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Electrical detection of single electron spin resonance

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- *Scheme/Theory*
- *Experiment*
- *Single qubit operations*
- *Detailed theory of tunneling*
  - *Polaronic slowdown*
  - *Fermi edge singularity*
  - *Kondo effect*

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Nature **430**, 435 (2004)
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cond-mat/0403491

August 2004, QUEST (Santa Fe)

Measuring a single spin

- *Applications:*
  - *Quantum computer qubit readout*
  - *Local surface characterization*
  - *Spintronics*
  - *Study of Kondo physics*

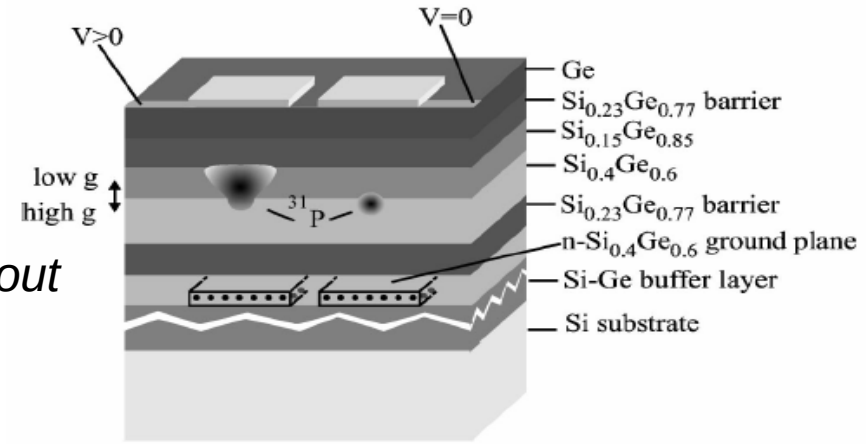


FIG. 5. The left transistor gate is biased $V>0$, producing single-qubit unitary transformations in the left SRT. The right gate is unbiased: $V=0$. The n-$Si_{0.4}Ge_{0.6}$ ground plane is counterelectrode to the gate, and it also acts as FET channel for sensing the spin.

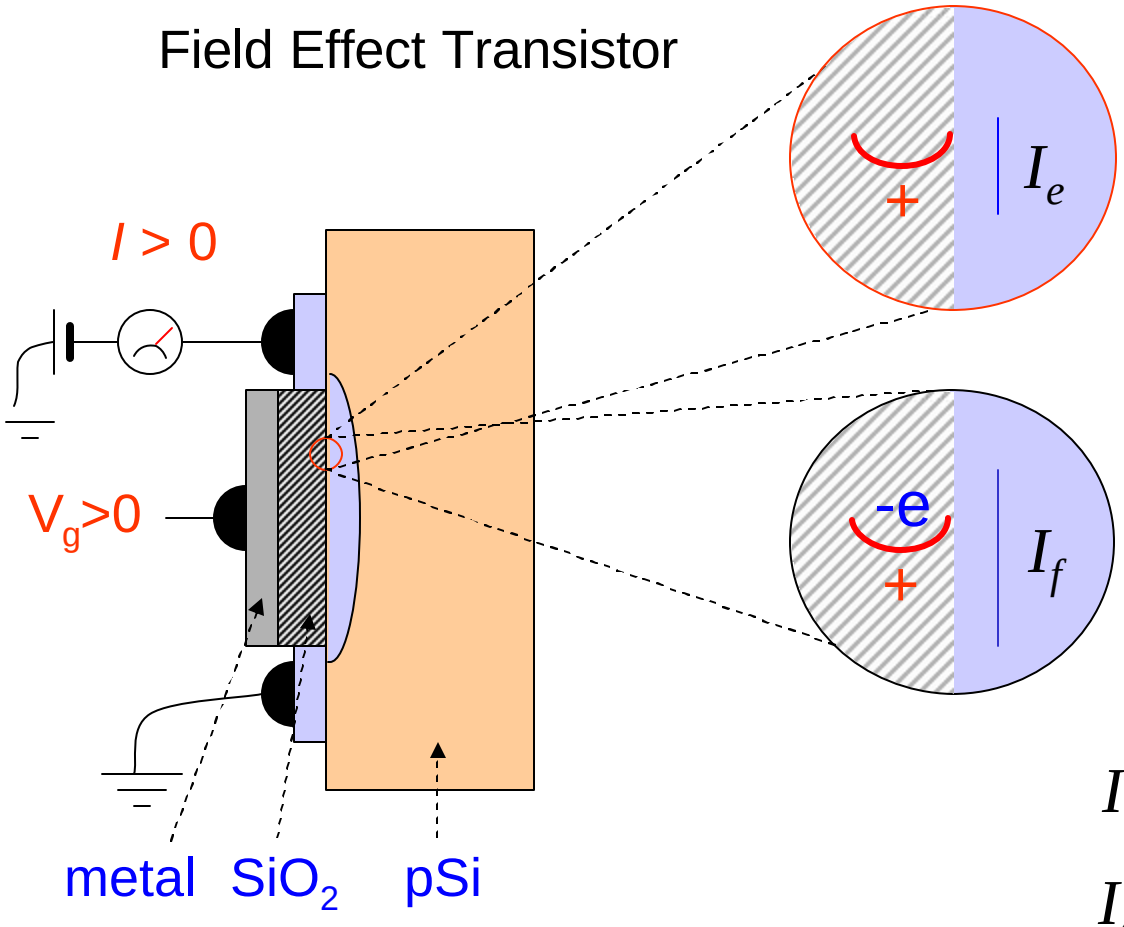
Vrijen et al, Phys. Rev. A, 2000

- *Challenge*
  - *Signals produced by a single spin are extremely weak*

Solution: Convert single spin into single charge signal

Traps and random telegraph signal (RTS)

