Current induced modulation of interfacial Dzyaloshinskii-Moriya interaction

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The Dzyaloshinskii-Moriya (DM) interaction is an antisymmetric exchange interaction that is responsible for the emergence of chiral magnetism. The origin of the DM interaction, however, remains to be identified albeit the large number of studies reported on related effects. It has been recently suggested that the DM interaction is equivalent to an equilibrium spin current density originating from spin-orbit coupling, an effect referred to as the spin Doppler effect. The model predicts that the DM interaction can be controlled by spin current injected externally. Here we show that the DM exchange constant in Ta/W/CoFeB heterostructures can be modulated with external current passed along the film plane: D increases linearly with current at low current density. As we find the polarity of current has little influence on the DM interaction, we infer the spin polarized current that flows within the FM layer is responsible for the current dependent DM interaction via the spin Doppler effect. These results imply that the DM interaction at the HM/FM interface partly originates from an equilibrium interface spin (polarized) current which can be modulated externally.

Surface and interface effects play an increasingly dominant role in thin film heterostructures with large spin orbit coupling[1]. In heterostructures with ultrathin ferromagnetic layers, perpendicular magnetic anisotropy (PMA) emerges owing to the modification of the interface electronic structure[2,3]. The magnetic exchange interaction can also be modified at interfaces[4,6]: when a magnetic layer is placed next to a non-magnetic layer with strong spin-orbit interaction, the Dzyaloshinskii-Moriya (DM) interaction[7,8] appears and influence the ordering of the magnetic moments. The DM interaction can stabilize a homochiral Néel domain wall[9,12] in systems that will otherwise favor a non-chiral Bloch domain wall[14].

Recent experiments have shown that chiral Néel walls can be driven by current[10,11,15,16]. When current is passed along thin film heterostructures that include a ferromagnetic metal (FM) layer and a heavy metal (HM) layer, the spin Hall effect (SHE)[17,18] of the HM layer generates spin current that diffuses into the FM layer and exerts spin torque on the magnetic moments[19,20], resulting in motion of domain walls. The efficiency of such current induced motion of chiral Néel walls is determined by the strength of the DM interaction as well as the current-spin conversion efficiency, often parameterized by the spin Hall angle of the HM layer. Identifying systems with large DM interaction is one of the focuses in the field of spin orbitronics.

Experimentally, it has been shown that the material used for the HM layer defines the sign and strength of the DM interaction[15,21,22]. Microscopically, a number of models have been proposed to describe the effect[24–27]. A recent report suggests that the DM interaction is equivalent to an equilibrium spin current density originating from spin-orbit coupling[27]. Such model, referred to as the spin Doppler effect, suggests that the DM interaction is not a given material parameter and non-equilibrium spin current injected externally to the system can modify its magnitude[28].

Here we show that the interfacial DM interaction in CoFeB-based heterostructures can be modulated by current. In Ta/W/CoFeB/MgO heterostructures, the DM interaction is studied using current induced motion of domain walls. We find that the DM exchange constant increases with increasing current at low current but drops at larger current. The current flow direction plays little role in setting the DM interaction. We show that the current density dependence of the DM exchange constant results from the spin Doppler effect via spin polarized current that passes through a domain wall.

RF sputtering is used to deposit thin films on thermally oxidized silicon substrates. The film structure is sub. / dTaTa / 1 W / 1 CoFeB / 20 / 2 MgO / 1 Ta (thickness in nm). dTa is varied using a moving shutter during the deposition process to linearly change the Ta layer thickness across the substrate. We show representative results from two samples with different dTa: dTa ∼ 0.5 nm for sample A and dTa ∼ 2.3 nm for sample B. The two samples exhibit different DM interaction strength. Optical lithography and Ar ion milling are used to pattern wires. The width and length of the wires are typically ∼ 5 µm and ∼ 30 µm, respectively. 10 Ta / 100 Au (thickness in nm) electrodes are made using optical lithography and lift-off processes.

The saturation magnetization per unit volume Ms and the effective magnetic anisotropy energy density Keff are measured using vibrating sample magnetometry (VSM). VSM is performed on individual films with constant film thickness across the substrate. See Supplementary Material (Fig. S1) for the dTa dependence of Ms and Keff. Ms and Keff for samples A and B are obtained by interpolating the data: the values are listed in Table I.
The motion of domain walls are studied using magneto-optical Kerr microscopy (Fig. 1). The velocity of a domain wall is estimated by dividing the distance the wall traveled by the applied current pulse length. The current driven domain wall velocity of samples A and B are shown in Fig. 2(a) and 2(b) as a function of the applied pulse amplitude $I$. The pulse length is $\sim 9$ ns. The velocity saturates as the pulse amplitude increases, a characteristic often observed for spin Hall driven motion of chiral Néel walls.[10, 11, 15, 16, 29].

