

Research article

Impact of He⁺ ion irradiation on the domain wall dynamics in Pd/Co/Pd trilayers with perpendicular magnetic anisotropy

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ABSTRACT

Heavy metal/ferromagnetic-based heterostructures with perpendicular magnetic anisotropy (PMA) are prototypes for domain wall (DW)-based spintronic devices. We explored the impact of He⁺ ion irradiation on the bubble DW dynamics in Pd/Co/Pd trilayers with PMA. The effective magnetic anisotropy (K_{eff}) is enhanced by 20% when irradiated at the lowest fluence value, 1×10^{14} He⁺/cm² and further, it decreases with an increase in fluence. Field-induced domain wall motion studies revealed that the sample irradiated at this fluence required a higher magnetic field for bubble domain walls to attain the same velocity as in the pristine sample. The bubble domain walls in the sample irradiated at this fluence expand at a rate of 1.1 mm/s, in contrast to the pristine sample's rate of 0.38 mm/s near the coercive region, and this expansion rate diminishes with increasing fluence. At the lowest fluence value, bubble domains increase in size while their number density diminishes. However, with increased fluence, the size of the bubble domains reduces and their number density rises. Higher fluence values increase the interlayer roughness, driven by ballistic collisions between low-energy ions and atoms. The enhanced intermixing at higher fluence results in reduced saturation magnetization and anisotropy energy. Thus, by engineering the interfaces of the heterostructure and the magnetic anisotropy, ion interactions can be used to tune the pinning-controlled dynamics of magnetic bubble domains in Pd/Co/Pd based spintronic devices.

1. Introduction

Perpendicular magnetic anisotropy (PMA) - where spin finds its easy axis normal to the film plane - in heavy metal (HM)/Co-based multilayers is widely explored for the development and optimization of spin-orbit torque (SOT)-magnetic random-access memory (MRAM) [1]. All metallic HM/Co/HM thin film heterostructures, such as Pt/Co/Pt and Pd/Co/Pd with PMA host exotic magnetic structures such as stable room-temperature skyrmions [2] and magnetic bubble domains of a few nanometers [3,4], which are crucial for next-generation spintronic devices such as logic-in-memory architectures and racetrack memory [5]. The fundamental working principles of these devices are determined by several factors, such as interfacial Dzyaloshinskii-Moriya

interaction (iDMI) [6,7]- the anti-symmetric exchange interaction that stabilizes chiral Néel domains [8], spin-orbit torque (SOT) [9], high PMA [10], and domain wall (DW) dynamics [4,11]. Most of these factors are controlled by the quality of the HM/Co interfaces. iDMI causes an asymmetric propagation of bubble domains in Pd/Co/Pd systems [3], while the presence of PMA with iDMI stabilizes chiral DW. The iDMI and the spin Hall angle are controlled by the structure inversion asymmetry at the interfaces. In a nominally symmetrically designed HM/Co/HM layer system, chiral domains and asymmetric DW motion could arise from asymmetric interface structure at the HM-ferromagnet interfaces. Interestingly, in Pd/Co/Pd systems, rather than a smooth interface, an intermixed Co-Pd interface stabilizes skyrmions [12]. Thus, tuning the interface quality, such as roughness,

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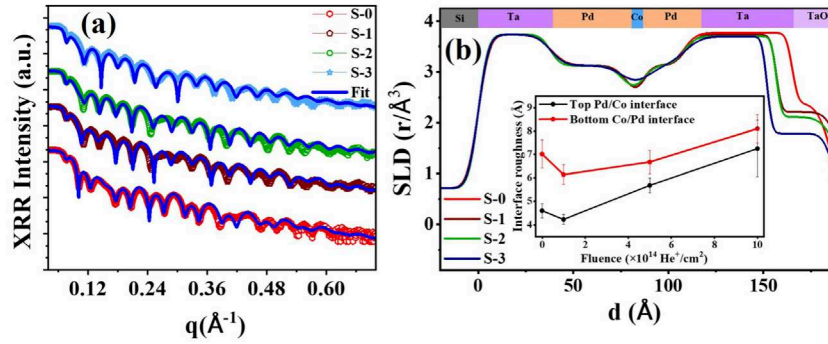


Fig. 1. (a) X-ray reflectivity (XRR) signals for all the samples presented in this study, the symbols are the experimental data, and the continuous blue line shows the best fit to each datum. (b) Scattering length density (SLD) profile showing depth-dependent electron density variations for each sample; the inset shows the variation of top Pd/Co and bottom Co/Pd interfacial roughness as a function of fluence.

interdiffusion, and alloying, enables control over magnetic properties, leading to control of magnetic bubbles.