Field Effect Transistor

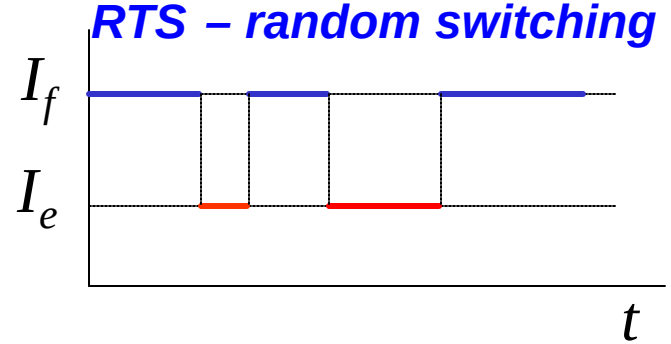


empty trap (positive)
higher resistance

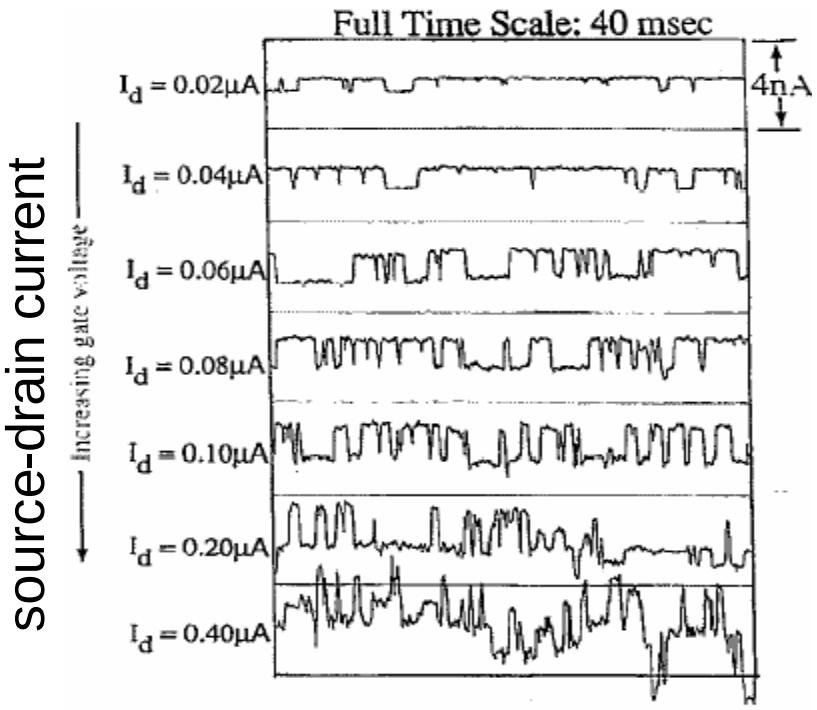
or

filled trap (neutral)
lower resistance

RTS – random switching

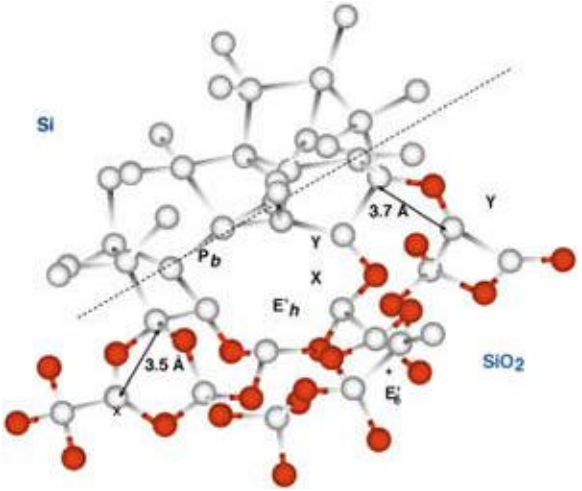


Random Telegraph Signal (RTS) – experiment



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

Defects at Si - SiO_2 interface



Single charge sensitivity ? → **single spin sensitivity**

ESR-RTS setup

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

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

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

NO RTS!

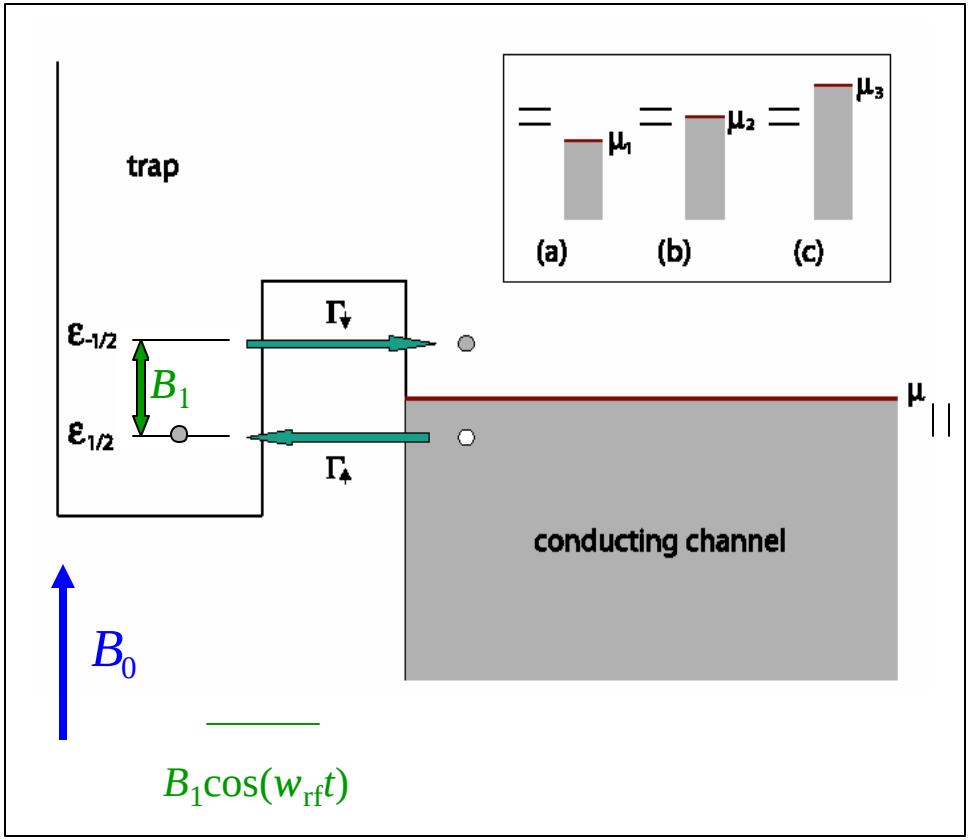
At $T = 0$ and resonant $B_1(t)$:

trap can be filled if $\varepsilon_{-1/2} < \mu$

e^- is promoted $\varepsilon_{1/2} \rightarrow \varepsilon_{-1/2}$

e^- can escape if $\varepsilon_{1/2} > \mu$

ESR-induced RTS!