The pulse amplitude ($I$) dependence of the wall velocity ($v$) can be fitted using the following semi-phenomenological equation[29, 32]

$$v(I) = \pm v_D \left[ 1 + \left( \frac{I_D}{I-I_C} \right)^2 \right]^{-\frac{1}{2}} \quad , \quad (1)$$

where $v_D = \frac{\pi}{2} \gamma \Delta H_{DM}$ is the saturation velocity, $\gamma$ is the gyromagnetic ratio. $\Delta = \sqrt{A_{ex}/K_{eff}}$ is the domain wall width, where $A_{ex}$ is the exchange stiffness. $H_{DM} = D/(M_s \Delta)$ is the DM exchange field and $D$ is the DM exchange constant. In Eq. (1), the saturation pulse amplitude $I_D$ and the threshold amplitude $I_C$ are phenomenological parameters introduced to describe the experimental results. We fit the data shown in Figs. 2(a) and 2(b) with $v_D$, $I_D$ and $I_C$ as independent fitting parameters: the solid lines show the fitting results. The fitting is in good agreement with the experimental results.

The DM exchange constant ($D$) extracted from the fitting is shown in Table 1. $D$ is obtained from the average $v_D$ of up/down and down/up domain walls driven by positive and negative currents. $D$ is $\sim 30\%$ larger for sample B ($d_{Ta} \sim 2.3$ nm) than sample A ($d_{Ta} \sim 0.5$ nm). We infer that the difference in $D$ with respect to $d_{Ta}$ may partly originate from structural and compositional differences[33] of the W/CoFeB interface.

To study the relation between the DM exchange constant and the current that flows across a domain wall, we have studied the in-plane field ($H_z$, field parallel to the $x$ axis) dependence of the domain wall velocity for the two samples. The results are shown in Fig. 3 for two different pulse amplitudes. As evident, the velocity varies linearly with $H_z$ and can be fitted with a linear line[10, 11, 15, 16, 22]. The field at which the velocity becomes zero provides information on the DM exchange field[30, 32]. The absolute values of the $x$-intercepts for the up/down and down/up walls driven by positive and negative currents are averaged to obtain the mean DM exchange field $H_{DM}$. Taking the mean value of the four cases eliminates effects of $H_z$, if any, that arises due to slight misalignment of the sample with respect to the field axis.

The DM exchange constant $D$ is estimated from $H_{DM}$ using the relation $H_{DM} = D/(M_s \Delta)$. The pulse amplitude dependence of $H_{DM}$ and $D$ are shown in Figs. 4(a) and 4(b), solid circles, for samples A and B, respectively. We find that $D$ depends on the pulse amplitude. For both samples, $D$ increases with increasing pulse amplitude for small pulses. The change in $D$ with current is significant: the difference between the maximum and minimum $D$ is $\sim 30 - 40\%$. We also find that $D$ tends to decrease at larger pulse amplitude for both samples. Interestingly, the pulse amplitude at which $D$ starts to decrease is close to that when the velocity saturates at zero field ($\sim 2I_D$ in Fig. 2).

These results show that the DM interaction depends on the current that flows through the heterostructure. Since we have used a constant $D$ to fit the pulse amplitude dependence of the velocity (Figs. 2 blue solid line), we recalculate the quantity using the results from Fig. 4. The pulse amplitude dependent $D$ is fitted with two linear functions, as shown by the black solid lines in Figs. 4(a) and 4(b). We assume the phenomenological parameter $I_D$ is linearly proportional to $D$[30], i.e. $I_D = aD$. The calculated velocity, with $a$ and $I_C$ as adjustable parameters, is shown by the red dashed line in Figs. 2(a) and 2(b). We find a relatively good agreement between the experimental results and the calculations.

According to the model based on the spin Doppler effect[27], the DM exchange interaction is due to an equilibrium spin current that flows at the interface for heterostructures with broken structural inversion symmetry, see Fig. 5(a). The model predicts that $D$ can be modulated using external sources of spin current, provided that spin current polarized in the $y$-direction flows along the $x$-direction[28]. The spin Hall effect of the HM layer does not, in general, generate such spin current that
TABLE I. Material parameters of the samples studied.

| Ta thickness (nm) | $M_s$ (kA/m) | $K_{\text{eff}}$ ($10^5$ J/m$^3$) | $D$ (mJ/m$^2$)$^a$ |
|------------------|--------------|----------------------------------|--------------------|
| 0.5              | 930          | 4.0                              | 0.24               |
| 2.3              | 1090         | 6.2                              | 0.33               |

$^a$ $D$ estimated from $v$ vs. pulse amplitude using Eq. 1 with current independent $D$. The fitting results are shown in Fig. 2(a,b), solid lines.

