Spin-orbit Effects in Single Electron Tunneling

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Motivation

1) Spin-orbit coupling

- Electrons moving in *E* field experience *B* field

$\Rightarrow$ Couples the electron's orbital motion with its spin

$$\boxed{H_{SO} \propto \left(\frac{\vec{v}}{c} \times \vec{E}\right) \bullet \vec{S} \propto \vec{L} \bullet \vec{S}}$$

- Pure spin states are no longer energy eigenstates

$\Rightarrow$ Mixes spin-up and spin-down states

- Spintronic devices are influenced by SO coupling

$\Rightarrow$ Generates spin polarized current (ex: Spin Hall Effect)

Motivation

2) Small Systems

- In quantum mechanics, energy spectrum is quantized for bounded system.
- Energy Level Spacing ~ 1/Volume

$\Rightarrow$ Discrete energy levels can be resolved for small systems but not easy for the condensed matter system

- The Single Electron Tunneling Spectroscopy made it possible to resolve discrete energy levels even for metallic nanoparticle systems.

Outline

1. Single Electron Tunneling (SET)

$\Rightarrow$ Discrete Energy Levels

2. SET in Nonmagnetic Nanoparticles

$\Rightarrow$ Reduced g^{eff} and avoided level crossing

3. SET in Ferromagnetic Nanoparticles

$\Rightarrow$ Non-monotonic dependence on B

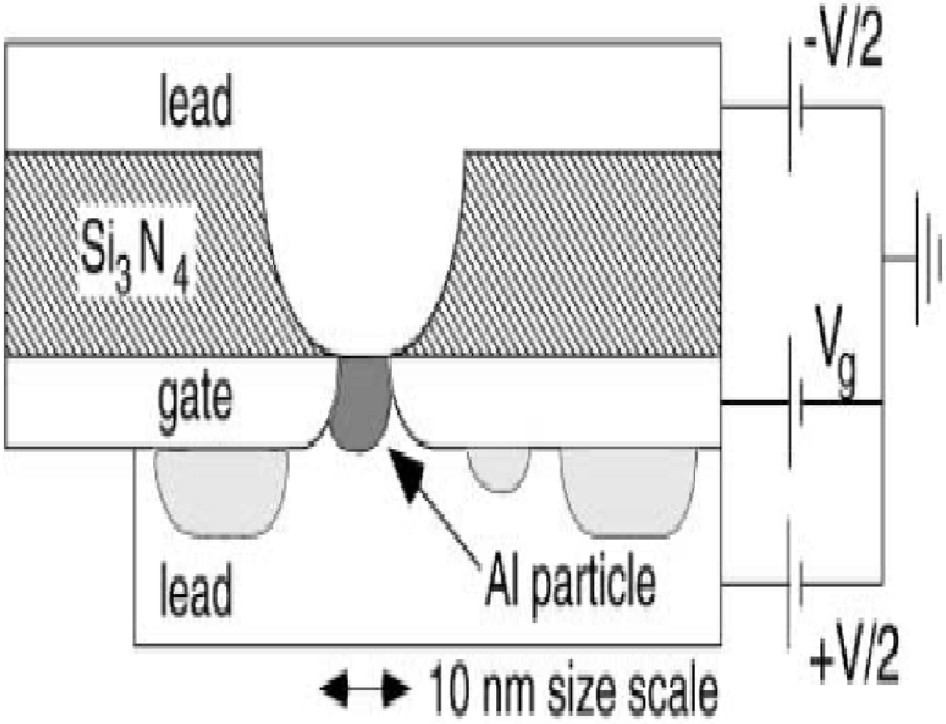
4. Summary

1. Single Electron Tunneling

1) Device Fabrication

- Si_3Ni_4 membrane with a hole
- Gate eletrode
- Upper Al electrode
- Al nanoparticles (diameter < 10 nm)