At finite temperature RTS is *modified* by resonant $B_1(t)$

Quantum rate equations for ESR-RTS

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

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

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

equations of motion for trap density matrix

$$\boxed{s_0 + s_{\uparrow\uparrow} + s_{\downarrow\downarrow} = 1}$$

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***

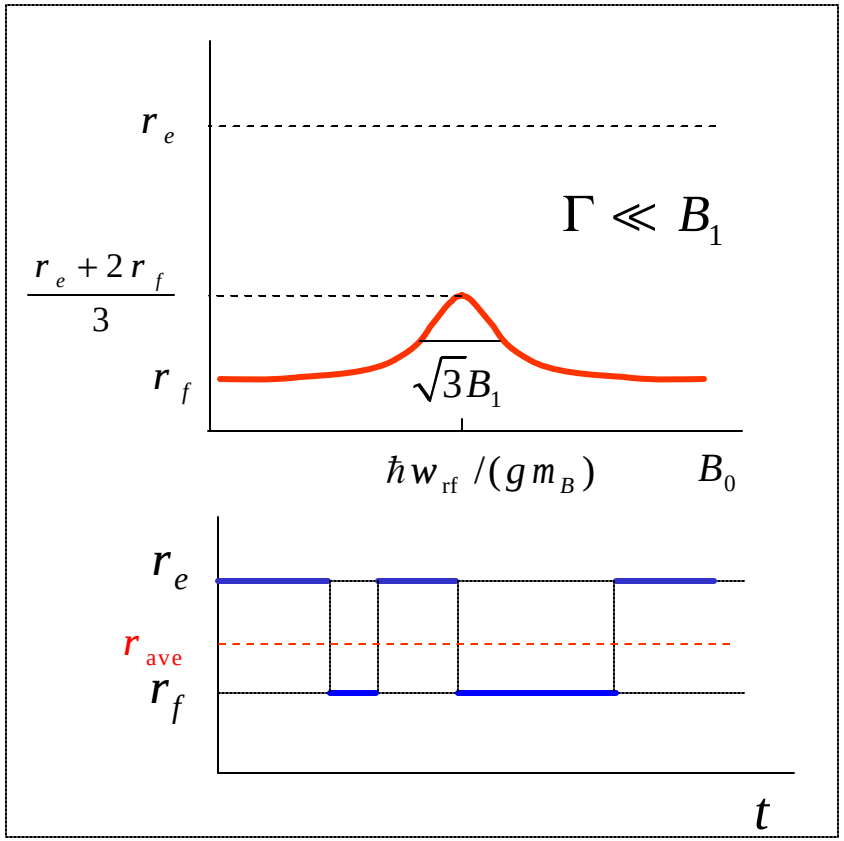
In presence of dephasing $1/T_2' >> \Gamma$:

peak width:

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

peak height:

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

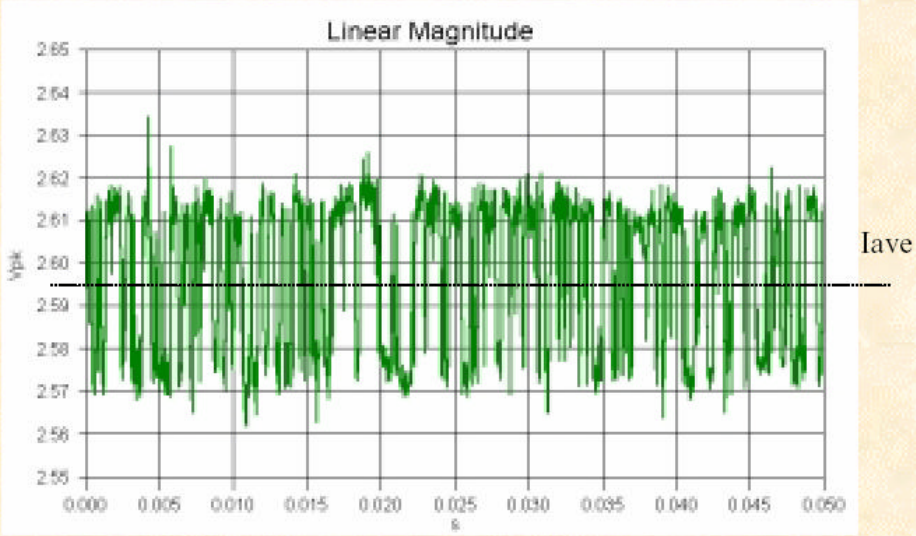


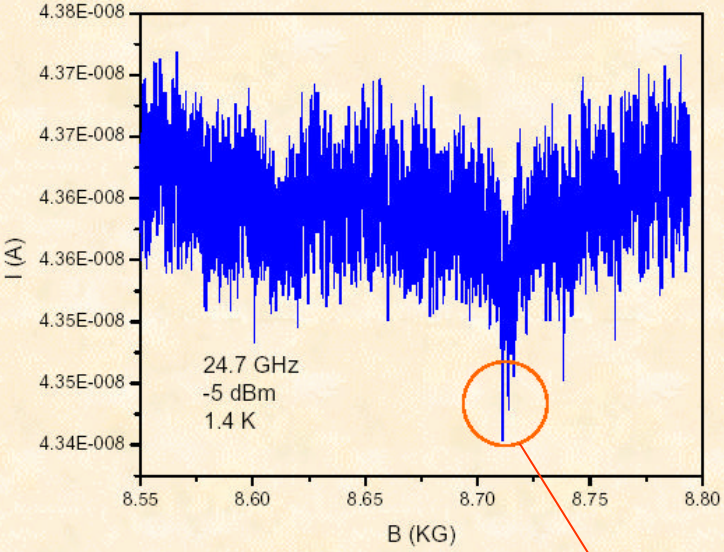
Phys. Rev. Lett. **90**, 018301 (2003)

ESR-RTS Experiment - average current (HWJ)

Measure average current: reflects the statistical occupation change:

