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Analysis and control of the Hanle effect in metal–oxide–semiconductor inversion channels

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The authors theoretically analyzed the output characteristics of a proposed Hanle-effect spin transistor based on a spin-MOSFET. The device can easily create oscillating Hanle-effect signals by applying an accelerating bias voltage. The behavior of the magnetic field interval of the oscillatory Hanle-effect signals for a sufficiently high accelerating bias is well correlated with the universality of the effective electron mobility in the Si MOS inversion channel, which is useful for revealing spin transport dynamics in the MOS inversion channel.

The magnetotransport properties of the Hanle-effect spin transistor were analyzed using the rate equation of spin-polarized electrons,

\[
\frac{\partial s(x,t)}{\partial t} = D \frac{\partial^2 s(x,t)}{\partial x^2} - v \frac{\partial s(x,t)}{\partial x} - \frac{s(x,t)}{\tau_{sf}},
\]

where \(s(x,t)\) is the spin density, \(D\) is the diffusion constant, \(v\) is the velocity, and \(\tau_{sf}\) is the spin lifetime. The spin density \(s\) is defined by \(n_1 - n_2\) using a spin-up electron density \(n_1\) and a spin-down electron density \(n_2\), and the total electron density \(n\) can be given by \(n_1 + n_2\). In this study, \(s\) and \(n\) were measured as normalized values for simplicity. In the calculation, we assumed that a MOSFET operation in the linear region was applied to the Hanle-effect spin transistor. The spin polarization of injected electrons at the source-side channel edge was assumed to be unity in order to extract a primary physical picture. In addition, the width of the ferromagnetic contacts was assumed to be sufficiently shorter than the channel length. The impulse response of \(s\) for the time domain can easily be obtained using the Laplace

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In recent years spin-functional MOSFETs (spin MOSFETs)1–4 have attracted considerable attention for future low-power logic circuits5,6 owing to their unique spin-dependent transistor characteristics. Understanding and controlling spin injection/transport/detection for Si MOS inversion channels are critical challenges for realizing spin-functional MOSFETs. The Hanle effect induced by the spin precession of traveling spin-polarized electrons in semiconductor channels7–10 is considered to be the most powerful mechanism. Furthermore, we found that the Hanle-effect signals are well correlated with the universality7 of the effective electron mobility \(\mu_{\text{eff}}\) in the MOS inversion channel. Note that although the carrier density in the MOS inversion channel could be important for this feature, it can be controlled by not only a gate bias but also a body (substrate) bias (not shown in Fig. 1). In this paper, we analyze the Hanle effect in the proposed spin transistor. The behavior of \(B_{H,m\text{osc}}\) is shown to obey the universality of the effective electron mobility in the MOS inversion channel, which is useful for investigating the spin transport dynamics in the MOS inversion channel.

The authors theoretically analyzed the output characteristics of a proposed Hanle-effect spin transistor based on a spin-MOSFET shown in Fig. 1. The device can easily create oscillating Hanle-effect signals by applying an accelerating bias voltage. The behavior of the magnetic field interval of the oscillatory Hanle-effect signals for a sufficiently high accelerating bias is well correlated with the universality of the effective electron mobility in the Si MOS inversion channel, which is useful for revealing spin transport dynamics in the MOS inversion channel.

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The magnetotransport properties of the Hanle-effect spin transistor were analyzed using the rate equation of spin-polarized electrons,
transform of Eq. (1) with an assumption of an infinite channel length. The effective spin polarization \( P_{\text{eff}}(B) \) at the drain-side channel edge can be expressed using the convolution of the impulse response with the phase factor caused by the Hanle effect.

\[
P_{\text{eff}}(B) = \int_0^\infty \frac{L}{2\sqrt{\pi Dt}} e^{-\frac{x^2}{2Dt}} e^{-\frac{B^2}{2D}} \cos \left( \frac{g\mu_B B t}{\hbar} \right) dt.
\]

where \( B \) is a magnetic field, \( L \) is the channel length, \( g \) is the g-factor (= 2) of Si, \( \mu_B \) is the Bohr magneton, and \( \hbar \) is the reduced Planck constant. \( D \) was estimated from the Einstein relation using the universal effective electron mobility \( \mu_{\text{eff}} \) in Si MOS inversion channels, in which the correction due to the Fermi integral was ignored. The following parameters were used as a central parameter set unless otherwise noted: \( L = 10 \, \mu\text{m}, \mu_{\text{eff}} = 600 \, \text{cm}^2/\text{V s} \) (at 300 K), \( \tau_{\text{sd}} = 8 \, \text{ns} \) (at 300 K), and operation temperature \( T = 300 \, \text{K} \). Here, we chose the value of \( \mu_{\text{eff}} \) from the phonon scattering region in the universal curve of \( \mu_{\text{eff}} \) for a channel with a low doping density of \( 3.9 \times 10^{15} \, \text{cm}^{-2} \) (Ref. 17). The detection current \( I_{\text{det}} \) is proportional to the effective spin polarization \( P_{\text{eff}}(B) \) of the transported electrons at the drain-side channel edge.

