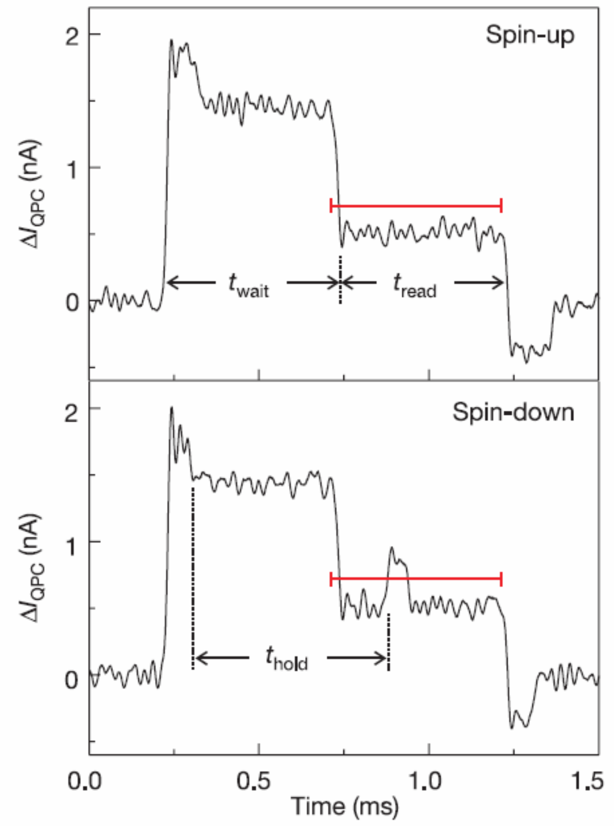


|Ψ> = |0> or |1>

Single Spin Measurement in Quantum Dots

Elzerman et al., Nature ***431****, 430 (2004)*





Demonstrated Spin Measurement Efficiency ~ 65%

The Readout Scheme: Experimental Facts

The scheme works in quantum dots with 65% efficiency
REF: J.M. Elzerman *etal.*, Nature **430**, 431(2004).

So far in FET traps the scheme does not work – no RTS signal

WHY? => spin is always in its ground state.

WHY? => fast spin relaxation => WHY?

Maybe because of the exchange interaction with electrons in the conduction channel ?!

Need to look at the microscopic structure of traps!

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- A scheme for Electron Spin Resonance: Experiment
- Single spin Detection

Inconsistency between expected and observed tunneling rates: Polaronic slowdown

Low temperature magnetic anomalies: Possible Kondo Effect

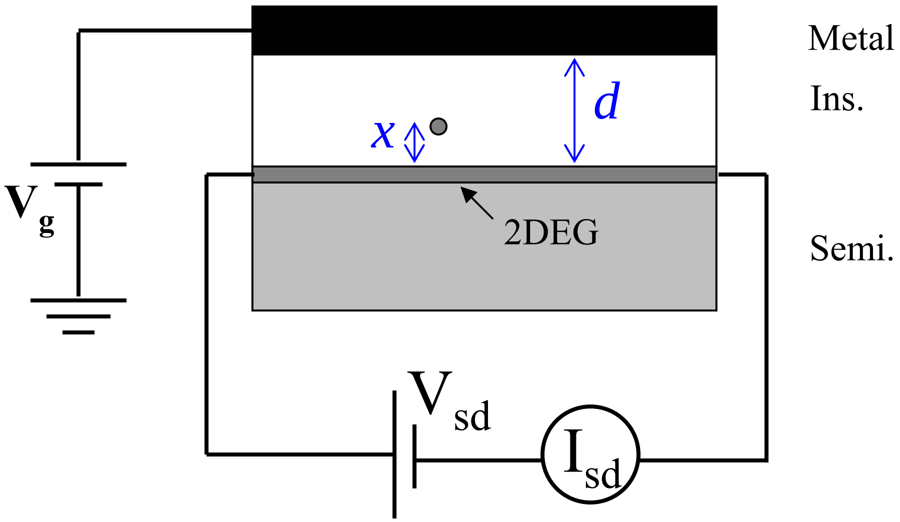
Summary and Open problems

Determination of Defect's Position. Surprise II

Experimentalists can measure the location of the trap (x) with respect to the conduction channel.