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



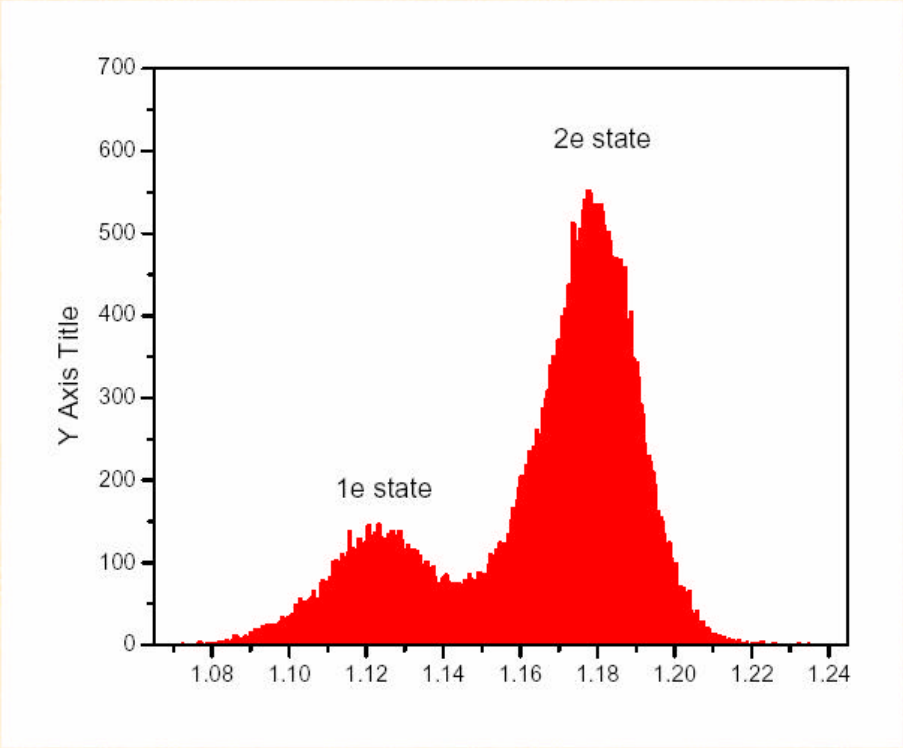


g = 2.02

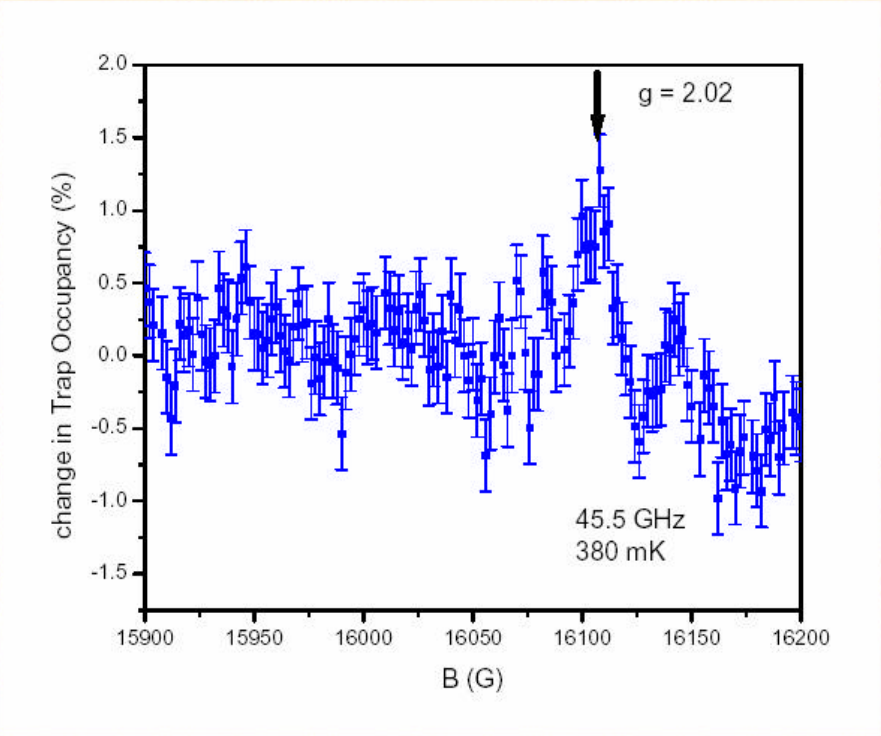
Only observed in the RTS region.

ESR-RTS Experiment – trap occupancy (HWJ)

Observed a change in the trap occupation probability

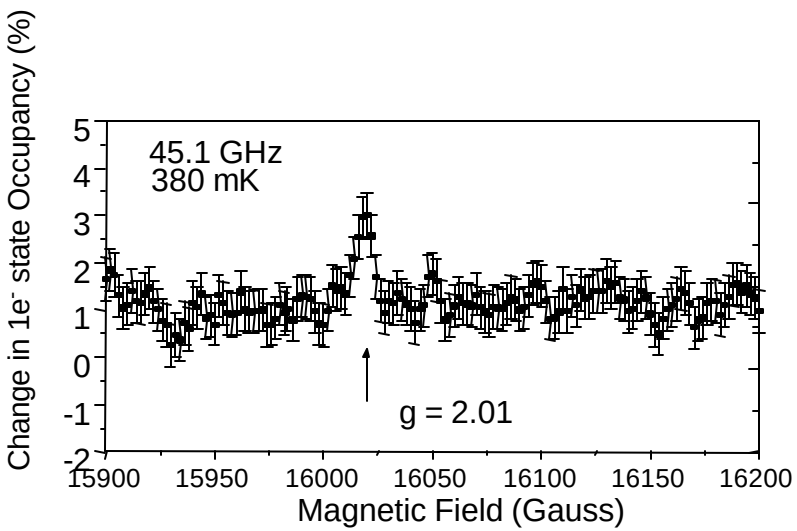


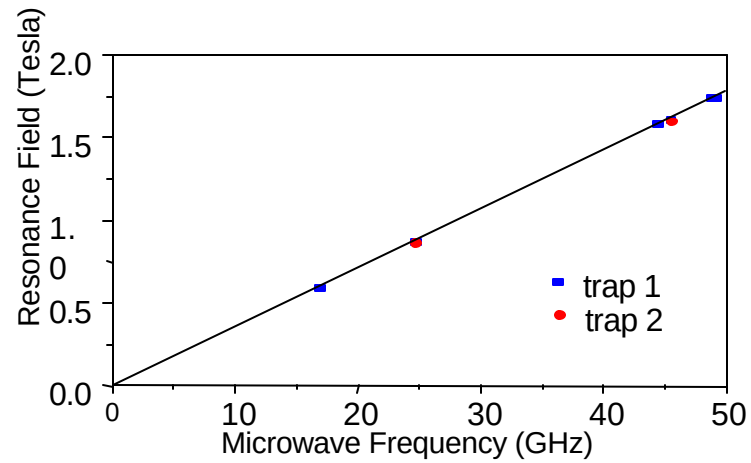
histogram of the raw data



obtained after the time-domain analysis

Surprise I: Signal changes sign for larger microwave power!