Figure 2(a) shows the impulse response of \( s \) (hereafter denoted as \( s_t \)) for several accelerating bias voltages \( V_{\text{acc}} \) under \( B = 0 \). The distribution of \( s_t \) sharpens with increasing \( V_{\text{acc}} \) owing to the effect of the drift transport. These sharp distribution shapes suppress the dephase effect caused by the phase factor in Eq. (2). The intensity of \( s_t \) increases with increasing \( V_{\text{acc}} \), and the average transit time \( t_{\text{ave}} \), which corresponds to the peak position of \( s_t \), is shortened with increasing \( V_{\text{acc}} \). This means that more spin-polarized electrons can reach the drain-side channel edge for higher \( V_{\text{acc}} \) without randomizing the phase information. These phenomena are also confirmed by Figs. 2(b) and 2(c). The spin polarization \( P_s (= P_{\text{eff}}(0)) \) is given by the ratio between the areas of \( s_t \) and \( n_t \) (which is the impulse response of \( n \)), and \( P_s \) is enhanced with increasing \( V_{\text{acc}} \). Figure 2(d) shows \( P_s \) as a function of \( B \) for \( V_{\text{acc}} = 0 \) to 10 V. Note that the curve for \( V_{\text{acc}} = 0 \) corresponds to the case of a four-terminal nonlocal measurement configuration. \( P_s \) decreases with increasing \( L \); however, the effective spin diffusion length is enlarged by applying \( V_{\text{acc}} \). Therefore, the intensity of the Hanle effect signals can be greatly enhanced relative to nonlocal measurements by the application of \( V_{\text{acc}} \).

A magnetic field \( B_x \) required to rotate the spin direction of the transported electrons by \( \pi \) is given by the interval \( B_{\text{osc}} \) between the 1st and 2nd oscillating peaks of \( P_{\text{eff}} \). However, its accuracy depends on whether \( V_{\text{acc}} \) is sufficient or not. Curves in Fig. 3(a) show \( P_{\text{eff}} \) as a function of \( B \) for \( V_{\text{acc}} = 0 \) and 3 V. For the nonlocal condition (thinner curve and inset), the peak intensity at \( B = 0 \) is highly weakened, and the multiple oscillation is unclear because of the strong dephase effect. Although the second peaks are severely reduced, they could be detected with the use of highly sensitive measurement techniques. However, these peaks cannot represent \( B_{\text{osc}} \) because of the effect of the diffusive transport with the considerable spin relaxation. In contrast, when \( V_{\text{acc}} \) is sufficiently applied, \( P_{\text{eff}} \) dramatically increases and the multiple oscillations become clear, as shown by the thick curve in Fig. 3(a). In this situation, the \( B_{\text{osc}} \) approximately represent \( B_{\text{osc}} \). This is due to the dephase effect’s being weakened by the application of \( V_{\text{acc}} \), as described in Figs. 2(a)–2(c).

The relation between \( B_{\text{osc}} \) and the phase of the integrand of Eq. (2) at \( t = t_{\text{ave}} \) can be expressed by the following formula:

\[
\frac{g\mu_B B_{\text{osc}}}{\hbar} \tau_{\text{ave}} = \pi - \theta,
\]

where \( \pi - \theta \) is the phase of the integrand of Eq. (2) at \( t = t_{\text{ave}} \), \( t_{\text{ave}} = t_e - \Delta t \) [in which \( t_e \) is the particle picture...
be approximated by  

be negligible when 

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t is sufficiently shorter than 

\( \tau_{sf} \), \( \beta_{osc} \) corresponds to \( \beta_{\pi} \). In contrast, when 

t is longer than \( \tau_{sf} \), \( \beta_{OSC} \) deviates from \( \beta_{\pi} \). In order to satisfy 

\( \beta_{OSC} = \beta_{\pi} \), a higher \( V_{acc} \) is required for shorter \( \tau_{sf} \). These behaviors can be attributed to the \( V_{acc} \)-dependent \( \Delta \beta \). When a sufficiently high \( V_{acc} \) is applied so that the relation 

t < \( \tau_{sf} \) is satisfied, \( \beta_{OSC} \) is identical to \( \beta_{\pi} \) regardless of \( \tau_{sf} \).

