Transient Analysis of Oblique Hanle Signals Observed in GaAs

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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_2MnSi/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 $\mathbf{I}_{\mathbf{av}}$ and resultant Overhauser field $\mathbf{B}_{\mathbf{n}}$ in the presence of external magnetic field **B** are given by [2]

$$\mathbf{I}_{\mathbf{av}} = \frac{(I+1)\mu_I}{3\Theta}\mathbf{B}, \tag{1}$$

$$\mathbf{B}_n = b_n \mathbf{I}_{\mathbf{av}} / I, \tag{2}$$

where I is the value of nuclear spin, μ_I is the nuclear magnetic moment, Θ is the spin temperature in unit of energy, b_n is the effective field due to the polarization of nuclear spins, which takes the negative value of –17 T 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]

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

where T_P is the characteristic time for DNP and Θ_0 is the steady-state nuclear spin temperature, which is given by

$$\frac{1}{\Theta_0} = f\frac{4I}{\mu_I}\frac{\mathbf{S}\cdot\mathbf{B}}{\mathbf{B}^2+\xi\mathbf{B}_{\mathbf{L}}^2}, \tag{4}$$

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

Since the electron spin precession is induced by $\mathbf{B} + \mathbf{B}_{\mathbf{n}}$, 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_2MnSi 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 $B_{ob} < 0$ 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 Θ to a change in **B**.

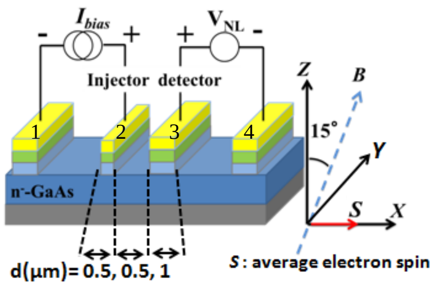

Fig. 1. Schematic of a four-terminal nonlocal device and circuit configuration for oblique Hanle effect measurement.

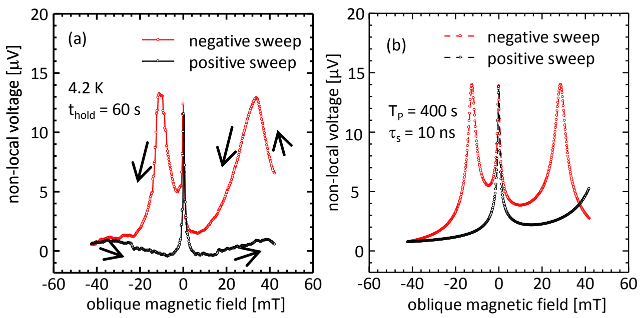

Fig. 2. (a) Experimental result of oblique Hanle signal observed in GaAs with a Co_2MnSi spin source. (b) Simulation result of the oblique Hanle signal.

References

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