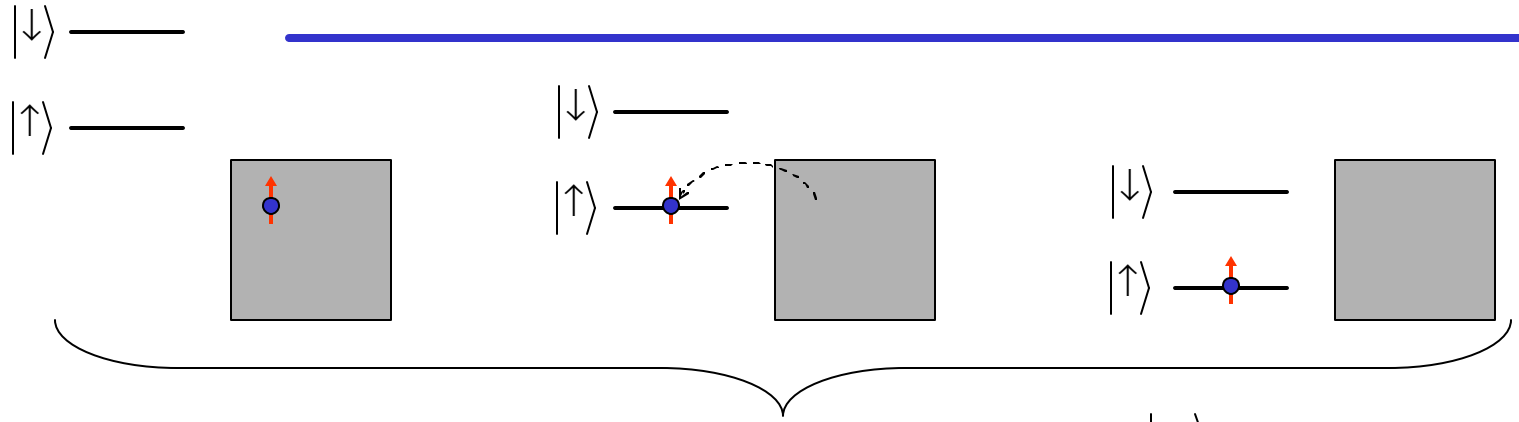


- *Signal changes sign when* $G \sim w_{Rabi}$
- *Improved signal-to-noise*
- *Tunneling rate is reduced on the resonance*

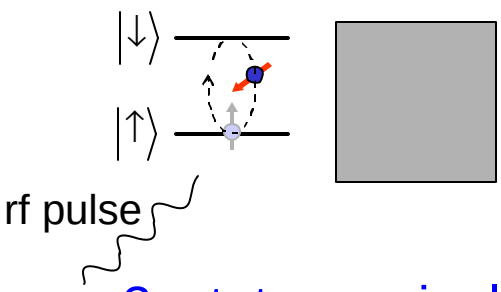
Summary of evidence to support single-spin ESR

- The g-factor value rules out channel electrons.
- ESR signature in average current is only been observed in RTS cross-over region.
- Change in single trap occupation probability has been confirmed.

