Comparison of spin lifetimes in $n$-Ge characterized between three-terminal and four-terminal nonlocal Hanle measurements

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Received 20 September 2012, in final form 6 November 2012
Published 4 December 2012
Online at stacks.iop.org/SST/28/015018

Abstract

We compared the temperature dependence of spin lifetime in $n$-Ge characterized from three-terminal (3T) and four-terminal (4T) Hanle measurements using single-crystalline Fe/MgO/$n$-Ge tunnel junctions. The bias conditions of the two schemes were chosen to be about the same in order to compare the spin lifetimes ($\tau_{3T}$ and $\tau_{4T}$). The temperature dependences of $\tau_{3T}$ and $\tau_{4T}$ behave in a very similar way at the low temperature region ($T \leq 10$ K), and both $\tau_{3T}$ and $\tau_{4T}$ decrease as the temperature increases, which is consistent with the dominating Elliot–Yafet spin relaxation mechanism in bulk Ge. However, when the temperature is higher than 10 K, $\tau_{4T}$ is longer than $\tau_{3T}$, which may be explained by the fact that 3T Hanle measurements are more easily affected by additional scattering effects caused by the accompanied charge current and electric field in the 3T geometry.

(Some figures may appear in colour only in the online journal)

Combining the spin degree of freedom with the traditional bandgap engineering of semiconductors is envisioned to have profound impacts on existing electronics [1]. Over the past few years, significant progress has been made in semiconductor spintronics. Spin injection and detection in Si have been demonstrated since 2007 using optical [2] and electrical means including hot-electron transport [3] and spin-dependent tunneling [4–6]. Recent reports also present spin transport studies in Ge nanowires [7] and Ge with optical [8] and electrical [9–15] methods. For electrical methods, 3T local and 4T nonlocal schemes are two major approaches used to study spin transport. While most electrical spin injection studies used Hanle measurements with 3T geometry to characterize spin lifetimes in $p$-Ge [9] and $n$-Ge [10–14], Zhou et al first unambiguously demonstrated spin transport in $n$-Ge with a 4T spin valve geometry up to 225 K [15]. The advantages of 3T Hanle techniques include the simplicity of both device fabrication and the ability to extract spin lifetime. However, since the same contact is used for both spin injection and detection, care must be taken to distinguish between the desired signals attributed to the spin injection and transport in the semiconductor from anomalous signals due to anisotropic magnetoresistance [16], surface roughness [17] or localized states at the interface [18]. On the other hand, 4T techniques show that the nonlocal voltage signal depends on the relative magnetization orientations of the injector and detector [4, 15, 19], and it is used to avoid the above-mentioned spurious signal [16–18] because the charge current is separated from the spin diffusion path into the detector terminal. However, the spacing between the injector and detector usually has to be comparable to the spin diffusion length, which increases the complexity of device fabrication.
Indeed, both 3T and 4T techniques have been extensively used to measure the spin lifetime [4–6, 10–19]. The discrepancy between the spin lifetimes from 3T ($\tau_{3T}$) and 4T nonlocal ($\tau_{4T}$) Hanle measurements has not been carefully examined. Although it was demonstrated recently that the spin lifetimes measured in Si from those two techniques are similar [20], the difference between the two schemes on the same system has not been reported. In this paper, we studied the temperature dependence of spin lifetime in n-Ge characterized by both 3T and 4T nonlocal measurements under the similar bias condition at the spin injector since it has been shown previously that the spin injection efficiency is a strong function of bias condition [21–24].

To fabricate the spin injection devices, an unintentionally doped Ge wafer ($n \sim 10^{14}$ cm$^{-3}$) was used as a starting substrate. Low-temperature solid-source molecular beam epitaxy (MBE) [25] was used to grow a lightly doped ($n = 1 \times 10^{16}$ cm$^{-3}$) Ge layer (300 nm thick), followed by a transition layer (15 nm thick) and then a degenerately doped ($n = 2 \times 10^{19}$ cm$^{-3}$) surface layer (15 nm thick). For 3T devices, the MgO (1 nm) and Fe (20 nm) films were subsequently grown on Ge and capped by a 20 nm Al layer [26] in another MBE chamber. The electrodes were patterned with photolithography, followed by reactive ion etching and wet chemical etching. Ti/Au (10/100 nm) bonding pads were fabricated by electron beam evaporation and lift-off process. Finally, as the back contact, silver epoxy was applied to the backside of the whole wafer. A standard lock-in technique was used for spin injection measurements. Figure 1(a) shows the schematic of the 3T device structure and the measurements setup. A dc bias voltage ($V_b = -5$–$+2$ V) coupled with a ac modulation voltage ($V_{ac} = 0.1$ V) was applied to the active contact (3 × 50 $\mu$m$^2$) to create spin polarization in the Ge channel. The 3T spin polarization voltage is linearly proportional to the spin accumulation given by $\Delta V = \Delta \mu \times \gamma / 2e$, where $\gamma$ is the tunneling spin polarization of the Fe/MgO interface, and $\Delta \mu = \mu^+ - \mu^-$ is the difference between the electrochemical potentials of spin-up and spin-down electrons. By applying a transverse magnetic field, the spin polarization voltage decreases due to the Hanle effect, in which the spin precesses around the magnetic field, the spin polarization voltage decreases due to the Hanle effect, in which the spin precesses around the magnetic field ($2\gamma B_z \Delta \tau_s$), and the blue arrows indicate the magnetization directions of the injector and detector. The solid (dashed) lines were fitting based on the 1D spin drift-diffusion model [15], under which