Defect position determination:

$$\frac{\tau_{in}}{\tau_{out}} = \frac{\exp[(E_d - \mu)/T]}{1} = \exp\left(\frac{V_g - V_{g0}}{T}\frac{x}{d}\right)$$



One finds x~1-3 Å.

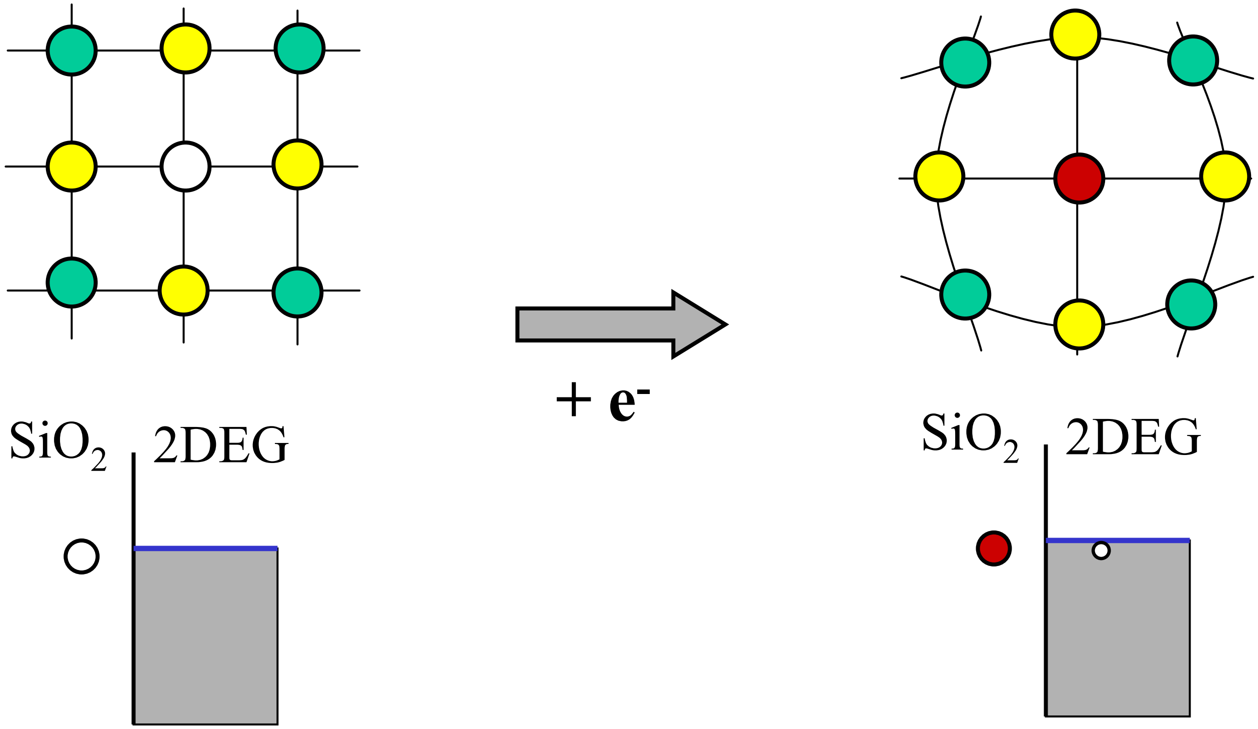
Estimate for tunneling time yields ~ (ps – ns)

Observed ~ (ms – s) ???

Polaronic Slowdown

SiO_2 is a polar crystal ⇒ strong coupling to optical phonons

Empty Trap **Trap with an extra electron**



Tunnel rate in the presence of lattice deformations

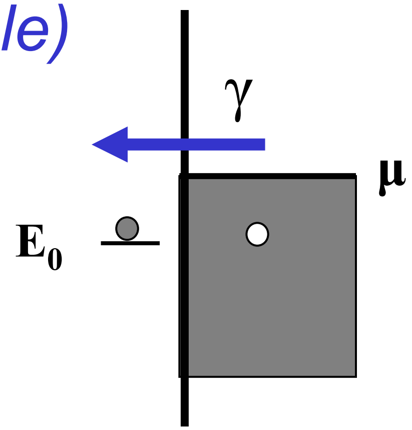
$$H = \underbrace{\sum_k E_k c_k^\dagger c_k}_{\text{conduction electrons}} + \underbrace{E_0 d^\dagger d}_{\text{defect level}} + \underbrace{d^\dagger d\, g(a^\dagger + a)}_{\text{electron-phonon interaction}} + \underbrace{\omega_0 a^\dagger a}_{\text{optical phonon}} + \underbrace{\Delta \sum_k (c_k^\dagger d + d^\dagger c_k)}_{\text{tunneling (} \mathbf{H_T} \text{)}} + \underbrace{V d^\dagger d \sum_{k,k'} c_k^\dagger c_{k'}}_{\text{Coulomb interaction}}$$

