Electron Spin Relaxation in a Moving Quantum Dot

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arXiv:1208.1284

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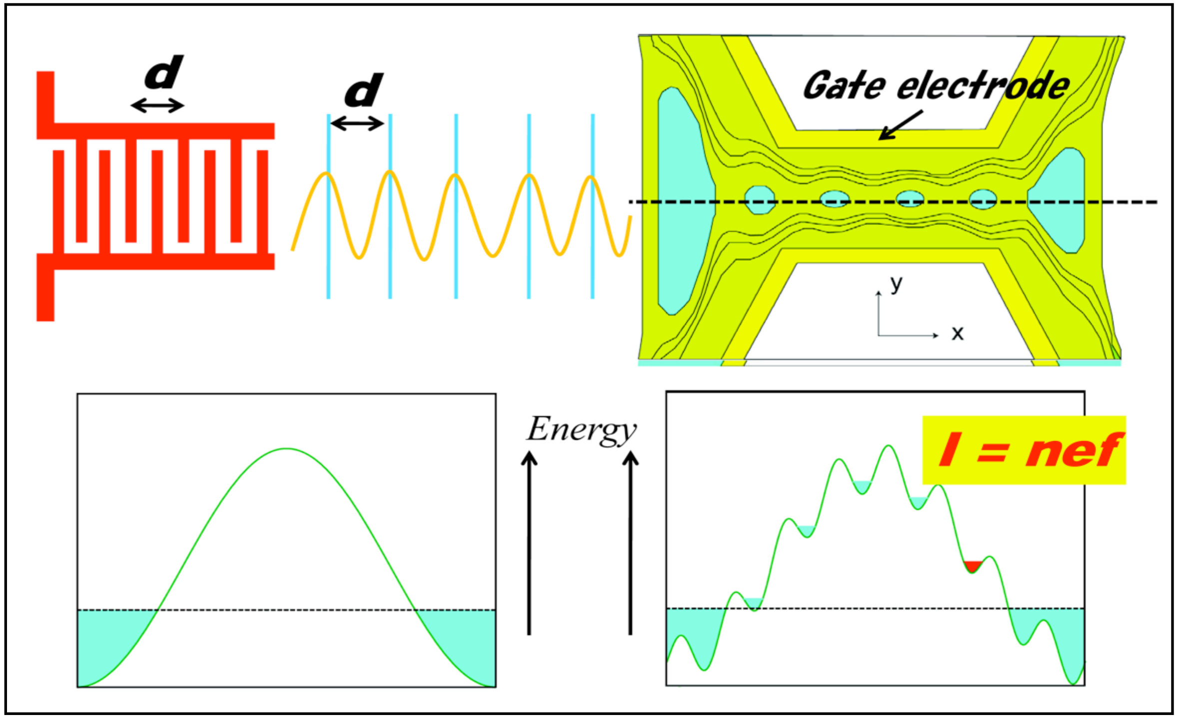
Remember Taruchas talk?



Talk Tarucha, Varenna 2012

Electron transport between two QDs by surface acoustic waves (SAW)

