

Inhomogeneity of magnetic anisotropy and damping in nanoscale magnetic tunnel junctions

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We investigate the Gilbert damping constant α and the inhomogeneity of the effective magnetic anisotropy field H_K^{eff} in nanoscale magnetic tunnel junctions (MTJs) with various free-layer diameters D , which have two different structures possessing different magnetic properties around the pattern edge. Homodyne-detected ferromagnetic resonance (FMR) is used, allowing to disentangle the inhomogeneous broadening ΔH_0 owing to the spatial variation of H_K^{eff} from the effects of damping in the linewidth of spectra. We find that ΔH_0 increases with decrease in D , while α is almost constant. The degree of the increase in ΔH_0 is found to change with the MTJ structure. We show that these results are explained by a model considering the distribution of a demagnetizing field that increases with the decrease in D . The obtained findings provide important insights for the development of nanoscale MTJs with high reliability and high efficiency.

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I. INTRODUCTION

Magnetic tunnel junctions (MTJs) have progressed to demonstrate promising performance, enabling their use in practical applications such as spin-transfer torque magnetoresistive random access memory (STT-MRAM), which has already been commercialized at 50 nm in diameter [1,2] and is being further scaled toward 20 nm [3,4]. With MTJs entering a new regime at single-digit-nanometer scales where shape anisotropy becomes dominant [5–9], the demagnetizing field plays a key role. In such device

regimes, it is necessary to experimentally understand how device scaling influences operational characteristics, which include not only the underlying magnetic properties but also device process effects that determine the switching current. The switching current, one of the most important metrics characterizing the MTJ, depends critically on the Gilbert damping as STT competes with a torque caused by the damping. Homodyne-detected ferromagnetic resonance (FMR) [10] is a powerful tool to evaluate the damping [11,12] as well as other parameters such as anisotropy [13,14], STT [15,16], and exchange stiffness [17–19] in nanometer devices. Accordingly, extensive efforts have been made to characterize the damping constant α in relevant devices based on this technique [20–25]. Previously, we reported that the error rate of the STT switching is described by an effective α , which is larger than the one determined by the homodyne-detected FMR and attributed this discrepancy to extrinsic contributions that disturb the coherence of magnetization

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dynamics during the switching [26]. Spatial inhomogeneity of magnetic anisotropy inside the MTJ device is a possible factor causing the large effective α because nanoscale MTJs inherently possess this built-in inhomogeneity that could disturb the coherence of magnetization dynamics [27]. In fact, an inhomogeneity of interfacial magnetic anisotropy in a CoFeB/MgO blanket film was reported to increase the extrinsic contribution to FMR linewidth, i.e., the effective α [28]. Therefore, it is important to distinguish the intrinsic damping from extrinsic contributions such as the spatial inhomogeneity of magnetic anisotropy, which may become increasingly relevant in the scaling of MTJ characteristics toward the single-digit nanometer regime, where demagnetization field plays an important role. Unlimited to the STT switching, inhomogeneity of magnetic anisotropy is known to give rise to nontrivial effects as it affects magnetization reversal processes [29]. For example, the retention time of MTJs was reported to be sensitive to the inhomogeneity of magnetic anisotropy in superparamagnetic regime [30,31], which may be useful for neural-like [32] or probabilistic computing [33]. Also, magnetic skyrmions can be formed in nanoscale MTJ with the aid of the inhomogeneous distribution of stray fields [34,35]. Furthermore, for other applications utilizing MTJs, such as microwave generators [36]/detectors [37,38], reservoir computers with spin-torque oscillators [39,40], magnetic-field sensors, [41], and true random number generators [42,43], the inhomogeneity of magnetic anisotropy, together with α , should crucially affect their performance. Despite its importance, little attention has so far been paid to the inhomogeneity of magnetic anisotropy in MTJ devices unlike α .

In this study, we evaluate α and the inhomogeneity of magnetic anisotropy of nanoscale MTJs with different pattern-edge conditions using the homodyne-detected FMR. The measurement is performed with various MTJ sizes to gain insights into the scaling of MTJs [7]. We discuss the mechanism accounting for the obtained size dependence of the inhomogeneity of magnetic anisotropy.