Calculation of Tunnel Rate for V = 0 (Golden Rule)

$$\gamma^{GR} = 2\pi \sum_{\text{final states}} |\langle \text{initial}|H_T|\text{final}\rangle|^2 \; \delta(E_{\text{initial}} - E_{\text{final}})$$

$$|\text{initial}\rangle = |0\rangle_{\text{electrons}} \otimes |0\rangle_{\text{phonon}}$$

$$|\text{final}\rangle = |1_k\rangle_{\text{electrons}} \otimes |n\rangle_{\text{shifted phonon}}$$



cond-mat/0312503

Estimate for Si Field Effect Transistor

Mozyrsky, Martin, Shnirman cond-mat/0312503

$$\Gamma = 2\pi\nu\Delta^2 e^{-\frac{E_p}{\omega_0}}$$

Assuming Fröhlich electron-phonon coupling

$$E_p = 5e^2/(16a_d)(\epsilon_\infty^{-1} - \epsilon_0^{-1})$$

For SiO$_2$ $\varepsilon_0 = 4,\ \varepsilon_\infty = 2, a_d \sim 1\ \text{Å}$ → $E_p \approx 1.2\ e\text{V}$

For bulk optical phonons in SiO$_2$: $\omega_0^{\text{bulk}} \approx 60\ me\text{V}$

exp ($-E_p/\omega_0$) ~ exp(-20) ~ 10^{-8}

Qualitative agreement with observed rates !

Strong electron-phonon interaction is responsible for long tunneling time in Si FET

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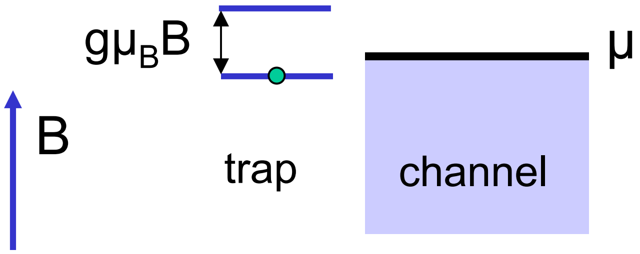
Summary and Open problems

Magnetic field dependence at low temperatures. Surprise III

Xiao *et al.*, Phys. Rev. Lett. 91, 078301 (2003)

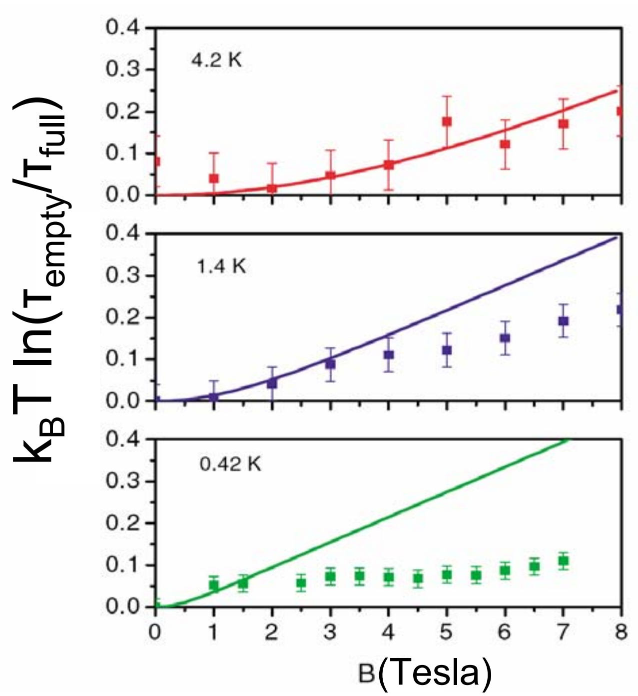


For a paramagnetic spin

$$(\tau_{empty}/\tau_{full}) \approx \exp(g\mu_B B / k_B T)$$

No agreement between simple model and experiment at low T!

