Manipulation of spin currents in metallic systems

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The transport properties of diffusive spin currents have been investigated in lateral ferromagnetic/non-magnetic metal hybrid structures. The spin diffusion processes were found to be strongly dependent on the magnitude of the spin resistances of connected materials. Efficient spin injection and detection are accomplished by optimizing the junction structures on the basis of the spin resistance circuitry. The magnetization switching of a nanoscale ferromagnetic particle and also room temperature spin Hall effect measurements were realized by using an efficient pure-spin-current injection.

Keywords: spin current; spin injection; spin torque; spin Hall effect; spin–orbit interaction

1. Introduction

There has been a great deal of interest in studying spin-electronic properties in ferromagnetic (F)/non-magnetic (N) hybrid structures since the discovery of the giant magnetoresistance (GMR) effect [1,2], where a spin current, i.e. a flow of spin angular momentum, is a key ingredient [3,4]. Therefore, understanding the physics responsible for spin currents and establishing efficient ways for manipulation are indispensable for further advancement of spin-electronic devices.

In N metals, the spin current flows with the non-equilibrium spin polarization, the magnitude of which decays via spin relaxation. The length scale over which spin current flows is known as the spin-diffusion length, typically a few hundreds of nanometres. Most experiments on spin transport have been carried out so far with vertical structures configured to have current perpendicular to the plane [5]. In this way, the travelling length for the spin current in a non-magnet can be shortened below the spin-diffusion length. However, the vertical structures only give limited information about series resistances of magnetic multi-layers. On the contrary, laterally configured F/N hybrid devices have great advantages of developing multi-terminal devices. Recent nanofabrication techniques enable us to prepare structures where the travelling length of the spin current is comparable.

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Figure 1. (a) Scanning electron microscope image of a typical lateral spin-valve consisting of two Py wires and a Cu wire. (b,c) Schematic illustrations of non-local detection of spin accumulation. The positive and negative voltages are induced between the F and N voltage probes for (b) parallel and (c) anti-parallel configurations, respectively. (Online version in colour.)

Despite the device dimension being smaller than the spin-diffusion length, it has been difficult to detect spin-dependent signals in lateral structures owing to the spurious magnetoresistance effects, such as anisotropic magnetoresistance and anomalous Hall effects. Non-local spin injection, by which the spin and charge currents are well separated, is thus a useful means for detecting the spin current-induced signals in lateral configurations because irrelevant magnetoresistance changes can be removed [6,7]. In this section, we explain the principle of the electrical detection of the spin accumulation induced by a non-local spin injection.

Figure 1a shows a scanning electron microscope (SEM) image of a typical lateral spin-valve consisting of two permalloy (Py) wires bridged by a Cu wire. Lateral spin-valve is prepared by means of the undercut resist mask and shadow evaporation technique. First, the Py layer of 20 nm in thickness is formed by oblique evaporation at a pressure of $10^{-9}$ torr. After the Py deposition, the Cu of 100 nm in thickness is evaporated from the normal to the substrate in a different chamber with a base pressure of $2 \times 10^{-7}$ torr. In order to reduce the magnetic impurity in the Cu film, the chamber for the Cu evaporation is separated from that for the Py evaporation. Note here that these two chambers are connected in vacuum.

As shown in figure 1a, the electric current is injected from Py1 into the left-hand side of the Cu wire. Thereby, non-equilibrium spin accumulation is induced in the vicinity of the junction. The accumulated spins diffuse not only into the left-hand side of the Cu but also into the right-hand side of the Cu as shown in figure 1b. In this way, a spin current is produced with carrying no charge current (pure spin current) in the right-hand side. When another ferromagnet Py2 is connected to the right-hand side of the Cu, spin splitting in the electrochemical
potential is induced in Py2 sufficient for the continuity condition of the chemical potential at the interface. The stationary point for the chemical potential in Py2 shifts from the central point because of the spin-dependent conductivity. Therefore, the voltage appears between Py2 and the right-hand side of the Cu wire as shown in figure 1b and the induced voltage changes its sign according to the relative magnetic configuration between Py1 and Py2. When Py1 is parallel (antiparallel) to Py2, the induced voltage is positive (negative). Figure 2a shows the field dependence of the non-local spin-valve (NLSV) signal, where the magnetic field is applied along the Py wires. Here, in the vertical axis, the non-local signal in ohms is given by the induced voltage divided by the injecting current. The non-local signal exhibits the clear spin-valve effect corresponding to either parallel (high) or antiparallel (low) state. We define here the spin signal as the resistance change between the parallel and antiparallel states.