The DW dynamics of topologically stable bubbles exhibit three distinct dynamical regimes: creep, depinning, and flow regimes. In systems with PMA, at zero temperature, the DW behaves as an elastic interface that is subjected to pinning by local inhomogeneities in the sample under the application of external forces, such as current or a magnetic field [4]. At room temperature, DW exhibits a non-zero velocity against these pinning sites driven by thermal fluctuations under an applied external force, as described by the creep scaling law. The creep regime of DW dynamics follows the universal creep law given by $V = V_0 \exp(-\frac{\alpha}{k_B T} (\mu_0 H)^{\frac{1}{4}})$ [4]. Here, V_0 , α , $\mu_0 H$, k_B , and T are the velocity prefactor, creep constant, applied magnetic field, Boltzmann constant, and temperature, respectively. The creep constant α represents the energy barrier (U_C) due to disorder-induced pinning. A fundamental understanding of how U_C influences the micromagnetic phenomena and the universality of the creep law is required. A deep understanding of the creep regime is crucial for developing devices with tailored properties. The accuracy and scalability of various techniques for regulating creep dynamics are crucial for the development of DW-based devices. Since properties such as the spatial distribution and correlation length of pinning centers strongly influence DW motion, it is useful for applications to control them through various processes. Post-fabrication methods can be used to engineer these nanoscale pinning environments. Here, ion beam irradiation serves as a powerful tool for tailoring interfaces of heterostructure to tune their functional properties [13–22]. By influencing the interfacial structure and altering defect densities in heavy-metal (HM)/ferromagnet (FM), ion irradiation can affect PMA gradients, creep exponents, and thus magnetic DW velocity. Irradiation using light ions (H^+ , He^+) can be used to tune the anisotropy, saturation magnetization, depinning field (H_{dep}), etc. of MTJ structures. Recent studies show that irradiation using swift heavy ions can enhance the ferromagnetic properties and PMA in metallic heterostructures [23]. Recently, He^+ irradiation has been used to tune iDMI, thereby engineering the skyrmion size and density in CoFeB/MgO using focused Ga^+ irradiation [24]. Irradiation with 30 keV He^+ ions induces alloying at HM/Co interfaces, thereby increasing the Barkhausen length [25].

In this work, we demonstrate the tuning of magnetic bubble domain dynamics in He^+ irradiated Ta/Pd/Co/Pd/Ta heterostructures. We employ symmetric field-induced domain wall motion using Kerr microscopy to study DW dynamics in the creep regime and to correlate changes in DW velocity and static magnetic properties with structural properties and interface variations in pristine and irradiated heterostructures.

2. Experimental section

Ta(4)/Pd(4)/Co(0.5)/Pd(2)/Ta(5) sample was deposited on Si (001) substrate using dc-magnetron sputtering. The deposition was performed

at room temperature in an ultrahigh vacuum chamber with a base pressure below 2×10^{-9} mbar and an Argon pressure of 5×10^{-3} mbar. The nominal thickness of each layer is expressed in nanometers (nm) in parentheses. Prior to the deposition, the sputtering rate of each material in the stack was calibrated. After deposition, the sample was diced into pieces each of 1 cm^2 and irradiated with 45 keV He^+ ions at room temperature with a beam current density of 66 nA/cm^2 corresponding to a flux of 4.10×10^{11} ions/ cm^2/s , using a tabletop accelerator with a Penning ion generator facility at IUAC, New Delhi. The entire sample was within the irradiated beam area to ensure the coverage of the whole surface. The irradiation was carried out at three different fluences, viz. 1×10^{14} , 5×10^{14} , and 1×10^{15} He^+/cm^2 and samples are designated as S-1, S-2, and S-3, respectively, and S-0 for the unirradiated (pristine) sample from now on. To evaluate the effects of irradiation on the heterostructure, structural characterization was performed using X-ray reflectivity (XRR) to probe interlayer thickness and interfacial roughness and X-ray diffraction (XRD) to investigate crystallographic modifications. XRR measurements were performed in $\theta - 2\theta$ geometry from 0.03° to 10° using Cu- $K\alpha$ radiation, with a wavelength $1.54 \text{ \AA}$ (Emperian Malvern Panalytical), a step size of 0.01° , and a time per step of 3 s. XRD measurements were performed in 2θ range of 35° to 45° (Cu- $K\alpha$ source) with a step size of 0.04° and a time per step of 5 s. To study changes in magnetization reversal and DW velocity with irradiation, a magneto-optical Kerr effect (MOKE) magnetometer setup equipped with a Kerr microscope (M/s Evico Magnetics, Germany) was used, applying an external magnetic field ($\mu_0 H$) in the out-of-plane (OOP) direction. The hysteresis measurements were performed with a sweep rate of 1 mT/s , where we waited for 0.2 s at each field value. To study the dynamics of DW, we employed the field-induced domain wall motion (FIDWM) [26,27]. To quantitatively estimate the anisotropy field ($\mu_0 H_K$) and saturation magnetization (M_S), superconducting quantum interference device-vibrating sample magnetometry (SQUID-VSM, Quantum Design) measurements were carried out in the in-plane direction.

