Hydrogen tunes magnetic anisotropy by affecting local hybridization at the interface of a ferromagnet with nonmagnetic metals

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(Received 6 May 2020; revised 10 August 2020; accepted 15 September 2020; published 28 October 2020)

Ionic control of magnetic properties, dubbed magneto-ionics, has gained much attention in recent years due to the sizable effects that can be induced by electrically controlled ion motion. Here we assess the mechanism by which hydrogen affects magnetic anisotropy in representative ferromagnetic/nonmagnetic metal layers. We take Co/Pd film as a model system that is widely used in spintronics. First-principles calculations demonstrate that the magnetic moment can be switched by 90° via hydrogen insertion at the Co/Pd interface. This control results from hydrogen-induced changes in magnetic anisotropy originating from modifications to the electronic structure. Accumulation of hydrogen at the Co/Pd interface affects the hybridization between neighboring Co and Pd layers, leading to a decrease of the perpendicular anisotropy component, and eventually changes the net magnetic anisotropy to in-plane. Hydrogen penetration into the interior Co layers has the opposite effect, promoting perpendicular magnetic anisotropy. These changes are governed by competing contributions of the $d_{yz}$, $d_{xy}$, and $3d_{z^2}$, $3d_{x^2}$ states, which are mainly responsible for the perpendicular and the in-plane magnetocrystalline anisotropy, respectively. By using this understanding, we predict that hydrogen accumulation at Fe/V interfacial layers causes the opposite spin reorientation effect, promoting perpendicular magnetic anisotropy.

DOI: 10.1103/PhysRevMaterials.4.104416

I. INTRODUCTION

Magnetic anisotropy is one of the key properties of magnetic materials that determines a preferred spin orientation and switching dynamics. The ability to manipulate magnetization direction plays a crucial role in the development of spintronics, including emerging spin-transfer [1] and spin-orbit torque [2] memory devices. Therefore, new strategies to control magnetic anisotropy are in high demand. Previous investigations demonstrated several ways to alter magnetization direction by using applied mechanical stress [3], electric field [4,5], electric polarization [6], or adsorption of chemicals [7].

Much of the recent studies have focused on the electrical field control of magnetic anisotropy [8–10] in ferromagnetic/heavy metal [11] and ferromagnetic/metal oxide [12] multilayers. These materials exhibiting perpendicular magnetic anisotropy (PMA) have traditionally gained a lot of attention for practical applications such as high-density magneto-optical recording media [13]. Perpendicular magnetic anisotropy in these films originates from the spin-orbit-coupling (SOC) interaction at the interface, while magnetic anisotropy switching occurs due to modulation of the electronic structure by applying an electric field [14]. However, the direct effect of an electric field in metallic layers is quite small [4] because of the strong Coulomb screening, which significantly limits the energy efficiency of this method.

More recent investigations [10,15–17] have opened an alternative mechanism for low-power gate-voltage switching of magnetization. This approach relies on the electrical gating of mobile ionic species such as oxygen or hydrogen defects to effectively manipulate the interfacial magnetic anisotropy. For instance, it was shown that electrical gating to insert/extract hydrogen allows for reversible switching of magnetic anisotropy in thin films made of ferromagnet and nonmagnetic metal layers, such as Co/Pd [17]. At ambient conditions, these films show an easy magnetization axis that is perpendicular to the film plane, while after hydrogen insertion, magnetization undergoes a 90° rotation to become in-plane. The applicability of a Co/Pd heterostructure as low-pressure hydrogen sensors has also been recently demonstrated based on the H2-dependent variation of magnetic anisotropy observed through ferromagnetic resonance [18,19] or magneto-optic Kerr effect measurements [20]. In addition to magnetic anisotropy, hydrogenation of magnetic structures was employed to manipulate noncollinear magnetic states by reversibly tuning the Dzyaloshinskii-Moriya interaction [21,22] and stabilizing the formation of skyrmions (e.g., at the Fe/Ir interface [23,24]).

