Spin-current signal amplification by a geometrical ratchet

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Received 22 July 2014, revised 25 September 2014
Accepted for publication 6 October 2014
Published 13 November 2014

Abstract

We report the demonstration of spin-current amplification in a lateral spin-valve with a non-local configuration. A geometrical ratchet has been implemented in a non-magnetic nanowire bridging two ferromagnetic nanowires. Such geometry induces a difference in resistivity for diffusive electrons travelling in opposite directions by differentiating the scattering coefficients. This difference amplifies the total spin current by a factor of more than 7. Amplification by a geometrical ratchet can be predicted by simple two channel electrical transport calculations and provides a method to increase the efficiency of pure spin current flow in lateral spin valves.

Keywords: spintronics, lateral spin valve, nanowires

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

Spin polarised electron currents have been employed to investigate the fundamental behaviour [1] and to develop new spintronic devices [2]. Spin-polarised current can be generated by flowing charge current into a non-magnetic material through a ferromagnetic, spin polarising layer. By attaching another ferromagnetic detection layer at the other end of the non-magnet, a spin-valve (SV [3, 4]) and magnetic tunnel junction (MTJ [5, 6]) can be formed by selecting a non-magnetic metal or an oxide barrier respectively. Progress in nanofabrication techniques has allowed the development of lateral spin-valve (LSV) structures, which enables the modulation of an injected spin-polarised electron current by gate operation. The first LSV was fabricated by Johnson \textit{et al} [7] and was revisited by Jedema \textit{et al} [8]. A lateral spin-valve utilises a pure spin current in the absence of charge current using a non-local configuration to minimise Joule heating. This has encouraged much research activity on such systems [9–11]. The main disadvantage, however, of lateral structures is their efficiency in introducing a pure spin current into a non-magnetic material, which is typically three orders of magnitude lower than electrical injection in a local configuration [8].

In this paper, we report spin-current amplification in an LSV using a Geometrical Ratchet Effect (GRE). A triangular ratchet implemented in the middle of the non-magnetic nanowire of our LSV has been found to achieve a maximum amplification of more than a factor of 7. Simple electrical transport calculations show qualitative agreement with our experimental finding.

In a triangular non-magnetic channel, such as that shown in figure 1, electrons flowing from left to right experience a smaller resistance than those flowing in the opposite direction. This can be phenomenologically understood by taking electron distributions and their corresponding scattering into account. The original electrons see an abrupt increase in the width of the Cu non-magnetic wire and are distributed gradually into the triangular regions. These distributed electrons
then see a gradual decrease in the Cu wire width which induces weak scattering, i.e. a lower resistance. The electrons flowing from right to left in figure 1 come across a gradual increase in the Cu width, resulting in almost equal electron distributions across the cross-section of the Cu nanowire. These distributed electrons then feel the abrupt change in the wire width, causing strong scattering, i.e. a large resistance.

In order to envisage the spin amplification by the GRE, simple electrical transport calculations were carried out by assuming constant conductance and diffusion coefficient throughout a non-magnetic Cu nanowire in an LSV. In our model, a packet of spin-polarised electrons was injected into the Cu nanowire which induces non-equilibrium spin accumulation at the Fermi level. The accumulated spin-polarised electrons decay diffusively along the Cu nanowire with a finite decay coefficient \( \tau \). The spin-up electron flow was calculated by a packet of electrons introduced at the left Py/Cu junction and monitored at the right junction \( V_{LR} \), while the same number of the spin-down electrons was introduced at the right junction \( V_{RL} \) to compensate for the imbalance of the spin density of states at the Fermi level. In both cases, the far end of the detector side (2300 nm away from the detector) was grounded to achieve linear voltage potential distributions over the device calculated. These electrons flow in the opposite directions as expected in the non-local geometry, as schematically shown in the inset of figure 2. In the straight wire region, these two opposite spin-polarised electron flows are identical. However, spin-polarised electrons can randomly travel into the geometrical ratchet, leading to an increase in diffusion length. This generates more spin-polarised electrons at the detector point and in turn, a larger energy potential.

