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Effective nonlocal spin injection through low-resistance oxide junctions

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ABSTRACT

Many (> 40) nonlocal spin valves on the same substrate have been characterized at 6 K and 295 K by using a probe station. Low-resistance oxide junctions (0.2–0.8 Ω) are used to inject spin current into mesoscopic Cu channels. Spin signals exceeding 10 mΩ at 6 K have been consistently observed, indicating efficient spin injection and detection. However, complex switching behavior and possible variations between devices pose a challenge to using a standard fitting method to quantify the spin signals. Two methods are used for quantitative analysis. The range of the effective spin polarizations can be estimated by assuming a reasonable range for the Cu spin diffusion lengths. A nonlocal spin polarization is introduced to evaluate the spin current in the Cu channels.

1. Introduction

Nonlocal spin valves (NLSV), [1–3] also known as lateral spin valves, are devices in which pure spin currents are generated in nonmagnetic channels made of metals, [3] semiconductors, [4–6] or graphene. [7] They have the unique trait that a pure spin current can be transported across a lateral distance of micrometers on a substrate and remain detectable. The pure spin current in metallic NLSVs has been used to achieve inverse and direct spin Hall effects [8,9] and spin Seebeck effects. [10] The spin relaxation in the metallic nonmagnetic channels has prompted interesting studies. [11–15] Metallic NLSV devices have been proposed as read-head sensors for high-density magnetic recordings. [16] In light of the growing interest in metal-based magnetic memory and logic devices, the pursuit of high-quality metallic NLSVs is desirable.

In this work, we demonstrate effective nonlocal spin injection through low-resistance aluminum oxide (AlO_x) junctions. The area of the junctions is $330 \times 170\ nm^2$, and the resistance is estimated to be 0.2–0.8 Ω. An array of such NLSV structures is fabricated on the same substrate, and more than 40 devices are characterized by a variable temperature probe station. Despite the low resistance of the junctions, large spin signals are observed at 295 K and 6 K, indicating efficient spin injection and transport. Quantifying the results using the standard fitting methods poses challenges, however, because of the complex switching behaviors and the possible variations in properties from one device to another. We can estimate the range of the effective spin injection (detection) polarizations by assuming a reasonable range for the Cu spin diffusion lengths. The spin current in the Cu channel can also be quantified with a nonlocal spin polarization.

2. Experiments

We fabricated 400 $Py/AlO_x/Cu$ NLSV devices and arranged them in a 20×20 matrix within a $6 \times 6\ mm^2$ area on a $10 \times 10\ mm^2$ silicon substrate during a single fabrication batch. Fig. 1(a) shows a scanning electron microscope (SEM) image of a single device. The structure is formed by electron beam lithography followed by a shadow evaporation process. [3,13,17,18] Two Py (permalloy or $Ni_{81}Fe_{19}$ alloy) pads 330 nm wide are used as the spin injector (F_1) and the spin detector (F_2). The thicknesses of F_1 and F_2 are 31 nm and 15 nm respectively. The center-to-center distance (L) between F_1 and F_2 ranges from 400 nm to 700 nm. The Cu channel is 110 nm thick and 160–180 nm wide. A layer of 3 nm AlO_x is directly evaporated between Py and Cu, forming $Py/AlO_x/Cu$ junctions with an average area of $330 \times 170\ nm^2$.

Using cross-junctions, the resistance–area (RA) product of the $Py/AlO_x/Cu$ barriers is measured with a four-probe method to be

