Spin and pseudo-spin states in silicon for QC: lifetimes

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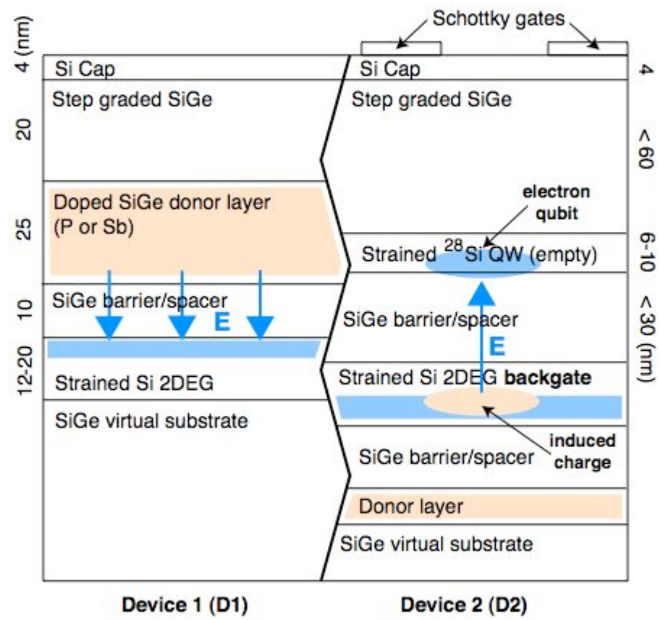
Charles Tahan,

Physics Dept.,

Wisconsin-Madison

and

Bob Joynt
Mark Friesen
S. N. Coppersmith
J. Truitt
M. A. Eriksson
et. al.



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New theory results for silicon

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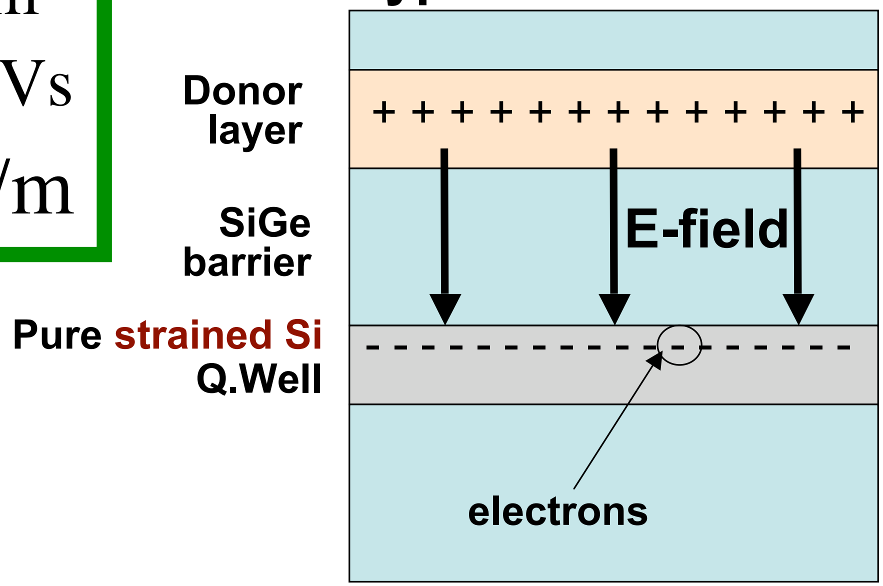
1. **2DEG spin relaxation**: ***Correct anisotropy and magnitudes. Times will increase with mobility and B.***
2. **Rashba Coefficient**: $\alpha \approx 1-6 \text{ m/s}$
3. **T_1 in Si quantum dots**: ***Rashba SOC usually dominates. Time increases with smaller dots and smaller B-fields.***
4. **Valley-state lifetimes**: ***Microseconds to milliseconds. Long-lived pseudo-spin states.***

SiGe quantum wells for QDQC

Our device:

$$n_s = 4 \times 10^{11} \text{ e/cm}^2$$
$$\mu = 40{,}000 \text{ cm}^2/\text{Vs}$$
$$E = 6 \times 10^6 \text{ V/m}$$

Typical SiGe Device



Friesen, *et. al.*, PRB **67**, 121301R (2003)