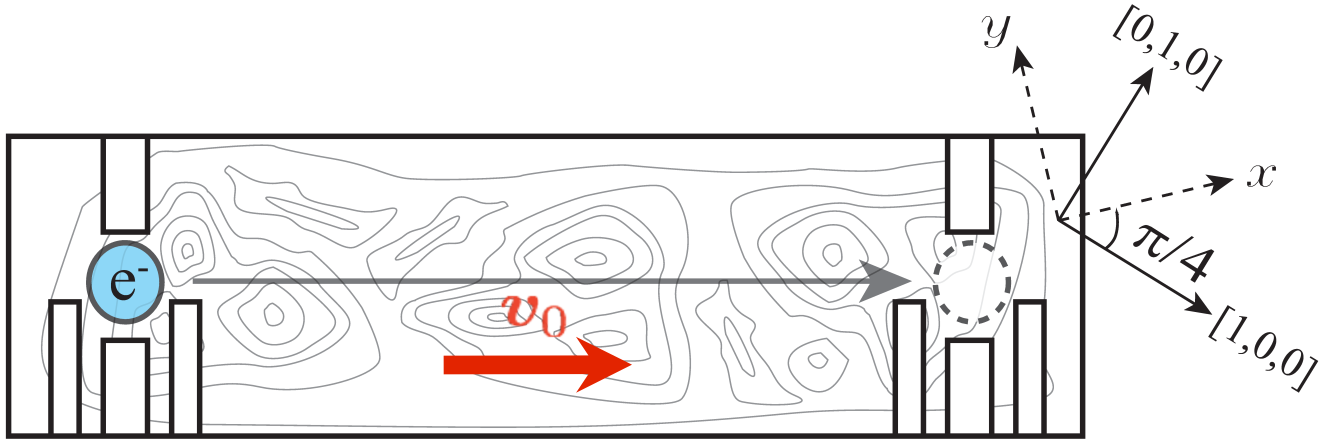
Distance: ~3µm
Time: ~1ns

$$v_{\mathrm{SAW}} = 3000\mathrm{m/s}$$

Question:
Spin relaxation/decoherence during transport?

Hermelin *et al.*, Nature 2011
McNeil *et al.*, Nature 2011
Sanada *et al.*, PRL 2011

Setup



Gate defined QD in 2DEG

Move QD:
In 2DEG plane by gate tuning,
adiabatically slow (preserves orb. ground state), v=1-100 m/s,
Later: Consider SAWs, v=3000m/s

Moving electron:
Sees random potential due to ionized dopants at interface,
SOI couples movement to spin

Hamiltonian

Moving frame: $\boldsymbol{r} = \boldsymbol{r}' + \boldsymbol{v}_0 t$

$$H = H_d + H_Z + H_{\mathrm{SO}} + \delta V(\boldsymbol{r}_0(t) + \boldsymbol{r}')$$

random electrical potential, assoc. field $\boldsymbol{\varepsilon}(t)$

QD:

$$\frac{\boldsymbol{\pi}'}{2m^*} + \frac{1}{2} m^* \omega_0^2 r'^2$$

$$\boldsymbol{\pi}' = -i\hbar\nabla + \frac{e}{c}\boldsymbol{A}(\boldsymbol{r}') + \frac{e}{c}\boldsymbol{A}_0(t) - m^*\boldsymbol{v}_0$$

Zeeman:

$$\frac{1}{2} g\mu_B \boldsymbol{B}\cdot\boldsymbol{\sigma}$$

$$\boldsymbol{B} = \boldsymbol{B}_{\mathrm{ext}} + \Delta\boldsymbol{B}$$

Rashba & Dresselhaus SOI:

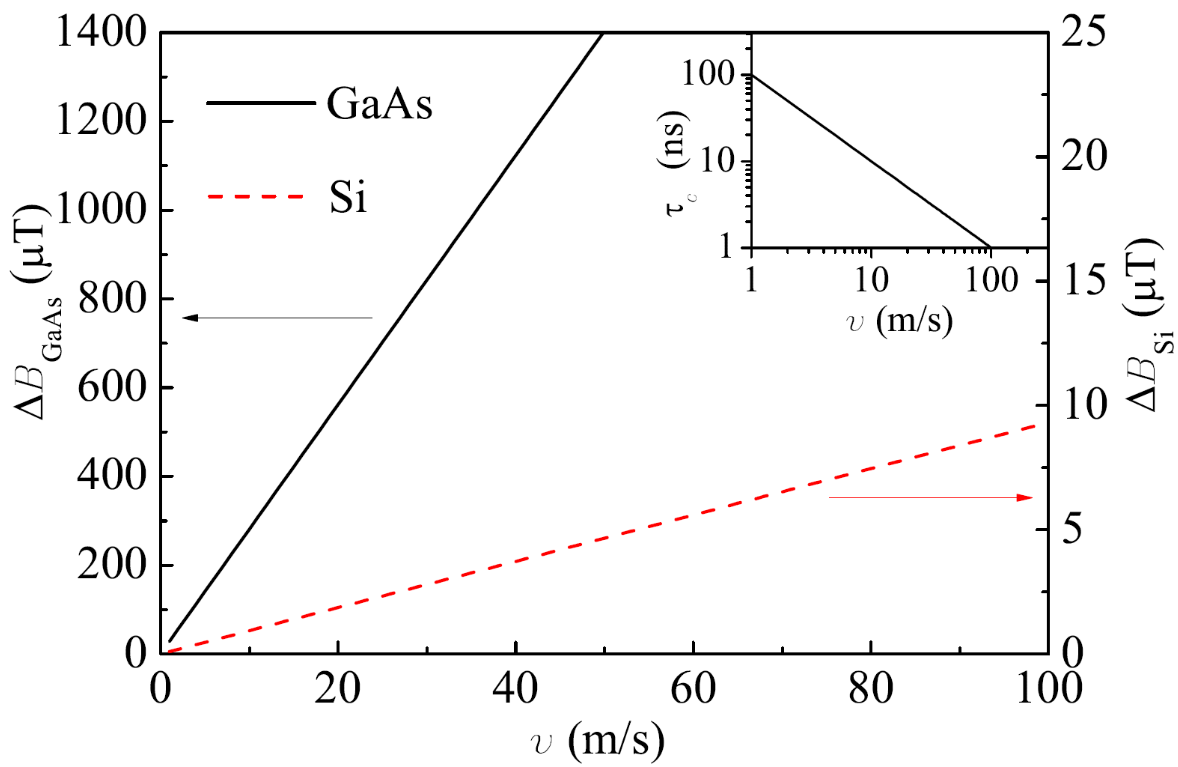
$$\beta_- \pi'_{y'} \sigma_{x'} + \beta_+ \pi'_{x'} \sigma_{y'}$$