We here evaluate the spin-diffusion length of the Cu wire from the spin signal measured as a function of separation \( d \). The spin signals for various separations from 250 to 1650 nm measured at 290 and 10 K are shown in figure 2b. The spin signal decreases monotonically with the separation. From the one-dimensional spin-diffusion model with the transparent Py/Cu interface, the dependence of the spin signal \( \Delta R_S \) on the separation \( d \) is deduced as [8,9]

\[
\Delta R_S \approx \frac{P_{Py}^2 R_{SPy}^2}{2 R_{SPy} \exp (d/\lambda_{Cu}) + R_{SCu} \sinh (d/\lambda_{Cu})}.
\]

Here, \( P_{Py} \) is the spin polarization for Py and \( \lambda_{Cu} \) is the spin-diffusion length of Cu. \( R_{SPy} \) and \( R_{SCu} \) are the spin resistances for Py and Cu, respectively. The spin resistance is defined as \( 2\rho \lambda/((1 - P^2)S) \), with polarization \( P \), resistivity \( \rho \), spin-diffusion length \( \lambda \) and the effective cross-sectional area for the spin current \( S \). We show in the following sections that the spin resistance is an important measure to design the spin-dependent transport property of the system.

From the curve fitting, we obtain the spin-diffusion length for the Cu wire as 400 nm at 290 K and 1000 nm at 10 K. The spin polarization and the spin-diffusion length for Py are 0.49 and 4.5 nm at room temperature and then 0.58 and 5 nm at 10 K. The spin-diffusion length of the Py is in good agreement with previously reported values [7,9].
3. Temperature dependence of the spin relaxation

According to Elliot [10] and Yafet [11], the intrinsic spin-relaxation is initiated by ordinary momentum scattering such as electron–phonon or electron–impurity scattering with the spin–orbit coupling. Such electron–phonon interaction is suppressed at low temperature, and the spin-diffusion length in the system may increase. However, in reality, polycrystalline metallic thin films contain inelastic scatterers, such as magnetic impurities, defects and boundaries. These extrinsic scatterers also contribute to the spin-relaxation process. This implies that the spin relaxation in such metals is dominated by the electron–phonon scattering at high temperature, but by other scattering events at low temperature. The spin-diffusion length in a normal metal can be evaluated from the separation $d$ dependence of the spin accumulation using a conventional lateral spin-valve. Here, we discuss the temperature dependence of the spin accumulation in lateral spin-valves with Py/Cu ohmic junctions [12].

We measure the temperature dependence of the spin signal in the lateral spin-valve with various separation $d$. As shown in figure 3a, in all devices, the spin signal monotonically decreases with temperature above 30 K. This reduction at $T > 30$ K is mainly owing to the spin relaxation induced by the electron–phonon scattering in the Cu wire. However, the spin signal is found to decrease also at $T < 30$ K as the temperature decreases. This is against naive expectation that the spin signal may increase with decreasing temperature and saturate at low temperature as the contribution of the electron–phonon scattering is lowered. Therefore, another mechanism for the reduction of the spin accumulation at low temperatures is required to explain the above mentioned behaviour.

Figure 3b shows the temperature dependence of the spin-diffusion length of the Cu wire determined by using equation (2.1). The temperature variation of $\lambda_{\text{Cu}}$ above 40 K exhibits a monotonic decrease, which is inversely proportional to $\rho_{\text{Cu}}$ as in the inset of figure 3b. This implies that the spin-diffusion length is proportional to the mean free path, confirming the presence of the electron–phonon interaction. However, surprising is that $\lambda_{\text{Cu}}$ is a maximum at 40 K below
which \( \lambda_{\text{Cu}} \) decreases rapidly with temperature. It should be noted that the spin-diffusion length and spin polarization of Py determined from the experiments only slightly decrease in this temperature range.