Shallow Traps for Quantum Computing

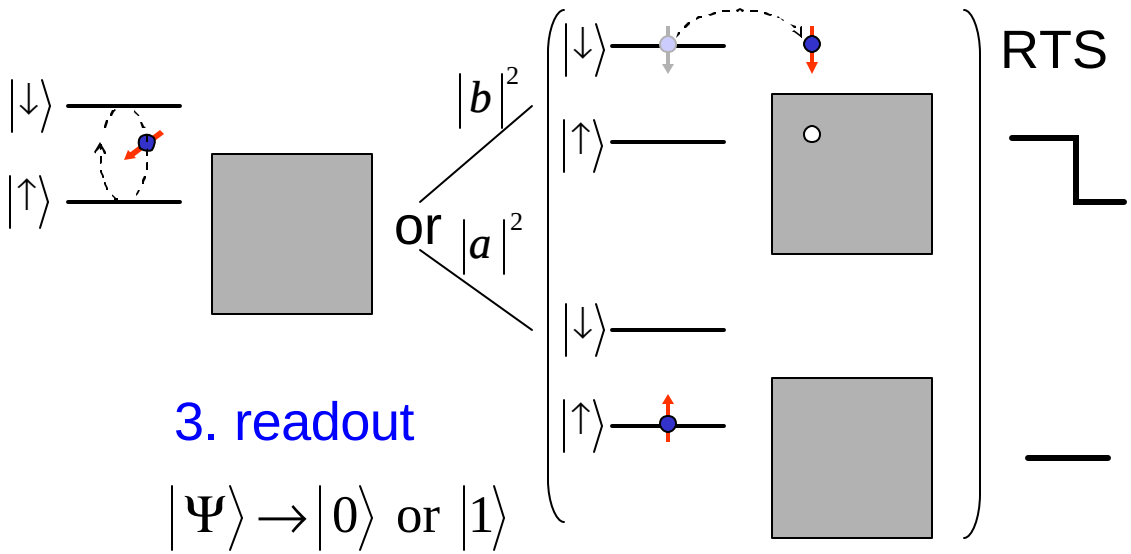


1. reset and initialization to $|0\rangle$



2. state manipulation

$$|0\rangle \rightarrow |\Psi\rangle = a\,|0\rangle + b\,|1\rangle$$



3. readout

$$|\Psi\rangle \rightarrow |0\rangle \text{ or } |1\rangle$$

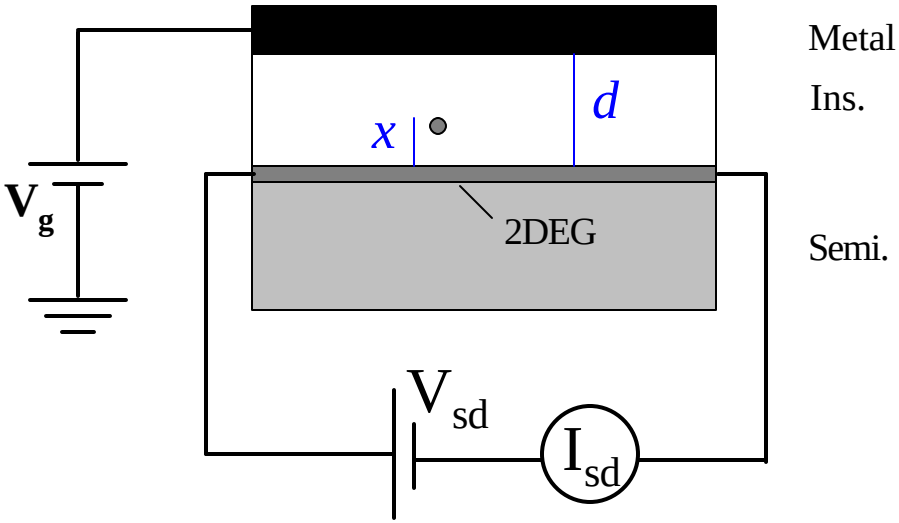
Tunneling “details”

Surprise II: Expected and measured tunneling times

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

Defect position determination:

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



One finds x~1-3 A.

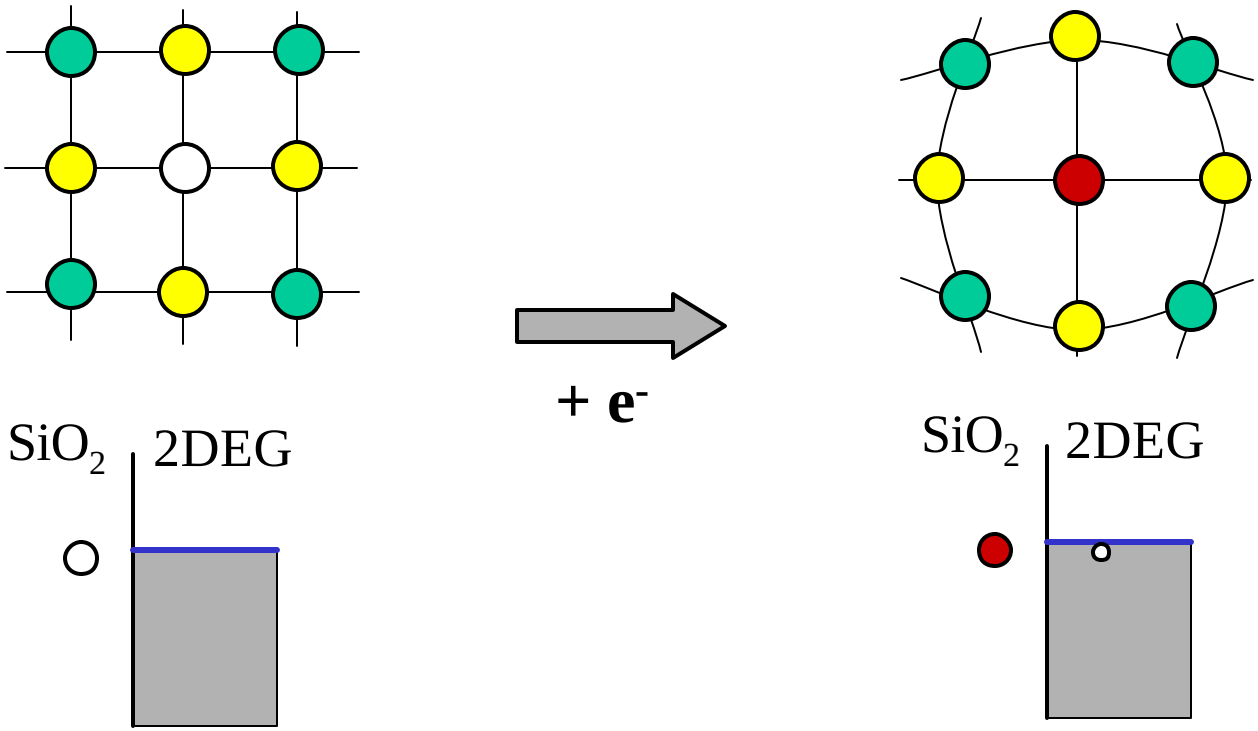
Estimate for tunneling time yields at most t_{RTS} ~10^{-9} s

Observed t_{RTS} are in 10^{-3}s – 1s range ???

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

$$H = \sum_k E_k c_k^\dagger c_k + E_0 d^\dagger d + d^\dagger d\, g(a^\dagger + a) + \omega_0 a^\dagger a + \Delta \sum_k (c_k^\dagger d + d^\dagger c_k) + V d^\dagger d \sum_{k,k'} c_k^\dagger c_{k'}$$

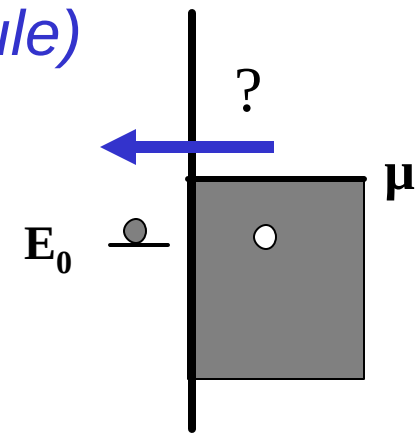
conduction electrons | defect level | electron-phonon interaction | optical phonon | tunneling (H_T) | Coulomb interaction

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

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

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

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



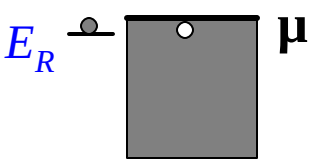
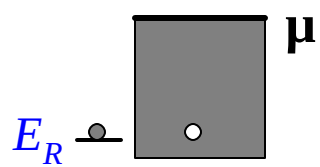
cond-mat/0312503

Phonon renormalization results

$$\gamma^{GR} = 2\pi \sum_{n,\ k} |\langle 0|n\rangle^{\text{shifted}}_{\text{phonons}}|^2 \ \ |\langle 0|H_T|1_k\rangle_{\text{electrons}}|^2 \ \delta[0-(E_0-E_k+n\omega_0-E_p)]$$

$$= 2\pi\nu\Delta^2 \sum_{n}^{E_0-E_p-n\omega_0>0} |\langle 0|n\rangle^{\text{shifted}}_{\text{phonons}}|^2 \quad ,$$