II. RESULTS

A. Device structure

A stack structure of, from the substrate side, Ta (5 nm)/PtMn (20 nm)/Co (2.6 nm)/Ru (0.9 nm)/CoFeB (2.4 nm)/MgO (1.1 nm)/CoFeB (1.8 nm)/Ta (5 nm)/Ru (5 nm) is deposited by dc/rf magnetron sputtering on a sapphire substrate. The numbers in parentheses are nominal thicknesses. The top CoFeB layer and the bottom synthetic ferrimagnetic layers correspond to the free layer with a perpendicular easy axis and the reference layer possessing in-plane magnetizations pinned by an exchange bias of PtMn, respectively. Using this orthogonal magnetic configuration, we can electrically detect FMR spectra under a

perpendicular magnetic field H alone [12,44], allowing us to disentangle the effects of α and the inhomogeneity of magnetic anisotropy as discussed later in detail. We fabricate MTJ devices with various free-layer diameters D . Two structures of MTJ devices are prepared, which have different sizes of the reference layer: step and standard structures as depicted in Fig. 1(a). The step structure has a much larger reference layer than the free layer, whereas the standard structure has the same size. The magnetic properties near the pattern edge were found to be virtually unchanged (changed) from those of the blanket film for the step (standard) structure due to different ion-beam milling conditions used to pattern the free layer [14,19,45,46].

B. Ferromagnetic resonance measurement

The measurement setup for the homodyne-detected FMR is depicted in Fig. 1(b). The FMR measurement is performed on one representative device for each free-layer size. The representative devices are selected from MTJs exhibiting typical FMR characteristics. All measurements are performed at room temperature. We first focus on the step-structure MTJ. A representative spectrum is shown in Fig. 1(c). We fit the sum of symmetric and anti-symmetric Lorentz functions to spectra corresponding to the lowest mode [19] collected at various radio frequency f_{rf} , where amplitude, resonance field H_r , and linewidth ΔH are fitting parameters [10,19]. Figure 1(d) shows the obtained relationship between ΔH and H_r for the step-structure MTJs with D of 33 nm and 80 nm. These results are well described by a linear function expressed as

$$\Delta H = \Delta H_0 + 2\alpha H_r, \quad (1)$$

where ΔH_0 is the phenomenological inhomogeneous broadening, an extrinsic contribution to ΔH due to the inhomogeneity of magnetic anisotropy. From the slope and intercept of the vertical axis, α and $\mu_0 \Delta H_0$ are determined to be 0.012 and 2.1 mT, respectively, for $D = 80$ nm (μ_0 is the permeability in free space). Such intercepts ΔH_0 have also been observed in previous studies in nanoscale MTJ devices [47,48].

Blue squares in Figs. 1(e) and 1(f) show ΔH_0 and α , respectively, as a function of D from 33 nm to 100 nm for the step structure. The smallest free-layer size investigated in this study is 33 nm, which falls within the size range relevant to the current and near-future STT-MRAM technologies [2]. It is clearly seen that ΔH_0 increases in a monotonic manner with the decrease in D . This trend is also reproduced in micromagnetic simulations, as detailed in the Appendix. In contrast, α is almost constant with respect to D , consistent with previous studies [12], and the value of around 0.01 is in good agreement with the previously reported values for blanket films [28,49–51] and nanoscale MTJs [12] with the same CoFeB/MgO stack