Spin relaxation in SiGe 2DEGs

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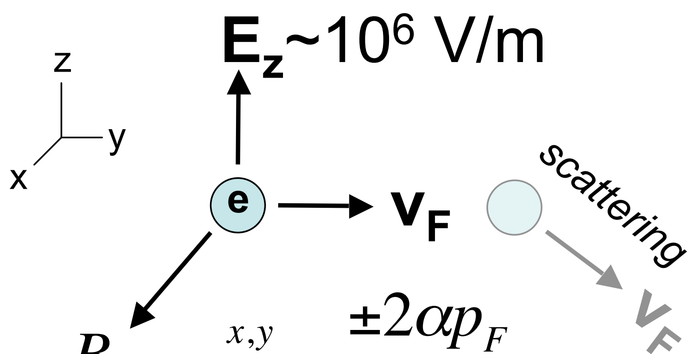
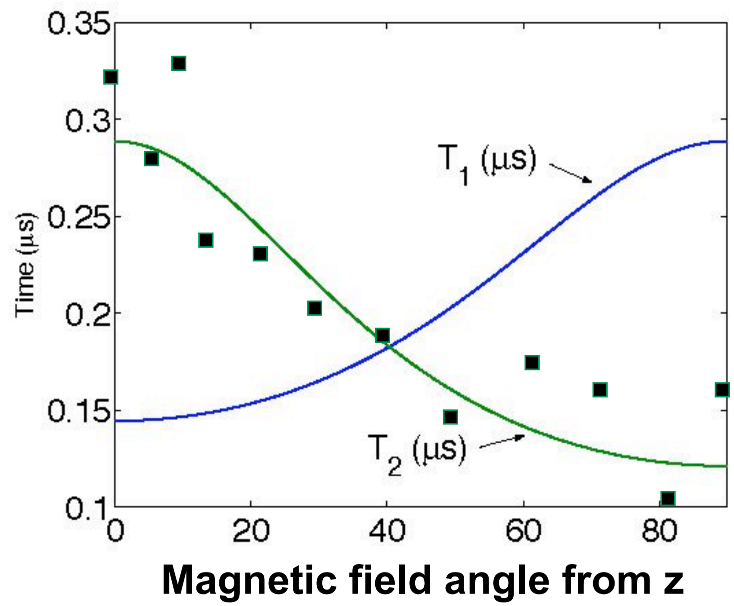
- Rashba SOC + scattering = fluctuating B-field in-plane
- Anisotropic T_1 and T_2

T ~ 5 K



$$B_{Rashba}^{x,y} = \frac{\pm 2\alpha p_F}{g\mu_B}$$



General range: $\frac{1}{T_1} \approx \frac{1}{T_2} \approx 0.1 - 20\ \mu s \sim \alpha^2$