The electron density was calculated for 1 nm steps from the injected position and the final density was calculated at 200 nm position from the injector. This simplified diffusion transport is governed by the diffusion equation [14, 15]:

\[
\frac{\partial \mu_s (x, y, t)}{\partial t} = D \Delta \mu_s (x, y, t) - \frac{\mu_s (x, y, t)}{\tau},
\]

where \( \mu_s (x, y, t) \) is the density of free electron carriers in a (2D) nanowire domain, \( \Omega \), \( D \) is the diffusion constant, \( \Delta \) is the Laplacian operator and \( \tau \) is the decay time constant. The boundary conditions for equation (1) are given by

\[
\mu_s (x, y, t = 0) = \delta (x - X),
\]

\[
\mu_s (x, y, t) \bigg|_{t = \pm \infty} = 0,
\]
where $\mu_i$ is the density of injected electrons at $t = 0$ and $\delta$ is the Dirac delta function which represents the injected electron packet at any position $X$ in $\Omega$.

A finite element method (FEM) using FreeFem++ software [16] was employed to obtain numerical solutions for equation (1). The calculated area was divided into a uniform triangular mesh with the base and height of 1 nm. In order to satisfy equation (3), and to converge the results with respect to the grid parameters, the boundary condition at the detector end was set to be 5 times longer than the spin diffusion length ($5 \times \lambda$) in order to avoid any electron interference due to the reflection at the end of the wire. The values of the transport parameters, $D = 0.012136 \text{m}^2\text{s}^{-1}$ and $\tau = 11 \text{ps}$ are taken from [8].

Figure 2 shows the time-dependence of the electron distributions in our LSV with the geometrical ratchet. The electrons injected at 50 nm away from the triangular shapes diffuse into the Cu nanowire as expected. After 0.1 ps, the electrons start to enter the triangular regions. The electrons flowing from left to right reach the end of the triangular region at 0.85 ps. Those flowing from right to left reach the other end of the triangular region at 0.86 ps. This delay agrees with our phenomenological model. The distributions of electrons in the triangular regions are found to be different after ~0.33 ps. The electrons from left to right show weaker distributions than those flowing in the opposite direction, as seen at the end of the triangular ratchet in figure 2(a). This again agrees with our phenomenological explanation, as discussed above. $\Delta V_{\text{calc}}$ is calculated at the detector position, as shown in figure 2(b), providing a measure of spin-current amplification of the non-local signals.

Since our measurements were performed with a dc current, the steady-state of the electrons injected in opposite directions...
was also calculated. In the steady state, $\mu_y(x, y, t)$ becomes time-independent and hence equation (1) can be rewritten as

$$D\mu_y(x, y) = \frac{\mu_x(x, y)}{\tau}.$$  \hspace{1cm} (4)

Here, the boundary conditions for $\mu_x(x, y)$ are equation (3) together with:

$$\mu_x(x, y) \big|_{y=0} = \mu_0,$$  \hspace{1cm} (5)

where $\mu_0$ is the electron density injected at the Py/Cu interface at $t = 0$. Figure 3 shows the steady-state electron distributions for the LSVs with triangular shapes ($0 \leq h \leq 60$nm), which corresponds to the devices measured. The entire area of a straight wire is used uniformly as a spin polarised electron channel, as shown in figure 3(a). With the introduction of triangles on the wire, the effective path for spin polarised electrons becomes narrower due to geometrical scattering, as shown in figures 3(b)–(d). These images clearly indicate that the electron distributions due to the GRE survive in their steady states. Figure 3(e) is the plot of the steady-state $V_{LR}$ calculated at the detection point as a function of $h$. It can be seen that the spin diffusion rate in the steady-state has increased with increasing $h$ and with taking the maximum at $h = 37$ nm. This again agrees with our phenomenological explanation.

Our model provides a measure of the non-local signal by taking the difference between the chemical potentials, i.e. the voltages, induced by the up- ($V_{LR}$) and down-spins ($V_{RL}$) ($\Delta V = V_{LR} - V_{RL}$) 50 nm away from the edge of the ratchet, as indicated in the inset of figure 2. The difference between the energy potentials for the up- and down-spins is experimentally measured by taking the change in magnitude, $\Delta V_{\text{meas}}$, of the non-local signals for parallel and antiparallel magnetic configurations.