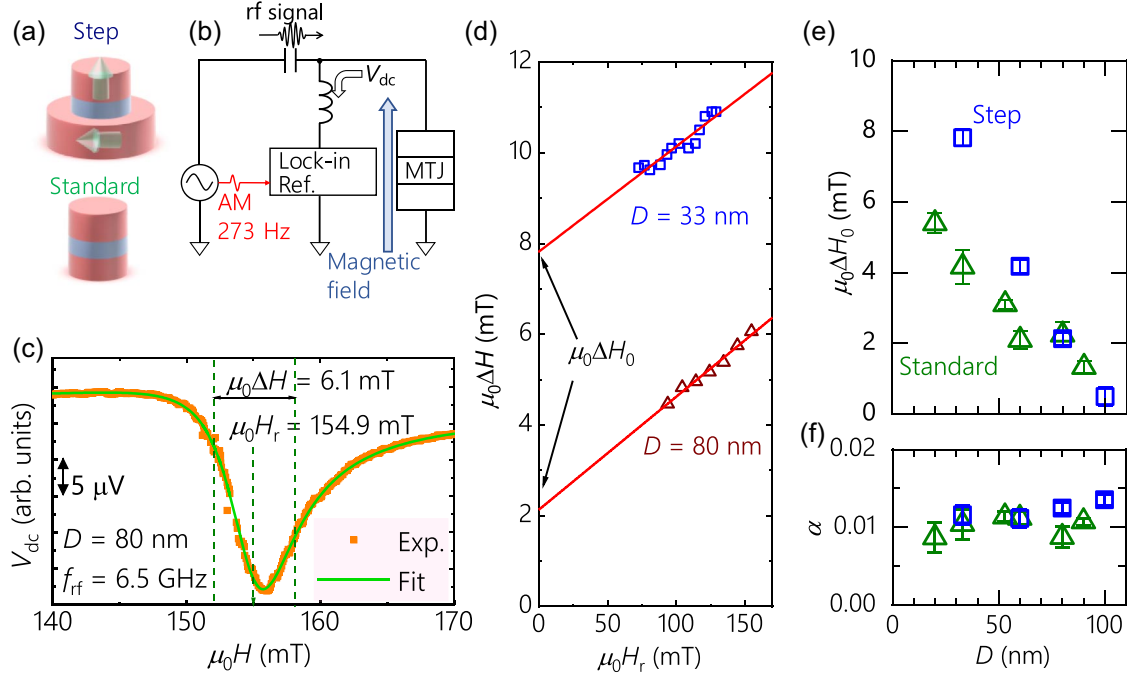


FIG. 1. (a) Illustrations of step and standard MTJ structures. (b) Measurement setup for homodyne-detected FMR. Amplitude of radio frequency signal is fixed to be -25 dBm and modulated at 273 Hz. (c) Representative homodyne-detected FMR spectra at $f_{\text{rf}} = 6.5$ GHz for step structure with D of 80 nm. (d) Resonance-field dependence of linewidth of spectra for step structure with D of 33 nm and 80 nm. D dependence of (e) inhomogeneous broadening and (f) damping constant. Blue squares and green triangles indicate step and standard structures, respectively.

structure. For the α derived by this procedure, spin pumping is considered to be a major extrinsic contribution [52,53]. Other extrinsic effects such as two-magnon scattering [28] are expected to be suppressed because the magnetization always precesses about the device normal during the FMR in the present magnetization configuration. Micromagnetic simulations shown in the Appendix suggest that any additional damping contribution arising from the simulated device structure remains small under the present conditions, including dynamic coupling between the free and reference layers. Note also that the effect of spin pumping is sensitive to the CoFeB thickness [52,53] but not to D . Therefore, it is reasonable to assume that the obtained α and ΔH_0 are independent, allowing us to discuss the respective underlying mechanisms for the two parameters.

III. DISCUSSION

A. Model calculation of the inhomogeneity of magnetic anisotropy field

The inhomogeneity of magnetic anisotropy, which is found to increase with the decrease in D , is expected to relate to a demagnetizing field H_{demag} . Thus, we calculate the radial profiles of H_{demag} and a resultant H_K^{eff} in the nanoscale MTJs. First, the x - y plane of the free layer is divided into 0.1×0.1 nm² square meshes, and the local

demagnetizing field $H_{\text{dz}}(r)$ is calculated as dipole fields from each mesh, where r represents the radial distance from the center of an MTJ. From $H_{\text{dz}}(r)$, averaged demagnetizing factors N_z^{ave} and N_x^{ave} along the z and x directions, respectively, are obtained with their definitions as

$$-\frac{N_z^{\text{ave}} M_S}{\mu_0} = \frac{1}{\pi(D/2)^2} \int_0^{D/2} H_{\text{dz}}(r) 2\pi r dr, \quad (2)$$

$$N_x^{\text{ave}} = \frac{1 - N_z^{\text{ave}}}{2}, \quad (3)$$

where M_S is the spontaneous magnetization, determined to be 1.39 T from a magnetization measurement. Next, we calculate the anisotropy field H_K originating from bulk and interfacial anisotropies as