Previous investigations demonstrated that the effect of hydrogen intercalation on the magnetic properties varies with hydrogen concentration and synthesis conditions. The underlying mechanism of magnetic anisotropy changes in relation to the concentration and position of hydrogen is not yet completely understood. In particular, a large set of experimental investigations demonstrated that H2 absorption leads

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to a reduction of PMA for nanopatterned Co/Pd films, alloys, and multilayers [19,25]. It was hypothesized that the reduction of PMA could be attributed to magnetoelastic effects or modification of the electronic structure and orbital moments at the interface [26,27]. However, other studies revealed an enhancement of PMA and coercivity for multilayered Pd/Co nanopatterns [28] and alloys [29], at low hydrogen concentrations.

To provide a mechanistic understanding of how hydrogen induces changes in magnetic anisotropy, and thus to advance our ability to control it, atomistic scale and theoretical calculations are desirable. In the present work, we have performed density functional theory calculations to assess the mechanisms by which hydrogen affects the magnetic properties of Co/Pd heterostructures. Our calculations have revealed that hydrogen atoms accumulated at the interface modify the strength of magnetic anisotropy through the modulation of electronic $d$ states. The resulting magnetic properties are affected by hydrogen concentration and distribution profiles. Furthermore, we showed that hydrogen gating could be applied to manipulate the magnetic properties of other materials such as Co/Pt, Fe/Pd, and Fe/V thin films.

II. COMPUTATIONAL METHODS

Density functional theory (DFT) calculations were performed using the projector augmented wave (PAW) method as implemented in VASP [30]. We employed the gradient-corrected exchange-correlation functional of the Perdew-Burke-Ernzerhof revised for solids (PBEsol) [31]. An energy cutoff of 500 eV and $12 \times 12 \times 1$ k-point sampling were used for atomic relaxations in the absence of spin-orbit coupling (SOC) until the Hellmann-Feynman forces on each atom used for atomic relaxations in the absence of spin-orbit coupling are less than 5 meV. Atomistic scale and theoretical calculations with a finer mesh of $36 \times 36 \times 3$ k point, which results in a change of the magnetic anisotropy energy of less than 0.04 meV. Atom-resolved contributions to MCA are evaluated based on second-order perturbation theory [34],

$$\frac{EMCA}{\sum_{k_o} \sum_{a,u} |\langle k_o|L_z|k_u\rangle|² - |\langle k_o|L_z|k_u\rangle|²} \frac{\epsilon_{k_u} - \epsilon_{k_o}}{\epsilon_{k_u} - \epsilon_{k_o}} \propto \sum |\langle k_o|L_z|k_u\rangle|² \frac{\epsilon_{k_u} - \epsilon_{k_o}}{\epsilon_{k_u} - \epsilon_{k_o}},$$ (1)

where $k_u$ and $k_o$ specify the occupied and unoccupied states with the wave vector $k$, $L_z$ and $L_u$ are angular momentum operators, and $\epsilon_{k_u}$, $\epsilon_{k_o}$ are the orbital energies. In this work, we also refer to the Bruno model, which describes a correlation between magnetocrystalline anisotropy and orbital moments for transition-metal atoms [35] and multilayered systems [36]. In the latter case, if exchange splitting is small and spin-flip terms can be neglected, orbital moment anisotropy becomes proportional to the MCA energy.

The second magnetic anisotropy term originates from a classical magnetostatic (dipolar) interaction and is associated with the shape of the magnetic sample. It was calculated numerically based on DFT optimized structures and magnetic moments using the following equation and cutoff radius of 150 Å:

$$EMSA \propto \sum_{i\neq j} \left[ \frac{m_i \cdot m_j}{r_{ij}^3} - 3 \frac{(m_i \cdot r_{ij}) \cdot (m_i \cdot r_{ij})}{r_{ij}^5} \right].$$ (2)

The magnetocrystalline anisotropy and magnetic shape anisotropy energies are calculated as a difference between energies corresponding to the magnetization in the in-plane and out-of-plane directions [e.g., $EMCA = (E_\perp - E_\parallel)/5$]. Therefore, a negative (positive) value of MAE indicates the out-of-plane (in-plane) easy axis.