Thus, the reduction of the spin signal below 40 K is likely owing to the reduction of \( \lambda_{\text{Cu}} \). The spin-diffusion length \( \lambda \) is given by \( \sqrt{D\tau_{\text{sf}}} \), where \( D \) and \( \tau_{\text{sf}} \) are the diffusion constant and the spin-relaxation time, respectively. As seen in the inset of figure 3b, the resistivity of the Cu wire slightly decreases even below 40 K with temperature, implying that the mean free path \( l \) for the electrons in the Cu wire increases with decreasing temperature. Since \( D \) is proportional to the mean free path, the reduction in \( \lambda_{\text{Cu}} \) should be owing to the reduction of \( \tau_{\text{sf}} \).

A possible reason for the reduction is the surface oxidation. As Cu surfaces are known to be reactive in air, the top and side surfaces of the Cu wire may be oxidized. The oxidized regions provide stronger spin-flip scatterers than the inside of the Cu wire [13]. Therefore, the spin-flip scattering owing to the oxidized Cu is more pronounced as the mean free path is increased at low temperatures. This explains the reduction of the spin-diffusion length at low temperatures below 40 K. The ratio of the elastic scattering time to the spin-flip scattering time, \( \tau_e/\tau_{\text{sf}} \), represents the strength of the spin–orbit interaction. The relation \( \tau_e = l/v_f \) with the Fermi velocity \( v_f \) yields the ratio \( \tau_e/\tau_{\text{sf}} = 2.74 \times 10^{-3} \) at 290 K and \( 4.64 \times 10^{-3} \) at 10 K, agreeing with the scenario that the spin-flip scattering is mediated by the exchange interaction with small magnetic moment in the copper oxide. This means that the spin–orbit interaction becomes large at low temperatures, supporting that the reduction of \( \tau_{\text{sf}} \) is due to the scattering of the oxidized layer.

4. Influence of an additional ohmic contact

In the NLSV measurement, an F wire is commonly used to detect the spin accumulation in the N wire. However, we have to take into account that the ferromagnet with a low interface resistance significantly affects the distribution of the spin-dependent electrochemical potential in the N wire because the spin current is preferably absorbed and equilibrated in the F wire. In this section, we show the non-trivial influence of an additional ohmic contact on the spin accumulation and also spin current using a lateral spin-valve device with a middle wire [14].

Figure 4 shows the suppression of the spin accumulation can be demonstrated in the NLSV measurement using a lateral spin-valve consisting of three Py wires and a Cu wire. As mentioned above, the Py middle wire connected to the Cu wire reduces the spin splitting of the chemical potential and also the spin signal measured with the Py1 and Py3 leads. The obtained small spin signal of 0.04 m\( \Omega \) coincides well with the above expectation. The geometrical defect owing to the additional F contact lying beneath the Cu wire may also violate the distribution of the spin accumulation. However, we believe that such an effect is negligible because of large difference in thickness between Cu and Py.

For comparison, we also fabricated a lateral spin-valve consisting of two Py wires separated by 600 nm spacing, longer than the spacing of 460 nm between Py1 and Py3 in figure 4a. The thickness and the width of Py and Cu wires are the same as those of the previous spin-valve device consisting of three Py wires. The SEM image of the fabricated device is shown in the inset of figure 4b. If there is no suppression owing to an additional Py wire in the previous experiment, the
Figure 4. (a) Non-local spin-valve signal for a lateral spin-valve consisting of three Py wires with the middle Py wire. The inset shows an SEM image of the device and the probe configuration for the measurement. (b) Non-local spin-valve signal for a lateral spin-valve consisting of two Py wires with a spacing of 600 nm. The inset shows an SEM image of the device and the probe configuration for the measurement.

Spin signal of figure 4b should be smaller by a factor of about 0.7 than that of figure 4b. Figure 4b shows the spin signal measured in the probe configuration shown in the inset. The obtained spin signal is 0.2 mΩ, much larger than that of figure 4a. These results support that the spin accumulation in the N wire is reduced by the F wire connected to the N wire. Note here that no change is observed in the spin signal with the middle Py wire indicating that the magnitude of the spin current absorption does not depend on the magnetization configuration of the middle wire.