FIG. 2. Pulse amplitude dependence of the domain wall velocity. (a,b) Pulse amplitude dependence of domain wall velocity of (a) sample A and (b) sample B. The circles (squares) show velocity of up/down (down/up) domain walls. The blue solid lines show the fitting results using Eq. 1. The parameters used are: $v_D \sim 72(84)$ m/s, $I_D \sim 15(7)$ V, $I_C \sim 10(5)$ V for sample A(B). The dashed lines include the current dependent $D$ obtained from Fig. 4 when calculating the velocity with Eq. 1. The parameters used are: $a \sim 8.6 \times 10^4(3.1 \times 10^4)$ Vm$^2$/J and $I_C = 10(5)$ V for sample A (B).

FIG. 3. Extraction of the DM exchange field from the in-plane field dependence of domain wall velocity. (a,b) $H_x$ dependence of the domain wall velocity. The pulse amplitude is (a) $\sim 14$ V, (b) $\sim 8$ V, (c) $\sim 25$ V and (d) $\sim 18$ V. The red circles (blue squares) show velocity when positive (negative) current is applied. The filled (open) symbols correspond to the velocity of up/down (down/up) walls. The solid lines show linear fit to the data. (a,c) sample A, (b,d) sample B.
FIG. 4. Current dependent Dzyaloshinskii-Moriya interaction. (a,b) Pulse amplitude dependence of the DM exchange constant $D$. The right and top axes display the corresponding $H_{DM}$ and current density that flows through the FM layer, respectively. The solid circles show the experimental data, the open squares represent results from numerical calculations. The parameters used in the calculations are shown in Table SI. The solid lines show linear fit to the data in appropriate current range. (a) sample A, (b) sample B.

FIG. 5. Spin Doppler effect caused by the spin polarized current at the domain wall. The thick arrows indicate magnetization of the FM layer. The yellow sphere represents an electron, the arrow cutting through it denotes its spin moment direction. (a) A stationary right handed Néel wall. The spin Doppler effect dictates that an equilibrium spin current is the source of the DM interaction. (b) When the right handed Néel walls are driven by current via the spin Hall effect of the HM layer, the domain wall magnetization rotates. The direction to which the magnetization rotates is defined by the current flow direction and the sign of the spin Hall angle of the HM layer. Spin polarized current, illustrated by the electron motion, flows across the domain wall which causes the spin Doppler effect. The effect is the same for up/down and down/up walls as well as positive and negative currents.
flows along the current direction (i.e. along the x-axis). However, in the system under consideration, spin polarized current that flows within the FM layer may meet the requirement and cause changes in the DM interaction. When stable Néel walls are driven by current via the SHE of the HM layer, the wall magnetization rotates and becomes a Bloch-type \[10, 31, 32\]. Under such circumstance, spin polarized current with spin polarization along y flows along the x-axis locally at a domain wall (Fig. 3(b)). We thus infer that spin Doppler effect can take place locally at the domain wall while it is driven by current.

The spin Doppler effect \[27, 28\] dictates that \( D \) linearly scales with the external spin current density \( J_s \), that is,

\[
D = D_0 + 2J_s, \tag{2}
\]

where \( D_0 = 2J_s^0 \) is the equilibrium DM exchange constant without the external source and \( J_s^0 \) is the equilibrium spin current density. The factor of 2 in front of \( J_s \) (and \( J_s^0 \)) is inserted to account for the definition \[27, 28\] that \( J_s \) represents a flow of angular momentum of \( \hbar \). A spin polarized current density that flows in the FM layer \( P_{\text{FM}} \) can be converted to spin current density \( J_s \) via the relation \((e)J_s \sim \frac{\hbar}{e} P_{\text{FM}}\), where \( P \) is the current spin polarization of the FM layer. As noted above, electrons with spin polarization along the y-axis contribute to the spin Doppler effect. We thus replace \( P \) at the domain wall with \( P_{\text{eff}}(-\sin \phi) \), where \( P_{\text{eff}} \) is the effective spin polarization at the domain wall (implication of \( P_{\text{eff}} \) is discussed later) and \( \phi \) is the magnetization angle of the domain wall with respect to the x-axis. The minus sign is introduced to account for the fact that the spin angular momentum is anti-parallel to local spin magnetic moment. Substituting these relations into Eq. (2) gives

\[
D = D_0 + \frac{\hbar}{e} P_{\text{eff}} J_{\text{FM}} \sin \phi. \tag{3}
\]

