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Transient oblique Hanle signals observed in Co_2MnSi/CoFe/n-GaAs with non-local four-terminal configuration

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1. Introduction

The interplay between electron spin and nuclear spin due to the hyperfine interactions has attracted much attention for creating novel spintronic devices. A transfer of angular momentum from polarized electrons to nuclear via the hyperfine interactions enables effective polarization of nuclear spins, referred to as dynamic nuclear polarization (DNP) [1]. On the contrary, polarized nuclear spins affect electron spins as an effective magnetic field or Overhauser field. In order to detect the Overhauser field the oblique Hanle effect measurement has been widely used [1,2]. Recently all-electrical injection and detection of spin polarized electrons have been demonstrated in GaAs [3-6], Si [7], and Ge [8] through the non-local four terminal configurations. Furthermore the DNP and its resulting Overhauser field were detected in Fe/GaAs Schottky tunnel junctions [2] through the steady-state oblique Hanle effect measurement, in which the magnetic field was swept slowly to ensure that the nuclear spin polarization is in equilibrium. In order to fully understand the dynamics of DNP, however, transient analysis is indispensable. The purpose of our present study is to understand the transient behavior of the oblique Hanle signals. For that purpose we investigated spin-dependent transport properties of a Co_2MnSi/CoFe/n-GaAs system in the non-local geometry. Compared to the steady-state oblique Hanle signals, we observed hysteretic nature depending on the sweep direction of the magnetic field and an additional suppression of the Hanle effect in the transient oblique Hanle signals. These transient characteristics can be qualitatively explained by the magnetic-field induced nuclear reversal.

2. Experimental Method

We grew layer structures consisting of undoped GaAs (250 nm)/n^--GaAs (Si = 3×10^{16} cm^{-3}, 2.5 μm)/n^+-GaAs (Si = 5×10^{18} cm^{-3}, 30 nm) by MBE at 590 ºC on GaAs(001) substrates. A 5-nm-thick Co_2MnSi ferromagnetic layer was grown by magnetron sputtering on n-GaAs at room temperature via a 1.1-nm-thick CoFe insertion layer. Using Ar ion milling technique and EB lithography, four-terminal non-local devices were fabricated. The size of the injector contact (contact-2) and detector contact (contact-3) were 0.5 × 10 μm and 1.0 × 10 μm, respectively, and the spacing between them was 0.5 μm. We measured spin dependent transport properties using a four-terminal non-local geometry in which the non-local voltage(V_{NL}) between contact-3 and contact-4 was measured under a constant current (I_{bias}) supplied between contact-2 and contact-1, as shown in Fig. 1. The bias voltage was defined with respect to the n-GaAs.

3. Results and Discussion

From the evaluation of tunneling anisotropic magnetoresistance [9] for both the injector and the detector, we confirmed that the easy axis of Co_2MnSi/CoFe ferromagnetic electrode is parallel to x-axis due to strong uniaxial-type magnetocrystalline anisotropy (see definition of coordinate system in Fig. 1). Figure 2(a) plots V_{NL} measured at 4.2 K at I_{bias} = –40 μA as a function of in-plane magnetic field of B_x. We observed a clear spin-valve-like signal at $B_x \approx \pm 30$ mT due to parallel (P)/anti-parallel (AP) switching in the magnetization configuration between the injector contact-2 and the detector contact-3. The V_{NL} as a function of out-of-plane magnetic field (B_z) for both the P and AP configurations is shown in Fig. 2(b). The V_{NL} for the AP (P) configuration gradually increases (decreases) as the magnitude of B_z increases and the two curves merge at a large B_z. These results clearly indicate the Hanle effect; that is, the spins injected in the GaAs channel dephased due to the precession by B_z, resulting in decreased spin accumulation in the GaAs channel. The spin lifetime estimated from the Hanle curve is approximately 40 ns at 4.2 K, which is comparable to that reported in n-GaAs with a doping concentration of around 3×10^{16} cm^{-3} [10]. These spin-valve signal and Hanle signals in the non-local geometry are rigorous evidences for injection, transport, and detection of spin-polarized electrons.

Now we will describe the results of oblique Hanle effect measurements. We applied oblique magnetic field of $\mathbf{B} = B_{ob}\mathbf{u}$, where $\mathbf{u}$ = (sin15°, 0, cos15°) is a unit vector of the magnetic field direction. Figure 3(a) shows V_{NL} vs. B_{ob} for P configuration. The device was first initiated at B_{ob} = +30 mT for a hold time (t_{hold}) of 30 sec. at I_{bias} = –40 μA so that nuclear spins get dynamically polarized. Then B_{ob} was swept from +30 mT to –30 mT and was swept back from –30 mT to +30 mT with a sweep rate of 0.25 mT/sec. The calculated steady-state oblique Hanle signal is also plotted in Fig. 3(b). Compared to the steady-state signals, we observe another satellite peak in the V_{NL} vs. B_{ob} at B_{ob} = –16 mT when the magnetic field is swept in the negative direction. Furthermore, the observed transient signal shows a clear hysteretic nature depending on the sweep direction, and no satellite peak appears in the positive sweep direction.

