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Magnetic domain wall engineering in a nanoscale permalloy junction
Electrical spin transport in cylindrical silicon nanowires with CoFeB/MgO contacts

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We examined electrical spin transport in cylindrical silicon nanowires (Si NWs) using the lateral nonlocal spin-valve (NLSV) geometry with CoFeB/MgO contacts. The use of a thin MgO layer as the tunnel barrier in the NLSV devices provided an optimum resistance-area product for spin transport measurements in the Si NWs. A robust NLSV spin signal of over 3.95 kΩ and clear minor loops were observed at 1.8 K in the Si NWs heavily doped with phosphorous. Furthermore, the NLSV magnetoresistance was strongly influenced by the local magnetizations resulting from the ferromagnetic (FM) electrodes being attached to the cylindrically shaped Si NW, with these magnetizations differing from those of bulk ferromagnets. These local micro-magnetic configurations of the FM electrodes led to intriguing NLSV spin signals associated with the Hanle effect. Our study of spin transport in the heavily doped Si NWs provides a sound basis for developing applications of nanoscale semiconductor spintronic devices. Published by AIP Publishing.

Semiconductor spintronics holds great promise for the development of future electronics by conferring on their semiconductors the advantages of both non-volatile ferromagnetism and gate tunability.1–5 The generation, manipulation, and detection of spin-polarized electrons in semiconductors are crucial features for the fabrication of semiconductor spintronic devices.2–4 Silicon (Si), a mainstream semiconductor, is the most promising material for semiconductor spintronics due to its compatibility with complementary metal-oxide semiconductors and its long spin-relaxation time with very weak spin-orbit interactions.2–9 Semiconductor nanowires (NWs) have been considered as building blocks for nanoelectronics due to their quasi-one-dimensional confinement of charge carriers and their high-quality crystalline nature as well as their excellent electronic, photonic, thermal, electrochemical, and mechanical properties and hence have been studied for various nanoscale applications, including field-effect transistors, chemical/biological sensors, and energy conversion devices.10–14 Therefore, Si NWs can provide an outstanding platform to study the role of dimensionality and size effects in semiconductor spintronic devices.

In addition, spin-relaxation in one-dimensional nanostructures has been theoretically expected to be significantly suppressed because of their discontinuous density of states.15,16 Recently, there have been significant advances in our understanding of spin accumulation and transport in one-dimensional semiconductor NWs such as Si,16–18 germanium (Ge),19,20 indium nitride (InN),21 and gallium nitride (GaN) NWs.22,23 To achieve efficient electrical spin injection and detection in these NWs, careful control of the interface resistance between the spin injecting/detecting ferromagnetic (FM) metal and the semiconductor NW is required to mitigate the conductivity mismatch between them. Inserting various oxide tunneling barriers has been widely employed for this purpose.17,18,20–23 However, it is hard to maintain a high-quality tunnel oxide layer without pinholes due to the cylindrical morphology of the NW. Furthermore, the cylindrical shape of the NW inevitably distorts the part of the FM electrode attached to the NW, and this distortion produces local changes in the micromagnetic configurations in the electrode. These local magnetizations of the FM electrodes can be expected to influence the spin signals in nonlocal spin-valve (NLSV) devices composed of NWs. Although several reports on smooth and continuous FM tunnel electrodes placed across NWs have demonstrated that fewer complex magnetic domains were formed by using a planarization process and graphene as a tunnel barrier,16,21 these reports could not completely rule out the influence of such complex magnetic domains on the spin signals. There have been few studies about the contribution of the geometry and topography to the spin signals in semiconductor NWs. In this work, by using contact resistance engineering with CoFeB/MgO/Si NW junctions that we here designed, single-crystal Si NWs were found to show a robust NLSV spin signal (~3.95 kΩ at 1.8 K). Of greater importance, we demonstrated the intriguing NLSV spin signals associated with the Hanle effect, which was related to the unusual sample topography of CoFeB/MgO/Si NW junctions.
The Si NWs used in this study were grown by carrying out chemical vapor deposition using a silane (SiH₄) gas stream and an Au catalyst [the inset of Fig. 1(a)]. Phosphorus was doped into the Si NWs by introducing phosphine (PH₃) gas along with SiH₄ gas stream. Figure 1(a) shows a high-resolution scanning electron microscopy (SEM) image of the as-grown Si NWs. NWs with diameters ranging from 40 to 80 nm were observed. Electrical measurements of a Si NW device with four-probe geometry showed the resistivity of the NW to be low ($\sigma \approx 10^{-5}$ Ω cm at 300 K), and ohmic contacts formed with no annealing process because the Si NW was a heavily doped $n$-type semiconductor (doping concentration $>3 \times 10^{19}$ cm$^{-3}$). These characteristics of Si NWs are beneficial for spin injection and detection measurements in NW systems.