Tahan and Joynt, condmat/0401615

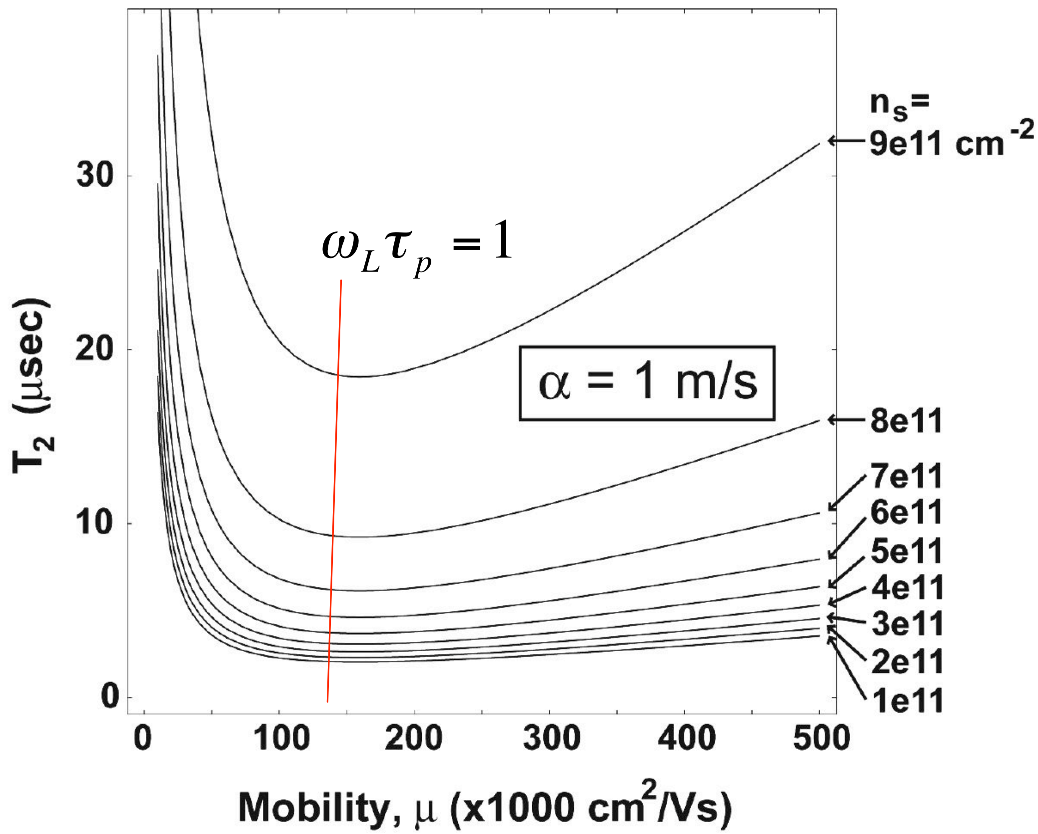
***Charles Tahan**, March Meeting 2004*

T_1 & T_2 increase with mobility

…in high mobility limit

- **In a static B-field**

$$\omega_L = \frac{g\mu B}{\hbar}$$



Tahan and Joynt, condmat/0401615

Rashba coefficient in silicon

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- **Spin-orbit coupling due to large E_z**

$$H_{Rashba} = \alpha\left(p_x\sigma_y - p_y\sigma_x\right)$$

- **Kane-like 8 band calculation for Si**

$$\alpha(\mathbf{E}_z) \approx \sqrt{2}\,\frac{PP_z\Delta_d}{\hbar}\,\frac{e}{\left(E_{v1}+\Delta_d\right)^2 E_{v2}}\,\mathbf{E}_z$$

Our theory: $\alpha \approx 1-6\ \mathrm{m/s}$

Rashba spin-splitting: $\Delta_R \sim 1\ \mu\mathrm{eV}$

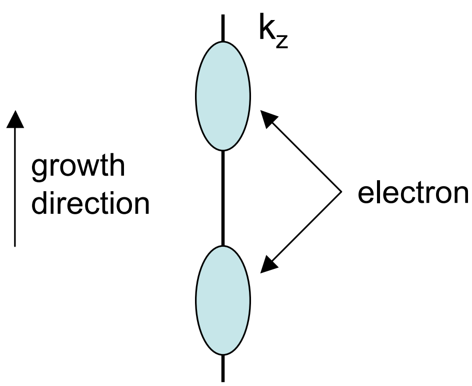
Rashba field: $B_R^{\,x,y} = 10-40\ \mathrm{G}$

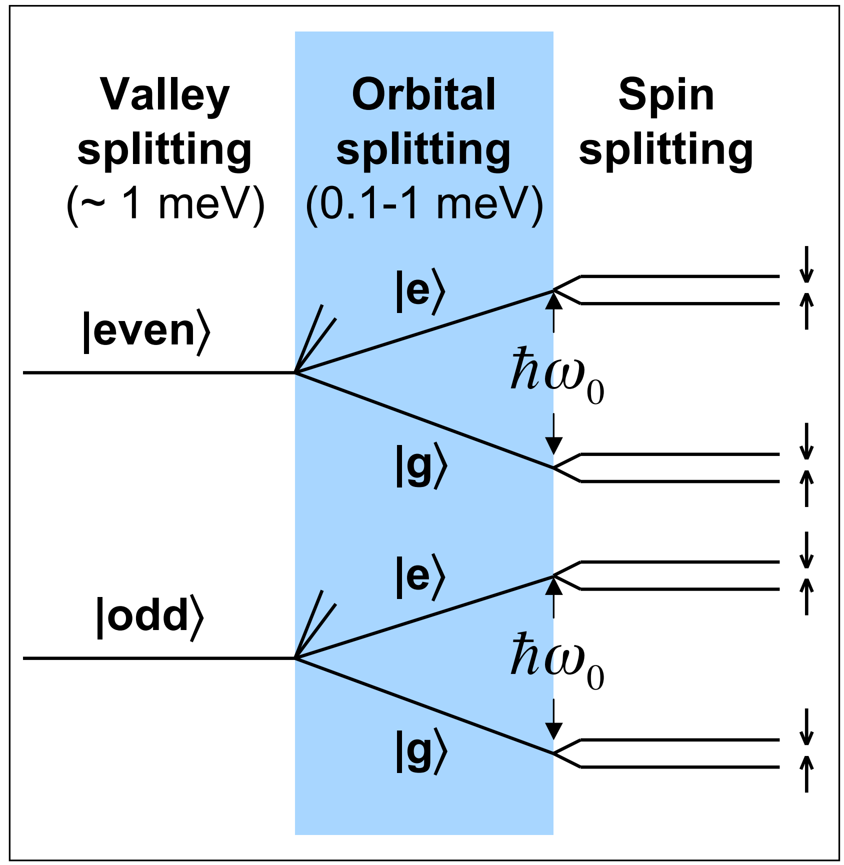
In-line with experimental evidence.