$$H_K = H_{K,\text{FMR}}^{\text{eff}} - H_{\text{demag}}^{\text{ave}} = H_{K,\text{FMR}}^{\text{eff}} + (N_z^{\text{ave}} - N_x^{\text{ave}}) \frac{M_S}{\mu_0}, \quad (4)$$

where $H_{K,\text{FMR}}^{\text{eff}}$ is the effective anisotropy field obtained by the homodyne-detected FMR [14] and $H_{\text{demag}}^{\text{ave}}$ is the averaged demagnetization field calculated using N_z^{ave} and N_x^{ave} from Eqs. (2) and (3). We can also introduce a local

effective anisotropy field, i.e., the inhomogeneity of anisotropy, as

$$H_K^{\text{eff}}(r) = H_K + H_{\text{dz}}(r). \quad (5)$$

Note that in-plane stray fields from the reference layer with an in-plane easy axis are neglected because of the employed synthetic ferrimagnetic structure. The calculated second term on the right-hand side of Eq. (5) represents the distribution of H_{demag} , which is shown in Figs. 2(a) and 2(b) for $D = 80$ nm and 33 nm, respectively. $H_{\text{demag}}(r)$ is almost constant in the central region and decreases abruptly near the edge for both cases. In the case of $D = 33$ nm, the magnitude of $H_{\text{demag}}(r)$ in the central region is smaller than that for $D = 80$ nm. The corresponding $H_K^{\text{eff}}(r)$ calculated from Eq. (5) for various D is shown in Fig. 2(c). As D decreases, the effect of the abrupt increase in $H_K^{\text{eff}}(r)$ near the edge becomes predominant, and the magnitude of $H_K^{\text{eff}}(r)$ in the central region increases. Figure 2(d) shows the distribution of the magnetic anisotropy field H_{Dist} defined as

$$H_{\text{Dist}} \equiv \sqrt{\frac{1}{N\pi(D/2)^2} \sum_{r=0}^{D/2} [H_K^{\text{eff}}(r) - H_{K,\text{FMR}}^{\text{eff}}]^2 2\pi r}, \quad (6)$$

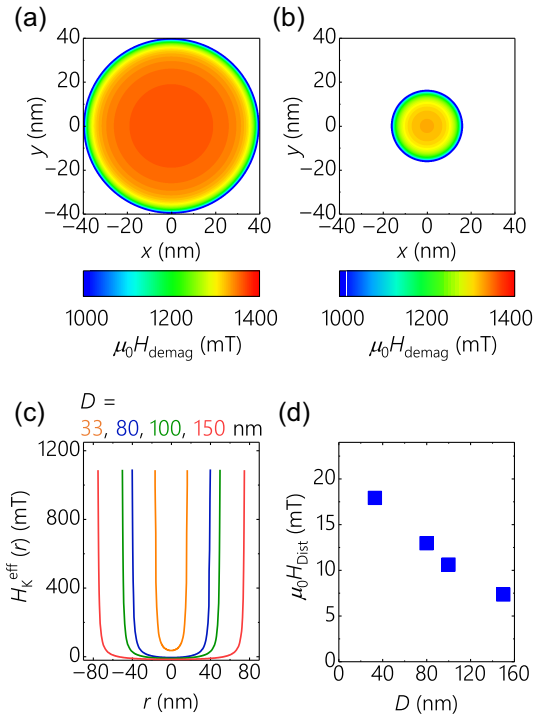


FIG. 2. Demagnetizing-field distribution in the top view of MTJs with (a) $D = 80$ nm and (b) $D = 33$ nm. (c) Radial profiles of the effective magnetic anisotropy field for various D . (d) D dependence of the magnetic-anisotropy-field distribution. All figures are obtained from numerical calculations.

where N is the total number of meshes along the radial direction. H_{Dist} , considered to be directly relevant to the inhomogeneity of magnetic anisotropy, increases with the decrease in D , qualitatively consistent with the behavior of ΔH_0 shown in Fig. 1(e). This suggests that the distribution of H_{demag} is a dominant factor for the inhomogeneity of magnetic anisotropy, rather than previously suggested factors related to crystalline magnetic anisotropy [54], surface- or interfacial-roughness-induced distribution [55] of interfacial magnetic anisotropy [28], or local magnetization angle [52].