$$\beta_\pm = \beta \pm \alpha$$

Induced effective magnetic field

SOI of moving electron:

$$\Delta \boldsymbol{B} = \frac{2\hbar}{g\mu_B}(v_{0y}/\lambda_-, v_{0x}/\lambda_+, 0) \qquad \lambda_\pm = \frac{\hbar}{m^*\beta_\pm}$$



Small velocities: $\Delta B \ll B_{\mathrm{ext}}$ (negligible) $\qquad B_{\mathrm{ext}} = 1\mathrm{T}$

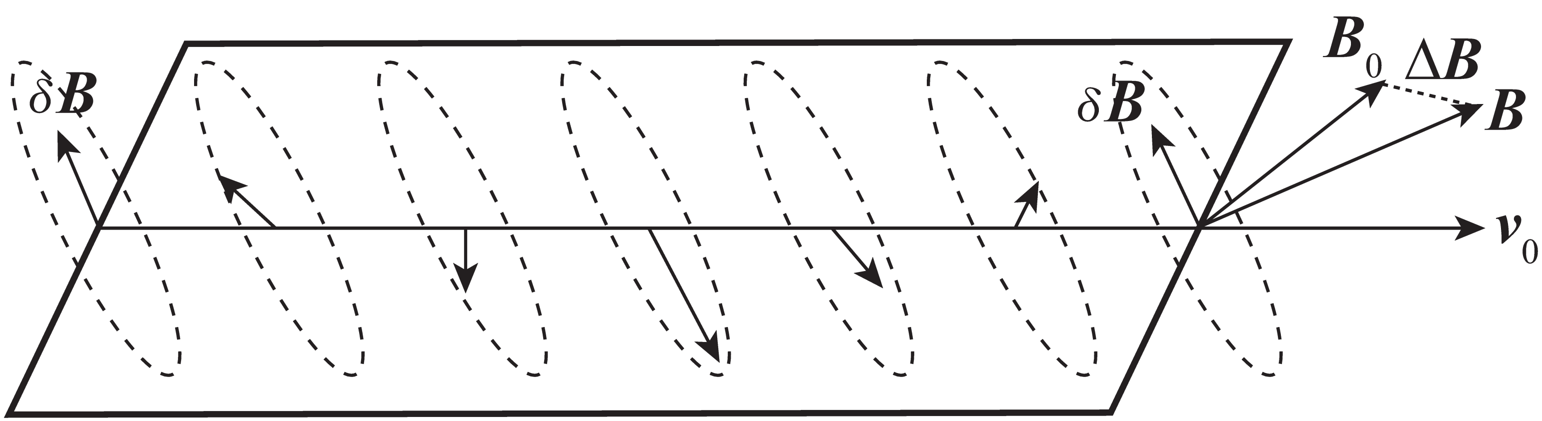
Effective spin Hamiltonian

Remove SOI to leading order (Schrieffer-Wolff):

