Features and Peculiarities of Gate-Voltage Modulation of Spin-Orbit Interaction in FeCoB Nanomagnets: Insights into the Physical Origins of the VCMA Effect

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The paper investigates the systematic dependencies of the anisotropy field and the strength of spin-orbit (SO) interaction on gate voltage in Ta/FeB/MgO nanomagnets. Our findings reveal an intriguing opposite polarity in the gate-voltage dependencies of the anisotropy field and the coefficient of SO interaction across all studied nanomagnets. This opposite polarity signifies that both the strength of spin-orbit interaction and the demagnetization field are effectively modulated by the gate voltage, exhibiting an increase with higher gate voltages. This finding indicates that the gate voltage modulation of spin- orbit interaction and the demagnetization field are two major contributions to the Voltage-Controlled Magnetic Anisotropy (VCMA) effect in FeB nanomagnets. Due to the opposite polarities of these contributions, they effectively counterbalance each other, resulting in a reduction of the VCMA effect. Optimizing the balance between these contributions could potentially lead to a substantial enhancement of the VCMA effect. Our measurements did not detect any modulation of in-plane component of spin accumulation by the gate voltage.

The voltage controlled magnetic anisotropy (VCMA) effect [1, 2] refers to the phenomenon that in a capacitor, in which one of electrodes is made of a thin ferromagnetic metal, the magnetic properties of the ferromagnetic metal changes, when a voltage is applied to the capacitor. Despite the gate voltage being applied only to the boundary of the ferromagnetic metal, it can influence the magnetic properties of the entire ferromagnet, in some cases leading to a complete reversal of its magnetization [3, 4]. This mechanism, which allows for magnetization switching controlled by gate voltage, can serve as an effective method for data recording. When an electrical pulse reverses the magnetization direction, data is stored within the ferromagnetic metal through its two opposing magnetization states. Such a recording mechanism is fast and energy-efficient and, therefore, is promising for use in the magnetic random access memory (MRAM).

The VCMA effect presents a fascinating yet not fully understood phenomenon in the realm of magnetism. Various plausible physical mechanisms have been proposed to explain its mechanism [5, 6]. It is currently understood that the gate voltage has the capability to influence solely the interfacial properties of the nanomagnet, leaving the bulk properties unaffected.

Within a metal, the electric field is shielded by conduction electrons, preventing its deep penetration into the material. Consequently, the voltage applied to the dielectric gate at the nanomagnet interface can only permeate and influence the few uppermost atomic layers of the metal near the gate. Nevertheless, the alteration of magnetic properties in these uppermost layers by the gate voltage can exert a significant influence on magnetic characteristics of the whole nanomagnet.

Such a significant interface-related effect can only occur when the gate voltage influences the interfacial perpendicular magnetic anisotropy (PMA), given its considerable impact on the overall magnetic properties of the nanomagnet. However, the underlying reasons and specific details of how and why the gate voltage alters PMA remain unclear, adding to the complexity of understanding the VCMA effect. Further exploration and research are required to unravel the intricacies of this intriguing phenomenon.

Spin-orbit interaction (SO) is a fundamental phenomenon that plays a critical role in determining the existence of PMA. The substantial modulation of PMA suggests that the gate voltage modulates SO strength. However, whether this modulation solely explains the VCMA effect or if there are additional contributing factors remains uncertain. Spin-orbit interaction refers to a magnetic field H_{SO} of relativistic origin [7] experienced by an electron while moving within an electric field E:

$$H_{so} = \frac{v}{c^2} E \tag{1}$$

where v is a component of the electron velocity perpendicular to E.

Recently, an innovative method for measuring the strength of spin-orbit interaction (SO) has been introduced [8, 9], offering valuable insights into this intricate fundamental phenomenon. The measurement method provides deep experimental insights into the physical processes that influence spin-orbit interaction and consequently govern magnetic anisotropy. The present paper provides a systematic investigation into the modulation of spin-orbit (SO) strength by a gate voltage, along with an exploration of the mechanisms through which the gate voltage impacts SO strength.