Using the one-dimensional (1D) model of a domain wall with the current dependent \( D \) (Eq. (3)), we calculate the domain wall velocity as a function of \( H_x \) to mimic the experimental procedure. \( H_{\text{DM}} \) is obtained from the x-axis intercept of the velocity and converted to \( D \). As the only adjustable parameter in Eq. (3) is \( P_{\text{eff}} \), we vary its size to fit the experimental results. (See Table SI of the supplementary material for the parameters used in the calculations). The calculated current dependence of \( D \) is shown in Fig. 4 open squares. We find \( P_{\text{eff}} \sim 0.64 \) and \( \sim 0.43 \) gives the best fit for samples A and B, respectively. In experiments, we find that \( D \) increases for both positive and negative currents. The spin Doppler effect caused by the current spin polarization at the domain wall can account for such observation. In Eq. (3), when the sign of \( J_{\text{FM}} \) is reversed, the sign of \( \sin \phi \) also reverses, giving rise to an increase in \( D \) for both current polarities (see Fig. 4(b)). Note that \( D \) increases for both up/down and down/up domain walls, also consistent with experiments.

The effective spin polarization \( P_{\text{eff}} \) at the the domain wall differs from the bulk spin polarization \( P \) since \( P_{\text{eff}} \) is influenced by the relative size between the domain wall width \( \Delta \) and the transverse spin diffusion length \( \lambda_T \) of the FM layer. In the limit of zero \( \lambda_T \), the conduction electron spin is always parallel to the local magnetization. Under such circumstance, one do not expect to observe the spin Doppler effect as it requires components of conduction electron spin to be perpendicular to the local magnetization. On the other hand, in the limit of \( \lambda_T \gg 0 \), the electrons’s spin will not be polarized along the Bloch wall’s magnetization axis (i.e. the y-axis) within the domain wall, and again the spin Doppler effect will not manifest itself. Thus to observe the spin Doppler effect one requires \( \lambda_T \sim \Delta \). In CoFeB, recent experiments \[19\] find \( \lambda_T \sim 1 \text{ nm} \). Together with the estimated \( \Delta = \sqrt{A_{\text{ex}}} / K_{\text{eff}} \sim 5 \text{ nm} \), we consider such condition is met in CoFeB.

Finally, we discuss other sources that may influence the change in \( D \) with current. The 1D model shows that the adiabatic (and non-adiabatic) spin transfer torque (STT) contributes to the velocity and therefore influences the estimation of \( H_{\text{DM}} \). However, for domain walls moving along the current flow direction (via the SHE of the HM layer), \( H_{\text{DM}} \) is expected to decrease when STT is taken into account \[10\]. We thus consider the STT is not responsible for the increase in \( D \) with current. Taking into account contribution of the STT will result in finding a larger modulation of \( D \) induced by current.

Domain wall pinning can cause changes in the velocity. According to the 1D model, the \( H_x \) dependence of the velocity can no longer be fitted with a linear line when pinning is strong. However, here the pinning is small (pinning field is typically less than \( \sim 1 \text{ mT} \)) and the relation between the velocity and \( H_x \) is linear in almost all cases (see Fig. 3). We thus consider pinning plays a minor role in the current dependent \( D \).

With regard to the source of spin polarized current that causes the spin Doppler effect, there is a possibility that the Rashba-Edelstein effect at interfaces can generate such current \[33\]. In fact, the spin Doppler effect is based on a model which employs a Hamiltonian with spin momentum locking. However, when electric field is applied along the film plane, simple model calculations show that current induced spin polarization due to the Edelstein effect cannot account for the spin Doppler effect: the amount of spin polarized current created by the electric field is compensated by the reduction in spin polarized current with opposite spin moving against it, both of which contribute to the spin Doppler effect in the same way.

We thus conclude that the spin Doppler effect induced by the spin polarized current in the FM layer is the most likely cause of changes in \( D \) with current. The reduction in \( D \) at large pulse amplitude in Figs. 4(a) and 4(b), however, cannot be described by the model. Further investigation is required to clarify the effect.

In summary, we have studied the interfacial
Dzyaloshinskii-Moriya interaction against current that flows within the film plane of Ta/W/CoFeB heterostructures. We find that the DM exchange constant linearly increases with current at lower current and tends to decrease at larger current. The current flow direction has little impact on the DM exchange constant. The linear increase in the DM exchange constant with current can be accounted for by the spin Doppler effect caused by the spin polarized current that flows in the CoFeB layer. These results indicate that the DM interaction at the interface of heavy metal/ferromagnetic metal interface, if not entirely, originates from the exchange of equilibrium spin current at the interface. Our finding thus demonstrates that DM interaction is not a given material parameter of each interface but can be controlled externally using current. Such external control of DM interaction can significantly expand the scope of research on chiral magnetism in thin film heterostructures.

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