We also demonstrate that the spin accumulation is reduced by connecting the N wire with a small spin resistance. For this purpose, lateral spin-valves consisting of triple junctions were prepared with various middle (M) wires as in figure 5a. Figure 5b shows the spin signal of the device with the Au M wire. The obtained spin signal is 0.08 mΩ, showing the large reduction in the spin signal similar to that of the Py M wire. This implies that the Au wire has smaller spin resistance.

The spin signal $\Delta R_S$ can be approximated to be a function of spin resistance $R_{SM}$ of the middle wire [9]:

$$\Delta R_S \approx \frac{P_{Py}^2 (R_{SPy} / R_{SCu})^2 R_{SM}}{4(\cosh(d/\lambda_N) - 1) + (R_{SM} / R_{SCu}) \sinh(d/\lambda_N)}.$$  \hfill (4.1)

By putting into equation (4.1) the values of spin resistances $R_{SPy}$ and $R_{SCu}$ determined in the previous double junction experiments, we obtain the following relation between the detected spin signal $R_{NLSV}$ and $R_{SM}$:

$$R_{SM}(\Omega) = \frac{7.02 R_{NLSV}(m\Omega)}{1.27 - 4.41 R_{NLSV}(m\Omega)}.$$  \hfill (4.2)

This equation provides a useful means to estimate the spin resistance and the spin-diffusion length of the middle wire from the magnitude of the spin signal without varying the spacing $d$. Below is described a test experiment for various materials: Cu, Au and Py. In this calculation, the spin signal with the middle wire insertion does not depend on the magnetization configuration of the middle wire.

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Figure 5 shows the spin resistance of the M wire \( R_{SM} \) as a function of \( R_{NLSV} \) deduced from equation (4.2). From the equation, we respectively obtain the spin resistances of the Cu, Au and Py wires as 2.67, 0.62 and 0.33 \( \Omega \). The experimental values for the Py and Cu M wires are quantitatively in good agreement with those obtained from the double junction confirming the validity of equation (4.2). For the Au wire, the resistivity of 5.24 \( \mu \Omega \) cm of the Au strip yields a spin-diffusion length of 60 nm. This is in good agreement with the other reported values [15] and proves that the Au wire has short spin-diffusion length owing to the strong spin–orbit interaction [16].

5. Efficient spin accumulation by reducing junction size

As discussed above, the spatial distribution of the spin current and accumulation can be calculated by introducing the spin resistance [9]. The calculation shows that the spin accumulation and current depend not only on the electrode spacing but also on the spin resistance of each constituent segment, whose magnitude varies with the effective cross-sectional area \( S \). Therefore, the spin polarization induced in N should depend on the effective cross-sectional area, equivalent to F/N junction size. In this section, we experimentally demonstrate that the size of the ohmic F/N junction is an important structural factor for obtaining large spin accumulation in N and that both the spin polarization and the spin resistance of F are enhanced by optimizing the junction size [17,18].

The difference in the junction size between injector and detector gives rise to a significant difference in the spin resistance. In a cross-shaped Cu wire, the effective spin resistances of the vertical Cu arms are much smaller than those of the horizontal Cu arms because the vertical Cu arms have additional ohmic contacts with the Py pad and wire. This allows us to neglect the spin current...
diffusion into the horizontal Cu arms. The spin signal in this device is thus given by

\[ \Delta R \approx \frac{P_{Py}^2 R_{SPy}^P R_{SPy}^W}{R_{SCu} \sinh (d/\lambda_{Cu})}. \]  

Here, \( R_{SPy}^P \) and \( R_{SPy}^W \) are, respectively, the spin resistances of the Py pad and the Py wire.

As mentioned above, reducing the size of the ohmic junction between the Py pad and the Cu wire increases the spin resistance of the Py pad. The size of the junction area can be reduced by cutting the Cu wire on the Py pad, as seen in the SEM images in figure 6a,b. We change the size of the Py/Cu junction with keeping the same electrode spacing of 600 nm and study the dependence of the spin signal on the junction size. The spin signal is plotted as a function of the junction size in figure 6c. The spin signal increases with reducing junction size and is well reproduced by equation (5.1), where the spin signal is inversely proportional to the junction size. From the fitting parameters, the spin diffusion length of the Cu wire is found to be 1.5 \( \mu m \) at 77 K, longer than the values in Jedema et al. [7] and Albert et al. [19]. The spin polarization and the spin-diffusion length of the Py wire are, respectively, 0.25 and 3.5 nm, reasonable values when compared with previous experiments [7,9].