$$H_{\text{eff}} = \frac{1}{2} g\mu_B (\mathbf{B} + \delta\mathbf{B}(t)) \cdot \boldsymbol{\sigma}$$

$$m^*(\beta^2 + \alpha^2) \ll g\mu_B B \ll \hbar\omega_0$$

$$\delta\mathbf{B}(t) = 2\mathbf{B} \times \mathbf{\Omega} \qquad \mathbf{\Omega} = \frac{-e}{m^*\omega_0^2}[\varepsilon_{y'}(\boldsymbol{r}_0(t))/\lambda_-, \varepsilon_{x'}(\boldsymbol{r}_0(t))/\lambda_+, 0]$$



Relaxation and decoherence

Bloch equations describe spin dynamics

Golovach, PRL **93**, 016601 (2004)
Borhani, PRB **73**, 155311 (2006)

$$\delta\mathbf{B}(t) \perp \mathbf{B} \;\Rightarrow\; \frac{1}{T_1} = \frac{2}{T_2}$$

$$\boxed{\frac{1}{T_1} = \frac{2v_0}{l_\varepsilon}\left[\frac{e\sigma_\varepsilon}{\hbar\omega_0^2}\right]^2 F_{\mathrm{SO}}^2(\theta,\phi)}$$

$$F_{\mathrm{SO}}^2(\theta,\phi) = (\beta^2+\alpha^2)(1+\cos^2\theta) + 2\alpha\beta\sin^2\theta\cos 2\phi$$

$$\boldsymbol{B} = B(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$\langle\varepsilon_i(\boldsymbol{r}_1)\varepsilon_j(\boldsymbol{r}_2)\rangle = \delta_{ij}\sigma_\varepsilon^2 e^{-|\boldsymbol{r}_1-\boldsymbol{r}_2|/l_\varepsilon}$$

assume isotropic $\boldsymbol{\varepsilon}(\boldsymbol{r})$

$$\langle\delta B_i(0)\delta B_i(t)\rangle = \left[\frac{2eB\sigma_\varepsilon}{\Lambda_\pm m^*\omega_0^2}\right]^2 e^{-|t|/(l_\varepsilon/v_0)}$$