The measurement method is rooted in a fundamental characteristic of spin-orbit interaction, which is its manifestation only in the presence of broken time-reversal symmetry (T-sym), which is the case, for example, in presence of an external magnetic field. This dependency of SO strength on the degree of broken T-sym leads to an enhancement in the strength of spin-orbit interaction under an external magnetic field H_{ext}. Since in the absence of H_{ext}, T-sym remains unbroken and H_{so} equals

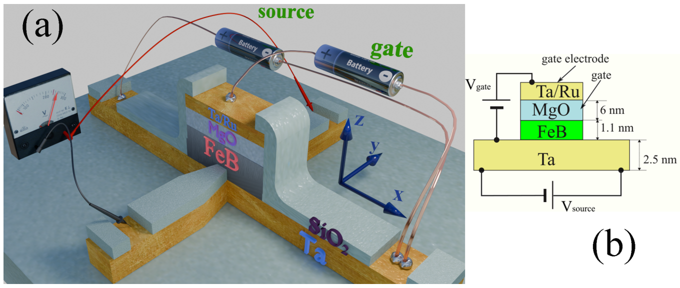

FIG. 1. (a) Experimental setup for measuring strength of spin- orbit interaction of FeB nanomagnet under gate voltage. (b) Layer stack

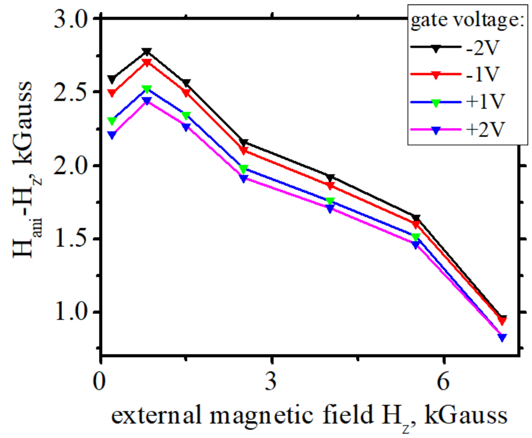

FIG. 2. Anisotropy field H_{ani} as a function of external perpendicular-to-plane magnetic field H_z measured at a different gate voltage V_{gate}.

zero, there exists a linear relationship between H_{so} and H_{ext}:

$$H_{so} = k_{so} \cdot H_{ext} \tag{2}$$

where k_{so} is the coefficient of spin- orbit interaction, which defines the strength of spin-orbit interaction.

Since the strength of the magnetic anisotropy is inherently linked to the strength of the spin-orbit interaction, the most intuitive and direct approach for a measurement of the SO strength is through measurements of magnetic anisotropy. Indeed, both theoretical and experimental evidence [8] has shown that the anisotropy field H_{ani} linearly increases with an increase in the external magnetic field H_z applied along the magnetic easy axis. This relationship is found to be as:

$$H_{ani} = H^0_{ani} + H_z + k_{so} H_z \tag{3}$$

where H^0_{ani} is the anisotropy field in absence of H_z.

This relation derives k_{so} from a linear fit of the measured dependency of H_{ani} versus H_z.The second term in the equation accounts for the bulk contribution, indicating the alignment of magnetization along H_z, which doesn't provide informative insights. Therefore, during data analysis, it is more beneficial to focus on the relationship between $H_{ani} - H_z$ and H_z. This strategy ensures that the substantial bulk contribution doesn't overshadow a potentially weaker dependence on k_{so}.

In order to investigate the dependency of the spin-orbit (SO) strength on gate voltage, a 1.1-nanometer-thick FeB nanomagnet was fabricated atop a 400-nanometer-wide nanowire using a Hall probe. Additionally, a 6-nanometer-thick MgO gate oxide layer and Ta gate electrode were constructed on top of the nanomagnet (See Fig. 1). Nanomagnets are specifically utilized due to their lack of magnetic domains, simplifying data analysis. However, this measurement method allows for its application to larger samples without significant issues.