Tahan and Joynt, condmat/0401615

SiGe QW quantum dot

Si dot energy levels





T_1 from Rashba in Si QDs

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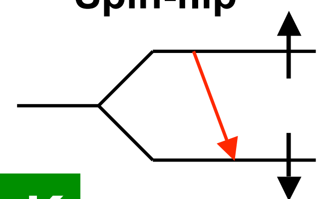
- **Confined state:** $\langle \mathbf{p}_{x,y} \rangle << p_F^{2DEG}$ **=> 2DEG mechanism gone**
- **Rashba spin-orbit mixing + phonon = relaxation**

unexpected: **GaAs** and **bulk Si:** $\sim (g\mu B)^5$

$$\frac{1}{T_1} \sim \frac{\Xi_u^2}{v_t^7} \frac{\alpha^2}{(\hbar\omega_0)^4} B^7$$

Dot size dependent

Spin-flip



T < 100 mK

- **Non-zero for all directions of B**

T_1	$B = 0.33$ T	$B = 2$ T
$\hbar\omega_0 = 0.1$ meV	5 s	0.002 s
$\hbar\omega_0 = 1$ meV	56,000 s	24 s

Orbital relaxation in strained Si

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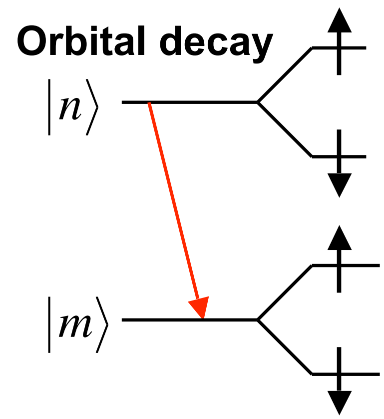
- Deformation interaction (no piezo-phonons in Si)
- Strained Si => transverse phonons contribute

$$\Gamma_{mn}\left(\mathrm{s}^{-1}\right) \sim \left|\langle m|z|n\rangle\right|^2 \frac{E^5_{mn}}{v_t^{\,7}}$$

transverse phonons: $v_t = v_l/2$



- Speed comparable to GaAs

$$\Gamma_{mn}\left(\mathrm{s}^{-1}\right) \approx \text{ns to ps} \;\; \left(\hbar\omega_0 = 0.1\text{-}1\ \text{meV}\right)$$