Kondo effect?

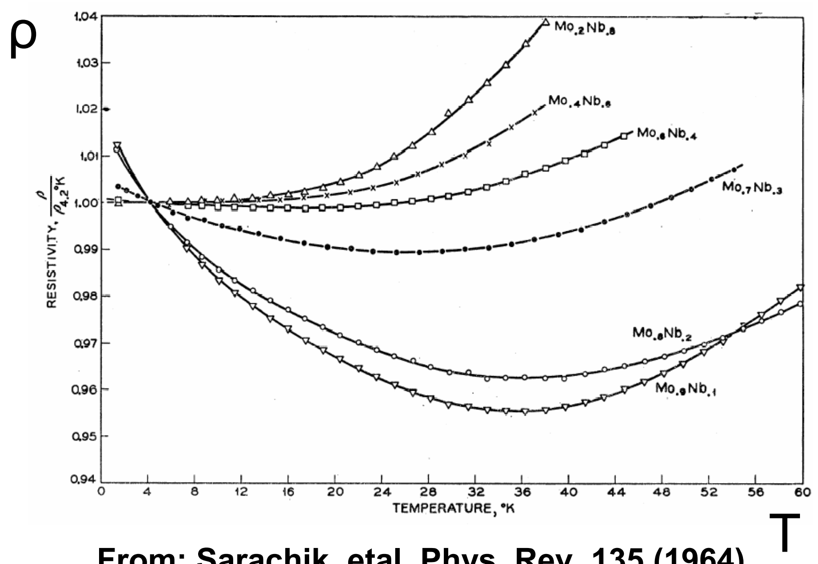


Solid lines: theoretical fits for a paramagnetic trap

Bullets: experimental data

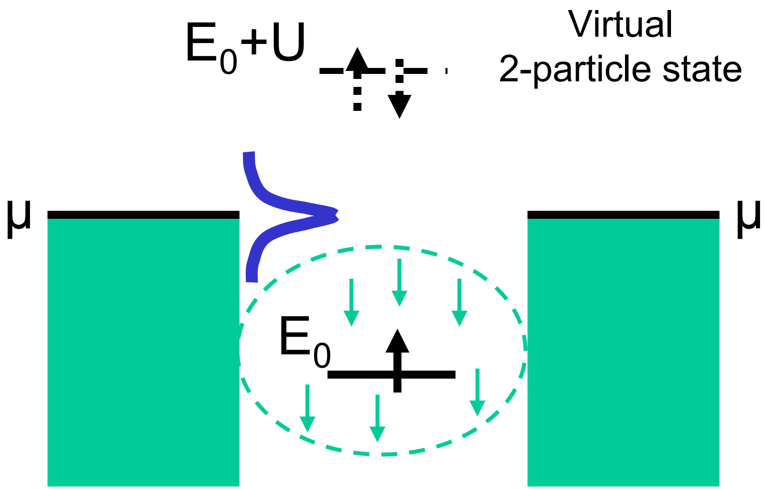
Kondo Effect

Resistivity of metals doped with magnetic impurities



From: Sarachik, etal, Phys. Rev. 135 (1964)

Magnetic impurity in a metal



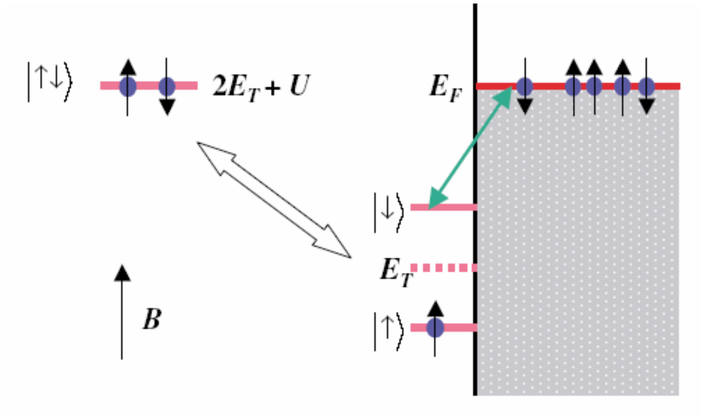
A localized impurity spin is screened by spins of conduction electrons

At low energy scale (below T_K) the magnetic impurity creates a strong resonance at Fermi surface => scattering => resistivity

Kondo?