⇒ Single Electron Transistor

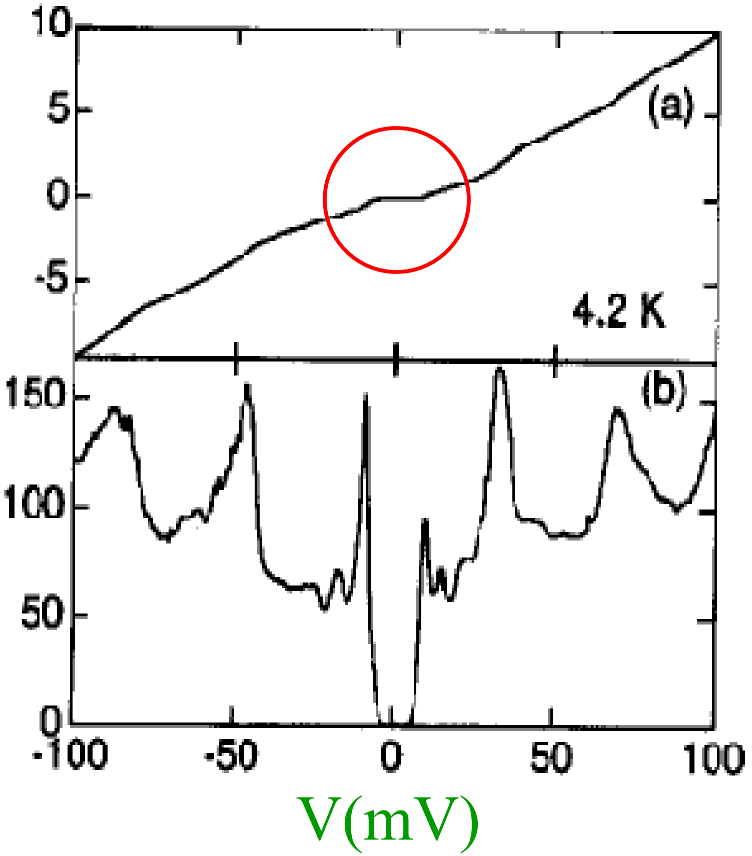


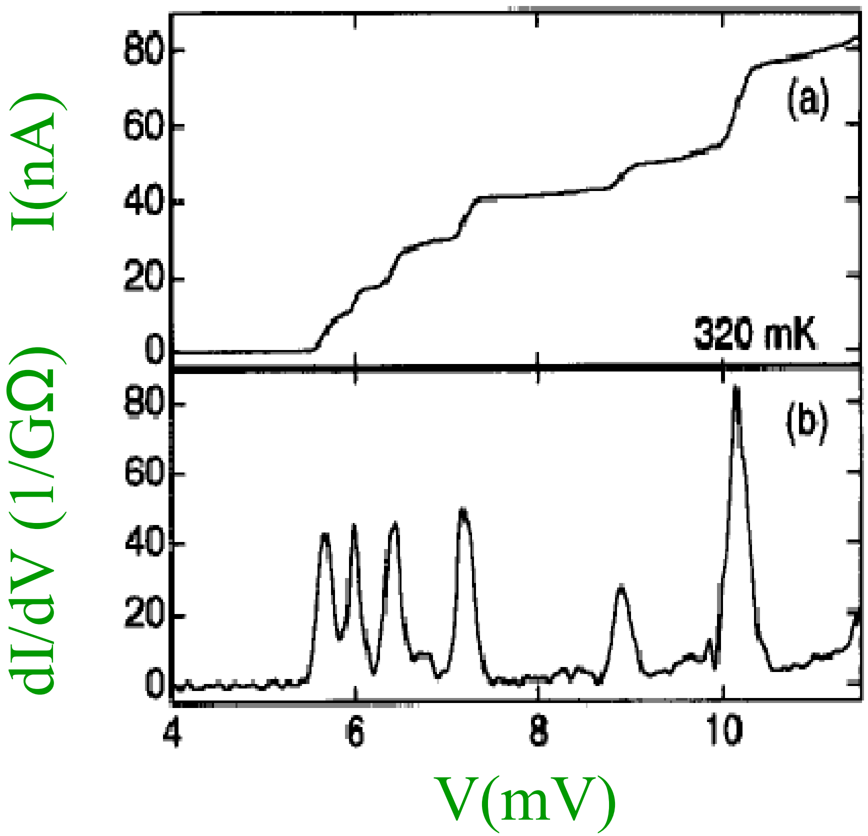
Ralph et al, PRL **78**, 4087 (1997)