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Figure 7. (a) Schematic illustration of non-local spin injection using lateral spin-valve geometry. Only spin current is injected into the small F particle. (b) SEM image of the fabricated lateral spin-valve. The device consists of a large 30 nm thick Py injector, a Cu cross 100 nm wide and 80 nm thick and a Py nanoscale particle, 50 nm wide, 180 nm long and 6 nm thick. (c) Field dependence of the non-local spin signal. The changes in resistance at low and high fields correspond to the relative magnetic switching of the Py injector and particle, from parallel to anti-parallel states and vice versa. (d) Non-local spin-valve signal after pulsed current injection as a function of the current amplitude with corresponding magnetization configurations. (Online version in colour.)

6. Magnetization switching owing to spin current absorption

Current-induced magnetization reversal is one of the key technologies for developing spintronic devices. The switching mechanism owing to spin torque is explained with a model proposed by Slonczewski in which the torque exerted on the magnetization is proportional to the injected spin current. This clearly indicates that the spin current is essential to realize the magnetization switching owing to the spin injection. Most of the present spin-transfer devices consist of vertical multi-layered nanopillars in which typically two magnetic layers are separated by an N metal layer [19,20]. In such vertical structures, the charge current always flows together with the spin current, and thereby undesirable Joule heat is generated. As discussed in §4, the spin currents are effectively absorbed into an additionally connected metallic wire with a small spin resistance. This implies that the spin current without a charge flow can be selectively injected into an F particle with a small spin resistance, such as a Py particle, once replaced with the wire so that the pure spin current may contribute to the spin torque. To test this idea, a nanoscale F particle is configured for a lateral non-local spin injection device as in figure 7a,b [21].
The device consists of a large Py pad 30 nm in thickness, a Cu cross 100 nm in width and 80 nm in thickness, and a Py nanoscale particle, 50 nm in width, 180 nm in length and 6 nm in thickness. A gold wire of 100 nm in width and 40 nm in thickness is connected to the Py particle to reduce the effective spin resistance, resulting in high-spin current absorption into the Py particle. The magnetic field is applied along the easy axis of the Py particle. Note here that the dimensions of Py pad and Cu wires are chosen large enough to carry a charge current up to 15 mA.

To confirm whether the spin current from the Py injector is absorbed into the Py particle, NLSV measurements are performed. As in figure 7c, the field dependence shows a clear spin signal with a magnitude of 0.18 mΩ, ensuring that the spin current reaches the Py particle. Then, we examine the effect of the non-local spin injection into the Py particle using the same probe configuration. Before performing the non-local spin injection, the magnetization configuration is set in the anti-parallel state by controlling the external magnetic field. The non-local spin injection is performed by applying large pulsed currents up to 15 mA in the absence of magnetic field. As shown in figure 7d, when the magnitude of the pulsed current is increased positively in the anti-parallel state, no signal change is observed up to 15 mA. While for the negative scan an abrupt signal change is observed at −14 mA. The change in resistance at −14 mA is 0.18 mΩ, corresponding to that of the transition from anti-parallel to parallel states. This means that the magnetization of the Py particle is switched only by the non-local spin current. The spin current responsible for switching is estimated from the experiment to be about 200 mA, which is reasonable compared with the values obtained for conventional pillar structures. However, the observed switching was only from the anti-parallel to parallel state in the device. This is mainly owing to the low spin injection efficiency.

To improve the efficiency of the injecting spin current, we have fabricated the newly designed sample shown in figure 8a consisting of two Py/Au nanopillars on a Cu wire [22]. As shown in figure 8a, the junction size between the Py/Cu in the new sample is effectively diminished, leading to the enhanced spin resistance for the Py. Figure 8b shows the NLSV signal as a function of the external field. The obtained spin signal is around 4 mΩ, much larger than previously reported values. Then, non-local spin injection with variable DC current between contacts 3 and 6 is applied to switch the magnetization of the Py/Au nanopillar. The sample is set in a parallel state (denoted as A) at which both magnetizations are aligned in the positive field direction. As can be seen in figure 8c, when the current is increased, the NLSV signal exhibits a sharp drop at about 5 mA, corresponding to a clear magnetization reversal from the parallel state A to the anti-parallel state (denoted as B), which is switched back to the parallel state A by a negative DC current of 5 mA. In this way, reversible magnetization switching between anti-parallel and parallel states is demonstrated by means of non-local spin injection with the specially developed device consisting of perpendicular nanopillars and lateral magnetic nanostructures.