Renormalized level position $\boldsymbol{E_R = E_0 - E_p}$

Small Bias $\lvert E_R\rvert < w_0$	Large Bias $\lvert E_R\rvert > E_p$
 $g = 2pn\Delta^2 e^{-\frac{E_p}{w_0}}$	 $\gamma = 2\pi\nu\Delta^2$
Suppression of tunneling	No suppression of tunneling

Results and Estimates

Small bias

$$\gamma = 2\pi\nu\Delta^2 \exp\left(-E_p/\omega_0\right)$$

Assuming Fröhlich electron-phonon coupling

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

For SiO_2 $e_0 = 4,\ e_\infty = 2, a_d \sim 1$ Å

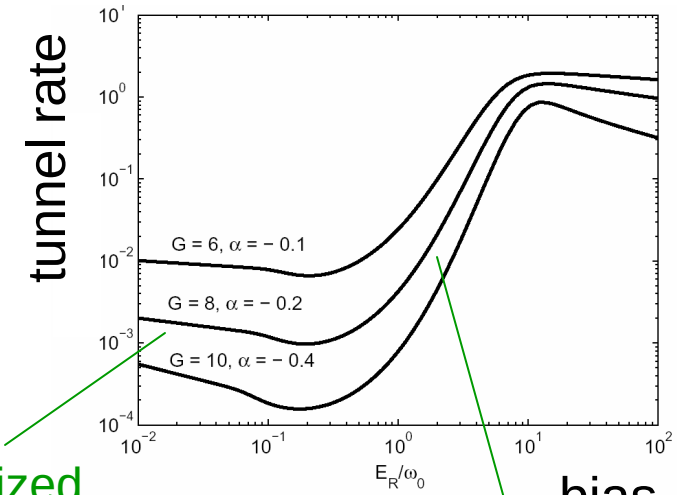
→ E_p » 1 eV

For bulk optical phonons in SiO_2:

? $_0^{bulk}$ » 60 meV

? = $10^{11\pm3}$ exp(-17) s^{-1} ~ $10^{3\pm3}$ s^{-1}

Any bias + Coulomb



renormalized Fermi-edge singularity

polaronic suppression

REF: *cond-mat*/0312503

Qualitative agreement with observed rates !

For comparison, in GaAs E_p= 4 meV => no tunneling slowdown

Surprise III: Magnetic field dependence

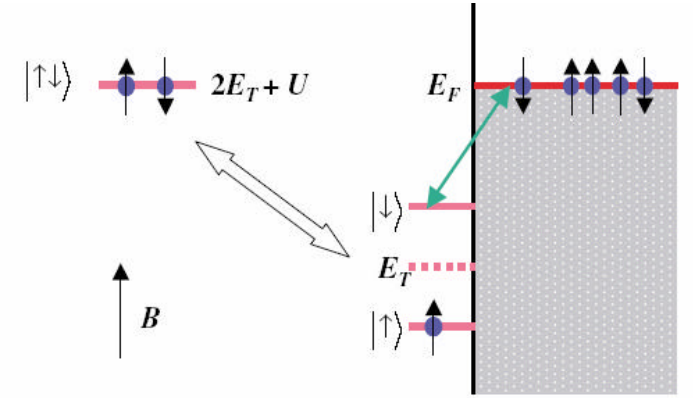


FIG. 4 (color online). The energy diagram of the single trap and FET channel bath. The electron levels for the trap and the FET channel are indicated.

$$\frac{t_{high}}{t_{low}} = \frac{t_1}{t_2} = \frac{\exp[-(E_T + E_Z/2 - m)/T] + \exp[-(E_T + E_Z/2 - m)/T]}{\exp[-(2E_T + U - 2m)/T]}$$
$$= 2\exp[(E_T + U - m)/T]\cosh(E_Z/2T)$$

Phys. Rev. Lett. **91**, 078301 (2003)

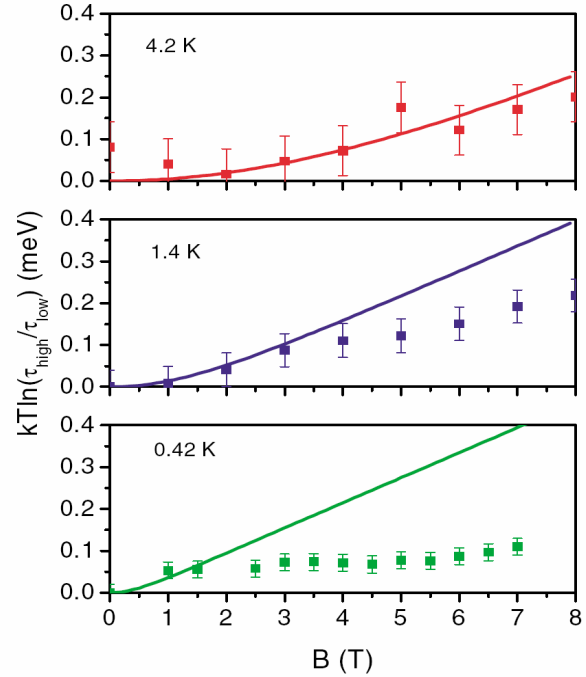
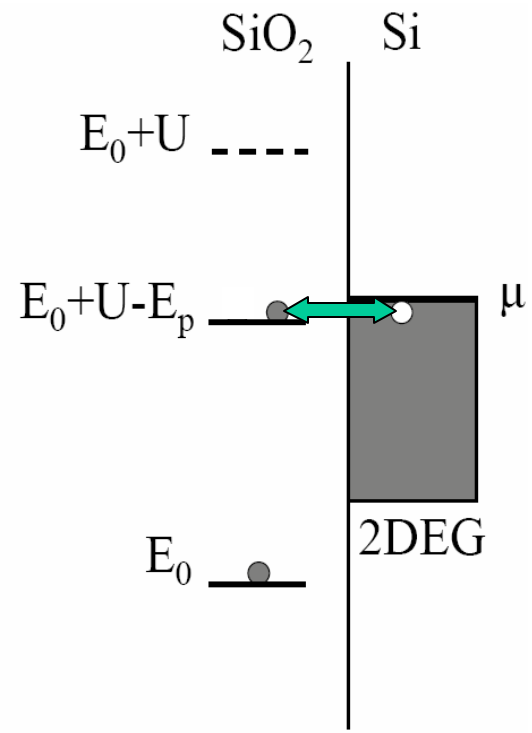
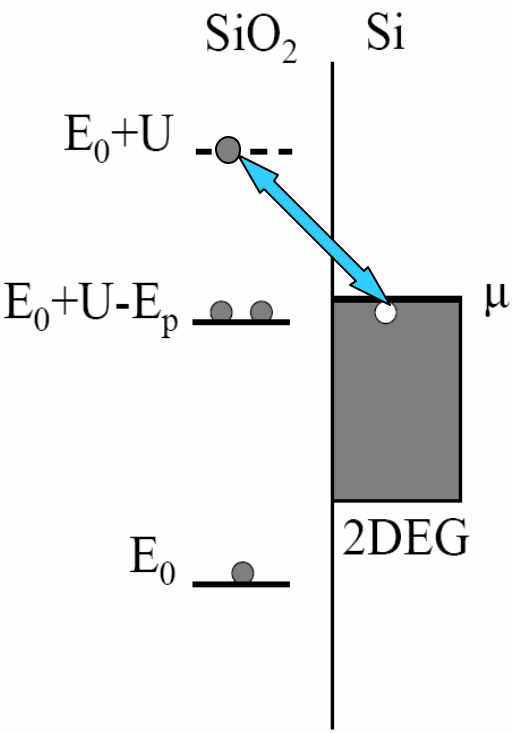