3. Results and discussions

Fig. 1a shows the XRR for samples S-0–S-3. Data were fitted using GenX [28] software, employing the Parratt recursion algorithm [29] to determine the interlayer thickness and roughness and to identify irradiation-induced changes at the interfaces. The fitting for all samples was performed by keeping the thickness, roughness values of each layer, and the density of the upper Ta layer as variables. The density of other layers was fixed to its nominal value. From the fitting, we observed that nearly 2.5 nm of the top Ta layer is oxidized. Analysis revealed that the layer thickness and the density of the top oxidized Ta layer varied significantly with fluence. Fig. 1b shows the scattering length density (SLD) profile for all the samples. SLD provides depth-resolved electron density profiles in thin-film heterostructures. For an

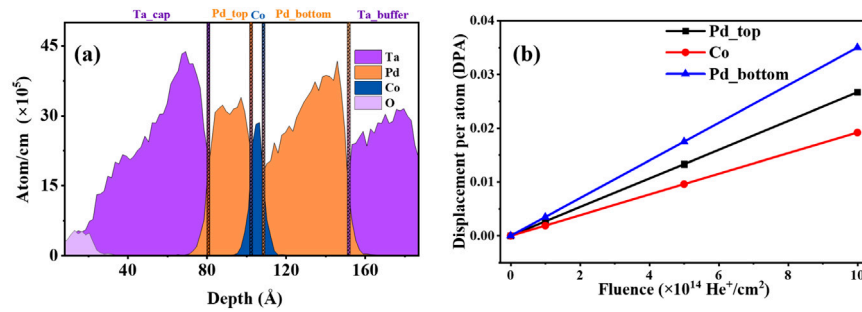


Fig. 2. (a) Atom displacement distribution in Ta/Pd/Co/Pd/Ta heterostructure obtained from SRIM simulation. (b) Displacement per atom (DPA) for non-magnetic top and bottom Pd layers and ferromagnetic Co layer as a function of fluence. DPA increases linearly with fluence.

Table 1

Interface roughness for the top Pd-Co (σ_{top}) and bottom Co-Pd (σ_{bottom}) derived from XRR fitting. The figure of merit (FOM) values obtained from XRR fitting for the S-0, S-1, S-2, and S-3 samples are 0.16, 0.16, 0.19, and 0.18, respectively.

Sample	σ_{top} (Å)	σ_{bottom} (Å)
S-0	4.60 $\pm$ 0.30	7.02 $\pm$ 0.60
S-1	4.23 $\pm$ 0.20	6.14 $\pm$ 0.42
S-2	5.68 $\pm$ 0.47	6.68 $\pm$ 0.53
S-3	7.25 $\pm$ 1.21	8.10 $\pm$ 0.60

ideal sample with a smooth interface, the SLD profile resembles a step function, with each step corresponding to the scattering density of an individual layer in the multilayer stack. SLD profiles reveal that the SLD of Co in S-3 is 10% higher than that in S-0. The variation in the top Pd-Co and bottom Co-Pd interfacial roughness with fluence is shown in the inset of Fig. 1b and summarized in Table 1. It is observed that for S-0, the interfacial roughness of the top Pd/Co interface (4.60 $\pm$ 0.30 Å) is lower than that of the bottom Co/Pd interfaces (7.02 $\pm$ 0.60 Å), i.e. $\sigma_{top} < \sigma_{bottom}$. A comparison of XRR fits for S-0 with different combinations of σ is given in the supplementary section (Figure S1). XRR analysis reveals that the interfacial roughness at the HM/FM region in S-1 is reduced relative to the pristine sample (S-0) and later increases with fluence. The enhanced density (SLD) observed in S-3 is consistent with the intermixing that occurred during irradiation [22].