III. RESULTS AND DISCUSSIONS

A. The origin of PMA in Co/Pd layers

We first investigated magnetic anisotropy at a pristine Co/Pd interface and further used these results as a reference to understand the origin of magnetic anisotropy changes after hydrogen insertion. In accordance with previous experimental data [32], our calculations showed that Co/Pd trilayers exhibit pronounced magnetocrystalline anisotropy (MCA) with $-1.82 m^3/m^2$ energy favoring the perpendicular orientation of magnetic moments. The magnetic moment on Co atoms is found to be in the range of 1.76–1.86 $\mu_B$, while adjacent Pd also acquires a weak magnetization corresponding to 0.28 $\mu_B$ per atom, which decays fast with decreasing proximity to the interfacial Co layers [see Fig. 1(a)]. The local orbital moments...
of Co atoms at the interface have a strong anisotropy [see Fig. 1(a)] with an orbital moment $m_{\text{orb}} = 0.092 \mu_B$ for the in-plane and $0.123 \mu_B$ for the perpendicular magnetization orientation. These results agree well with the Bruno model [35,36], which predicts a linear correlation between orbital and magnetic anisotropies for systems with a low spin-flipped contribution such as Co/Pd [37].

The important insights into the origin of MCA can be obtained using second-order perturbation theory, which relies on the electronic structure near the Fermi level [34]. As seen from Fig. 1(b), interfacial Co and Pd layers strongly promote perpendicular magnetic anisotropy, which originates from hybridization between $3d$ Co and $4d$ Pd orbitals. In particular, $d_{x^2-y^2}$ and $d_{xy}$ orbitals of interfacial Co and Pd atoms give the largest contribution to magnetic anisotropy, in agreement with the previous theoretical analysis [37].

Another very important impact on magnetic anisotropy arises from the dipole–dipole interaction of magnetic moments, giving rise to magnetic shape anisotropy. To mimic a planer trilayer of Pd/Co/Pd used in experiments [17], we employed a Co/Pd supercell with a fixed number of Co layers along the $z$ direction and an infinite number of layers along the $x$ and $y$ directions. This model estimates a shape anisotropy energy of $0.58 \text{ mJ/m}^2$ that favors an in-plane orientation of the magnetic moments. Therefore, the total magnetic anisotropy energy (MAE) calculated as a sum of magnetocrystalline and shape contributions is equal to $-1.24 \text{ mJ/m}^2$ for four layers of Co.

Increasing the number of Co layers diminishes the absolute value of MAE, causing anisotropy reorientation in thicker films, as observed experimentally [32]. The MCA contribution does not show any significant dependence on the number of Co layers, varying in the range of $-1.75$ to $-1.85 \text{ mJ/m}^2$ (see Fig. S1 in the Supplemental Material [45]), which confirms the interfacial origin of PMA. On the other hand, the increased shape anisotropy contribution ($-1.73 \text{ mJ/m}^2$ for eight Co layers) becomes dominant for Co layers thicker than $\sim 1 \text{ nm}$.

### B. Effect of H insertion on magnetic properties of Co/Pd

To understand the effects of hydrogen insertion on the magnetic properties of Co/Pd thin heterostructures, we first considered a fully hydrogenated Co/Pd interface and further investigated the magnetic properties for various hydrogen concentrations and distribution profiles.