A thick solid curve in Fig. 4(b) shows \( \beta_{osc} \) as a function of \( E_{eff} \). \( \beta_{\pi} \) is also plotted as a thin curve in Fig. 4(b). In this figure, a constant \( \tau_{sf} = 8 \) ns (Ref. 18) is assumed for the entire \( E_{eff} \) region, and \( V_{acc} \) is set to 3 V so that \( t_e = 0.56 \) ns becomes much shorter than \( \tau_{sf} \). \( \beta_{osc} \) corresponds to \( \beta_{\pi} \), and obeys the universal curve17 of \( \beta_{eff} \). This behavior becomes the crucial evidence of spin transport in the MOS inversion channel. In contrast, when \( V_{acc} \) decreases, \( \beta_{osc} \) starts to deviate from the universal curve of \( \beta_{\pi} \). This feature is beneficial in attempts to experimentally determine \( \tau_{sf} \). Because the dominant scattering mechanisms for \( \beta_{eff} \) can be changed by \( E_{eff} \) (Ref. 17), the relation between the scattering mechanisms and \( \tau_{sf} \) can be investigated using the presented universality behavior of \( \beta_{OSC} \).

representation of the transit time given by 

t = \( L/\mu_{eff}(V_{acc}/L) = L^2/\mu_{eff}V_{acc} \), and \( \Delta t \) is the difference between \( t_{ave} \) and \( t_e \). (\( \Delta t \) originates from the diffusive transport with the considerable spin relaxation.) \( \Delta t \) depends on \( \tau_{sf} \) and cannot be negligible when \( V_{acc} \) is small, as shown in Fig. 2(b). \( B_{osc} \) gives the phase different from \( \pi \), and thus the correction factor \( \theta \) is added in Eq. (3). \( B_{osc} \) can be expressed as

\[
B_{osc} = \beta_{\pi} \frac{V_{acc}}{L^2} + \Delta B, \tag{4}
\]

where \( \beta_{\pi} \) is given by \( \pi \hbar \mu_{eff}/g_{\mu B} \) and \( \Delta B \) is the correction factor due to \( \theta \) and \( \Delta t \). Here, \( \beta_{osc} \) is defined as \( \beta_{osc} = B_{osc}L^2/V_{acc} \). When \( \Delta B \) can be neglected, \( \beta_{osc} \) corresponds to \( \beta_{\pi} \). The thick solid curves in Fig. 3(b) show \( \beta_{osc} \) as a function of \( V_{acc} \) for \( L = 5, 10, \) and 15 \( \mu m \). \( B_{osc} \) linearly increases according to \( V_{acc}/L^2 \) (shown by the thin solid lines in Fig. 3(b)) for higher \( V_{acc} \) (Also, see Refs. 7, 8 and 16), since the drift mechanism dominates in this region. For small \( V_{acc} \), \( B_{osc} \) deviates from \( V_{acc}/L^2 \), owing to the diffusive transport (in which \( t_{ave} \) cannot be approximated by \( t_e \) because of the considerable spin relaxation and, thus, large \( \theta \); i.e., \( \Delta B \) cannot be negligible). The dotted curves in Fig. 3(b) show \( \Delta B \) as a function of \( V_{acc} \). \( \Delta B \) decreases with increasing \( V_{acc} \) and tends to saturate at a constant value depending on \( L \). Therefore, when \( V_{acc} \) is sufficiently high, \( \Delta B \) can be neglected and \( \beta_{\pi} \) can be obtained from \( \beta_{osc} \).

\( \beta_{osc} = \pi \hbar \mu_{eff}/g_{\mu B} \) is proportional to \( \mu_{eff} \), and \( \mu_{eff} \) in MOS inversion channels is governed by the vertical effective electric field \( E_{eff} \) induced by a gate bias \( V_{gate} \), which is known as the universality of \( \mu_{eff} \). \( \beta_{\pi} \) also shows the same universality of \( \mu_{eff} \). Figure 4(a) shows \( \beta_{OSC} \) as a function of \( V_{acc} \) for \( E_{eff} = 0.15 \) MV/cm, in which \( \tau_{sf} \) is varied from 0.1 to 10 ns. The top horizontal axis shows \( t_e \). When \( t_e \) is sufficiently shorter than \( \tau_{sf} \), \( \beta_{OSC} \) corresponds to \( \beta_{\pi} \). In contrast, when \( t_e \) is longer than \( \tau_{sf} \), \( \beta_{OSC} \) deviates from \( \beta_{\pi} \). To satisfy \( \beta_{OSC} = \beta_{\pi} \), a higher \( V_{acc} \) is required for shorter \( \tau_{sf} \). These behaviors can be attributed to the \( V_{acc} \)-dependent \( \Delta B \). When a sufficiently high \( V_{acc} \) is applied so that the relation \( t_e < \tau_{sf} \) is satisfied, \( \beta_{OSC} \) is identical to \( \beta_{\pi} \) regardless of \( \tau_{sf} \).