Accordingly, the LSV devices were fabricated by conventional electron-beam lithography and lift-off processes. Figure 4(a) shows a scanning electron microscopy (SEM) image of a typical LSV device. The device consists of two Ni$_{81}$Fe$_{19}$ (Py) nanowires bridged by a Cu nanowire. Both Py wires were 30 nm thick and 200 nm wide with different shapes at their ends: the first with square ends and the second with more corners and sharp ends to assist domain nucleation for reversal at lower magnetic fields [17]. These two nanowires were patterned by $e$-beam lithography (JEOL, JBX-6300FS) with approximately 140 nm thick resist (Zeon, ZEP520A), on a thermally oxidised Si substrate. Two Py nanowires were then fabricated by $e$-beam evaporation at a base pressure of $5 \times 10^{-5}$ Pa, followed by lift-off with cyclopentanone. The Cu nanowire was then fabricated using the same process. The thickness and width of the Cu nanowire was 70 nm and 100 nm, respectively. It should be noted that the distributions of the Py/Cu junction area across all the devices are measured to be $<7.8\%$. Triangular wings were attached to the Cu nanowires with fixed base length of 100 nm and height ($h$) between 0 and 60 nm. These wings were located at 50 nm away from the Edges of the Py/Cu junctions. The resistivities of the Py and Cu nanowires were measured at room temperature (RT) to be $(24.1 \pm 0.7) \mu\Omega$ cm and $(3.9 \pm 0.9) \mu\Omega$ cm respectively. The non-local magnetoresistance measurements were performed using a ‘dc reversal’ method [18] under an electrical current of $45 \mu$A at RT. An external magnetic field ($H$) was applied of up to $\pm 1.2$ kOe along the Py nanowires.

Figure 4(b) shows the evolution of the non-local signals with respect to the heights of the geometrical ratchets ($0 \leq h \leq 60$ nm). Here, the measured voltage is divided by the injected electrical current of $45 \mu$A. The antiparallel resistance decreases with increasing $h$. This agrees with our phenomenological model discussed above. The differences in the non-local signals, $\Delta V/I$, for parallel and antiparallel configurations were measured to be $(2.81 \pm 0.04) \mu\Omega$ for $h = 0$ (conventional LSV) and $(21.5 \pm 0.9) \mu\Omega$ for $h = 60$ nm (LSV with geometrical ratchet), resulting in a factor of 7 increase in $\Delta V_{\text{meas}}$. Such a significant increase is ideal for the future device implementation.

Figure 5 shows measured values of $\Delta V_{\text{meas}}$. $\Delta V_{\text{meas}}$ increases with increasing $h$ and has a maximum value at $h = 60$ nm. In our calculations, we took the difference in the

![Figure 5](image-url)
electron flow from left to right and vice versa ($\Delta V_{\text{calc}}$). Here, we assumed an ideal case: 100% spin-polarised electrons (e.g. up spins) are injected into the left Py to the right, while the opposite spins with 100% polarisation (e.g. down spins) flow from right to left for compensation. We therefore need to consider the reduction of the spin polarisation by the Py electrodes and the scattering at the Py/Cu interfaces. A typical spin polarisation has been reported to be 2% at a Py/Cu junction in a similar system due to the interfacial scattering [19]. By implementing such reduction into our model, $\Delta V_{\text{calc}}$ can be reduced to $0.3 \mu V$, which is in the same order with $\Delta V_{\text{measured}}$. Therefore, we conclude that the amplification in $\Delta V$ is induced by the GRE on a pure spin current generated in the LSV and can be understood by a simple electrical transport model.

In summary, we have demonstrated pure spin-current amplification due to the geometrical ratchet effect. Our measurement shows that approximately 7 times amplification is achieved with triangular shapes with a base of 100 nm and a height of 60 nm. Our simple calculations based on electron diffusion qualitatively explain the spin amplification. Such amplification has never previously been reported and can overcome the long-standing obstacle of low efficiency in introducing a pure spin current into a non-magnetic material in a lateral spin-valve device.

Acknowledgments

The authors wish to thank Profs K O’Grady and S Thompson for the use of their facilities to measure the non-local spin-valve signals. This work was partially supported by Precursory Research Embryonic Science and Technology (PRESTO) programme of the Japan Science and Technology Agency (JST) and Critical Mass Grant (EP/I000933/1) and the Engineering and Physical Science Research Council (EPSRC) in the UK. R M A also acknowledges the support of the Ministry of Higher Education–Kurdistan Region (MHE–KRG) in Iraq.

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