Transient Analysis of Oblique Hanle Signals Observed in GaAs

Zhichao Lin, Masafumi Yamamoto, Tetsuya Uemura
Graduate School of Information Science and Technology, Hokkaido Univ.
E-mail: lin-zhichao@nsed.ist.hokudai.ac.jp

1. Background

The understanding of nuclear-spin dynamics in semiconductors is a major prerequisite for creating viable spintronic devices, such as a nuclear-spin based qubit. Recently, we demonstrated dynamic nuclear polarization (DNP) in all-electrical spin injection devices with Co$_2$MnSi/ultrathin CoFe/n-GaAs Schottky tunnel junctions, and experimentally investigated the transient response of nuclear spins to a change in the magnetic field through transient oblique Hanle effect measurements \[1\]. However, its full understanding has not been established yet. In this study, we analyzed a transient response of nuclear spins in GaAs to a change in a magnetic field based on a time evolution of nuclear spin temperature.

2. Simulation Model

The average nuclear spin $I_n$ and resultant Overhauser field $B_o$ in the presence of external magnetic field $B$ are given by \[2\]

$$ I_n = \frac{(l + 1) \mu_n B}{h}, \quad (1) $$

$$ B_o = b_o I_n / I, \quad (2) $$

where $I$ is the value of nuclear spin, $\mu_n$ is the nuclear magnetic moment, $\Theta$ is the spin temperature in unit of energy, $b_o$ is the effective field due to the polarization of nuclear spins, which takes the negative value of $-17$ K in GaAs for the theoretical ideal case. The time evolution of nuclear spin temperature under the DNP process is described by the following equation \[2\]

$$ \frac{d}{dt} \left( \frac{1}{\Theta} \right) = \frac{1}{T_p} \left( \frac{1}{\Theta} - \frac{1}{\Theta_0} \right), \quad (3) $$

where $T_p$ is the characteristic time for DNP and $\Theta_0$ is the steady-state nuclear spin temperature, which is given by

$$ \frac{1}{\Theta_0} = \frac{4 I}{\mu_n} \frac{S \cdot S}{\mu^2 B^2 L^2}, \quad (4) $$

where $f (\leq 1)$ is the leakage factor, $S$ is the average electron spin ($S = 1/2$ corresponds to $P_{GaAs} = 100\%$), $B_L$ is the local dipolar field experienced by the nuclei, and $\xi$ is a numerical coefficient which depends on the nature of the spin-spin interactions.

Since the electron spin precession is induced by $B + B_o$, the nonlocal voltage $V_{NL}$ between contact 3 and 4 (Fig. 1) was approximately calculated by using the conventional spin diffusion model \[3\].

3. Results and Discussion

Figure 2 shows (a) a typical oblique Hanle signal observed in GaAs with a Co$_2$MnSi spin source and (b) its simulation result by using eqs. (1)-(4). The details of the device structure and experimental conditions were described in Ref. \[1\]. The experimental result was well fitted with the simulation result, indicating the validity of the simulation model used in this study. Compared to the steady-state signal, the transient signal has two features: (1) an additional side peak was observed at $B_{sd} < 0$ for the negative sweep direction, and (2) no side peak was observed for the positive sweep direction, showing a clear hysteretic nature depending on the sweep direction. From the analysis, we found that these features can be understood by the delay of time response of $\Theta$ to a change in $B$.

![Fig. 1. Schematic of a four-terminal nonlocal device and circuit configuration for oblique Hanle effect measurement.](image)

![Fig. 2. (a) Experimental result of oblique Hanle signal observed in GaAs with a Co$_2$MnSi spin source. (b) Simulation result of the oblique Hanle signal.](image)

**References**

