Spin (in)coherence of phosphorous donor electron qubits near the c-Si/SiO$_2$ interface

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Spin will play an increasingly important role in (silicon based) electronics

Quantum Information Processing

Electron spin $T_2$ time of $^{31}$P donor > 600ms (electron spin) *

How does the readout of $^{31}$P qubit work?  SPIN – SELECTION RULES!

*A. M. TYRYSHKIN et al. PHYSICAL REVIEW B 68, 193207 (2003)
PHOSPHOROUS SPIN READOUT AT THE SILICONDIOXIDE INTERFACE

The c-Si (111)/SiO₂ interface


³¹P SPIN READOUT USING SPIN-SELECTION RULES

OBSERVATION OF THE PHOSPHOROUS – INTERFACE DEFECT TRANSITION

\[ |\Psi\rangle = |\Psi\rangle(\tau, B_1, \omega) \]

\[ Q = Q(\tau, B_1, \omega) \]

\[ Q \propto |\langle S | \Psi \rangle|^2 \]

T = 5K

$|\Psi (r = 0)|^2 \propto \Delta \text{HFS} = 4.2 \text{ mT} \propto a^{-3}$

ELECTRICAL DETECTION OF $^{31}$P DONOR STATES

$T = 5K$


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$T = 5K$

$Q \propto \left| \langle S | \Psi \rangle \right|^2$

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Weakly coupled $^{31}$P-P$_b$ spin pairs

ELECTRICALLY DETECTED HAHN-ECHOES OF NEAR INTERFACE $^{31}$P

Increase dephasing time $\tau$  →  Echo intensity decays  →  Decay time: $T_2$ coherence time

T$_2$ time at interface is constant at different temperatures.

ESR T$_2$ has temperature dependence: T$_1$ limits T$_2$ in the ESR measurement.*

T$_2$ time at interface is much shorter than in bulk T$_2$ at low temperature.

ELECTRICALLY DETECTED INVERSION RECOVERY EXPERIMENT

Is spin relaxation time truly limited by electronic transition or is field fluctuations at interface?


$T_1 = 4.0(5) \mu s$

$T_2 = 1.3(8) \mu s$ at low HF $^{31}\text{P}$ peak

$T_2 = 2.1(7) \mu s$ at high HF $^{31}\text{P}$ peak
ELECTRICALLY $T_1$ RELAXATION AT LOWER INTERFACE STATE DENSITIES

$c$-Si/$SiO_2$ INTERFACE WITH 4 TIMES SMALLER INTERFACE DENSITY

CONCLUSIONS

- EDMR $T_1$, $T_2$ times are much shorter than ESR $T_2$ time.

- Electronic transition time probably limits $T_1$ relaxation time.

- Incoherence time $T_2$ of $^{31}\text{P}$ qubit is shortened due to the interface states.

<table>
<thead>
<tr>
<th>$T = 5K$</th>
<th>High field $^{31}\text{P}$</th>
<th>Low field $^{31}\text{P}$ / $P_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDMR $T_1$</td>
<td>14(3)$\mu$s</td>
<td>13(3)$\mu$s</td>
</tr>
<tr>
<td>EDMR $T_2$</td>
<td>4.0(5)$\mu$s</td>
<td>1.0(2)$\mu$s</td>
</tr>
</tbody>
</table>

Silicon-based QCs using $^{31}\text{P}$ qubits (AND READOUT) need to overcome the limitation imposed by interface defects.

Spin-Dependent Trapping at Bulk Phosphorous in Silicon

- **Spin Trapping**


  Quasi-optical
  Superheterodyne EPR System

Spin-trapping is only visible when electrons are strongly polarized – at very high magnetic fields


See Gavin Morley's talk that will come next

Questions?

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