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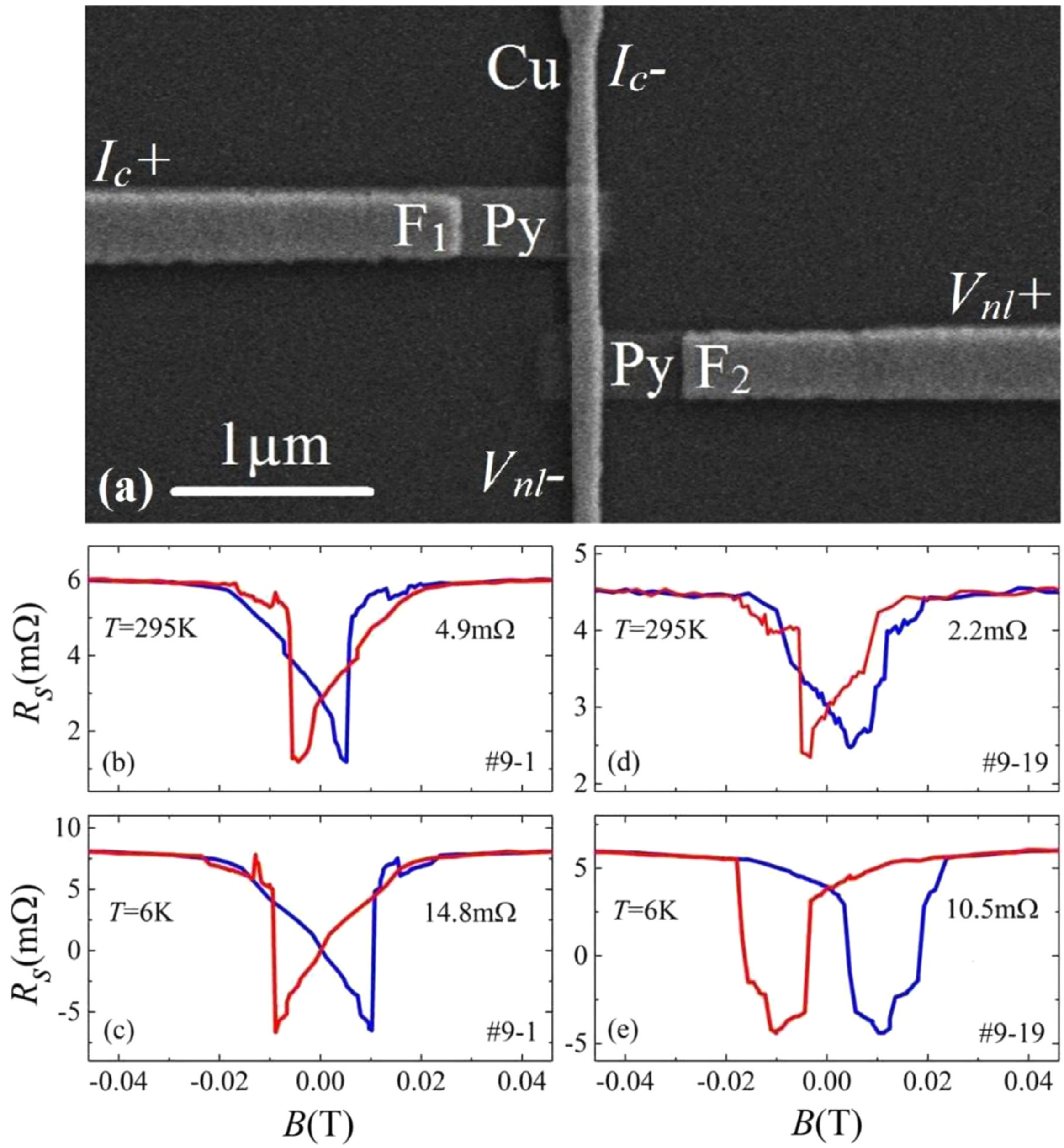

Fig. 1. (a) An SEM picture of an NLSV device with injector-to-detector distance of $L=700$ nm. (b) The R_s versus B curve for device # 9–1 ($L=400$ nm) at 295 K, showing $\Delta R_s=4.9$ mΩ. (c)The R_s versus B curve for device # 9–1 at 6 K, showing $\Delta R_s=14.8$ mΩ. (d) The R_s versus B for device # 9–19 ($L=600$ nm) at 295 K, showing $\Delta R_s=2.2$ mΩ. (e) The R_s versus B for device # 9–19 at 6 K, showing $\Delta R_s=10.5$ mΩ.

0.01–0.04 Ω μm^2, which is much lower than that of a tunnel junction. The resistance of the Py/AlO_x/Cu interfaces for our NLSVs is therefore estimated to be 0.2–0.8 Ω. As we show later, the low-resistance oxide barriers can mitigate the spin resistance mismatch [19] between the Py and the Cu and provide substantial injection (detection) spin polarizations.

The devices are labeled using the row and column numbers of the 20 × 20 matrix. For example, device # 9-1 is the device in row #9 and column #1. There are 5 subgroups in each row, each consisting of 4 adjacent devices with $L=400$, 500, 600, and 700 nm. A variable temperature probe station with an electromagnet (LakesShore EMPX-HF) is used to access each device individually. An alternating current (*a.c.*) I_c is applied between F_1 and the upper end of the Cu channel as shown in Fig. 1(a). A nonlocal voltage V_{nl} is measured between F_2 and the lower end of the Cu channel by lock-in method and recorded as a function of the magnetic field B (applied parallel to F_1 and F_2). At 295 K, 32 devices are measured, and at 6 K, 46 devices are measured. All measured devices show spin signals with large magnitudes. The un-measured devices on the substrate are likely to have similar qualities.

Fig. 1(b) shows the R_s ($=V_{nl}/I_c$) versus B curve at 295 K for device # 9–1 ($L=400$ nm). The spin signal of $\Delta R_s=4.9$ mΩ is substantial, considering that $L=400$ nm and $T=295$ K. The R_s versus B curve at 6 K for device # 9-1 is shown in Fig. 1(c), and $\Delta R_s=14.8$ mΩ. Fig. 1(d) and (e) show $\Delta R_s=2.2$ mΩ at 295 K and $\Delta R_s=10.5$ mΩ at 6 K, respectively, for device #9–19 ($L=600$ nm). Similar measurements of R_s versus B were performed to extract ΔR_s for other devices.

These ΔR_s values are at least comparable to the spin signals of NLSVs with smaller junction sizes (100 × 80–150 × 120 nm^2) but similar L distances. [13,20–23] Therefore, the spin injection is effective through these low-resistance oxide junctions with larger areas (330 × 170 nm^2). The drastic decrease of ΔR_s with an increasing junction size, as observed in ohmic junctions, [24] is