1. Single Electron Tunneling

2) I-V measurements

Tinkham, Am. J. Phys **64**(3), March 1996





Charging Energy=5~50 meV

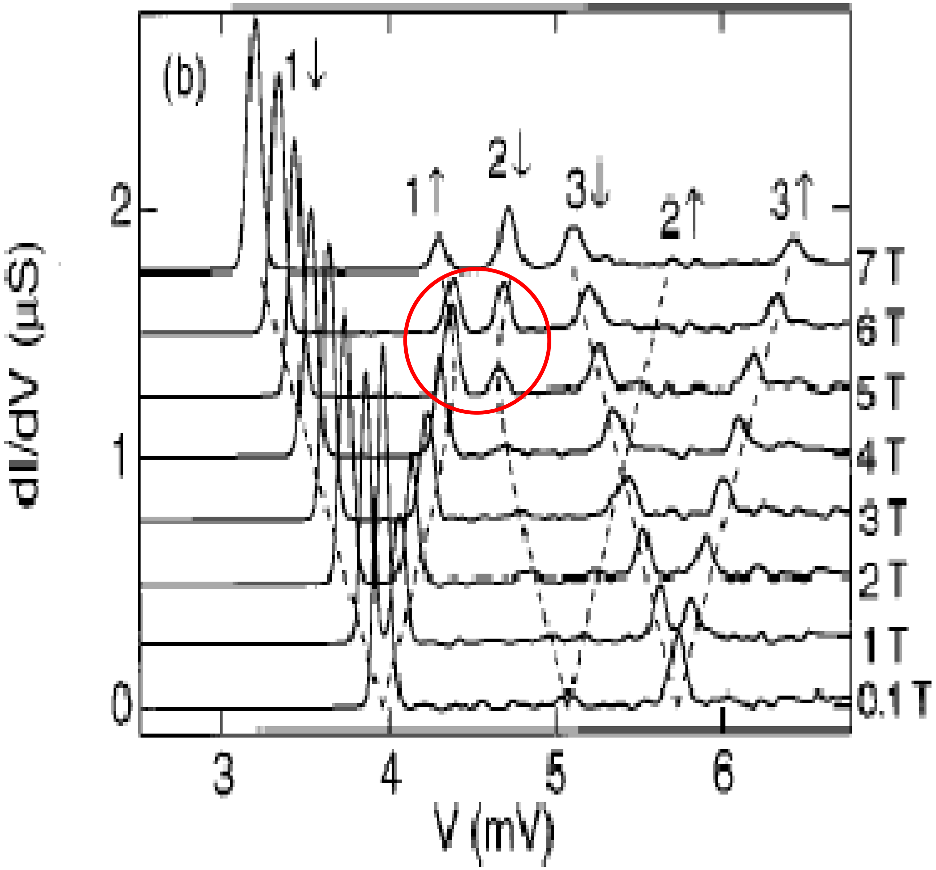
Level Spacing=0.02~0.3 meV

2. SET in Nonmagnetic Nanoparticles

1) Discrete Energy Levels

- *B* field is applied parallel to the device
- Each peak splits into two linearly with *B*
- In some devices, tunneling spectra show marked deviations

⇒ Reduced g factors, avoided level crossing



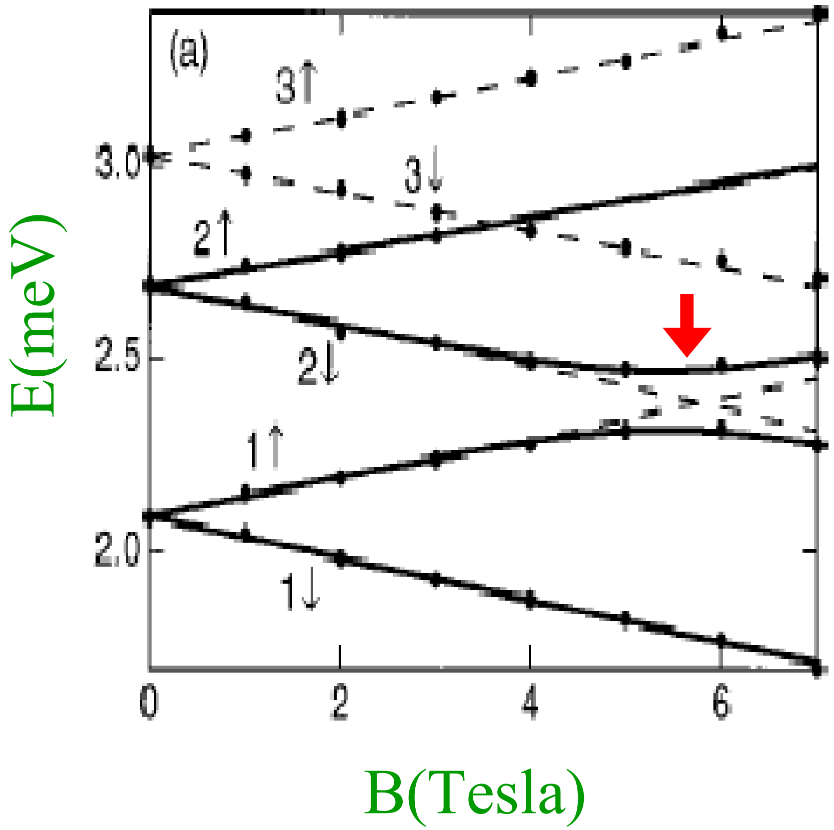
Salinas et al, PRB **60**, 6137 (1999)

