Nuclear Spin Dynamics in Spin Injection Devices

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Motivation

- spintronics:
  logic and memory devices

- spin qubit quantum computing

source of decoherence:
  interaction with environment, fluctuating Overhauser field

\[ \text{goal: understand and control nuclear spin effects} \]
• spin-LED
  + nuclear spins

• spin valve devices
  + nuclear spins

• nuclear spin relaxation in GaAs
Spin dynamics

dynamic of the electron spin in semiconductors:

\[
\frac{dS}{dt} = \Omega \times S - \frac{S}{\tau_s} - \frac{S - S_0}{\tau}
\]

\[
\Omega = g^* \mu_B B_{\text{app}} / \hbar
\]

precession – relaxation - recombination

steady state solution

\[
S = \eta \frac{B_{1/2}^2 S_0 + (S_0 \cdot B_{\text{app}}) B_{\text{app}} + B_{1/2} (B_{\text{app}} \times S_0)}{B_{1/2}^2 + B_{\text{app}}^2}
\]

\[
B_{1/2} = \hbar / (g^* \mu_B T_s)
\]

characteristic field of full precession
Dynamic Nuclear Polarization

hyperfine interaction

\[ \mathcal{H} = -\frac{16\pi}{3I} \mu_B \mu_n |\Psi(R)|^2 \hat{I} \cdot \hat{S} \]

- electron/nuclei flip-flop process leads to transfer of polarization (DNP)
- Zeeman energy mismatch compensated by secondary process involving phonons / photons

steady state nuclear field:

\[ B_N = \frac{f_i b_N (I + 1) (S \cdot B_{\text{app}}) B_{\text{app}}}{s(s + 1) B_{\text{app}}^2 + \xi B_L^2} \]

- \( b_N \) maximum effective nuclear field
  - in GaAs: \( \sim 5.3 \) Tesla
- \( B_L \) local dipole field
  - in GaAs: \( \sim 1 \) mT

[Paget PRB, 15,5780 (1977)]
Spin-LED

- quantum well LED
- ferromagnet cathode
- electron spin injection across Schottky barrier

[Strand et al. PRB, 72,155308 (2005)]
[Van Dorpe et al. PRB, 72,035315 (2005)]
 Optical spin detection

- observation direction of electro-luminescence:
  along growth direction

- shape anisotropy:
  Fe easy-axis in-plane

- detection of polarization:
  photoelastic modulator, lin. polarizer, monochromator, optical chopper, avalanche photo diode
  2 lock-ins (ref. by PEM or chopper)
  \[ P_{EL} = \frac{V_{PEM}}{V_{chop}} \]
Signatures of DNP

steady state polarization in this configuration:

\[
S_z = \frac{S_0^h \cos(\theta)\sin(\theta)}{1 + (B_{1/2}/B_{app})^2}, \quad S_0^h = \pm S_0
\]

signature of large internal magnetic field of \( \sim 4 \) kG!
nuclear polarization signature:
- bias dependence
Nuclear spin dynamics

- relaxation

\[ I_{av}(t) = I_{av}(0) e^{-t/T_1} \]

- polarization

\[ I_{av}(t) = I_{av}(\infty) \left\{ 1 - \exp\left[ -t \left( \frac{T_1 + T_{pol}}{T_1 T_{pol}} \right) \right] \right\} \]
Nuclear magnetic resonance

Further proof of nuclear spin effect:

- **field-driven NMR**

- **current-driven NMR**
Outline

• spin-LED
  + nuclear spins

• spin valve devices
  + nuclear spins

• nuclear spin relaxation in GaAs
Spin Valve devices

all-electrical semiconductor spin device:
– spin injection from ferromagnet
– electrical detection with 2nd Fe-contact

Spin Valve devices

electron spin dynamics: drift and diffusion

\[
\frac{\partial \tilde{S}}{\partial t} = -v_d \frac{\partial \tilde{S}}{\partial y} + D \frac{\partial^2 \tilde{S}}{\partial y^2} - \frac{\tilde{S}}{\tau_s} - \vec{\Omega}_L \times \tilde{S}
\]

\text{drift} \quad +\text{diffusion} -\text{relaxation} -\text{precession}

resulting parallel detector voltage:

only sensitive to component along Fe magnetization

\[
V_{\parallel}(x_1, x_2, B) = V_0 \int_0^\infty \frac{1}{\sqrt{4\pi Dt}} e^{-\frac{(x_2 - x_1 - v_d t)^2}{4Dt}} \cos(\Omega t) e^{-t/\tau_s} dt
\]

Hanle line shape

Nuclear spin signature

depolarization peak in spin valve measurement

\[ T \sim 40 \text{K} \]

\[ T = 4 \text{K} \]

z-component of the nuclear field:
precession and dephasing of diffusive e\(^{-}\) spins

[Ciorga et al. PRB. 79, 165321(2009)]
[Salis et al. PRB 80, 115332(2009)]
Long nuclear timescales

slow time-dependence suggests nuclear spin effect

[Salis et al. PRB 80, 115332(2009)]
Hanle satellite peaks

steady state $B_N$ (high field limit):

$$B_N = b_N^0 \frac{B_{ext} \cdot \langle S \rangle}{B^2} B_{ext}$$

for $B_{ext} \cdot \langle S \rangle < 0$ : $B_{ext}$ canceled by $B_N$

(partial) recover of spin polarization

whenever $|B_{ext}| = |B_N|$
fast Hanle measurements:

\[ B_N \approx b_N^0 B_x S_0 \left\langle \frac{1}{B} \right\rangle \]

- linear dependence on \( B_x \)
- dependence on spin polarization \( S_0 \)
Outline

• spin-LED
  + nuclear spins

• spin valve devices
  + nuclear spins

• nuclear spin relaxation in GaAs
- prepare saturated nuclear field
- let evolve/relax in unpolarized environment
- probe $B_N$ with fast Hanle-sweep
Relaxation measurement

(a) Initialize with $I_{\text{inj}}$, then decay with $B_Z = 0$. During the delay $\tau$, the system is probed.

(b) The time evolution of the system is shown with $I_{\text{DC}} = 20 \mu\text{A}$ initially and then $I_{\text{DC}} = 0$.

(d) The $B_N$ versus delay $\tau$ at $T = 4.2\text{ K}$ is shown with $T_1 = 946\text{ s}$.

(c) The colormap shows the change in $\lambda N_{\text{g}}$ with delay $\tau$ at $T = 4.2\text{ K}$.
Temperature dependence

relaxation measurement below 20 K:

\[ T^{1.0} \]

\[ 0.58 \pm 0.07 \]

[Lu et al. PRB 74, 125208(2006)]
Inhomogeneity

initialization with $B_z = 0$:
- same $T_1$ time
- increased line width
  $\Rightarrow$ inhomogenous nuclear spins
Double satellites

slow Hanle scans:
- appearance of double satellites
- peak splitting increases with $B_x$
  $\rightarrow$ contribution of drifting spins?
Summary

- DNP in spin injection devices
- Optical and all-electrical study of dynamics
- Increased $T_1$ and sublinear T-dependence in metallic GaAs at low temperatures
- Spin injection leads to inhomogeneous DNP
Temperature dependence

$T < 20$K: sub-linear temperature dependence

$\rightarrow$ deviation from Korringa relaxation

[Lu et al., PRB 3, 12508 (2006)]