SRIM [30] simulations were performed to calculate the displacement per atom (DPA) introduced by irradiation. The simulations were performed using detailed calculations with full damage cascade with 45 keV He⁺ replicating the actual experimental parameters. Simulation confirms that all ions pass through the entire multilayer stack and reach the Si substrate, with a projected range of 106 nm. Fig. 2a shows the atomic displacement density distribution obtained from SRIM. The presence of foreign atoms at the interfacial region of heterostructures confirms intermixing due to ion-target atom interactions. The variation of DPA for top Pd, Co, and bottom Pd layers as a function of fluence is shown in Fig. 2b, which clearly shows that DPA increases linearly with fluence. Notably, an asymmetry is observed in the DPA of the top and bottom non-magnetic layers, with the bottom Pd layer exhibiting a higher DPA than the top Pd layer. The asymmetric DPA observed in the top and bottom Pd layers can be ascribed to the collision cascades. The incident ions in the mentioned energy range may lose energy primarily through elastic collisions with the target atoms. When the energy transferred during the collision exceeds the binding energy, it produces knock-on atoms. Subsequent collision of these primary recoil (knock-on) atoms, which have sufficient kinetic energy, with neighboring atoms may displace them [31]. This, in turn, leads to a cascade of atomic displacements that can range into the deeper part of the heterostructure. Consequently, the incident He⁺ ions that traverse till the substrate, along with the displaced knock-on atoms, contribute to additional vacancies, leading to a larger DPA

in the bottom Pd layer. The ion beam-induced short-range motion of atoms can enhance the interfacial roughness, while the displacement through a large range causes alloy formation [32]. The ion-matter interaction could be ballistic [20], favoring thermodynamic intermixing due to the positive enthalpy of mixing between Co and Pd. In addition to intermixing, differences in tensile strain can also influence the anisotropy of heterostructures [33]. XRD data of these samples are presented in the supplementary section (Figure S2). The observed peaks at 38.3° and 40.3° correspond to Ta (011) and Pd (111) planes, respectively. Since the He⁺ interaction with the present energy and fluence range only induces atomic displacement, the XRD shows that the system's crystalline nature is preserved even after irradiation. The 2 θ peak positions shift to a higher θ region after irradiation. This could be the relaxation of existing stress in the system, induced by the ion interaction. This stress relaxation in the heterostructures contributes to changes in the magnetic anisotropy [34]. While the FWHM of the Pd(111) peak in S-1 is lower than that of S-0 (shown in supplementary file Figure S2). This shows an enhanced crystallinity in S-1. Later, FWHM of Pd(111) decreases in S-2 and S-3.

Fig. 3a shows the MOKE hysteresis loops for pristine and irradiated samples under an OOP magnetic field. For all the samples, hysteresis loops exhibit a single-step sharp switching with a unit remanence ($\frac{M_R}{M_S} = 1$), revealing the presence of strong PMA even after irradiation. The variation in coercivity ($\mu_0 H_C$) with fluence is shown in Fig. 3b black symbols. $\mu_0 H_C$ of the pristine sample is 11.6 mT, while irradiation at a fluence of 1×10^{14} He⁺/cm² leads to an enhancement of $\mu_0 H_C$ (13.5 mT); thereafter, it decreases with increasing fluence. At the highest fluence, $\mu_0 H_C$ is 9.5 mT. Since all samples exhibit unit remanence and magnetization reversal is dominated by domain wall nucleation and propagation, the nucleation field $\mu_0 H_N$ is close to $\mu_0 H_C$. The difference between the coercive field and the nucleation field ($\Delta H = \mu_0 H_C - \mu_0 H_N$) is noted as 1.4, 1.2, 2.3, and 1.5 mT for S-0, S-1, S-2, and S-3 samples, respectively. The $\mu_0 H_C$ is influenced by defect distribution, domain wall pinning, and the effective magnetic anisotropy in each sample.

The in-plane M-H loops measured using SQUID-VSM for all the samples are shown in the supplementary file as Figure S3. The S-0 has a saturation moment M_S of 1634 ($\pm$ 52) $\times 10^3$ A/m, which is high compared to the reported magnetic moment of 1400 $\times 10^3$ A/m for fcc Co [35]. This enhanced moment observed in S-0 can be attributed to the induced moment in the few monolayers of the Pd layer in proximity to the Co layer, as we found in our previous studies on similar heterostructures of Pd/Co/Pd [36] and Pt/Co/Pt [37]. M_S for S-1 is 1695 ($\pm$ 57) $\times 10^3$ A/m. Later, as fluence increased, M_S decreased for S-2 and S-3. Further, S-1 exhibited an enhanced $\mu_0 H_K$ of 419 ($\pm$ 10) mT compared to that of S-0, for which $\mu_0 H_K$ is 370 ($\pm$ 10) mT. S-3 has the least $\mu_0 H_K$ of 280 ($\pm$ 10) mT. The effective anisotropy energy (K_{eff}) is calculated for each of the samples using the formula $K_{eff} = \frac{\mu_0 M_S H_K}{2}$, its variation with fluence is shown in Fig. 3b. The K_{eff} for each sample is also tabulated in Table 2. Variation of $\mu_0 H_C$ observed from MOKE hysteresis as a function of fluence is consistent with variation in K_{eff} .