The experiments were carried out at room temperature, well below the Curie temperature of FeB. The magnetization angle was measured by a Hall probe (See Fig. 1).The in-plane and perpendicular- to- plane components of the applied magnetic field are controlled individually. The measurement process involved recording the Hall angle α_{Hall} during the scanning of an in-plane external magnetic field H_x in two opposite directions. The perpendicular-to-plane magnetic field was employed as a parameter.

The anisotropy field H_{ani} was evaluated by fitting the linear relationship [10] between the in-plane magnetization component M_x and H_x. Even without an external magnetic field, there exists an in-plane magnetic field $H_{||}$, causing the magnetization to tilt from the magnetic easy axis. Both the magnetic field generated by spin accumulation and the Oersted field created by the current contribute to $H_{||}$ [11]. To prevent any systematic errors, $H_{||}$ was carefully evaluated and factored into the fitting process. Detailed information regarding the measurement procedures can be found in Refs. [8, 11].

Figure 2 displays the measured relationship between $H_{ani} - H_z$ and the external magnetic field H_z measured at a different gate voltage V_{gate}. The relationship shows an approximately linear trend with minor oscillations superimposed on it. The oscillations are a recognized characteristic of the spin-orbit (SO) interaction in the interfacial layer [8]. Notably, both the slope and the offset of this linear dependence significantly vary with the gate voltage. As V_{gate} increases, the offset decreases while the slope increases. This opposing relationship is clearly observed as a narrowing gap between the lines at higher H_z

As shown in Eq. 3, the slope is directly proportional to the spin-orbit coefficient k_{so}, while the offset is proportional to the anisotropy field H^0_{ani} in the absence of an external magnetic field. Figure 3 illustrates the relationship between H^0_{ani} and k_{so} with respect to V_{gate}, showcasing nearly linear dependencies for both parameters.

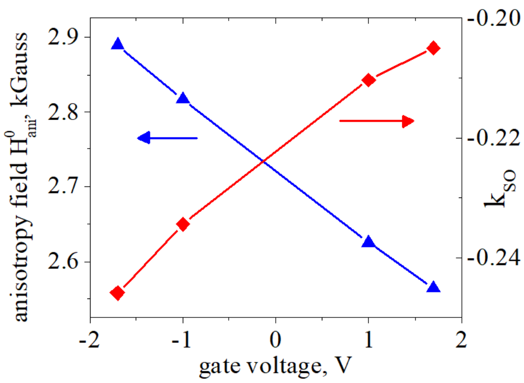

FIG. 3. Anisotropy field H^0_{ani} and coefficient of the spin orbit interaction k_{so} as a function of the gate voltage

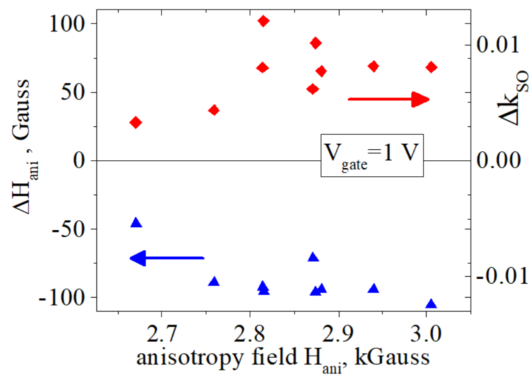

FIG. 4. The change of anisotropy field ΔH_{ani} and coefficient of SO interaction Δk_{so} under gate voltage of 1 V. Each dot corresponds to a measurement of one individual nanomagnets fabricated at a different place on the same wafer.

The opposite dependencies of H^0_{ani} and k_{so} on V_{gate} are systematic. Figure 4 illustrates the variations in H^0_{ani} and k_{so} when a gate voltage of 1 V is applied, as measured across different nanomagnets located at various positions on the same wafer. Due to variations in interface roughness, the measured values of H^0_{ani} and k_{so} slightly differ for each nanomagnet. In each case, Δk_{so} is positive, while ΔH_{ani} is negative.