As is seen from Fig. 1(c), hydrogenation of the Co/Pd interface leads to a reduction of the magnetic moments down to $1.31$ and $0.03 \mu_B$ for interfacial Co and Pd atoms, respectively. This is in a good agreement with recent experimental studies of hydrogenated Co/Pd alloys [38], where a decreased magnetization was observed after hydride formation. We also
demonstrated that hydrogenation affects the orbital moments of interfacial atoms, reducing perpendicular anisotropy and promoting the in-plane component. In particular, the local orbital moment of interfacial Co reduces to 0.043 and 0.053 \( \mu_B \) for out-of-plane and in-plane directions, respectively. In accordance with the Bruno model [35,36], an alteration of orbital moment anisotropy causes rotation of the magnetic moments. Our calculations confirm that magnetocrystalline energy changes its sign and becomes equal to 0.57 mJ/m\(^2\), favoring an in-plane orientation of magnetic moments.

A comparison between the layer-resolved decomposition of magnetocrystalline energy before and after hydrogenation [see Figs. 1(b) and 1(d)] demonstrates that magnetic anisotropy switching is caused by two key changes in the electronic structure. First is the sharply decreased contribution of \( d_{xy} \) and \( d_{x^2-y^2} \). Second is the dramatically increased occupancy of \( 3d_z \) and \( 3d_x \) Co orbitals at the interface with Pd (see, also, Fig. S2 in the Supplemental Material [45]), which promotes in-plane magnetocrystalline anisotropy. Simultaneously, the reduced magnetic moments diminish the contribution of the shape anisotropy down to 0.32 mJ/m\(^2\). This leads to a total anisotropy of 0.88 mJ/m\(^2\) favoring in-plane magnetization. We next show that the effect of hydrogen incorporation into the Co/Pd lattice also depends on the hydrogen distribution and concentration profiles.

C. Hydrogen distribution profiles and concentration effect on magnetic anisotropy of Co/Pd

Since the solubility of hydrogen in bulk Pd layers is known to be considerably higher compared to that in bulk Co [19], we first assumed that hydrogen accumulates in the Pd layers and does not reach the interface with Co. However, in this case, no significant changes of magnetic anisotropy were observed. Our calculations revealed that the change in the electronic structure decays very fast with the distance of the Co/Pd interface. Therefore, we can reasonably assume that hydrogenation of highly textured Co/Pd layers could lead to the formation of CoH\(_x\), similar to what was reported for Co-containing compounds hydrogenated using an arc discharge method [40].

Assuming a homogeneous distribution of hydrogen atoms within the Co/Pd interface, we calculated the dependence of magnetic anisotropy on hydrogen concentration, as shown in Fig. 2(a). At small concentrations, H insertion enhances PMA, leading to MAE of 1.47 mJ/m\(^2\) for H per metal atom (H/M) equal to 0.2. On the other hand, larger concentrations of hydrogen provoke reduction of PMA and eventually causing anisotropy switching at concentrations of \( \sim 0.7 \) H/M. The nonmonotonic dependence of the magnetic properties on H concentration is caused by competing contributions arising from two factors: H atoms at the interface and hydrogenation of the interior Co layer. We found that hydrogen insertion...
at the interface between Co and Pd atoms diminishes PMA, affecting hybridization between 4d Pd orbitals and 3d orbitals of Co as described above. Hydrogenation of interior Co produces the opposite effect. These findings can help to reconcile the contradicting experimental data, where both PMA enhancement and reduction were observed depending on hydrogen concentration and material texture [28,29].

While the assumption of epitaxial growth is an appealing theoretical idealization, real Co films show some deviations from perfect epitaxial growth [32,39]. The substantial lattice mismatch may cause an introduction of interfacial dislocations to reduce the stress in interior Co planes. To address this scenario, we considered accumulation of hydrogen atoms only at the Co/Pd interface.