7. Electrical detection of spin Hall effect

Electron trajectories are influenced by the interaction between the electron spin and the orbital angular momentum. This is known as the spin–orbit interaction, which induces non-trivial physical properties such as anomalous Hall effects in...
ferromagnets [23]. Even in non-magnets, the spin–orbit interaction is a dominant mechanism for spin-flip scattering causing spin decoherence. However, recently, the scattering owing to the spin–orbit interaction has been found to induce the spin current in non-magnets via the spin Hall effect (SHE) [24,25]. There has been no experimental demonstration although the SHE was theoretically predicted a long time ago [26]. However, recent progress in spin injection and detection techniques enables us to study the SHEs in N materials. Since the SHE can be used for generating the spin current without ferromagnets, exploring materials with large SHE is a challenging issue from the technological viewpoint.

A first clear observation of the SHE in a metallic system was reported by applying non-local spin injection technique to a CoFe–Al hybrid structure [27]. However, the observation is limited to low temperature because of the small spin–orbit interaction in Al. To induce large SHE, the material should contain spin–orbit scatterers. Platinum is known to exhibit large spin–orbit interaction because of its large atomic number. The conventional lateral structure for non-local spin injection cannot be employed to measure the SHE for Pt because of the extremely short spin-diffusion length of about a few nanometres [28]. Here, we show clear observation of direct and inverse SHEs induced in a Pt wire at room temperature using the spin current absorption technique discussed in §4 [21]. This technique allows us to detect the spin Hall signal generated over the nanoscale spin-diffusion length.

An SEM image of the device used for the present SHE experiment is shown in figure 9a. The device consists of a large Py pad 30 nm in thickness, a Cu cross 100 nm in width and 80 nm in thickness and a Pt wire 80 nm in width and 4 nm in thickness. The distance from the centre of the injector to the centre of the Pt

Figure 8. (a) SEM image and schematic illustration of the improved non-local spin injection device. (b) Giant spin signal and (c) the reversible magnetization switching by pure spin current injection observed in the improved device. (Online version in colour.)
wire is 400 nm. When the charge current is injected from an F Py pad into an N Cu cross and drained from one of the two arms (figure 9b), the non-local spin current is preferably absorbed into the Pt wire with strong spin–orbit interaction.

The spin currents injected into the Pt wire are converted to the transverse charge current voltage via the spin–orbit scattering. When the spin current is polarized along the $x$-axis, the spin–orbit scattering induces the charge current along the Pt wire as schematically shown in figure 9c. Under the open circuit condition, the charge current is balanced with the electric field owing to the charge accumulation. Thus, the spin currents injected into the Pt wire produce the charge Hall voltage along the Pt wire. This phenomenon is known as the inverse SHE.

Figure 10 shows the field dependence of the voltage in the Pt wire induced by the inverse SHE measured at room temperature and 77 K. Here, the magnitude of the effect is conventionally given in ohms by the voltage divided by the injecting current in the Py/Cu junction. The angular dependence measurements of the inverse SHE reveal that the induced voltage is proportional to the in-plane $x$ component of the Py injector magnetization. This is an advantage in controlling the injector magnetization because of low saturation field of the order of a few hundred oersteds.

8. Conclusion

We have studied the spin-diffusion processes in lateral spin-valve structures consisting of Py/Cu ohmic junctions. The spin-diffusion length of the Cu wire is found to decrease at low temperature because of the enhancement of the

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surface spin-flip scattering. We also found that the spin current and the spin accumulation can be manipulated by additionally connected wires which act as spin absorber or spin-relaxation volume. The magnetization switching by pure spin current injection and electrical detection of the SHE were demonstrated by using efficient spin current absorptions.

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