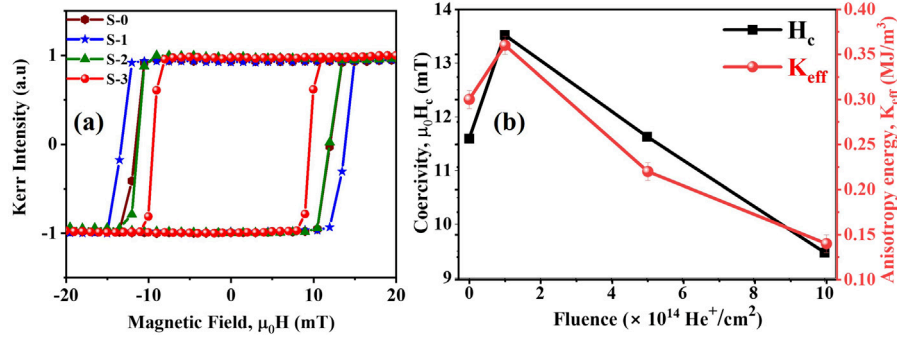


Fig. 3. (a) Polar MOKE hysteresis for pristine (S-0) and samples irradiated at 1×10^{14} (S-1), 5×10^{14} (S-2) and 1×10^{15} He^+/cm^2 (S-3), square loops confirms strong PMA in all the samples. (b) Variation of coercivity ($\mu_0 H_c$) calculated from the PMOKE hysteresis (black symbols) and anisotropy constant (K_{eff}) from SQUID-VSM (in red symbols) as a function of fluence.

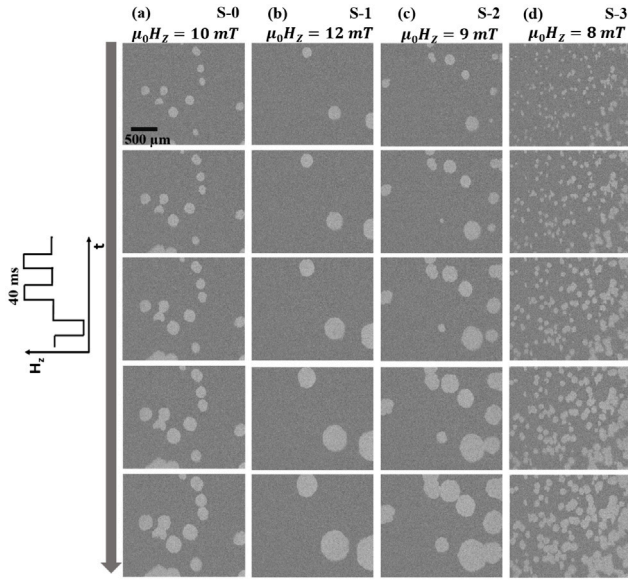


Fig. 4. Column (a) depicts the bubble domains observed using Kerr microscopy from (a) S-0, (b) S-1, (c) S-2, and (d) S-3. Each row represents domains under five continuous magnetic field pulses with a pulse width of 40 ms for respective samples. Magnetic field amplitudes of 10 mT, 12 mT, 9 mT, and 8 mT were used for each sample, respectively. One can see that the nucleation centers are reduced for S-1, while a large number of nucleation sites are present in S-3. The scale bar is the same for all the images.

Table 2

Nucleation field ($\mu_0 H_N$) calculated from Kerr microscopy, Anisotropy energy (K_{eff}), interface anisotropy energy (K_i), DW width (Δ) and DW energy (σ) calculated from SQUID-VSM measurements.

Sample	$\mu_0 H_N$ (mT)	K_{eff} (MJ/m ³)	K_i (mJ/m ²)	Δ (nm)	σ (mJ/m ²)
S-0	10.2	0.30 ± 0.01	1.10 ± 0.2	7.30 ± 0.1	8.76 ± 0.1
S-1	12.30	0.36	1.20 ± 0.2	6.67 ± 0.1	9.60
S-2	9.30	0.22	0.57 ± 0.1	8.53 ± 0.2	7.50
S-3	8.0	0.14	0.47 ± 0.1	10.69 ± 0.4	6.00

The interface anisotropy, K_i is calculated using the equation: $K_i = (K_{eff} + \frac{\mu_0 M_s^2}{2})t_{Co}$. Where t_{Co} (0.57 ± 0.02 nm) was determined from the XRR of the pristine sample. We have noted negligible variation in the thickness of Co (± 0.03 nm) with ion fluence. For S-0, K_i is obtained as $1.1 (\pm 0.2)$ mJ/m², while for S-1, it is $1.2 (\pm 0.2)$ mJ/m². Further, K_i reduces to $0.47 (\pm 0.1)$ mJ/m² for S-3.