$$R_{NL} \propto \pm \int_0^\infty \frac{1}{\sqrt{4\piDt}} \exp \left[ -\frac{L^2}{4Dt} \right] \cos(\omega t) \times \exp \left( \frac{-t}{\tau_{4T}} \right) dt. \tag{2}$$

In the above equation, $+$ (−) sign is for the parallel (antiparallel) magnetization configuration, $D$ is the diffusion constant and $\omega_\perp$ is the Larmor frequency as defined above. A spin lifetime of 770 ps at $T = 4$ K was obtained by fitting the Hanle curves with equation (2). The results from 3T and 4T nonlocal Hanle measurements turned out to be close at 4 K, which is consistent with the previous study on spin lifetimes in Si using 3T and 4T measurements [20]. Figure 1(f) shows the nonlocal spin voltage signal at 4 K. By applying an in-plane magnetic field ($B_z$), $V_{NL}$ depends on the relative magnetization orientations of the injector and detector, as a direct indication of the spin current injected into the Ge channel. Since the 3T and 4T nonlocal Hanle curves were measured from different devices, it is necessary to assess the junction properties of two devices. As shown in figure 1(c), the contact RA products for both devices were close and exhibited the same temperature dependence (slight increase as the temperature decreases),
which indicate that the junction properties for 3T and 4T nonlocal Hanle devices are similar.

Before comparing the temperature dependence of $\tau_{3T}$ and $\tau_{4T}$, we investigated the bias dependence of $\tau_{3T}$. In figure 2(a), the left (right) Y axis shows $\tau_{3T}$ ($Z_I$) as a function of the bias voltage at 10 K, respectively. Here the average penetration depth ($Z_I$) is determined by the spatial distribution of electron density

$$Z_I = \int_0^L z \times n_e(z) \, dz \Bigg/ \int_0^L n_e(z) \, dz, \quad (3)$$

where $L$ is defined from the position of back contact, and $n_e(z)$ is the electron density obtained from a self-consistent device simulator, Sentaurus device, using Fermi–Dirac statistics model, nonlocal tunneling model and incomplete ionization model at 10 K. In addition, the inset color bar shows the corresponding doping level of a 15 nm surface layer ($n = 2 \times 10^{19} \text{ cm}^{-3}$), followed by a 15 nm transition layer with the doping level from $n = 2 \times 10^{19}$ to $1 \times 10^{16} \text{ cm}^{-3}$. The position of spin accumulation should consider both electric field distribution and spin drift-diffusion equation [33], but the complete device simulation is beyond the scope of this
Figure 2. (a) The left Y axis shows the bias dependence of $\tau_{3T}$ (solid circle), and the right Y axis shows the bias dependence of the average penetration depth, $Z_t$ (open triangle) extracted from the device simulation at 10 K. The inset color bar shows the corresponding doping level of the Ge sample. Starting from the MgO/Ge interface, the 15 nm surface layer has $n = 2 \times 10^{19}$ cm$^{-3}$, followed by the 15 nm transition layer with the doping level from $n = 2 \times 10^{19}$ to $1 \times 10^{16}$ cm$^{-3}$. (b), (c), (d), and (e) The left Y axes show the simulated band diagram (solid line), and the right Y axes show the spatial distribution of electron density (dot line) under different bias voltages $V_b = +2$, 0, $-3$ and $-5$ V, respectively, where $E_C$ ($E_V$) stands for the conduction (valence) band edge, and $n_e$ ($N_D$) stands for the electron (donor) density, respectively.