We employed a spin injection/detection technique involving taking lateral NLSV magnetoresistance (MR) measurements as shown in Figs. 1(b) and 1(c). The spin-polarized current was injected into a Si NW from the FM electrode (FM1, spin injector) to build up the spin accumulation $M$ near the FM1/Si NW interface. The spin accumulation diffused along the NW and could be measured between the other FM electrode (FM2, spin detector) and a reference (without an MgO layer) electrode at the far left end, with this measurement depending on the relative magnetization orientations of FM1 and FM2, respectively [Fig. 1(c)]. FM1 and FM2 were made with different widths to ensure different values of coercivity and hence control the magnetization configuration (parallel and antiparallel states) of the FM electrodes when external field $H_y$ along the y-axis was swept between $-2.0$ and $+2.0$ kOe. The center-to-center channel length was set at approximately 1 μm [see Figs. 1(b) and 1(c)].

A single Si NW was transferred onto the $p^+$ Si substrate coated with a 300 nm-thick layer of SiO₂. We then carried out a two-step electron-beam lithography (EBL) process to form each NW-based NLSV device. The first EBL step was carried out to form FM1 and FM2, i.e., the spin injector and detector, respectively. The NW was dipped in hydrofluoric acid to remove the native oxide layer, and then a 1.5 nm-thick layer of MgO and a 30 nm-thick layer of CoFeB were deposited using the sputter to function as the tunnel barrier and ferromagnet, respectively. Then, a Ta/Ru (5/5 nm) bilayer was deposited as a capping layer to prevent the surface of CoFeB from becoming oxidized. The second EBL step was carried out to form the reference electrodes. A brief Ar ion mill etching was done to eliminate the native oxide layer on the Si NW, and then a Ti/Au (5/100 nm) bilayer was deposited using the sputter.

To investigate the structure of the FM tunnel junctions formed on the fabricated cylindrical Ru/Ta/CoFeB/MgO/Si NW in detail, we prepared a cross-sectional sample of our device by using a focused ion beam (FIB) slicing and lift-out process. Figure 1(d) shows a transmission electron microscopy (TEM) image of the cross-sectional sample of our device at this junction. The NW in this cross-sectional view was observed to have an elliptical shape with dimensions of about 40–60 nm. A selected area electron diffraction (SAED) pattern with the $\{001\}$ zone axis of the corresponding cross-sectional sample.
pattern of the cross-sectional sample revealed the NW to be a single crystal that grew in the \( (112) \) direction, as shown in Fig. 1(e).

Electrical characteristics of the FM tunnel contacts in the lateral NLSV device were determined by taking \( I-V \) measurements. Figure 2(a) shows the two-probe \( I-V \) characteristics of the NLSV device at 1.8 K; the two-probe \( I-V \) curve for the contacts between the reference electrodes (Au/Ti/Si NW/Ti/Au) was determined to be nearly linear [green [reference-to-reference] curve in the inset of Fig. 2(a)], while both two-probe \( I-V \) curves for the contacts between the spin injector/detector and reference electrodes (Ru/Ta/CoFeB/MgO/Si NW/Ti/Au) were non-linear [red [FM1-to-reference] and blue [FM2-to-reference] curves in the inset of Fig. 2(a)]. The tunnel resistance values of FM1 (~0.2 M\( \Omega \) at 1.8 K) and FM2 (~0.5 M\( \Omega \) at 1.8 K) were measured to be about one order of magnitude higher than that of the Si NW (~ tens of k\( \Omega \) at 1.8 K). These results involving FM1 and FM2, specifically their dramatically increased contact resistance values and nonlinear \( I-V \) curves, revealed the tunneling nature of the CoFeB/MgO/Si NW junctions.\(^{18,27}\) These tunnel characteristics of the FM electrodes were in good agreement with those reported for the Co/Al\(_2\)O\(_3\)/Si NW tunnel barrier contacts.\(^{18}\)

The spin-valve MR with FM tunnel contacts (spin injector and detector) to the semiconductor can only be observed if the product of the resistance-area (RA) product of both FM tunnel contacts is in a relatively narrow range,\(^{8,28}\) indicating that the RA product of the FM contact can play an important role in the spin-based devices. Figure 2(b) shows the two-terminal MR signals calculated using an \( \sim 10^{19} \) \( \text{cm}^{-3} \) density of the dopant in the Si NW, a channel length of \( \sim 550 \) nm, a temperature of \( \sim 1.8 \) K, and an \( \sim 10 \) ns spin lifetime of the electrons in Si as extracted from the spin transport data.\(^{9}\) This calculation showed that an MR signal can be observed in a narrow range of RA products close to the maximum spin signal. Namely, a significant MR in the Si NW can be expected when the RA product of the spin injector and that of the spin detector are both between \( 10^{-12} \) and \( 10^{-8} \) \( \Omega \text{m}^2 \) [see the green curve in Fig. 2(b)].