In order to understand the transient behavior, we will discuss the origin of the satellite peaks. The steady-state nuclear field is given by [1]

$$\mathbf{B_n} \cong fb_n \frac{\mathbf{B}\cdot\mathbf{S}}{\mathbf{B}^2}\mathbf{B} = fb_n\,|\mathbf{S}|\sin 15°\mathbf{u} \qquad (1)$$

where f (≤ 1) is a leakage factor that takes into account the possibility of nuclear-spin relaxation by other channels than through a hyperfine-induced flip-flop process, b_n is the maximum Overhauser field (b_n = –3.5 T in GaAs), **S** is an averaged electron spin in the semiconductor. From eq. (1), $\mathbf{B_n}$ and **B** are anti-parallel for $B_{ob} > 0$, while they are parallel for $B_{ob} < 0$ in the steady state. Therefore, at the initial stage of B_{op} = 30 mT the generated $\mathbf{B_n}$ is anti-parallel to **B**. The side peak in V_{NL} at B_{ob} = + 30 mT appears due to the suppression of the Hanle effect at the total field $\mathbf{B} + \mathbf{B_n} = \mathbf{0}$. Recently Salis, *et al.* reported in the spin-valve measurement for a Fe/n-GaAs system that the nuclear spins adiabatically follow the external field and their directions reverse in space when the magnetic field crosses zero [11]. Thus, when B_{ob} decreases from positive to negative through crossing zero, $\mathbf{B_n}$ reverse in direction, keeping **B** and $\mathbf{B_n}$ anti-parallel state. The side peak at B_{ob} = –16 mT, therefore, occurs when $\mathbf{B} + \mathbf{B_n} = \mathbf{0}$. However, since the steady-state $\mathbf{B_n}$ is parallel to **B** for $B_{ob} < 0$, the nuclear polarization first decreases and then repolarize into opposite direction, resulting in **B** and $\mathbf{B_n}$ being parallel state. Thus, no side peak appears when the magnetic field is swept in the positive direction.

If the model described above is applicable, the magnitude of the field at the satellite peaks is a measure of nuclear polarization. In order to confirm this, we plotted the magnitude of the field at both positive and negative satellite peaks as a function of t_{hold} in Fig. 4. Both fields show almost exponential dependence on t_{hold}, indicating that the repolarization peaks are related to DNP. The characteristics time for nuclear spins to be polarized is estimated to be approximately 77sec, value reasonable for the DNP.

4. Conclusions

We investigated transient behavior of the oblique Hanle signals in a $Co_2MnSi/CoFe$/n-GaAs system and found that repolarization peaks appeared in the signals are related to DNP.

References

[1] *Optical Orientation*, edited by F. Meiyer and B.P. Zakharchenya (North-Holland, New York, 1984)

[2] M. K. Chan, *et al.*, Phys. Rev. B **80** (2009), 161206(R).

[3] X. Lou, *et al.*, Nature Phys. **3** (2007), 197.

[4] G. Salis, et al., Phys. Rev. B **81** (2010), 205323.

[5] M. Ciorga, *et al.*, Phys. Rev. B **79** (2009), 165321.

[6] T. Uemura, *et al.*, Appl. Phys. Lett. **99** (2011), 082108.

[7] T. Sasaki, *et al.*, IEEE Trans. Magn. **46** (2010), 1436.

[8] Y. Zhou, *et al*., Phys. Rev. B **84** (2011), 125323

[9] T. Uemura, *et al.*, Appl. Phys. Lett. **94** (2009), 182502.

[10] R.I. Dzhioev, *et al.*, Phys. Rev. B. **66** (2002), 245204.

[11] G. Salis et al., Phys. Rev. B **80** (2009), 115332.

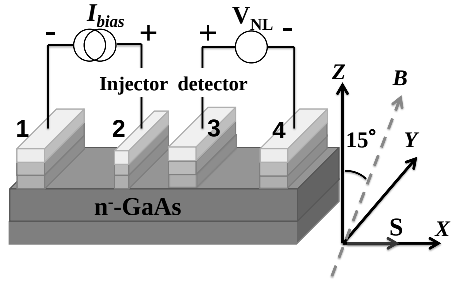

FIG. 1. Schematic configuration for non-local measurement.

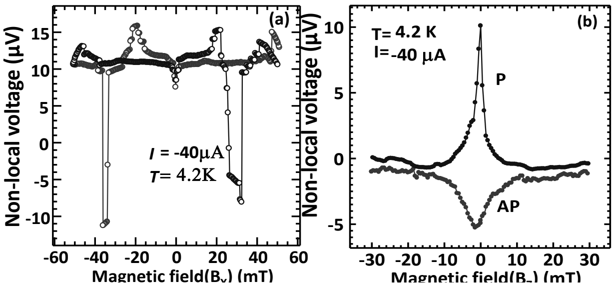

FIG. 2. Results of non-local measurements of (a) spin-valve effect and (b) Hanle effect.

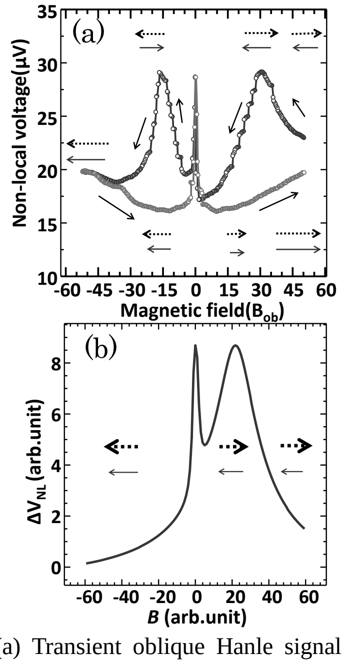

FIG. 3. (a) Transient oblique Hanle signal observed in a $Co_2MnSi/CoFe$/n-GaAs system. Dashed arrows represent external field and solid arrows represent nuclear magnetic field. (b) Simulated steady-state oblique Hanle signal.

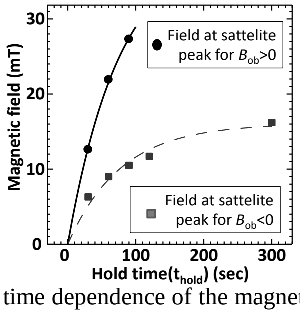

FIG. 4. Hold time dependence of the magnetic field at satellite peak.