$$\Lambda_\pm = \Lambda_\pm(\boldsymbol{B}/|\boldsymbol{B}|)$$

Spin relaxation rate

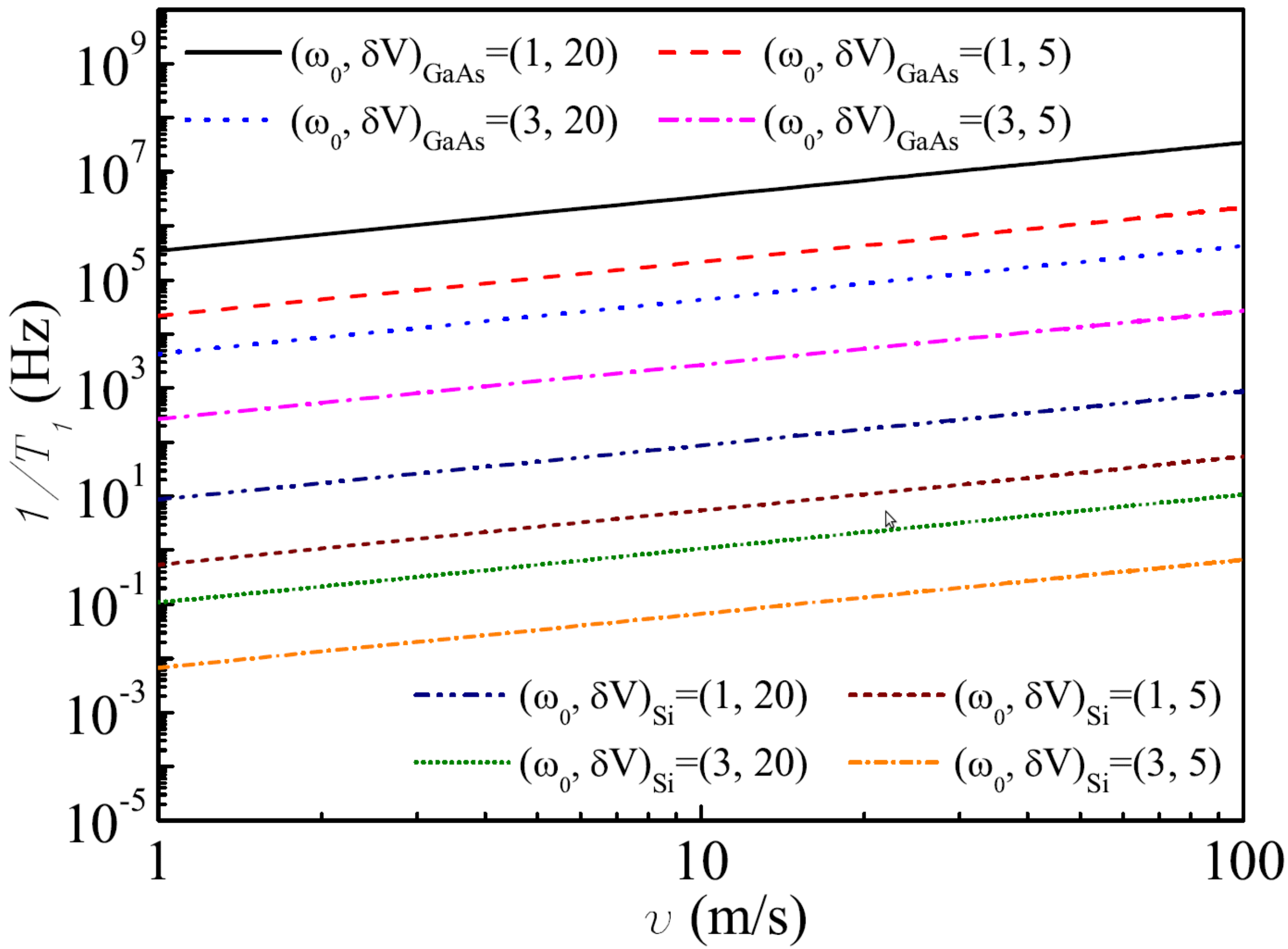
In-plane magnetic field

Material:

$GaAs/Al_xGa_{1-x}As$
Si/SiGe

$T_1(\mathrm{Si}) > T_1(\mathrm{GaAs})$

$B_{\mathrm{ext}} = 1\mathrm{T}$



$\alpha_{\mathrm{Si}} = 5\mathrm{m/s}$ $\beta_{\mathrm{Si}} = 0$

$\alpha_{\mathrm{GaAs}} = 0$ $\beta_{\mathrm{GaAs}} = 10^3\mathrm{m/s}$

SAW-confined transport in GaAs

$$v_{\mathrm{SAW}} = 3000\mathrm{m/s} \longrightarrow \Delta B \approx 0.1\mathrm{T}$$

not longer negligible

$$\Delta \boldsymbol{B} = \frac{2\hbar}{g\mu_B}(v_{0y}/\lambda_-, v_{0x}/\lambda_+, 0)$$

$$\boldsymbol{B} = \boldsymbol{B}_{\mathrm{ext}} + \Delta \boldsymbol{B}$$

Now (weak) dependence on direction of motion:

$$T_1 = T_1(\hat{\boldsymbol{v}}_0)$$

Realistic parameters

$$\frac{1}{T_1} \sim 10^9 \mathrm{s}^{-1}$$

Not negligible

Distance: ~3µm

Time: ~1ns

$$T_1 \propto \frac{v_0}{\omega_0^4}, \frac{\delta V^2}{l_\varepsilon^3}$$

Conclusions

Spin relaxation/decoherence in moving QD due to SOI

Longitudinal relaxation, no pure dephasing $T_2 = 2T_1$

Parameter dependence: $T_1 \propto \frac{v_0}{\omega_0^4}, \frac{\delta V^2}{l_\varepsilon^3}$

Important for materials with strong SOI and disorder due to doping