Fig. 4 shows the images of magnetic domains from each sample acquired using Kerr microscopy. The bubble domains observed in each sample (in column) during magnetization reversal and grown under an externally applied OOP magnetic field pulses with a pulse width of 40 ms are shown here. From the domain images, it is clear that magnetization reversal initiates with the nucleation of bubble domains, which then expand as the magnetic field increases. The nucleation field ($\mu_0 H_N$) for each sample is listed in Table 2. S-1 shows an enhanced $\mu_0 H_N$ of 12.3 mT, while it is 10.2 mT for S-0. It is observed that the bubble domain density decreases for S-1 compared to the S-0 and subsequently increases with increasing fluence. In comparison with other samples, S-3 has a large number of nucleation centers. These observations on DW nucleation and density can be correlated with the structural modifications induced by irradiation, which contribute to defect-assisted nucleation centers by changing the local magnetic energy landscape and the average effective anisotropy.

The values of K_{eff} , K_i , the Bloch DW width, $\Delta = \sqrt{\frac{A}{K_{eff}}}$, and the Bloch DW energy, $\sigma = 4\sqrt{AK_{eff}}$ (where A is the exchange stiffness of fcc Co) for all samples are tabulated in Table 2. The value of A is assumed to be independent of fluence, and a constant value of $16 \frac{\text{pJ}}{\text{m}}$ [38] is taken into account. The validity of this assumption was evaluated through a sensitivity analysis as described in the supplementary material, Table S1. Δ decreases for S-1 compared to the unirradiated sample (S-0) and then increases, while σ , since it is directly proportional to K_{eff} , exhibits a similar trend as K_{eff} . The DW energy compensates for the energy required to form a domain. The PMOKE hysteresis, together with Kerr microscopy images, reveals that irradiation considerably modifies the magnetic microstructural properties. Thus, nucleation density may depend on irradiation modified defect density, effective anisotropy and the applied field. S-1 ($K_{eff} = 0.36 \frac{\text{MJ}}{\text{m}^3}$) requires a larger reversed magnetic field to initiate the domain nucleation, representing an enhanced energy barrier of nucleation. Thus, a reduced nucleation density in S-1 is consistent with enhanced K_{eff} . While the nucleation density is significantly higher in S-3 (having a lower K_{eff} of $0.14 \frac{\text{MJ}}{\text{m}^3}$) compared to the other samples. The increased nucleation of domains in S-3 could be due to enhanced local inhomogeneities and defects introduced at higher fluence, which can reduce K_{eff} . The reduced K_{eff} and K_i in S-3 lead to rapid spontaneous demagnetization. The PMA in Pd/Co/Pd multilayers could be attributed to Co(3d)–Pd(4d) hybridization. Orbital interactions and bond anisotropy at the HM/FM interface could also contribute to PMA [39]. In our previous studies, an anisotropy in Pd-Co bond length was observed in Pd/Co/Pd trilayers with PMA using X-ray absorption spectroscopy (XAS) [36]. In the present case, for Pd/Co/Pd trilayers, the PMA remains intact under irradiation up to a fluence of $1 \times 10^{15} \text{He}^+/\text{cm}^2$, the highest fluence used in this study. As discussed before, XRR analysis reveals that both the top and bottom Pd/Co interfaces are affected by irradiation and that the interfacial roughness exhibits an asymmetrical