Relevant to:
- **Optical pumping/ Initialization**
- **Many-phonon processes**

Valley states in silicon QWQDs

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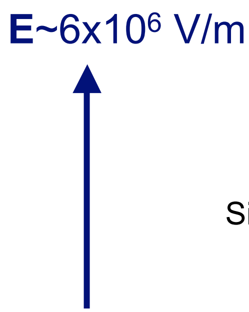
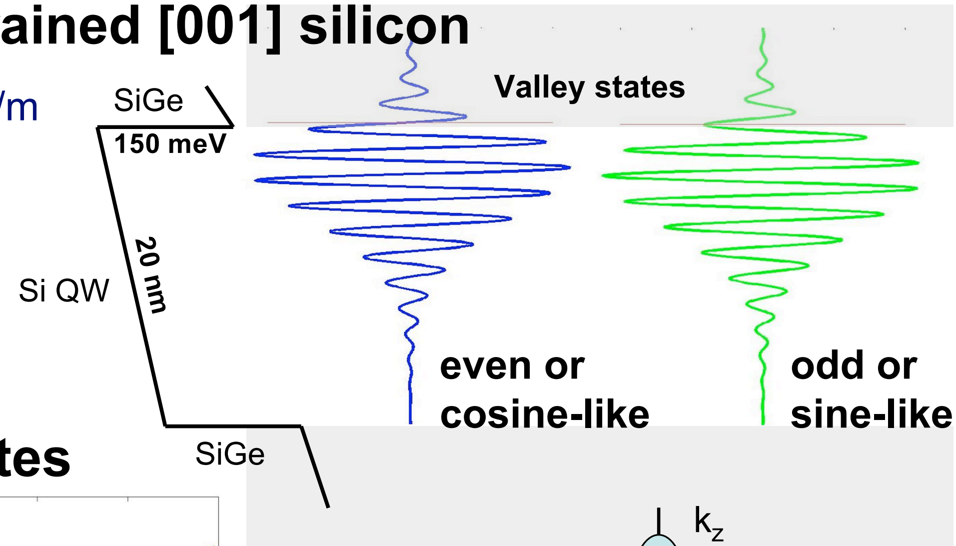
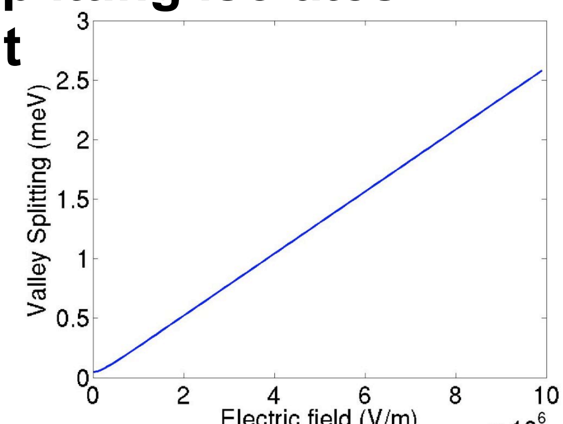
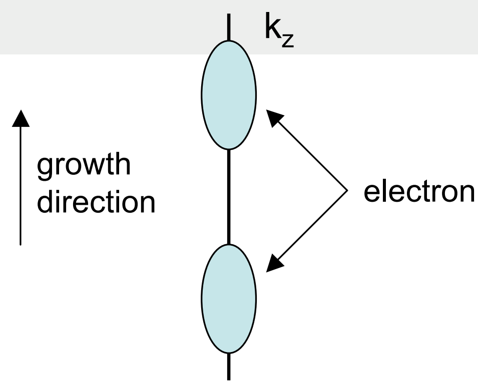
- **2-valley nature of strained [001] silicon**





- **Valley-splitting isolates spin qubit**



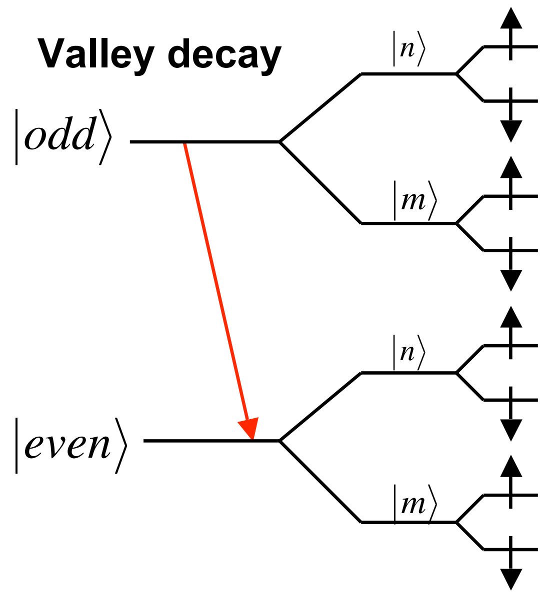


Boykin, Klimeck, Coppersmith, *et. al.*, APL **84**, 115 (2003)

Valley-state lifetimes

- **Same procedure as orbital relaxation**
- **Extremely small electric-dipole matrix element**

$$\Gamma^{v}{}_{mn}\left(s^{-1}\right) \approx \text{microsecs - millisecs}$$



- **Long relaxation times for non-spin-flip transitions**

- **Tunable with external E-field**

We have calculated for *silicon*…

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More info at…

cond-mat/? - coming soon…
cond-mat/0401615
cond-mat/0304422 - PRL
cond-mat/0203319 - PRB

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Orbach spin relaxation

- **Two phonon process**
- **Dominant mechanism in P:Si for T > 4 K**
- **Provides limited spectroscopy of first orbital energy gap**

Relaxation rate of level |1>

$$\frac{1}{T_1} \approx M^2{}_{SO}\Gamma_{1\rightarrow g}\, e^{\left[-E_{1g}/kT\right]}$$

SO mixing between |1> and |g>

Phonon DOS