B. Edge effect on effective magnetic anisotropy field

Next, we compare the step and standard structures, which are expected to have different H_{Dist} due to the different edge conditions. In Figs. 1(e) and 1(f), α and ΔH_0 for the standard structure are also plotted with green triangles. One can see that both the magnitude of ΔH_0 and degree of change with D of the standard structure are smaller than those of the step one. The smaller change of ΔH_0 in the standard structure can be qualitatively explained by the previous studies that the effective magnetic anisotropy field is reduced near the device edge [14,19,45,56–58], leading to the smaller H_{Dist} . This difference in ΔH_0 between the standard and step structures is reproduced by micromagnetic simulations that consider edge effects, as described in the Appendix. As for α , the tendency and obtained values are virtually the same between the two structures, indicating an insignificant edge effect on α . In the small MTJ, the material parameters reflect properties at the vicinity of the device edge because such region becomes dominant in the MTJ with reduced dimension. We call this edge effect. This fact suggests that an increase in an effective α with the decrease in D reported previously [23] can be explained by the D dependence of ΔH_0 shown in Fig. 1(e).

The model described above indicates that the edge effect could reduce the inhomogeneity of H_K^{eff} by the suppression of the abrupt decrease in H_{demag} near the edge. Thus, we calculate the radial profile of H_K^{eff} with the edge effect. Based on the previous studies of edge damage in nanoscale MTJs investigated by FMR [14,19], coercivity [45], and magnetization reversal [56], we assume a 90% reduction of H_K^{eff} in the vicinity of the device edge with the width w . The radial profiles of H_K^{eff} with various w (0 nm, 2 nm, and 4 nm) are shown in Fig. 3(a) for $D = 33$ nm, and spatially averaged H_K^{eff} across the MTJ device, given by

$$H_{K,\text{Cal}}^{\text{eff}} = \frac{1}{\pi(D/2)^2} \int_0^{D/2} H_K^{\text{eff}}(r) 2\pi r dr, \quad (7)$$

is plotted with respect to w [squares in Fig. 3(b)]. The pink dashed line in Fig. 3(b) is obtained from a naive model used in previous study [14], where the spatial distribution

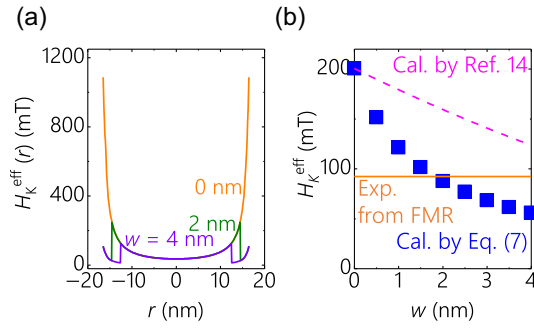


FIG. 3. (a) Radial profiles of effective magnetic anisotropy field with a 90% reduction in the vicinity of the device edge ($D = 33$ nm). (b) Edge-width dependence of effective magnetic anisotropy fields. Blue squares are calculated values in this study; pink dashed line and orange dash-dotted line are calculations assuming a uniform magnetic anisotropy field and experimental results from homodyne-detected FMR, respectively.

of H_{demag} as shown in Fig. 2(a) is not considered. Unlike the naive model, the elaborate model used here shows nonlinear dependence on w . The $\mu_0 H_K^{\text{eff}}$ ($= 92.2$ mT, experimentally determined from the relationship between H_r and f_{rf}) for the standard structure with $D = 33$ nm is also indicated by an orange horizontal line in Fig. 3(b). The averaged H_K^{eff} calculated by Eq. (7) crosses the experimental result at around $w = 2$ nm. Good agreement with our previous works [14,19,45,59] reinforces the validity of the developed model to describe various properties of nanoscale MTJs. Note that strain relaxation associated with different boundary conditions may affect the local magnetic anisotropy through magnetostriction and could potentially contribute to the observed inhomogeneity as well.

IV. CONCLUSION

In conclusion, we investigate α and ΔH_0 of the nanoscale MTJs with various D . The employed homodyne-detected FMR technique and MTJs with orthogonal magnetization configuration allow us to separate α and ΔH_0 . While α is almost constant with respect to D , ΔH_0 increases with the decrease in D . The trends hold true for two series of MTJs with different edge conditions, but the degree of the change in ΔH_0 with D differs between the two. The distribution of H_{demag} is one of the possible reasons for the enhancement of ΔH_0 . The model considering the distribution also describes well the experimentally determined H_K^{eff} with a reasonable edge effect.