FIG. 5 (color online). The characteristic energy shift, $kT\ln(\tau_{high}/\tau_{low})$, is plotted against the magnetic field at three temperatures. Continuous solid lines represent the theoretical curves, deduced from Eq. (2), and the experimental data are indicated by the symbols.

No agreement between model and experiment at low T! *Kondo?*

Kondo?





Real charge hopping
→ *Polaron suppression*

Fast ($t \sim 1/U$) *virtual* hopping
→ *Kondo*, $J = \Delta^2/U$

Model and calculation

Anderson Hamiltonian (→Kondo)

$$H_{\rm A} = \sum_{k\,\sigma} E_{k\,\sigma} c^\dagger_{k\,\sigma} c_{k\,\sigma} + \sum_{\sigma} E_{0\,\sigma} d^\dagger_\sigma d_\sigma + U n_\uparrow n_\downarrow + \sum_{k\,\sigma} \Delta (c^\dagger_{k\,\sigma} d_\sigma + d^\dagger_\sigma c_{k\,\sigma}) \,,$$

Our Hamiltonian (Polarons + Kondo)

$$H = H_{\rm A} + \lambda \left(\sum_\sigma n_\sigma - 1 \right) \hat{x} + \frac{\hat{p}^2}{2m} + \frac{m\omega_0^2 \hat{x}^2}{2}$$

$$\mathcal{Z} = \int \mathcal{D}[X,Y] \exp - \int_0^\beta d\tau \left(\frac{M\dot{X}^2}{2} + \frac{X^2}{2E_p} + \frac{Y^2}{2U} \right) \times \langle \mathcal{T} {\rm e}^{-\int_0^\beta d\tau H_\uparrow [X(\tau)+Y(\tau)]} \rangle \, \langle \mathcal{T} {\rm e}^{-\int_0^\beta d\tau H_\downarrow [X(\tau)-Y(\tau)]} \rangle \,,$$

$$H_\sigma[Z(\tau)] = \sum_k E_{k\,\sigma} c^\dagger_{k\,\sigma} c_{k\,\sigma} + [\tilde{E}_{0\,\sigma} + Z(\tau)] d^\dagger_\sigma d_\sigma + \sum_k \Delta (c^\dagger_{k\,\sigma} d_\sigma + d^\dagger_\sigma c_{k\,\sigma}) \,.$$

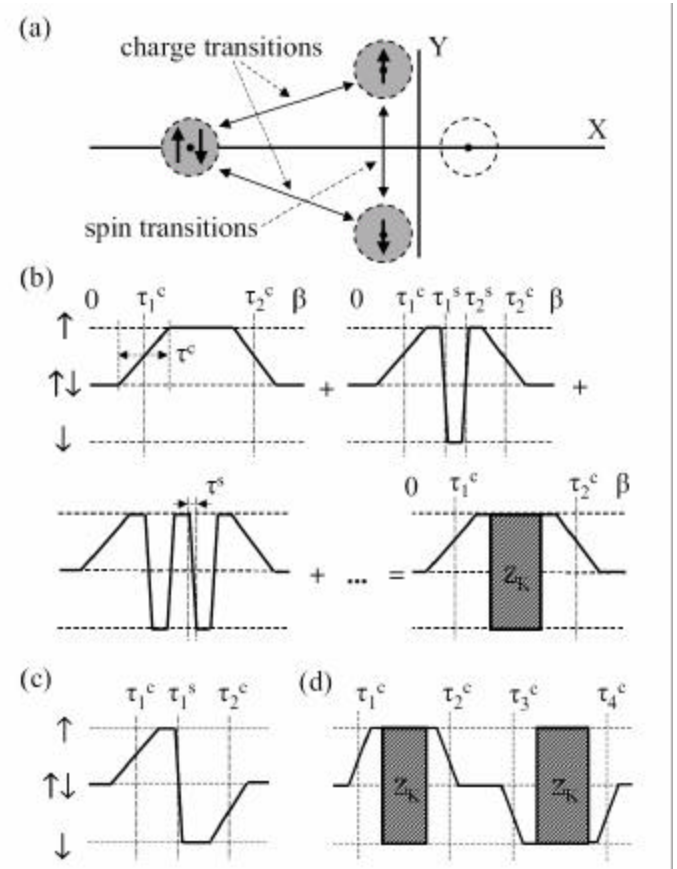


FIG. 2. (a) Schematics of MOSFETs; (b) Energy diagram for the impurity level and the conducting electrons. Coupling to optical phonons shifts the bare position of the level.

cond-mat/0403491

Summary

- *Single electron spin resonance in FET*
  - *DC measurement of the resonance*
  - *AC signatures in the current noise*
  - *Applications to quantum computing: pulses, etc.*
  - *Experimental results on average current and statistics*
- *Detailed models of tunneling*
  - *Interaction effects*
  - *Polaron slowdown, predictions*
- *RTS(B)*
  - *Experiment*
  - *Explanation: Kondo effect?*