We next evaluated the RA product of the CoFeB/MgO/Si NW contacts based on the two-probe \( I-V \) curves as shown in Fig. 2(a) because the resistance values of the FM tunnel contacts were found to be much higher than those of the Si NW and reference contacts. We defined the RA product of the CoFeB/MgO/Si NW contacts as the voltage (\( V \)) divided by the current density (I/A) at the spin injection condition (\( V = 0.2 \) V).\(^{8}\) Note that the elliptical cross-section of the Si NW cannot provide a coplanar interface between the FM tunnel electrodes and the NW. In this regard, the thin MgO layer serving as a tunnel barrier showed a nonuniform thickness [see Fig. 1(d)]. This nonuniformity led to the contact area (\( A \)), between where the spin injection and detection occurred being much smaller than the whole side area of the cylindrical Si NW. Therefore, the value of the current density at the spin injection condition of a Si NW may have depended on the thickness of the tunnel barrier. Injecting charge carriers at the one of either right- or the left-buckled segment of the Si NW would roughly decrease the effective area to about 5% of its whole side area. The minimum effective area can be roughly estimated to be \( 6 \times 600 \) \( \text{nm}^2 \), while the maximum whole area can be approximately calculated to be \( 125 \times 600 \) \( \text{nm}^2 \) from high-resolution TEM analysis. Based on this assumption, lower bounds of the RA products at FM1 (spin injector) and FM2 (spin detector) were estimated to be \( 7.04 \times 10^{-10} \) \( \Omega \text{m}^2 \) and \( 2.49 \times 10^{-9} \) \( \Omega \text{m}^2 \), respectively, at 1.8 K. Based on the assumption that the electrons flowed at the same speed throughout the surface of the NW during spin injection, the upper bounds of the RA products at both FM1 and FM2 were estimated to be \( 1.12 \times 10^{-6} \) \( \Omega \text{m}^2 \) and \( 4.01 \times 10^{-6} \) \( \Omega \text{m}^2 \). As shown in Fig. 2(b), the RA products of both FMs in our device were close to an optimum value for observing the maximum MR signal. These results and analyses suggested that the observation of the spin-valve MR signal in a lateral Si NW-based NLSV device is possible with CoFeB/MgO contacts.

The spin accumulation in the Si NW was electrically detected using the NLSV geometry [see Fig. 1(c)]. The measurements were taken using a current \( I = +100 \) nA at 1.8 K. Figure 3(a) shows NLSV MR data (\( R_{\text{NLSV}} = V_{\text{NLSV}}/I \)) with a field \( H_y \) applied along the y-axis. The nonlocal baseline resistance should be zero in principle because there is no net charge current flow. However, a nonzero baseline resistance was observed in all nonlocal measurement experiments. We observed a large value of the baseline resistance of 11.2 K\( \Omega \) at 1.8 K. Although several possibilities have been proposed for nonzero baseline resistance such as leakage current, thermal effect, or in homogeneous charge currents,\(^{29,30}\) we speculate

![FIG. 2. Electrical characteristics of the CoFeB/MgO/Si NW contacts. (a) Absolute value of current versus bias voltage of reference/Si NW/reference, FM1/MgO/Si NW/reference, and FM2/MgO/Si NW/reference contacts at 1.8 K. The inset shows two-probe I-V curves of these three contacts. (b) Calculation of local (two-terminal) MR as a function of the product of the contact resistance-area (RA) for a channel length \( L \) of 550 nm at 1.8 K. The red- and blue-highlighted regions represent the RA values for FM1 and FM2, respectively.](image-url)
that the nonuniform current path in our devices would be a major reason to the large value of the baseline voltage. The round shape of Si NW inevitably produces thickness variance of the junction as shown in Fig. 1(d), and such a thickness inhomogeneity can generate a nonuniform current path through a point contact. In the up- and down-sweep trances [top panel of Fig. 3(a)], hysteretic MR dips were observed in the range $|H_y| \leq 2\, \text{kOe}$. These MR dips apparently resulted from a field $H_y$-induced switch of the relative magnetization orientation between the FMs (i.e., between the spin injector and detector) from the parallel state to the antiparallel state. The middle and bottom panels of Fig. 3(a) show the “minor loops.” Namely, we observed two distinct values for the NLSV MR at zero field ($H_y = 0$), depending on the magnetic history of the FMs. This hysteresis effect can be explained by the switching of only one of the two FMs.\(^{31}\) These results showed that our sample preparation and measurement setups were capable of injecting and detecting the genuine spin accumulation in a Si NW with CoFeB/MgO contacts.