The present results provide an additional perspective on the understanding of scaling in nanoscale MTJs. In discussions based on the macrospin model, the damping constant is considered to contribute to the switching characteristics of perpendicularly magnetized MTJs, while

deviations from the expected simple scaling behavior have been experimentally reported as the device diameter decreases [60–63]. In this study, we show that the damping constant exhibits little dependence on the device diameter D , whereas ΔH_0 arising from the inhomogeneity of magnetic anisotropy increases with decreasing D . These results suggest that it is important to distinguish between intrinsic damping and the inhomogeneity of magnetic anisotropy, implying that part of the phenomena previously interpreted as an increase in damping may in fact originate from inhomogeneity. This perspective is expected to be important for understanding switching reliability in STT-MRAM and may also provide useful guidelines for the design of devices influenced by inhomogeneity, such as those for probabilistic computing.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

APPENDIX: MICROMAGNETIC SIMULATION OF FERROMAGNETIC RESONANCE IN NANOSCALE MTJS

In order to examine the validity of the appearance of ΔH_0 in nanoscale MTJs, we perform micromagnetic simulations including the SAF reference layer. Figure 4(a) shows a typical simulation result, in which the FMR signal is clearly observed. We simulate magnetic-field-swept FMR spectra at various rf frequencies for $D = 30$ nm. A linear relationship between ΔH and H_r is obtained as shown in Fig. 4(b), and the damping constant α is determined to be 0.013, which is in good agreement with the input parameter of 0.012. This small difference may reflect additional dynamic effects, including dipolar coupling between the free and reference layers. Next, we set simulation conditions for several junction sizes D with and without edge effect. Here, the size of the reference layer is set equal to that of the free layer. The value of ΔH_0 is determined by extracting ΔH at $f_{\text{rf}} = 6.25$ GHz and extending the linear relationship between ΔH and H_r with

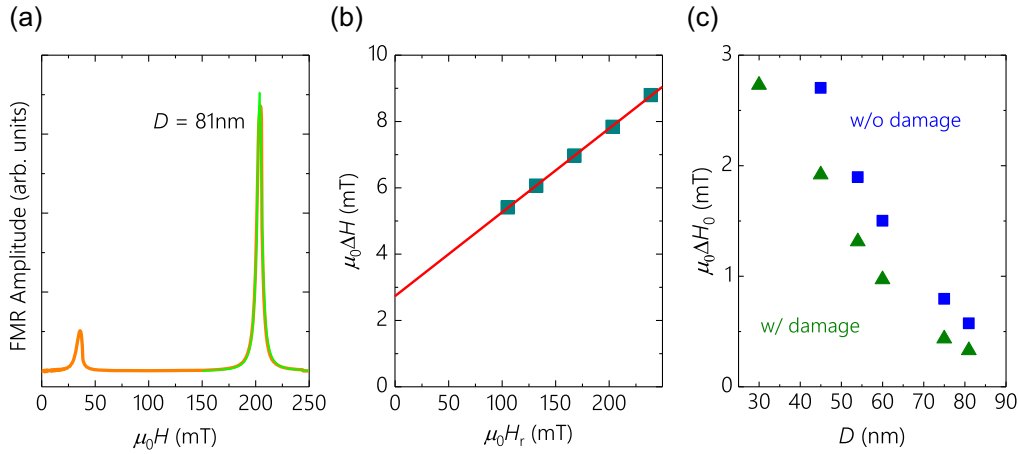


FIG. 4. (a) Micromagnetic simulation of FMR in an MTJ with $D = 81$ nm. The green line indicates the fitting result using a Lorentzian function. The left peak corresponds to the first excited spin-wave resonance. (b) Relationship between ΔH and H_r obtained from micromagnetic simulations for $D = 30$ nm. (c) Free-layer size D dependence of ΔH_0 obtained from micromagnetic simulations with and without edge effect.

$\alpha = 0.012$. Figure 4(c) shows that ΔH_0 increases with decreasing D and decreases when edge effect is introduced. These behaviors are consistent with the experimental results presented in this study.

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