Additionally, similar measurements were conducted on Ta/FeB/MgO, W/FeB/MgO, Ta/FeCoB/MgO, $[W/FeB]_n/MgO$, $[Ta/FeB]_n/MgO$ nanomagnets of a different structure, a different material composition and a different size [12, 13]. Remarkably, the observed trends remained identical. Specifically, for positive V_{gate}, Δk_{so} is consistently positive, whereas ΔH_{ani} is consistently negative.

The unexpected opposite dependencies of H^0_{ani} and k_{so} on gate voltage are intriguing, given that H^0_{ani} and k_{so} are not independent parameters. Specifically, H^0_{ani} is determined by k_{so} and the internal magnetic field H_{int} within the nanomagnet. This internal magnetic field is responsible for maintaining magnetization along the magnetic easy axis. Given the general similarity between external H_z and internal H_{int} magnetic fields, one would expect their effects on the nanomagnet to be identical. Utilizing this symmetry principle, Eq. 3 can be rewritten as

$$H_{ani} = (H_z + H_{int}) + k_{so}(H_z + H_{int}) \quad (4)$$

where

$$H^0_{ani} = (1 + k_{so})H_{int} \quad (5)$$

As shown in Eq. 5, H^0_{ani} is linearly proportional to k_{so}, suggesting that their dependencies should share the same polarity. However, an exception arises when another parameter, in addition to k_{so}, influences H^0_{ani} with a gate-voltage dependency opposite to that of k_{so}. The parameter that satisfies these properties is demagnetization field.

Demagnetization field refers to the magnetic field produced by the magnetic dipole formed at opposite surfaces of a magnetic film. The direction of the demagnetization field H_{demag} opposes the direction of the internal magnetic field, thereby reducing H_{int} and H^0_{ani}. In a scenario where V_{gate} simultaneously enlarges k_{so} and H_{demag}, it can lead to opposite polarities in the gate-voltage dependencies of k_{so} and H^0_{ani}.

The phenomenon where the changes in the anisotropy field and the coefficient of spin-orbit interaction exhibit opposite polarities is a known and studied effect [8]. This occurs when H^0_{ani} and k_{so} are influenced by interface roughness. The roughness of the interface impacts both the strength of spin-orbit interaction and the demagnetization field. When nanomagnets are produced in different areas of the same wafer, the interface roughness varies slightly for each nanomagnet, leading to distinct values of measured H^0_{ani} and k_{so}. However, these values do not follow a random distribution; instead, there exists a linear relationship between these two parameters [8].

For nanomagnets composed of a single ferromagnetic layer, the slope of the H^0_{ani} versus k_{so} dependence is positive. This implies that the change in k_{so} predominantly contributes to the change in H^0_{ani}. Conversely, in the case of multilayer nanomagnets, the slope is negative, indicating that the change in H_{demag} plays a dominant role in the change of H^0_{ani}.

As a similar trend is observed in the modulation of the anisotropy field by gate voltage, it suggests that the gate voltage impacts both the strength of spin-orbit interaction and the demagnetization field. Under an increased gate voltage, both the strength of spin-orbit interaction and the demagnetization field increase. The observed polarity implies that the modulation of the anisotropy field due to gate voltage is primarily influenced by changes in the demagnetization field.

The mechanism by which the gate voltage modulates the strength of spin-orbit interaction can be elucidated as follows. The spin-orbit interaction experienced by localized d-electrons originates from the electric field of the nucleus due to electron orbital motion. Since the d- electrons are quenched and thus lack an orbital moment, the SO magnetic field H_{so} generated by the clockwise- and counterclockwise- rotating components of their wavefunction cancels each other out, resulting in no net spin-orbit interaction. However, this balance is disrupted when internal H_{int} or external H_z magnetic field breaks it, leading to the emergence of overall H_{so}. The disparity between these two contributions to H_{so}, and consequently the overall H_{so}, substantially depends on specifics of the orbital distribution. Notably, a significant difference arises when the orbital center position diverges from the nucleus position. This explains why the spin-orbit interaction is markedly more pronounced for Fe orbitals at the interface compared to those in the bulk, a distinction clearly demonstrated in experimental measurements [8]. When a gate voltage is applied to the interface, it induces modifications in the orbital distribution. This, in turn, alters the discrepancy between the two H_{so} contributions and thereby affects the overall strength of the spin-orbit interaction.