2. SET in Nonmagnetic Nanoparticles

2) Energy Levels vs External Magnetic Fields

- Pure Al
  - $g^{eff} \sim 2$
  - ΔE depends linearly on B
- Al with impurity
  - $g^{eff} \sim 1.84, 1.68$ and 1.76
  - Avoided level crossing

⇒ Impurity as the source of Spin-orbit scattering



Salinas et al, PRB **60**, 6137 (1999)

2. SET in Nonmagnetic Nanoparticles

3) Simple Model

- Perturbation in weak spin-orbit coupling

$$H = H_0 + H_{SO}$$

$$\left| n_\uparrow \right\rangle \approx \left| n_\uparrow^{(0)} \right\rangle + \sum_{m \neq n} \frac{\left| m_\uparrow^{(0)} \right\rangle \left\langle m_\downarrow^{(0)} \right| H_{SO} \left| n_\uparrow^{(0)} \right\rangle}{E_n - E_m}$$

$$g_n^{eff} = g^{pure} \frac{\left\langle n_\uparrow \right| \sigma_z \left| n_\uparrow \right\rangle}{\left\langle n_\uparrow \middle| n_\uparrow \right\rangle}$$

2. SET in Nonmagnetic Nanoparticles

3) Simple Model

$$\boxed{g_n^{eff} \approx g^{pure}\left(1-2\sum_{m\neq n}\frac{\left|\left\langle m_{\downarrow}^{(0)}\right|H_{SO}\left|n_{\uparrow}^{(0)}\right\rangle\right|^2}{\left(E_n-E_m\right)^2}\right)}$$

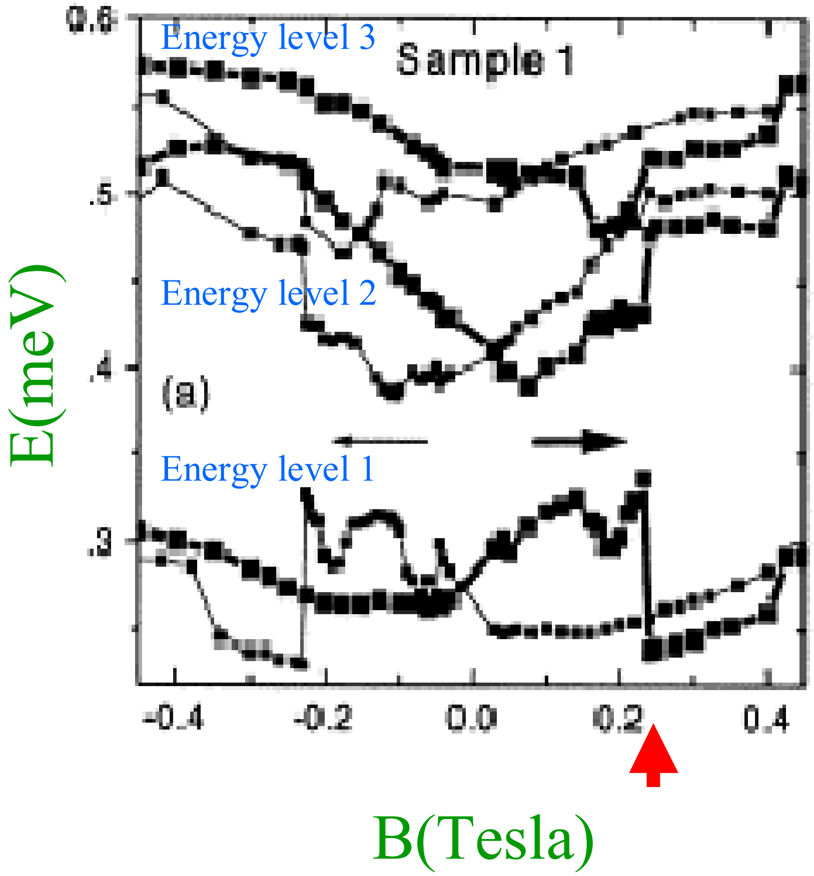
- For very small systems, energy level spacing is larger than SO matrix elements so the perturbation is weak.
- In bulk limit, the relevant energy denominator is the band width so the effect of SO interaction is small.

$\Rightarrow$ In the mesoscopic regime, SO plays an important role with mean level spacing comparable to or smaller than typical SO matrix elements.