The real position of spin accumulation should be offset $Z_t$ toward the low doped region. Figures 2(b)–(e) illustrated the simulated band diagrams (left Y axes, solid line) and electron density (right Y axes, dot line) under different bias voltages ($V_b = +2$, 0, $-3$ and $-5$ V), in which $E_C$ ($E_V$) stands for the conduction (valence) band edge, and $n_e$ ($N_D$) stands for the electron (donor) density, respectively. According to the bias dependence of $\tau_{3T}$ figure 2(a) can be roughly divided into three regions: region (I) stands for the forward bias region

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Figure 3. (a) and (b) Temperature dependences of 3T ($V_b = -3.5 \text{ V}$, $J_b = -20 \mu \text{A/\mu m}^2$) and 4T nonlocal Hanle ($V_b = -0.2 \text{ V}$, $J_b = -26 \mu \text{A/\mu m}^2$) measurements at different temperatures (1.5–50 K), respectively. The 3T Hanle curves are fitted by the Lorentzian shape, and the 4T nonlocal Hanle curves are fitted by the 1D spin drift-diffusion model. (c) Temperature dependences of and $\tau_{3T}$ and $\tau_{4T}$ under close range of bias current density. At low temperature ($T < 10 \text{ K}$), $\tau_{3T}$ and $\tau_{4T}$ behave very similar; at $T > 10 \text{ K}$, the fitting shows that $\tau_{3T}$ and $\tau_{4T}$ have similar phonon scattering behavior ($\tau_s \propto T^{-1.9}$) but $\tau_{3T}$ starts to drop at lower temperature. The inset shows the temperature dependent spin lifetime adopted from [20].
condition, we chose the specific bias voltage with about the same current density. Figure 3(a) shows 3T Hanle resistance peaks measured at different temperatures (1.5–50 K) with a dc bias voltage of −3.5 V, or equivalently an injection current density of −20 μA μm⁻², and figure 3(b) shows 4T Hanle resistance peaks in the same temperature range with a dc bias voltage of −0.2 V, or equivalently an injection current density of −26 μA μm⁻². In addition, 3T and 4T Hanle curves (open circle) are well fitted by equations (1) and (2) (solid line), respectively, and the extracted τ₃T (blue solid square) and τ₄T (red open circle) were plotted as a function of temperature in figure 3(c).

When we compared τ₃T and τ₄T under similar bias conditions at spin injector (J₀,₃T = −20 μA μm⁻², J₀,₄T = −26 μA μm⁻²), it appears that both 3T Hanle and 4T nonlocal Hanle are useful to characterize the spin transport at low temperatures (T < 10 K). As the temperature increases, both τ₃T and τ₄T decrease, and this result is consistent with the dominating Elliot–Yafet spin relaxation mechanism in bulk Ge [34, 35]. As predicted by Yafet [35], the spin relaxation rate (1/τₜ) in degenerately doped n-type Ge is proportional to momentum relaxation rate (1/τₗ) due to the phonon scattering:

\[ 1/τₜ = λ /τₗ = λ · T^{1.66} \text{, or } τₜ = λ^{-1} · T^{-1.66}, \]

where λ is a constant, and the temperature dependence of T^{1.66} for 1/τₗ is based on the experimental result [36]. The power-law fitting of the temperature dependence of our measured spin lifetimes shows that τₜ ∝ T⁻¹.⁹ for both 3T Hanle and 4T nonlocal Hanle measurements, which is in good agreement with the theoretical prediction. For comparison, Sasaki’s results [20] of 3T and 4T spin injection into Si are re-plotted as the inset of figure 3(c), in which the τ₃T and τ₄T behave very similar in the whole temperature range between 8 and 100 K. Although our measured τ₃T and τ₄T at high temperature (T > 50 K) show similar temperature dependence of τₜ ∝ T⁻¹.⁹ due to phonon scattering, τ₄T starts to drop from a lower temperature than τ₃T, which might be attributed to additional scattering mechanisms. The possible reasons for such a difference at the high temperature regime are discussed in the following. The active contact in the 3T geometry acts as both the injector and detector, while the detector in the 4T geometry is separated from the injector. Since the spin signal is measured under the detector, the electric field and current density are inevitably much higher for 3T than that for 4T. When the temperature increases and the carrier density becomes high, carrier collisions act as an important scattering mechanism [37] contributing to the increased momentum scattering in the 3T geometry.

In summary, we compared 3T and 4T methods to characterize the temperature dependence of spin lifetimes in n-Ge. At the low temperature regime (T ≤ 10 K), τ₃T and τ₄T behave very similar; however, the difference between τ₃T and τ₄T shows up in the high temperature regime (T > 10 K). The results show that both methods are useful to extract the spin lifetime, but τ₄T is more easily affected by the accompanied charge current and electric field at the high temperature regime (T > 10 K).

Acknowledgment

We gratefully acknowledge the financial support from the Western Institute of Nanoelectronics (WIN) through NRI. WH and RKK acknowledge support from NSF (CAREER DMR-0450037). The technical support from Jens Werner (IHT) and Dr Olaf Kirfel (IHT) is also acknowledged. We thank Dr Alexandros Shailos of California Nanosystems Institute, and Dr Dmitri Nikonorov, Dr Ajey Jacob, and Dr Charles Kuo of Intel Corporation and Dr An Chen of Globalfoundries Corporation for the valuable discussion.

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