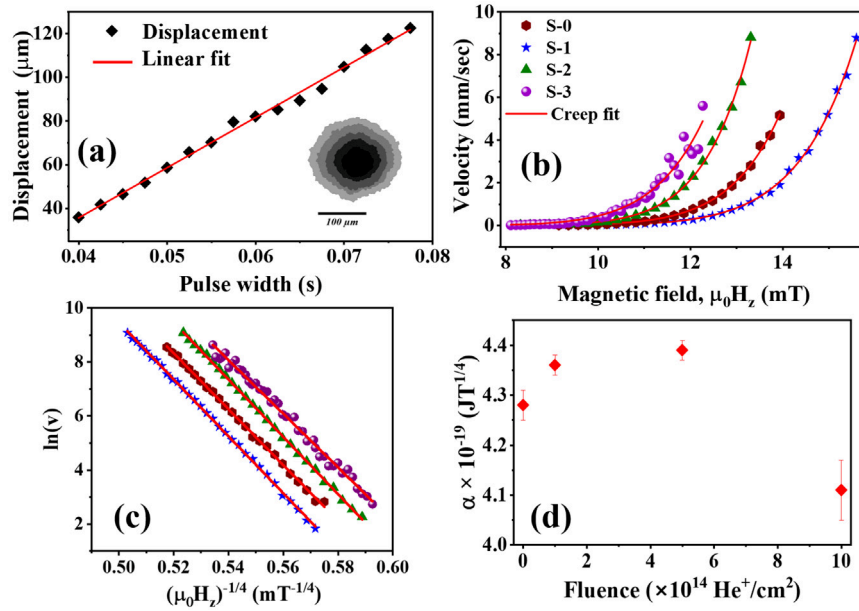


Fig. 5. (a) Representative pulse width–displacement graph from the field-induced domain wall motion (FIDWM) study, the data is linearly fitted (R-square value = 0.99) to calculate the velocity for the particular applied OOP magnetic field. FIDWM for S-0 obtained using the differential polar Kerr microscopy technique under an applied OOP field of 13 mT and pulse width of 2.5 ms is shown in the inset. The diameters of illustrated bubble domains after each applied magnetic field pulse are 66, 98, 119, 155, and 185 μm . (b) Magnetic field ($\mu_0 H$)–Velocity (V) response for each sample from the FIDWM experiment. (c) $\ln(V) - (\mu_0 H)^{-1/4}$ from the DW velocity profile shown in (b) with the same legend. The red line is the creep-law fit for each datum. (d) Variation of the creep constant (α), obtained from the slope of $\ln(V) - (\mu_0 H)^{-1/4}$, with fluence.

pattern. A non-symmetric chemical potential for mixing of Co and Pd may result in asymmetrical roughness across the interfaces [40]. Here, both the top and bottom Pd/Co interfaces contribute to PMA [39]. Corresponding to the XRR, the SLD profile becomes increasingly diffuse at higher fluence (S-3), indicating that He^+ irradiation induces significant interfacial modifications while preserving the overall layer structure. We have observed that S-1 has a smoother interface than S-0. Generally, in the as-deposited multilayer, the interfacial region can have a high defect density. Therefore, initially, irradiation-enhanced diffusion can result in partial annihilation of these pre-existing interfacial defects [41,42]. Such annihilation of defects via irradiation can enhance crystallinity and thereby the magnetic properties in HM/Co/HM multilayers [43]. The reduced interfacial roughness observed in S-1 in the present case may be attributed to this partial annihilation of existing defects. Further, combined PMOKE and magnetometry analysis reveals that irradiation causes a noticeable enhancement in $\mu_0 H_N$ and $\mu_0 H_K$, and a reduction in nucleation of bubble domains in S-1 due to a smooth interface. During the same time, the magnetization reversal mechanism is preserved till S-3. As mentioned before, irradiation can enhance intermixing across interfaces, leading to the formation of HM-FM alloys. The disruption of roughness correlation across the film typically influences the hybridization of HM-FM orbitals [44]. Also, an intermixed interface can exacerbate localized defects [45], cause pinning [46], affect both micro-magnetic and macro-magnetic properties of heterostructures [47], and even render magnetically inactive layers at interfaces [48]. Thus, the effect of K_i is more dominant at higher fluence, where a significant disruption of interface quality occurs. Further, this also leads to a reduction in the M_s .

Further, to study the DW dynamics of heterostructures after ion-beam interaction, a quasi-static method, field-induced DW motion (FIDWM), was performed. The central result of FIDWM is summarized in Fig. 5. Fig. 5a shows the representative pulse width-displacement graph, which represents the displacement of the bubble domain in S-0 obtained under an applied out-of-plane field pulse of 13 mT at an interval of 2.5 ms. The slope of the pulse width-displacement graph gives the steady-state velocity of the domains at the particular value

of the applied magnetic field. Thus, the pulse width-displacement data are linearly fitted to calculate the velocity for the specific OOP field, and this procedure is then repeated for various applied magnetic fields. The velocity (V) response to the applied magnetic field values $\mu_0 H$ for each of the samples is shown in Fig. 5b. The velocity curve for S-1 shifts to the right side, a higher magnetic field region, compared to S-0. At higher fluence (samples S-2 and S-3), the $\mu_0 H - V$ curve shows a leftward shift to the lower magnetic field region. This shift in $\mu_0 H - V$ characteristics can be attributed to a change in the depinning field ($\mu_0 H_{dep}$), where $\mu_0 H_{dep}$ is the minimum magnetic field to move the DW across a pinning site. In S-1, $\mu_0 H_{dep}$ could be higher than S-0; hence, it requires a higher magnetic field to attain the same velocity as that of S-0. In contrast, a decrease in PMA decreases the $\mu_0 H$ to attain the same velocity in other samples.