3. SET in Ferromagnetic Nanoparticles

1) Energy Levels vs External Magnetic Fields

- Ferromagnetic Co was used instead of nonmagnetic Al
- Small range of *B*
  - Strong, nonlinear dependence on *B*
  - Hysteresis
  - Magnetization reversal

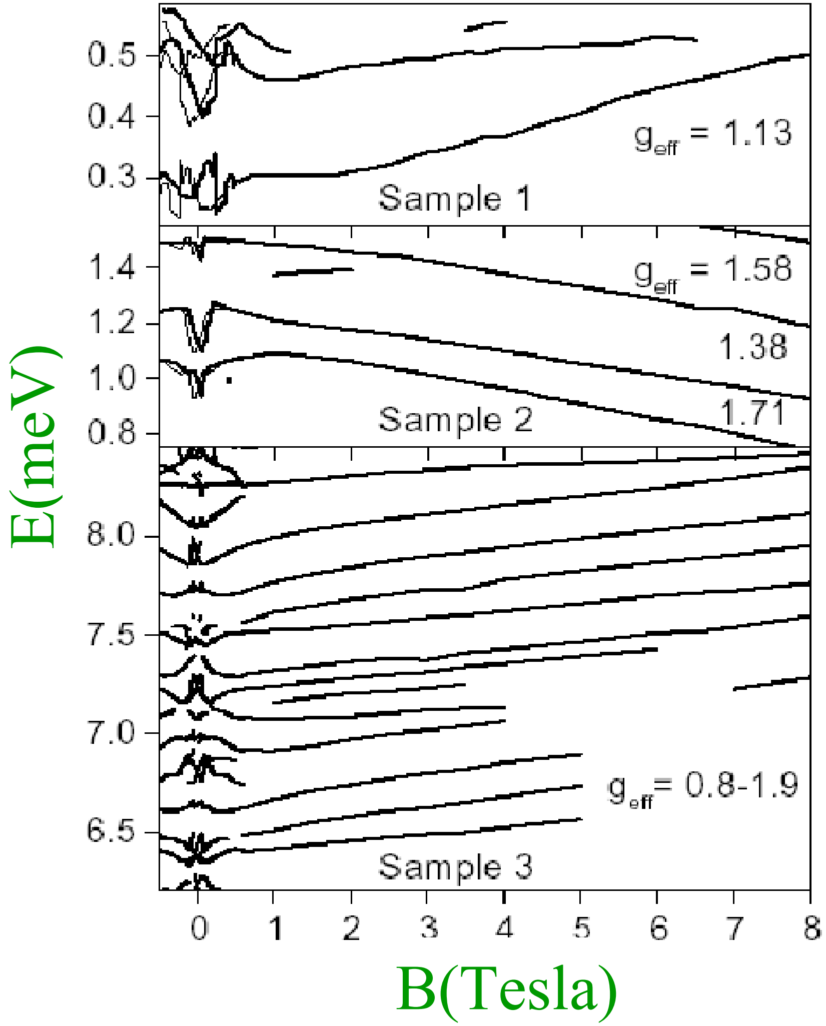


Gueron et al, PRL **83**, 4148 (1999)

3. SET in Ferromagnetic Nanoparticles

2) Energy Levels vs External Magnetic Fields

- Large range of *B*
  - $g^{eff} = 0.8 \sim 1.9$
  - g^{eff} fluctuates strongly from level to level
  - Same sign of slopes for energy shifts



Gueron et al, PRL **83**, 4148 (1999)

3. SET in Ferromagnetic Nanoparticles

3) Simple Model

- Model Hamiltonian

$$\boxed{H = g^{eff} \mu_B \vec{H} \bullet \vec{S} - K_m \mu_B S_z^2 / \sqrt{S(S+1)}}$$

⇒ Qualitatively recover hysteresis and jump behavior

- Unsolved Problems

— Same sign of the energy slope as a function of *B*

— Smaller energy spacing than expected

⇒ Microscopic approach might be necessary

4. Summary

- Single Electron Tunneling (SET)

⇒ Discrete Energy Levels

- SET in Nonmagnetic Nanoparticles

⇒ Reduced g^{eff} and avoided level crossing due to the spin-orbit scattering

- SET in Ferromagnetic Nanoparticles

⇒ Reduced g^{eff} with the same sign of slopes

- No detailed theory exists at present

References

- Delft and Ralph, Physics Reports **345**, 61 (2001)
  - Review Article
- Ralph et al, PRL **78**, 4087 (1997)
  - Nonmagnetic Nanoparticles
- Salinas et al, PRB **60**, 6137 (1999)
  - Spin-orbit Effects
- Gueron et al, PRL **83**, 4148 (1999)
  - Ferromagnetic Nanoparticles