The mechanism by which the gate voltage modulates the demagnetization field is not entirely clear, but it may share similarities with how interface roughness reduces the demagnetization field. The demagnetization field is largest for an ideally plain and ideally sharp interface. However, any curvature, roughness, or imperfect sharpness in the interface reduces the demagnetization field, because it introduces components of the demagnetization field that deviate from the interface normal and are effectively averaged out. The interface between a ferromagnetic material and a non-magnetic gate material is not perfectly sharp or smooth. The wavefunction of d-electrons of the interfacial Fe atoms gradually extends into the gate material, leading to a reduction in the demagnetization field. The application of a gate voltage alters the orbital distribution of these interfacial d-orbitals, potentially causing a modulation in the demagnetization field, as observed in experimental measurements.

As was explained above, the in-plane magnetic field $H_{||}$ is simultaneously measured alongside H_{ani} and k_{so}. Figure 5 illustrates the measured parallel- to- current and perpendicular- to- current components of $H_{||}$ under varying gate voltages. No discernible dependence of $H_{||}$ on V_{gate} was detected, contrasting with the substantial dependence of $H_{||}$ on the electrical current as reported in ref. [11]. There are two distinct contributions to the observed current dependence. The first contribution arises from the Oersted field, which is directly proportional to the current and remains independent of H_z. The second contribution is from the magnetic field generated by spin-polarized electrons accumulated due to the Spin Hall effect. The latter contribution is identified by its distinct features such as oscillations around H_z induced by spin precession and alignment along H_z due to spin damping [11]. In our measurements, the bias current density was 12 $mA/\mu m^2$, which is sufficient to create a detectable spin accumulation due to the Spin Hall effect. As depicted in Figure 5, the gate voltage does not influence this spin accumulation. It's worth noting that we were only able to measure the in-plane component of spin accumulation, while the perpendicular- to- plane component of spin accumulation couldn't be assessed with used setup. However, this component can be evaluated using the experimental setup described in Ref. [14].

It remains possible that the observed opposite polarities in the modulation of k_{so} and H^0_{ani} are not solely due to gate-voltage modulation of the demagnetization field. Other mechanisms may also contribute to this phenomenon. One potential explanation could involve the modulation of the perpendicular-to-plane component of spin accumulation [15, 16], or alternatively, the modulation of the effective spin of interfacial localized electrons [5]. These additional factors could play a role in shaping the observed behaviors and warrant further investigation to fully understand the underlying mechanisms.

In conclusion, the systematic experimental study of spin-orbit strength in FeB nanomagnets has revealed an intriguing opposite polarity in the gate-voltage dependence of the strength of spin-orbit interaction and anisotropy field. This opposite polarity suggests that both the strength of spin-orbit interaction and the demagnetization field are effectively modulated by the gate voltage. As these two major contributions display opposite polarities, they effectively counterbalance each other, resulting in a reduction of the VCMA effect. Optimizing the balance between these contributions could potentially lead to a substantial enhancement of the VCMA effect.

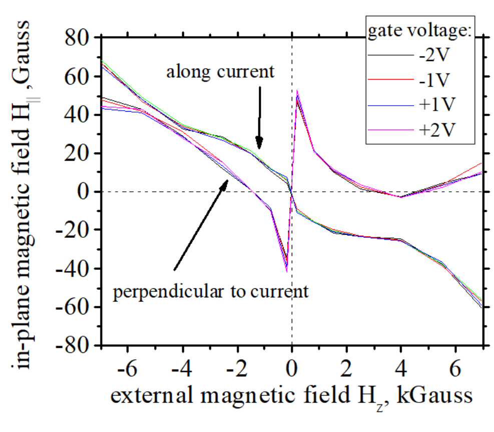

FIG. 5. The parallel-to-current and perpendicular-to-current components of the in-plane magnetic field $H_{||}$ measured under varying gate voltages.The data shows no discernible dependence of $H_{||}$ on the gate voltage within the measured precision.

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