The FIDWM was performed in the creep regime of DW dynamics, which can be realized by applying a magnetic field ($\mu_0 H$) that drives the motion of a thermally activated DW in a disordered medium [26]. Now the creep equation can be expressed as: $\ln V = \ln V_0 - \frac{\alpha}{k_B T} (\mu_0 H)^{-1/4}$ which represents a straight line with slope equal to $\frac{\alpha}{k_B T}$ and intercept equal to $\ln V_0$, shown in Fig. 5c. The red line is the creep law fit to each of the data set. One can see that these lines are nearly parallel to each other. The creep constant can be expanded as $\alpha = U_C (\mu_0 H_{dep})^{1/4}$. The creep scaling constant α has been calculated from the slope of the straight-line fit and is shown in Fig. 5d. For the pristine sample, α is $4.28(\pm 0.03) \times 10^{-19} \text{ JT}^{1/4}$, and for S-3, it is $4.11(\pm 0.06) \times 10^{-19} \text{ JT}^{1/4}$.

The variation of $\mu_0 H_{dep}$ [49] with fluence, is shown in Figure S4. Initially, the depinning field increased (from S-0 to S-1), then decreased. Further, the $\mu_0 H_{dep}$ is proportional to the K_{eff} [50], $\mu_0 H_{dep} \propto \frac{\sqrt{K_{eff} n_i^{2/3}}}{M_s}$. Thus, the enhanced $\mu_0 H_K$ requires a higher magnetic field to achieve the same velocity as in the unirradiated sample. While S-3, which has a lower $\mu_0 H_{dep}$ and shows a large number of nucleated domains, hence a lower anisotropy, requires a lower magnetic field to achieve the same velocity as other samples.

4. Conclusion

In summary, we have investigated the effect of He^+ irradiation on the magnetic properties of Pd/Co/Pd trilayers with perpendicular magnetic anisotropy (PMA). The samples were irradiated with He^+ ions of fixed energy at different fluence. Irradiation affects both the structural and magnetic properties, including the domain wall (DW) dynamics in Pd/Co/Pd trilayers. In this system, strong PMA stabilizes the magnetic bubble domains. Irradiation primarily modifies the Pd-Co interfaces, thereby altering their roughness. This is confirmed by the X-ray reflectivity and the scattering length density parameters. SRIM simulations reveal that the displacement per atom increases linearly with ion fluence. The displacement per atom of the bottom Pd layer is larger compared to the top Pd layer. SQUID magnetometry calculations reveal that the anisotropy energy (K_{eff}) and DW width evolve with fluence. The anisotropy energy of the sample irradiated at $1 \times 10^{14} \text{ He}^+/\text{cm}^2$ (S-1) was found to be higher than that of the pristine sample (S-0) due to the enhanced interface anisotropy (K_i). The DW density and dynamics change concurrently. In S-1, the enhanced anisotropy and pinning required a higher magnetic field to displace the DWs than in S-0. Later, as the fluence increases, the reduction in K_{eff} induced by irradiation-mediated changes in interface roughness, along with a reduction in the depinning field ($\mu_0 H_{\text{dep}}$), leads to an increase in domain wall velocity in Pd/Co/Pd systems. Our study demonstrates that ion irradiation is a promising tool for tuning the DW nucleation and dynamics in HM/Co/HM heterostructures for spintronics-based memory logic technology.

CRedit authorship contribution statement

Anurag Keloth: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Sakshath Sadashivaiah:** Writing – review & editing, Resources. **Parswajit Kalita:** Writing – review & editing, Resources. **Rakhul Raj:** Writing – review & editing, Resources. **V. Raghavendra Reddy:** Writing – review & editing, Resources. **Bikram Das:** Resources. **Bharti Pandit:** Writing – review & editing, Resources. **Ralf Röhlsberger:** Writing – review & editing, Resources. **P.S. Anil Kumar:** Writing – review & editing, Resources. **Ajay Gupta:** Writing – review & editing, Validation, Methodology. **Sarathlal Koyiloth Vayalil:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.jmmm.2026.174543>.

Data availability

Data will be made available on request.

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