Our first significant result was a very large value of the spin accumulation in a Si NW. The amplitude of the NLSV MR dip ($\Delta R_{\text{NLSV}}$) was measured to be 3.95 kΩ at 1.8 K and 3.20 kΩ at 10 K, as shown in Figs. 3(a) and 3(b). We suggest that the large value of spin accumulation was generated as a result of the optimum RA product and the highly confined geometry of the Si NW with CoFeB/MgO contacts.\(^{18}\) The temperature dependence of $\Delta R_{\text{NLSV}}$ is plotted in Fig. 3(c). $\Delta R_{\text{NLSV}}$ decreased with increasing temperature, and no spin accumulation signals were observed above 50 K.

Another interesting feature was the magnetic-field-dependent non-flat background spin signals [Figs. 3(a) and 3(b)]. In our NLSV devices with the Si NWs, neither FM located on the cylindrical NW provided a smooth planar interface with a well-defined magnetization orientation due to the non-planar topography [see Fig. 1(d)]. The spin-polarized electrons injected into the Si NW mainly accumulated at the specific interface between the thinnest part of the MgO layer and the Si NW because of the non-uniform charge current injection at the FM tunnel contact. We can expect that the spin-polarized electrons accumulated at either buckled segment of the Si NW because those regions likely had the lowest contact resistance. In the up-sweep of $H_y$, 1.8 K, the transition from the parallel to antiparallel relative orientation occurred at a magnetic field of about 160 Oe while the transition from antiparallel back to parallel occurred at about 1100 Oe at 1.8 K [see Fig. 3(a)]. The difference between these magnetic field strengths was markedly greater than those of the Si NW (diameter ~163–186 nm) with Co/Al$_2$O$_3$ contacts and the GaN NW (dimension ~80 nm) with CoFeB/MgO contacts.\(^{18,23}\) This result can be explained in terms of the local magnetization effects resulting from the contribution of the spin accumulation at the confined geometry.\(^{21}\) The injected spins in the Si NW had the same magnetization as did the spin injector at either
buckled segment of the Si NW (the region at the thinnest MgO layer). These injected spins were not aligned with $H_z$, and there was spin precession with the magnetic field applied along the y-axis. As a result, the injected spins showed the Hanle effect. When the dips were removed from the NLSV curves [top panel in Fig. 3(a)], the absorptive background spin signals were observed. These absorptive shape curves were strongly related to the Hanle effect between the injected spins and the applied magnetic fields. In previous studies, Johnson and Silsbee reported that, for the same parameters, the Hanle signal was absorptive in appearance (symmetric shape) when the spin injector and detector were aligned, while dispersive curves (antisymmetric shape) appeared when the injector and detector were orthogonal to each other. Note that one can imagine that each FM electrode may have one of a variety of local micro-magnetic configurations. The injected spins will not have orientations that are perfectly coplanar with a detecting interface. For arbitrary alignment between the spin injector and detector, the Hanle data will be a mixture of absorptive and dispersive curves. Therefore, the observed Hanle data of a Si NW should be analyzed using the optimum combination of absorptive and dispersive contribution. In our NLSV device with the Si NWs, the absorptive Hanle-shape curves were likely the reason for the alignment of the magnetization of the spin injector and detector.

In summary, we have demonstrated that efficient electrical spin transport in a cylindrical $n$-type Si NW can be obtained by performing contact resistance engineering with CoFeB/MgO/Si NW heterojunctions. Clear spin signals were observed in NLSV measurements up to 10 K. The NLSV spin resistance was large, with $\Delta R_{\text{NLSV}} = 3.95 \, \text{k}\Omega$ at 1.8 K. Remarkably, we found that unique NLSV spin signals consisting of hysteretic dips and the absorptive shape curves resulted from the unusual configuration of the local magnetization of the FM electrodes on the top of the cylindrical Si NW. In our NLSV devices with the cylindrical Si NW, we demonstrated that the spin accumulated at either buckled segment of the NW and showed the Hanle effect when the magnetic field was applied along the y-axis. The absorptive shape of the Hanle curve suggested that the injected spins were detected at the same-side-buckled segment of the spin injector. Our results indicated that the spin signals were strongly influenced by contact resistance and the detailed morphology of the FM electrodes, which could lead to the nanoscale semiconductor spintronic applications.

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