$T_K \sim \exp[-O(1)\, U/\Gamma\,]$

For $\Gamma \sim 1\ s^{-1}$ => $T_K \rightarrow 0$

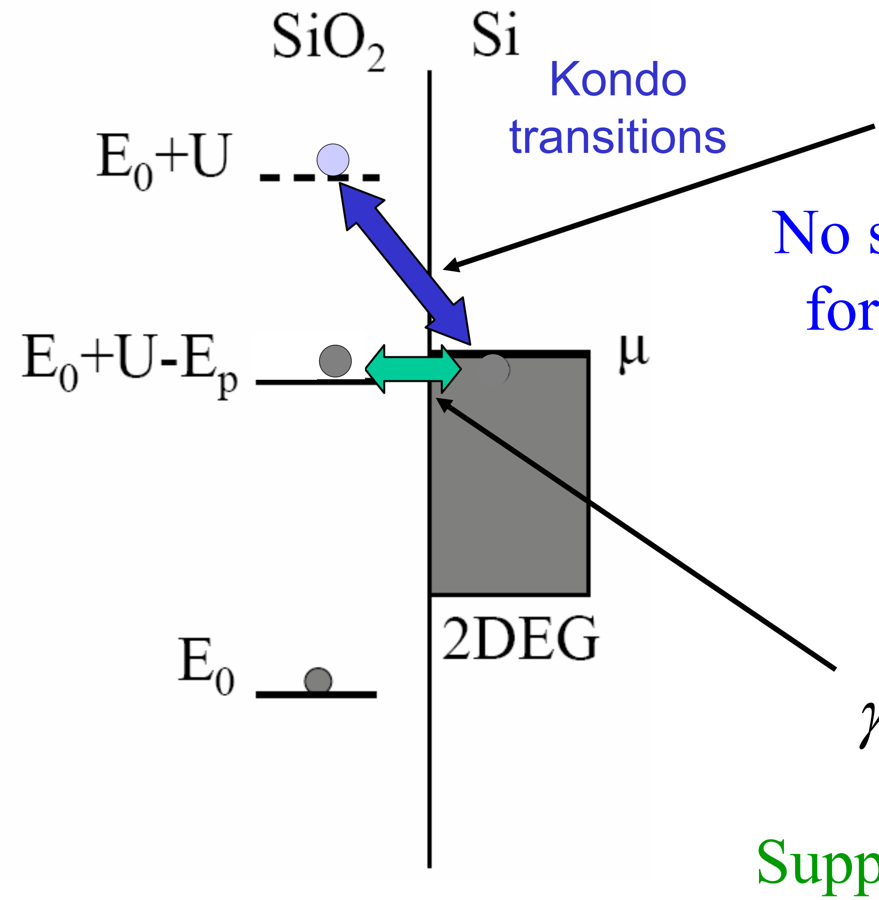


However, Γ is small only effectively – due to strong electron-lattice coupling! The “bare” hybridization (“bare” Γ_0) may be strong!

$$\Gamma = \underbrace{2\pi v \Delta^2}\, e^{-\frac{E_p}{\omega_0}}$$

Large bare Γ_0 relevant for Kondo if $U > \omega_0 \rightarrow$ finite T_K

Kondo!



$$\gamma = 2\pi\nu\Delta^2$$

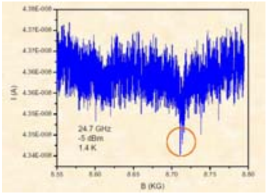
No suppression of transitions for virtual (fast) processes

$$\gamma = 2\pi\nu\Delta^2 e^{-\frac{E_p}{\omega_0}}$$

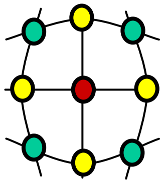
Suppression of transitions for real (slow) process

Summary and Perspectives

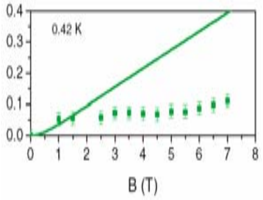
- ***Single electron spin resonance in FET***



- ***Tunneling slowdown (due to strong electron-lattice coupling)***



- ***Kondo Effect in FET traps ?***



- ***ESR signal inversion ?***

What's next?

A single nuclear spin?...