As is seen in Fig. 2(b), hydrogen accumulation at a single interface leads to a significant reduction of PMA. However, anisotropy switching is not observed even for high H concentration due to the significant impact of the second unaffected Co/Pd interface. To achieve anisotropy switching, one has to consider the presence of hydrogen atoms at both Co/Pd interfaces, which could be driven by H diffusion through a thin Co layer as observed experimentally [17]. In this case, anisotropy switching occurs at the moderate H/M concentration of ~0.4–0.5. These changes are followed by a reduction of magnetic moment for both Co and Pd atoms in the vicinity of H defects. An absorbed H atom reduces the magnetic moment of the nearest Co atoms by ~0.1 μB for a dilute concentration, while a more significant reduction of 0.6 μB is observed for a fully hydrogenated Co/Pd interface.

D. Effect of H insertion at the interface of various FM/NM trilayers

Using fully self-consistent calculations including the SOC effect, we carried out a screening of various trilayers made of a ferromagnet (FM= Co or Fe) a nonmagnetic metal (NM= Pd,Pt,V) commonly used in spintronics. We calculated their response to hydrogenation of interfacial layers. We limited our calculations to high hydrogen concentrations and assumed accumulation of hydrogen only at the interface between FM and NM materials, as shown in Figs. S3 and S4 in the Supplemental Material [45].

As is seen in Fig. 3, our calculations predict PMA for Co/Pd, Co/Pt, and Fe/Pd trilayers in accordance with previous experimental studies [13]. The analysis of orbital-resolved contributions (see Fig. S6 in the Supplemental Material [45]) to the magnetocrystalline anisotropy energy of (100) Fe/Pd thin films is associated with a change in the 3d Pd orbital occupation caused by H intercalation, which also correlates with orbital moment anisotropy switching (see Fig. S5 in the Supplemental Material [45]). In spite of slightly increased shape anisotropy of 0.77 m2/μm², the negative total magnetic anisotropy energy of ~0.11 μm² confines the magnetization to the out-of-plane direction, as shown in Fig. 3. As was discussed above, the main driving mechanism for magnetization switching is a change in the electronic structure near the interface. In the case of Fe/V trilayers, hydrogenation causes an increased contribution from d_{z^2−r^2} and d_{xy} orbitals (see Fig. S5 in the Supplemental Material [45]), which promotes perpendicular anisotropy in accordance with second-order perturbation theory [34].

IV. CONCLUSIONS

In summary, using first-principles calculations, we have resolved the effects of hydrogenation on magnetic properties of representative ferromagnet/nonmagnetic metal thin-film trilayers. In particular, we found that anisotropy switching in Co/Pd thin films is associated with a change in the 3d Co and 4d Pd orbital occupation caused by H intercalation, and both the position and the concentration of hydrogen affect the resulting behavior. First, hydrogen accumulation at
Co/Pd interfaces leads to a reduction of perpendicular magnetic anisotropy and further magnetic anisotropy switching to the in-plane direction. Second, progressive intercalation of hydrogen into the interior Co layers enhances perpendicular magnetic anisotropy. These two competing contributions can explain a nonmonotonic dependence of the magnetic coercive field on hydrogen concentration that was previously observed experimentally [28,29].

Furthermore, we demonstrated that hydrogenation of Co/Pt and Fe/Pd thin-film heterostructures may also cause spin reorientation, leading to in-plane anisotropy. We predict the opposite effect for Fe/V trilayers, which demonstrate a spin reorientation transition from in-plane to out-of-plane after hydrogen insertion. Hydrogenation appears to be a powerful tool to manipulate the magnetic properties of ferromagnet/nonmagnetic metal layers. Our results advance the understanding of how hydrogen couples to the interface electronic structure locally in manipulating the magnetic anisotropy, and will stimulate further experimental advances.

ACKNOWLEDGMENTS

This work was primarily supported by the National Science Foundation (NSF) through the Massachusetts Institute of Technology Materials Research Science and Engineering Center (MRSEC) under Award No. DMR-1419807. The DFT calculations were carried out using the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation Grant No. ACI-1548562 [46].

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